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Economic Risks of Nuclear Power Reactor Accidents

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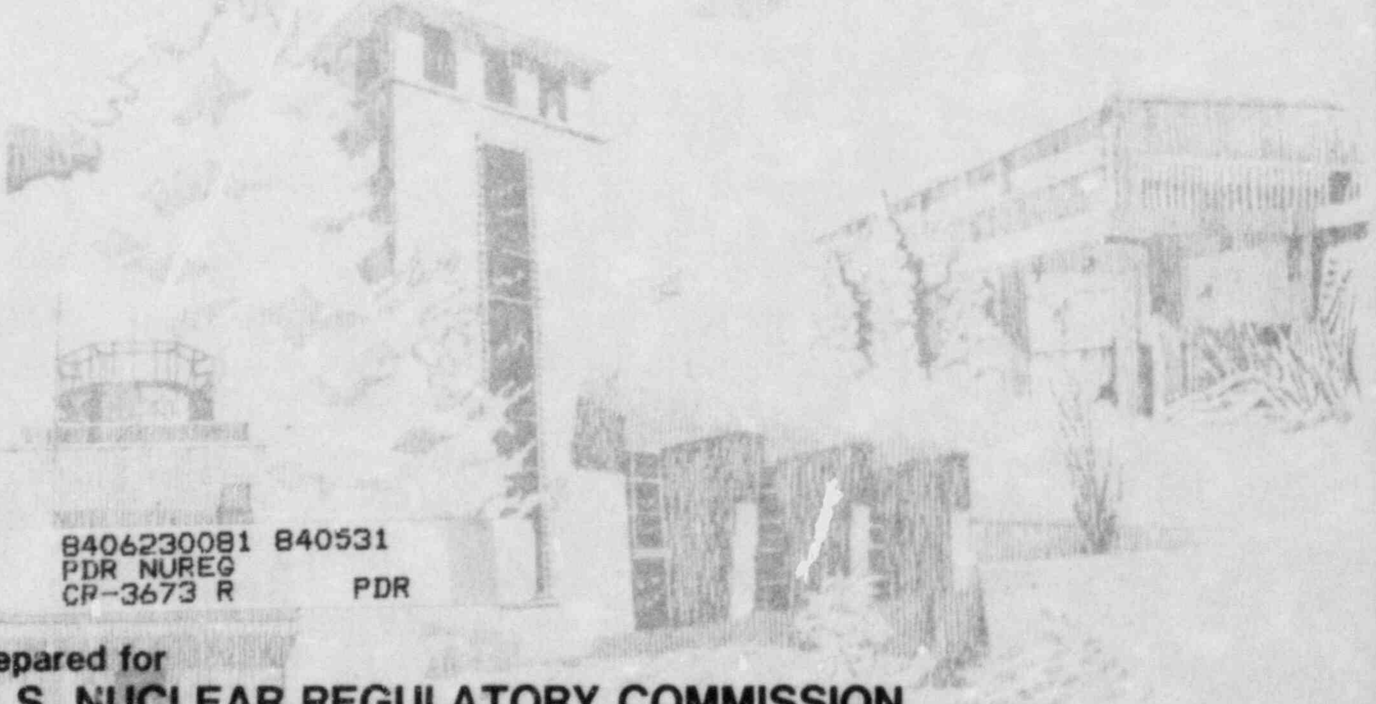

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ECONOMIC RISKS OF NUCLEAR
POWER REACTOR ACCIDENTS

ABSTRACT

Models to be used for analyses of economic risks from events which occur during U.S. LWR plant operation are developed in this study. The models include capabilities to estimate both onsite and offsite costs of LWR events ranging from routine plant forced outages to severe core-melt accidents resulting in large releases of radioactive material to the environment. The models have been developed for potential use by both the nuclear power industry and regulatory agencies in cost/benefit analyses for decision-making purposes.

The new onsite cost models estimate societal losses from power production cost increases, plant capital losses, plant decontamination costs, and plant repair costs which may be incurred after LWR operational events. Early decommissioning costs, plant worker health impact costs, electric utility business costs, nuclear power industry costs, and litigation costs are also addressed.

The newly developed offsite economic consequence models estimate the costs of post-accident population protective measures and public health impacts. The costs of population evacuation and temporary relocation, agricultural product disposal, land and property decontamination, and land interdiction are included in the economic models for population protective measures. Costs of health impacts and medical care costs are also included in the models.

The newly developed economic consequence models are applied in an example to estimate the economic risks from operation of the Surry #2 plant. The analyses indicate that economic risks from LWR operation, in contrast to public health risks, are dominated by relatively high-frequency forced outage events. The implications of this conclusion for U.S. nuclear power plant operation and regulation are discussed. The sensitivities and uncertainties in economic risk estimates are also addressed.

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EXECUTIVE SUMMARY

ECONOMIC RISKS OF NUCLEAR POWER REACTOR ACCIDENTS

This study develops and employs improved models to estimate the economic risks from unanticipated events which occur during U.S. LWR operation. The models have been used in example applications to estimate the economic risks from operation of the Surry #2 plant and to draw general conclusions concerning economic risks from LWR operations. The models can be employed by both the nuclear power industry and regulatory agencies in cost benefit analyses for decision-making regarding risk reduction measures.

The newly developed models estimate the onsite losses from power production cost increases, plant capital losses, plant decontamination costs, and plant repair costs which may be incurred after LWR events. Possible early decommissioning costs and plant worker health impact costs are included but do not contribute significantly to the expected onsite losses from forced outage events. The dominant cost for most LWR outage events is the power production cost increase caused by the need for using generating facilities with higher fuel-cycle costs. Replacement power costs, plant capital losses, and plant decontamination costs are important for severe LWR accidents resulting in core-damage or core-melt. Electric utility business costs, nuclear power industry costs, and litigation costs have also been addressed in the onsite economic consequence model development.

New models have been developed to estimate the offsite costs of post-accident population protective measures and public health impacts for severe LWR accidents which result in a release of radioactive material to the environment. The costs of population evacuation and temporary relocation, agricultural product disposal, land and property decontamination, land interdiction, and public health impacts and medical care costs are included in the new economic consequence models. The new offsite models offer several advantages over the economic models developed during WASH-1400, including increased flexibility and estimation of both costs and benefits of population protective measures.

A computer data base of LWR experience from 1974-1980 was developed to estimate the frequency-severity spectrum of unscheduled, unanticipated forced outage events at U.S. LWRs. Analysis of the data base indicates that unanticipated forced outage events occurred frequently (approximately 10 events per reactor-year) during the 1974-1980 study period. Forced outage events not caused by regulatory concerns resulted in an average 10% availability loss per reactor-year of U.S. LWR operation.

Forced outage events caused directly by regulatory concerns showed a consistently increasing trend, causing an average LWR availability loss of less than 1% in 1974, and increasing to approximately 6% in 1980.

The new onsite and offsite economic consequence models are employed in an example calculation to estimate the economic risks for the remaining lifetime of the Surry #2 plant. The analyses are based on frequency estimates for routine forced outage events (events resulting in no core-damage) from 1974-1980 historical data and on the median core-melt accident frequencies and source terms from the Reactor Safety Study. The present value of the expected costs of severe accidents for the remaining life of the Surry #2 plant is estimated to be less than 6 million dollars, which is small compared to the estimated present value of routine outage costs over the remaining plant lifetime (approximately 100-300 million dollars). The expected losses from routine forced outage events are large due to the high frequency (approximately 10 per reactor-year) and large power production cost increases for these events. Expected offsite losses are small relative to expected onsite losses at the Surry site, even for core-melt accidents.

The analyses of economic risks from LWR operation performed with the new models lead to the following conclusions:

1. Unlike public health risks, economic risks from LWR operation are dominated by high frequency, small consequence forced outage events. Most of the cost of these events results from reduced availability and capacity factors and the need for use of higher marginal cost fuel sources for generation of electricity.

2. The economic risks from LWR operation are dominated by onsite losses resulting from replacement power costs for short duration outages. Severe accident economic risks are also dominated by onsite losses including replacement power costs, plant capital losses, and plant decontamination costs. Only very low probability core-melt accidents with large releases of radioactive material result in offsite costs as large as onsite plant costs.

These conclusions have important implications for nuclear power industry operation and regulation in the U.S. Although reduction of core-melt accident frequencies and consequences is important for controlling public health risks, economic analyses indicate that limited societal resources might be productively used in controlling routine forced outage losses. Reduction of routine outage frequencies would also reduce the frequency of plant transients and would thus have some impact on core-melt accident frequencies and public health risks as well. The analyses indicate that focusing U.S. nuclear power regulation completely on severe accidents may be economically inefficient, and that the most productive expenditures for plant improvements might be made to increase the availability and capacity factors of operating LWR units by reducing forced outage frequencies and costs. Also, expenditures for core-melt accident prevention are likely to produce larger benefits than expenditures for systems which mitigate the offsite consequences of core-melt accidents since a large portion of the expected costs result from the loss of physical plant.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND SCOPE OF REPORT

The risk to society posed by potential accidents at commercial nuclear power reactors in the U.S. has been a focus of research for the past decade. Significant efforts have been made to estimate the potential public health impacts of severe LWR accidents. Another aspect of LWR accident risk involves the societal economic impacts or costs of an accident. Financial risk measures can be defined independently of accident public health risks, or cost measures can be defined to represent all of the negative attributes of the consequences of an event. This report develops and employs analytical methods to investigate the economic or financial risks posed by U.S. LWR accidents.*

Recent developments in the U.S. nuclear power regulatory process have created a need for analytical tools which provide estimates of the economic risks of reactor accidents. The U.S. Nuclear Regulatory Commission (NRC) has recently proposed safety goals for guidance in the regulatory decision-making process regarding LWR safety. The goals include criteria for public health risks imposed by plant operation, along with a cost/benefit criterion to be used in evaluating plant improvements for potential risk reduction [Nu80a, Nu82a]. The NRC should incorporate information regarding both costs and benefits (or costs avoided) into decisions regarding LWR accident risk reduction systems. It is necessary to understand the LWR economic risk spectrum to estimate the risk reduction potential of various plant safety system modifications and develop logical decision bases regarding the effectiveness of plant improvements. Also, it is important to identify the range of events for which licensee financial incentives for accident prevention exist so that regulation can be focused appropriately.

Another issue which has recently been under review by the NRC is the insurance requirements for U.S. nuclear power reactors. The requirements for licensee purchase of onsite property damage indemnity insurance have recently been upgraded by the NRC in light of the experience with severe accident costs at Three Mile Island Unit 2 [Lo82]. Requirements for offsite

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* The terms "economic risk" and "financial risk" are used synonymously in this study to refer to the frequencies and societal costs of LWR events. Costs include the benefits foregone and losses due to accident occurrence.

property damage liability, currently limited by the Price-Anderson Act, have also been under review recently. It is necessary to combine accident cost and frequency estimates to evaluate the spectrum of LWR economic risk to be considered in decisions regarding nuclear power reactor insurance requirements.

Analysis of LWR economic risks is useful for decision-making within the U.S. nuclear power industry. The accident at Three Mile Island Unit 2 dramatically demonstrated that plant licensees may incur very significant costs for events which have negligible offsite costs. After the accident at TMI, nuclear industry attention has focused on estimates of the financial risks borne by utilities which own shares of nuclear power plants [St81]. The nuclear insurance industry is also very concerned with the frequencies and costs of nuclear power reactor accidents for rate-making and risk coverage purposes.

The goal of this report is to develop LWR accident economic risk analysis methods and estimates for use in the regulatory decision-making process. Therefore, the estimates and methods developed focus on LWR accident costs from a societal viewpoint. There are many groups or organizations which may ultimately bear some of the costs of an LWR event. The transfer payments between parties which lead to the ultimate distribution of costs after an accident are addressed in less detail in this report. The potential transfers after accidents are complex because of the many groups with an interest in the nuclear power and electric utility industries. Societal costs are estimated in this report by accounting for losses which directly affect the plant licensee, the public, the nuclear industry, or the electric utility industry after LWR events. Clearly, a particular organization or group may be interested in specific costs and not interested in other costs based on liability for losses incurred. For specific interest groups it is important to carefully investigate the distributions of losses in addition to the societal cost estimates contained in this report. These issues are addressed in other economic studies, but are not included in detail in this investigation.

Societal accident costs are calculated in this report within a probabilistic risk framework. One of the most important and difficult aspects of this effort has been in estimating the uncertainties associated with the cost distributions presented. Estimation of accident costs must necessarily involve information regarding accident physical processes, radionuclide release and behavior in the environment, methods and costs for accident mitigation measures, costs for losses incurred, and future policy decisions which would be made after severe accident occurrence. Uncertainties exist in both event frequency and consequence estimates for LWR accidents. Both subjective and analytical analysis techniques are used to develop rough estimates of the uncertainties in the LWR economic risk values presented in this report. Clearly, further research is required to accurately estimate the uncertainties in LWR accident frequencies and consequences. As new information regarding LWR accident risks becomes available, updated uncertainty estimates should be incorporated.

1.2 LWR EVENTS AND ECONOMIC CONSEQUENCES

A wide range of possible events can occur during LWR operation which can have societal economic impacts ranging from benign to severe. Because of the range of economic consequences of LWR events, it is useful to discuss a spectrum of LWR economic risk. The spectrum can be represented by a distribution of event frequency versus cost (or event frequency versus severity). An example of the LWR risk spectrum which is discussed in this report is shown in Figure 1.1. This distribution is a complementary cumulative frequency distribution of LWR event costs which shows the frequency of events resulting in costs greater than a specified magnitude.

1.2.1 CATEGORIZATION OF LWR OPERATIONAL EVENTS

The events which comprise the LWR economic risk spectrum are divided for discussion in this study. Three event categories are defined based on the severity of LWR operational events which result in societal costs. This division of the economic risk spectrum and category definitions used in this report are shown in Figure 1.2. The discussion of LWR economic risk includes only those events which occur during the operational life of an LWR and not those events which might occur during plant construction or decommissioning.

Event category I is defined to include all forced outage events at LWR facilities which do not result in core-damage or significant plant contamination (small consequence events). These events, some of which occur routinely during the life of a nuclear power plant, are not scheduled or planned in advance (in contrast to refueling or scheduled maintenance outages). The events result in unplanned plant forced outage time (outage time refers to a time period of zero power production from the plant), and the maximum outage duration included in this category is on the order of a few years. The events in this category may result from spurious plant trips, operator errors, unscheduled maintenance requirements, external events, or a variety of plant system failures. There are no offsite radiation-induced public health impacts or property damage costs resulting from these events. Plant outages caused explicitly by regulatory

Figure 1.1 - Example of LWR economic risk distribution.

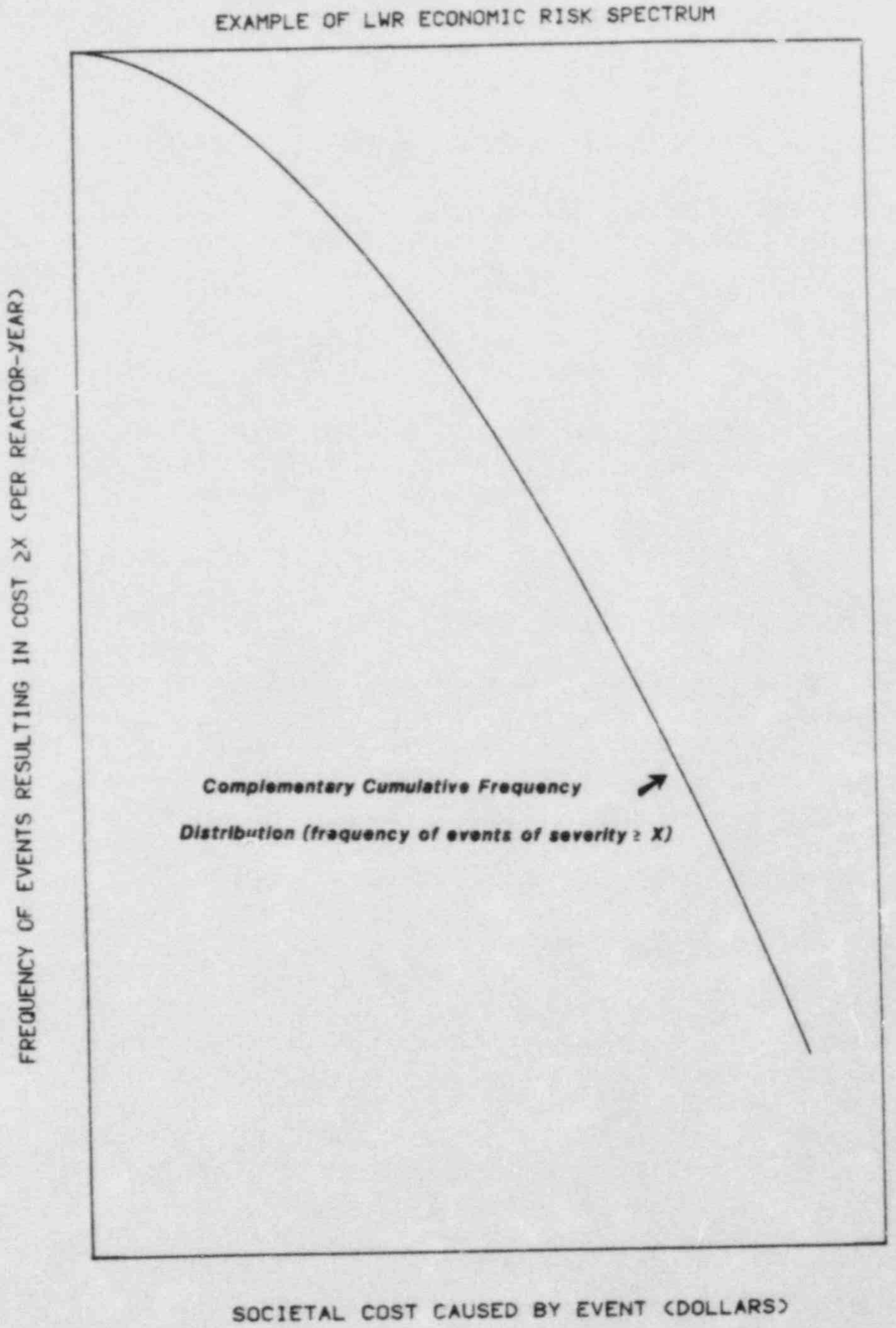
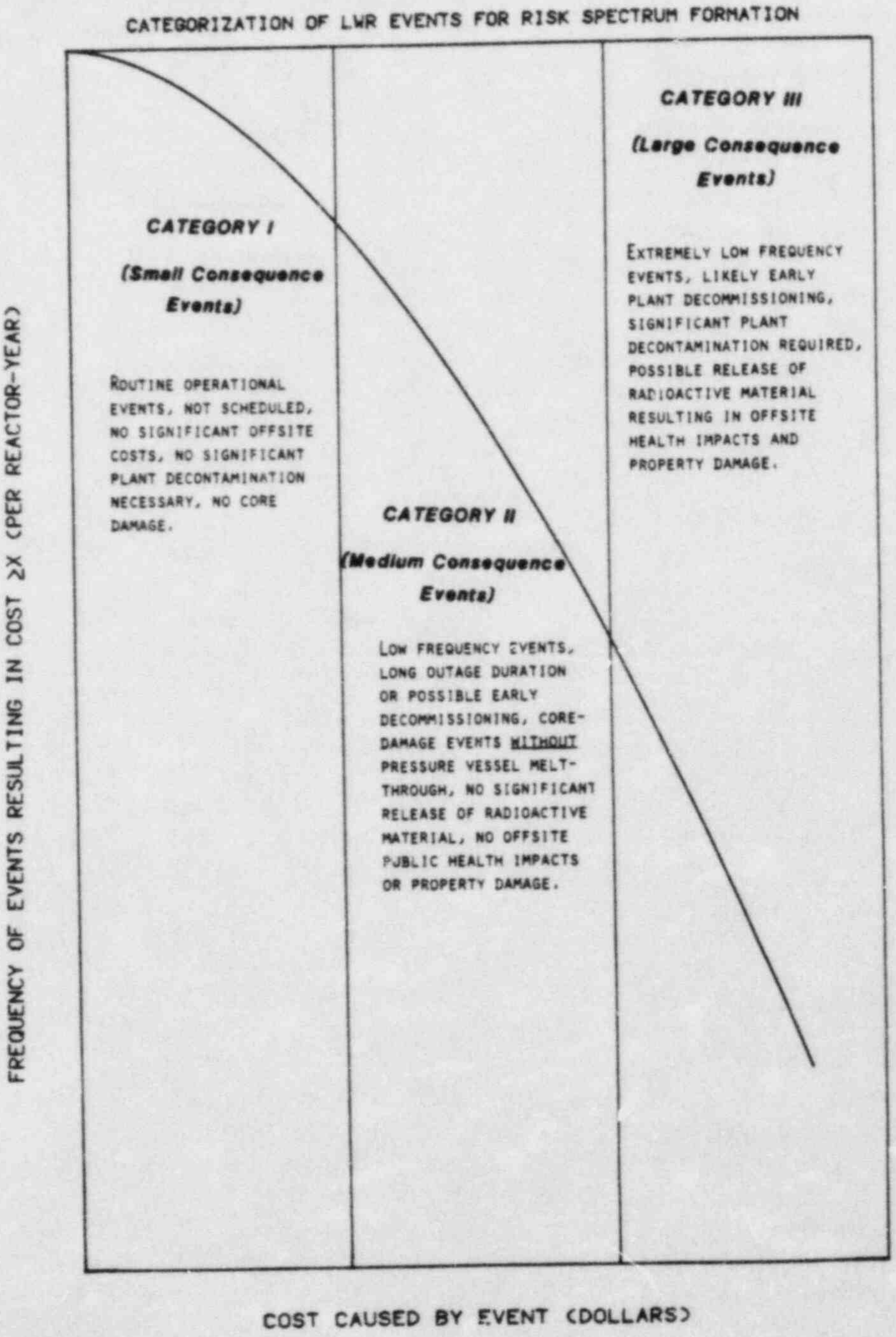


Figure 1.2 - Event severity categories defined for estimation of economic risks.



orders (i.e., plant shutdowns mandated by the NRC for regulatory reasons) are not included in this category but are discussed separately in Appendix B.

Event category II is defined to include LWR accidents resulting in core-damage and possible fuel melting but which do not result in breach of the reactor vessel or any significant release of radioactive material to the environment (medium consequence events). These accidents result in the need for a plant decontamination effort followed by either repair or decommissioning of the plant after cleanup. LWR events resulting in fuel damage or core-melt are included in this category only if the reactor vessel is not breached by molten material (i.e., vessel melt-through). There are no significant offsite health and property damage impacts resulting from category II events. Plant forced outages resulting from events in this category are likely to last many years if the plant is repaired, or may be permanent if decommissioning is begun immediately after plant cleanup.

Event category III is defined to include all LWR accidents which result in severe core-damage and either reactor vessel breach (i.e., vessel melt-through) or a significant release of radioactive material to the environment (large consequence events). This category includes severe core-melt accidents which have been predicted to dominate the public health risks from nuclear plant operation in the U.S. [Nu75a]. Severe accidents which do not result in releases of radioactive material to the environment but do result in reactor vessel melt-through are included in this category. The accidents in this category may result in offsite public health impacts and property damage costs. There is a need for a plant decontamination and cleanup program before plant repair or decommissioning. These events have not been experienced in U.S. commercial nuclear power plant operation to date and are predicted to be extremely rare.

1.2.2 DEFINITION OF "OFFSITE" AND "ONSITE" ECONOMIC CONSEQUENCES

The discussion of LWR accident economic consequences in this report is divided based on the location of occurrence of resulting losses and the organizations directly impacted by losses. Two groups of accident costs are discussed, one which encompasses mainly those costs which occur at offsite locations, and another which includes losses which directly affect the plant licensee, the nuclear power industry, the electric utility industry, or occur at onsite locations. This division of accident consequences is not strict in the sense that some costs may first affect the plant licensee, and ultimately be transferred to consumers at offsite locations.

"Offsite costs" include those costs which directly affect the public or occur at offsite locations. The offsite economic consequences of reactor accidents which are discussed in this report include costs associated with the countermeasures takento reduce population radiation exposure after a contaminating event, the offsite property damage or losses which occur as a result of an event, the costs of radiation-induced health effects and health care costs incurred by the population living at offsite locations, and indirect or secondary costs which may occur outside of contaminated areas at offsite locations. Specific offsite cost components include population evacuation and temporary relocation costs, agricultural product disposal costs, property decontamination costs, land area interdiction and permanent relocation costs, population health effects and health care costs, secondary economic effect costs, and offsite litigation costs. These costs are discussed in the development of LWR accident offsite economic risk models.

"Onsite" accident economic consequences include those cost components which most directly affect the plant licensee, electric utilities, the nuclear power industry, or occur at onsite locations. The onsite economic consequences of reactor accidents which are discussed in this report include replacement electric power costs, plant decontamination and repair costs, plant capital costs, early decommissioning costs, electric utility "business costs", nuclear industry impacts, plant worker health effect costs, and litigation costs which directly affect the plant licensees as a result of an accident. These cost components are discussed in the development of LWR accident onsite economic risk models.

Methods for estimating LWR accident economic consequences in this study were chosen in anticipation of three possible applications of the newly developed models:

1. Estimation of the absolute onsite and offsite economic risks posed by LWR operation in the U.S.,
2. Site-specific analysis of onsite and offsite economic risks for use in regulatory siting, cost/benefit, or risk reduction decisions,
3. Generic and site-specific analyses of offsite emergency response costs and consequence reduction benefits for use in decisions regarding emergency planning and post-accident population protective action implementation.

The projected model applications significantly influence the choice of economic consequence models and accident impacts which are examined in this study.

1.3 OUTLINE OF REPORT

Studies have been performed to estimate the economic risks resulting from events in specific portions of the LWR event spectrum. Chapter 2 of this report reviews results and conclusions from previous studies concerning the economic risks of LWR accidents. Previous and coincident studies of specific topics regarding LWR accident economic risk are discussed. Models previously developed to estimate the economic consequences of LWR events are also reviewed.

Onsite costs of LWR accidents are discussed in Chapter 3 of this report (see Table 1.1). Onsite cost component models and estimates are developed for all unanticipated LWR events. Available models are combined with historical data, insurance claim data, and engineering-based cost projections to form estimates of onsite accident costs. Impacts which are not easily quantified in economic terms are discussed, and uncertainties in event costs are also addressed.

The offsite economic consequences of severe LWR accidents are discussed in Chapter 4 of this report (see Table 1.1). A new offsite economic consequence model is developed for use in LWR economic risk calculations. The new offsite economic consequence model is compared to previous models, and data availability and limitations are discussed.

The economic risk of small consequence LWR events is discussed in Chapter 5 of this report. Historical U.S. nuclear plant operating experience from the years 1974-1980 is used to estimate the frequency of LWR events in this category. The data are used to estimate distributions of event frequencies and severities for U.S. LWRs. The frequency estimates are combined with onsite cost models to estimate the expected losses from small consequence LWR events. Potential risk reduction measures for small consequence LWR events are also discussed.

The economic risks of medium and large consequence LWR accidents are discussed in Chapter 6. The newly developed onsite and offsite economic impact models are applied to estimate societal risks from the operation of the Surry reactor plant which was studied in the RSS [Nu75a]. Model predictions are compared with the results of previous studies which employed the CRAC2 economic model to estimate economic risks. The sensitivities of predicted offsite costs to source term definition and post-accident protective action implementation criteria are examined. The new offsite cost models are used in an example cost/benefit analysis of offsite protective action implementation for severe accidents. The expected losses from core-melt accidents are compared with losses from less severe events to estimate the relative importance of low versus high frequency events. The large uncertainties in the probabilities of severe LWR accidents are also discussed.

Table 1.1 - LWR Event Costs Discussed in this Study

Chapter 3

Onsite Costs for Small, Medium, and Large Consequence Events

- Replacement Power Costs
- Plant Capital Costs
- Plant Decontamination/Cleanup Costs
- Plant Repair Costs
- Early Decommissioning Costs
- Onsite Litigation Costs
- Worker Health Effect Costs
- Worker Medical Care Costs
- Electric Utility "Business Costs"
- Nuclear Power Industry Costs

Chapter 4

Offsite Costs for Medium and Large Consequence Events

- Evacuation Costs
- Temporary Relocation Costs
- Agricultural Product Disposal Costs
- Decontamination Program Costs
- Land Area Interdiction Costs
- Permanent Relocation Costs
- Public Medical Care Costs
- Public Health Effect Costs
- Offsite Litigation Costs
- Secondary Impact Costs

Finally, conclusions and recommendations concerning the predicted accident economic risks and the use of models to estimate LWR accident economic risks are outlined in Chapter 7. Recommendations for further model development and applications of the newly developed models are also discussed.

CHAPTER 2

REVIEW OF STUDIES OF LWR ACCIDENT ECONOMIC RISKS

The results of previous studies of LWR accident economic risks are reviewed in this section. The discussion is divided into two sections which review studies which focus on "onsite" and "offsite" economic consequences of LWR accidents.

2.1 PREVIOUS STUDIES OF LWR ACCIDENT OFFSITE ECONOMIC RISKS

2.1.1 THE REACTOR SAFETY STUDY [NU75A, NU75B]

Estimates of the offsite economic risks of LWR accidents are contained in The Reactor Safety Study (RSS) [Nu75a, Nu75b] which was sponsored by the U. S. Nuclear Regulatory Commission (formerly the U. S. Atomic Energy Commission). The objective of the RSS was to estimate the public risks which result from the operation of commercial nuclear power plants in the U.S. The study formed realistic estimates of public risks from nuclear power plants and compared these risks with non-nuclear risks in society.

The property damage estimates in the RSS are based on cost estimates for public protective measures which may be taken after severe LWR accidents. No estimates of onsite damage or possible secondary* offsite costs from reactor accidents were included in the RSS. The economic risk estimates contained in the RSS are based on results calculated with the CRAC (Calculation of Reactor Accident Consequences) consequence model [Nu75b].

The offsite loss estimates presented in the RSS include the costs of population evacuation, milk and crop disposal, decontamination of contaminated areas, and interdiction (or the prohibition of the use) of land areas and tangible wealth and resultant population relocation from interdicted areas. The need for decontamination or interdiction of land areas was determined primarily by concentrations of surface-deposited long-lived isotopes (Cs-134, Cs-137) in the CRAC model. For a very large release of radioactive material, evacuation and milk and crop disposal costs each contributed approximately 10%, decontamination costs contributed about 20%, and land area interdiction costs contributed about 60% to the total offsite costs of a typical severe accident calculated with the CRAC model [Nu77a].

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* Secondary costs refer to potential accident offsite impacts outside of directly contaminated areas.

The offsite property damage risk profile estimated for a typical U.S. LWR in the RSS is shown in Figure 2.1. The damage estimates shown are in 1974 dollars. A comparison of property damage risk estimates for an industry of one hundred similar nuclear power plants and for man-caused and natural events in the U.S. is shown in Figure 2.2. The majority of man-caused property damage resulted from fires. Natural events causing significant property damage included forest fires, hurricanes, and earthquakes. Nuclear plants were estimated to be about one hundred to one thousand times less likely to cause comparable large dollar value accidents than other sources. All of the property damage estimates for LWR accidents contained in the RSS were based on the accident economic consequence model contained in the CRAC code which is discussed and compared to the newly developed economic consequence model in Chapters 4 and 6 of this report.

The property damage estimates included in the RSS provide important information concerning the off- site economic risks of LWR core-melt accidents. Core-melt accident atmospheric radioactivity releases with an estimated probability of $1X10^{-9}$ per reactor-year were predicted to result in ~$15 billion (1974 dollars) in offsite costs. Core-melt accident releases with probabilities larger than $1X10^{-6}$ per reactor year were predicted to result in less than $1 billion dollars in offsite costs.

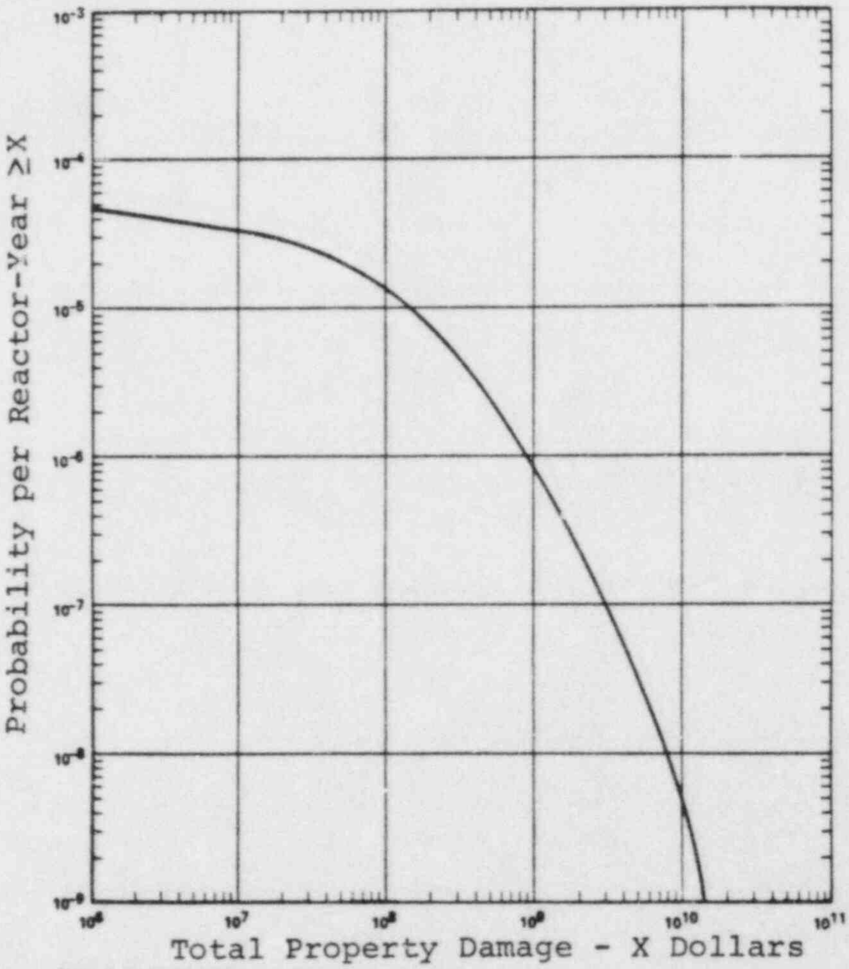
Studies have been performed since the RSS to provide improved estimates of the frequencies of core-melt accidents for specific LWR plants in the U.S. Because current nuclear plant risk analyses focus on potential public health effects of accidents, no substantial effort has been made to improve offsite cost estimates for severe LWR accidents. New models for estimating the offsite economic consequences of degraded-core and core-melt accidents at specific reactor sites are developed in Chapter 4 of this report.

2.1.2 ECONO MARC: A METHOD FOR ASSESSING THE COST OF EMERGENCY COUNTERMEASURES AFTER AN ACCIDENT[CL82]

A model has been developed for the purpose of assessing the costs of emergency countermeasures taken after an accidental release of radionuclides into the environment in the United Kingdom [Cl81,Cl82]. The model estimates the lost contribution to Gross Domestic Product (GDP) caused by population protective countermeasures implemented after an accidental release.

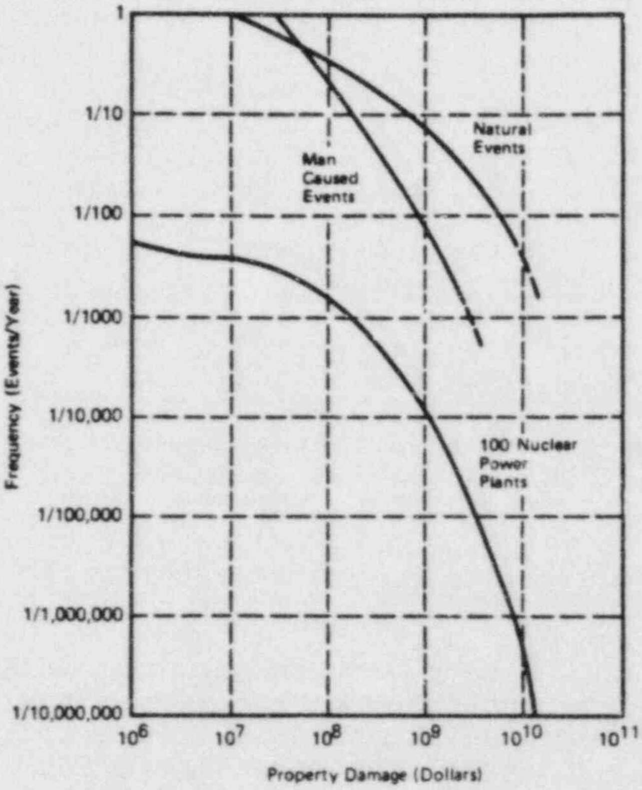
The basic assumption underlying the ECONO-MARC model is that the costs of countermeasures like land area interdiction will be a function of the area's contribution to Gross Domestic Product prior to the event. Gross Domestic Product is a

Figure 2.1 - RSS estimate of offsite economic risks from a typical U.S. nuclear power plant [Nu75b].



Note: Approximate uncertainties are estimated to be represented by factors of 1/5 and 2 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.

Figure 2.2 - RSS comparison of economic risks from 100 nuclear power plants and other sources [Nu75a].



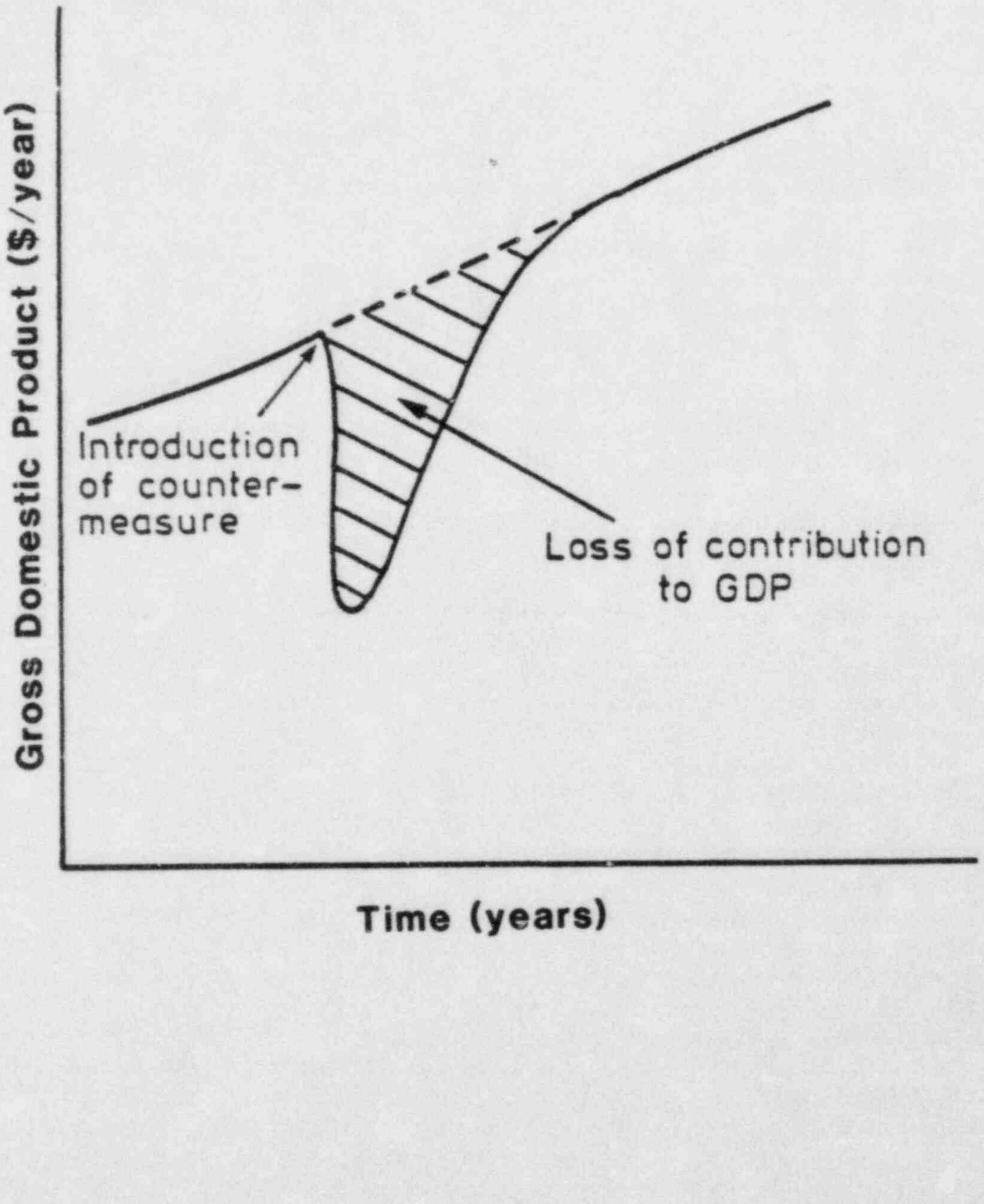
measure of economic output which is used in National Income and Product Accounts (NIPA) and reflects the level of activity in an economy [Sa79]. GDP is a broad macroeconomic measure which can be used to estimate the contribution of a specific region to national output. The ECONO-MARC model assesses the impact of countermeasure implementation on regional contribution to GDP.

The lost contributions to GDP due to population evacuation, agricultural product bans, and permanent population relocation which might result from a contaminating event were included in the ECONO-MARC model. Two approaches to the estimation of lost GDP were accommodated in the model; one based on detailed land usage and industrial output analysis, and another based on average GDP per-capita figures. The results of both methods of analysis using ECONO-MARC are very similar for a rural site. Results calculated using the two methods differ substantially for a semi-urban site. The difference in estimates is generally large for very small areas and gets smaller as the size of the area increases. The estimation of GDP losses based on per-capita information is advantageous because of its computational simplicity relative to the land usage approach which requires tedious manual sampling of data points from detailed land usage maps.

There are two significant problems in the estimation of accident impacts using the ECONO-MARC modeling approach. Because GDP measures the rate of output in an economy, it is necessary to integrate GDP losses over time to estimate the total costs of post-accident countermeasures. Projected GDP losses are likely to be temporary since the loss of production from a specific region may be substituted by increased output from a different region, or from new investment in the economy. This adjustment of the economy, demonstrated in Figure 2.3, is frequently observed after natural disasters and wars. The resilience of the U.S. economy to disasters has been demonstrated many times after earthquakes, hurricanes, and floods [ED74,Pe77]. After severe disasters, economies of impacted regions resume previous or even higher rates of growth in relatively short periods of time. Predictions of GDP loss due to accidents are sensitive to the time history of economic recovery assumed, which is difficult to specify without very detailed analysis. Another problem with the GDP approach is that the loss of regional tangible wealth (or assets accumulated prior to the accident) is not properly accounted for, particularly those assets which produce output which is not directly measured in market transactions. This is a very significant problem since results from the CRAC2 model predict tangible asset losses are very important.

The ECONO-MARC model provides a broad macroeconomic measure of the offsite impacts of reactor accident countermeasures for

Figure 2.3 - Temporary nature of GDP loss due to population protective measure implementation [C182].



Britain. Model predictions are not directly comparable to CRAC2 economic impact predictions which are based on microeconomic models and assumptions which may be specific to the U.S. Also, the CRAC2 model estimates the direct costs of countermeasures such as decontamination which are not considered in the ECONO-MARC model. Because of the limitations and accounting problems in estimating the GDP loss resulting from LWR accidents, this approach is not employed in this study.

2.1.3 ESTIMATING THE POTENTIAL IMPACTS OF A NUCLEAR REACTOR ACCIDENT [CA82]

A study has been performed to develop an industrial impact model that can be used to estimate the regional industry-specific economic impacts of severe nuclear reactor accidents [Ca82]. The impact estimates are based on reactor-specific information for core-melt accidents and regional economic models derived from the Regional Input-Output Modeling System (RIMS-II) developed at the Bureau of Economic Analysis (BEA) [Ca81]. The ultimate goal of the investigation was to develop models which could be used to evaluate the potential impacts of Class 9 (the most severe) reactor accidents for Environmental Impact Statements.

Estimates of reactor accident impacts were based on the results of interregional, interindustry analyses in the BEA studies. These analyses require large amounts of economic input data in the form of interindustry transaction tables for each specific region under consideration [Le66]. These transaction tables were defined in the BEA analyses based on county or SMSA* level data. The RIMS II economic model was used to predict changes in regional output resulting from changes in final demand or final payments caused by a reactor accident. The basic input-output methodology used and the results of BEA studies are analyzed in detail in Appendix C.

Results of the BEA analyses for the St. Lucie nuclear reactor site are shown in Table 2.1. This table shows predicted private sector employment losses due to emergency countermeasures taken after an SST1** accident at the St. Lucie site with a WNW wind direction. The "physically affected" area is defined to include all areas contaminated by the release of

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* Standard Metropolitian Statistical Area

**The SST1 accident category was defined for the Sandia Siting Study to represent a severe core-melt accident which results in a rapid, large release of radioactive material to the environment [Al82]. Accidents in this category result in release of approximately 100% of the reactor core inventory of noble gases and ~50% of the volatile radionuclides in a very short time period.

Table 2.1 - Results of BEA analysis of an SST1 release with WNW wind direction at the St. Lucie site [Ca82].

(Thousands of Annual Jobs)

Industry	Total employment		Direct losses in the physically affected area	Indirect losses in the physically unaffected area due to		
	U.S.	Study area		Decreased exports	Tourist avoidance	Supply constraints
Agriculture	3,417	119	35	0	0	
Mining	901	8	0	0	0	
Construction	5,387	208	4	2	0	
Nondurables manufacturing	8,377	147	2	1	0	30*
Durables manufacturing	12,519	197	4	0	0	
Transportation, communication, and utilities	5,159	164	3	0	0	
Wholesale trade	5,248	153	2	1	0	
Retail trade	16,198	582	14	0	4	
Finance, insurance, and real estate	5,190	202	4	0	0	
Services	20,630	742	12	0	3	
Total	**83,026**	**2,522**	**80**	**4**	**7**	

*Up to 30,000 annual jobs in the food and kindred products industry (a part of nondurables manufacturing) in the study area are vulnerable to the decreased availability of agricultural inputs.

radioactive material from the reactor plant. The physically unaffected area includes all other areas around the reactor plant. Table 2.1 shows that the SST1 accident with the WNW wind direction is predicted to result in ~80,000 annual job losses due to the reactor accident. The effects in the physically unaffected area are predicted to be relatively small compared to annual job losses in the physically affected area.

The BEA estimates of reactor accident industrial impacts were presented in terms of annual jobs lost. The impact estimates were intended to account only for the first year after core-melt accident occurrence. Also, many assumptions were required to adapt the LWR accident problem so that impact estimates could be be calculated using the RIMS-II models. In particular, the BEA impact estimates were based on areas defined at the county level. The definitions of areas impacted by post-accident countermeasures either include or exclude entire counties for estimation of economic impacts. Because this can lead to significant changes in the definition of areas affected by accidents, the BEA accident impact estimates cannot be directly compared to other accident cost estimates, particularly those from the CRAC or CRAC2 economic models. Also, the usefulness of input-output analysis techniques for modeling non-equilibrium post-accident situations is questionable. The input-output technique is far too costly and data-intensive for consideration in LWR risk analysis applications which require sampling of hundreds of meteorological conditions for each accident category.

2.2 STUDIES WHICH ESTIMATE ONSITE ECONOMIC RISKS

2.2.1 ESTIMATES OF THE FINANCIAL CONSEQUENCES OF NUCLEAR POWER REACTOR ACCIDENTS [ST82]

Preliminary estimates of the financial consequences of potential nuclear reactor accidents were developed as part of the current NRC program to develop methods for estimating reactor accident financial risks. The onsite and offsite financial consequences of LWR core-melt accidents were estimated based on results of calculations performed with the CRAC2 economic consequence model and estimates of onsite costs for worker health effects, replacement power, and accident cleanup costs. Dollar values were assigned to radiation induced health effects based on a review of societal expenditures for life-saving safety measures. Health effect values of $1,000,000 per early fatality, $100,000 per early injury, and $100,000 per latent cancer fatality were used in the analysis. Site-specific, life-cycle core-melt accident financial risk estimates were developed for reactor-site combinations in the U.S.

The study outlined discounting methods to calculate life-cycle core-melt accident economic risks. These methods were used to calculate risks from core-melt accidents based on the remaining years in the LWR plant life, which is assumed to be forty years from the plant start-up date. This type of analysis is valuable for estimating the expected cost avoided by installation of a specific accident prevention system in an operating LWR. Equations were presented for calculating the life-cycle risk at a particular LWR based on probability estimates for various classifications of LWR accidents. The assessment or tabulation of site-specific accident probabilities was not addressed in the report.

The mean total predicted risks from this study for the SST1, SST2, and SST3 core-melt accident release categories at the Surry plant are shown in Table 2.2*. Discounted economic risks for the remaining productive lifetime of the Surry plant are presented in the table. To calculate the discounted present value core-melt accident risks over the remaining plant lifetime, estimates of accident frequencies f_1, f_2, and f_3 (per reactor year) must be multiplied out in Table 2.2. These multiplications yield the total discounted risks in 1981 dollars. Onsite cost components were predicted to dominate all other cost components for the smaller releases, and to be comparable to other costs for the SST1 release. The onsite costs were large because it was assumed that the plant would be decommissioned after any core-melt accident. Replacement power costs were integrated over the remaining life of the reactor plant to estimate the loss of benefit to society provided by plant operation. Assuming a core-melt accident frequency of approximately 10^{-4} per reactor-year, the life-cycle core-melt financial risk at this plant is estimated to be on the order of 10^6 to 10^7 dollars. The estimated risks did not include costs for any accidents less severe than core-melt accidents.

The results of this study are useful for estimating the financial risks of core-melt accidents at specific sites given a core-melt accident severity versus probability spectrum. The onsite cost estimates were based on rough estimates of onsite

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* The SST1-SST3 accident source terms were defined in the Sandia Siting Study [A182] to represent the range of potential releases of radioactive material resulting from core-melt accidents with containment failure. The SST1 release category includes accidents which result in containment failure due to rapid overpressurization and release of a large fraction of the core inventory to the environment. The SST2 accident category includes core-melt accidents with slight containment leakage. The SST3 release category includes core-melt accidents followed by basement melt-through which result in small releases of radioactive material and minimal offsite consequences.

Table 2.2 - Mean Financial Risk Estimates for Core-Melt Accidents
at Surry Unit #2 [St82].

Total Lifetime Core-Melt Financial Risk Estimates for Surry Unit #2
(must multiply by f_1, f_2, and f_3 to obtain total accident category
discounted costs for remaining plant life in dollars)

RELEASE CATEGORY	OFFSITE HEATLH COSTS	OFFSITE PROPERTY COSTS	ONSITE COSTS	TOTAL COSTS
SST1	3.33E+09 × f_1	1.89E+10 × f_1	3.68E+10 × f_1	5.91E+10 × f_1
SST2	1.16E+08 × f_2	3.53E+08 × f_2	3.66E+10 × f_2	3.71E+10 × f_2
SST3	3.87E+05 × f_3	7.25E+07 × f_3	3.66E+10 × f_3	3.67E+10 × f_3

SST1-SST3 source terms are defined in [A182].

f_1= frequency of SST1 release (per reactor-year)
f_2= frequency of SST2 release (per reactor-year)
f_3= frequency of SST3 release (per reactor-year)

societal costs for core-melt accidents (large consequence events). The report incorporated the replacement power cost model which is discussed and utilized later in this study. Also, the use of present value discounting in calculating life-cycle risk discussed in the study is useful for the utilization of risk estimates in regulatory decision-making.

2.2.2 "COPING WITH NUCLEAR POWER RISKS: THE ELECTRIC UTILITY INCENTIVES" [ST81]

As a result of the accident at TMI-2 in March 1979, much interest has shifted to the potential onsite economic consequences of LWR accidents. A 1981 study by C. Starr and C. Whipple of EPRI [St81] estimated the financial risks from nuclear plant events by interpolating between frequency-severity data from routine outages and the results of the Reactor Safety Study. The study included rough estimates of both the onsite and offsite consequences of reactor accidents in estimating LWR financial risk. The results of the analysis are used to suggest that utility self-interest and the public interest in nuclear reactor accident prevention are coincident.

An estimated event frequency versus forced outage duration (or time to repair) curve was combined with a cost versus outage duration curve to form the frequency versus cost curve (shown as cost to the utility before insurance recovery) in Figure 2.4. Curves were also estimated for utility risks with insurance coverage. The curves for public risk shown in Figure 2.4 are taken from the Reactor Safety Study [Nu75a] and modified by multiplying public health effects by constant dollar values. The values assumed for health effects and the expected values of public risks are compared to the expected utility risks in Table 2.3. Based on the analysis, it was argued that utility financial risks dominate public risks.

The need for consideration of both onsite and offsite risks over a broad range of possible events was emphasized in the results of this study. Although the study was performed using scoping-type estimates of event frequencies and costs, the conclusion that utility risk dominates public risk was determined to be insensitive to uncertainties in parameters.

2.3 SUMMARY OF RESULTS OF PREVIOUS STUDIES

Previous studies have estimated the risks from the offsite economic consequences of severe LWR accidents. Three separate models have been developed to estimate the offsite economic impacts of severe accidents, each of which employs a fundamentally different economic methodology for estimation of accident costs. The three models, CRAC (or CRAC2), ECONO-MARC, and

Figure 2.4 - Estimated utility and public economic risks for reactor outages and accidents [St81].

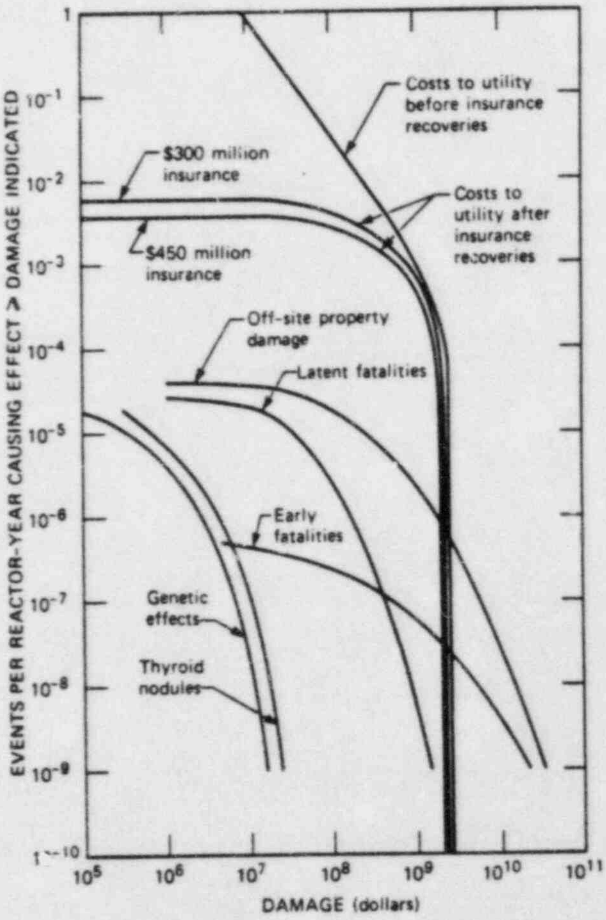

Table 2.3 - Expected values of public and utility risks from LWR outages and accidents [St81].

PUBLIC RISKS-EXPECTED VALUE PER REACTOR-YEAR

Effect	*Expectation**	*Value ($)*	*Expected Cost ($)*
Early fatalities	3×10^{-5}	5×10^{6}	150
Early illness	2×10^{-3}	10^{4}	20
Latent fatalities	7×10^{-4}	10^{6}	700
Thyroid nodules	7×10^{-3}	3×10^{3}	20
Genetic effects	1×10^{-4}	10^{5}	10
Property damage	$20,000	Twice WASH-1400	40,000

*Source: *WASH-1400*, Table 5-6.

UTILITY RISKS-EXPECTED VALUE PER REACTOR-YEAR

	Dollars
With $450 million insurance	2.1×10^{6}
With $300 million insurance	2.9×10^{6}
No insurance (includes accidents causing 10 days outage or longer)	24×10^{6}

RIMS-II, estimate different attributes of the impacts of severe LWR accidents, and therefore their results cannot be directly compared. The results of previous studies of offsite economic consequences and risks indicate a potential for significant offsite economic impacts for very low probability accident sequences.

In light of the accident at TMI-2, interest has focused in large part on the potential onsite losses resulting from LWR accidents. Recent studies performed at EPRI and Sandia National Laboratories have attempted to include onsite costs in examinations of LWR economic risks. Both studies concluded that onsite accident costs are likely to dominate offsite accident costs except in the case of very low probability core-melt accidents accompanied by large atmospheric radionuclide releases. This conclusion is supported by the TMI-2 accident experience, where offsite costs (of evacuation only) were very small compared to the costs of onsite property damage and replacement power. To maintain proper perspective it is important to examine both onsite and offsite costs of LWR accidents, particularly in performing cost-benefit or risk-reduction calculations.

CHAPTER 3

ONSITE ECONOMIC CONSEQUENCES OF LWR EVENTS

LWR event economic consequences which most directly affect the plant licensee or occur at onsite locations are discussed in this section. Models used in estimating the onsite economic consequences of LWR events are developed. Onsite cost components are estimated for each category of LWR operational events.

3.1 ONSITE COST COMPONENTS DISCUSSED

The onsite economic consequences which are important in estimating the societal benefits foregone or costs caused by an LWR outage or accident depend on the severity of the event which causes the loss. The cost components discussed in this section include power production cost increases, reactor plant capital investments lost, plant decontamination costs, plant repair costs, costs due to early decommissioning, worker health effect and health care costs, electric utility "business costs," nuclear power industry costs, and onsite litigation costs which may result from an LWR event. These costs either directly affect LWR plant licensees, electric utilities, the nuclear power industry, or occur at onsite locations and are therefore considered to be onsite costs. Each onsite cost component is discussed in detail. The discount rate used in the analysis of post-accident cash flows is also discussed.

3.2 DISCOUNT RATE USED IN ESTIMATING SOCIETAL COSTS

Present-value discounting is a method of representing the time-value of money in financial analyses. Discounting is used to convert all cash flows which occur at different points in time to a common time basis. Standard textbooks on economics or finance review the basis and formulas used in present value-discounting [Br81,Sa79,Ar76].

The discount rate used in financial analyses is normally chosen to represent the "opportunity cost of capital" based on the level of risk associated with a particular investment strategy [Br81]. This rate is estimated by adding a risk premium for a given investment to the risk-free discount rate. The rate of return which can be earned on investments with zero risk is defined to be the risk-free rate (normally taken to be the available real rate of return on short-term U.S. Treasury bills). Risk premiums are estimated based on the risk associated with specific investments. Higher levels of risk imply higher risk premiums. The risk free rate plus the risk premium for an investment corresponds to the rate of return which can be earned by investing the same amount of capital in a different project with equal risk.

Discount rates are commonly estimated from interest rates charged in capital markets. Market interest rates include allowances for general inflation in the economy. A real interest rate can be estimated from the nominal (or observed) market rate using:

$$r = \frac{(1 + r_a)}{(1 + i)} - 1 \tag{3.1}$$

where

r_a = the apparent interest rate observed in the economy,

i = the inflation rate in the economy

r = the real interest rate.

It is appropriate to use real discount rates in performing analyses of future cash flows to avoid projecting future inflation rates, and because real cash flows and discount rates show less variation than nominal flows and rates.

A societal discount rate is chosen in this study to represent the value judgement of society for consumption of capital today versus consumption at some point in the future. The rate can also be interpreted as the opportunity cost of capital to society for low-risk investments. To estimate the societal discount rate, the prime rate, which is the interest rate charged by large U.S. money centers to their best business borrowers, is corrected for inflation to arrive at a real discount rate. This real discount rate has averaged approximately 4% per year in recent years. This estimate of the societal discount rate is used in performing all present value analyses in this study.

The appropriate discount rate for present-value analyses must be chosen based on the characteristics of the case under consideration. The rate used in this study may not be appropriate for analysts in the electric utility industry performing financial risk analyses for nuclear power plant accidents. In general, the opportunity cost of capital to industry is higher than the societal discount rate [CR82]. Also, the Office of Management and Budget of the U.S. Government recommends the use of a 10% discount rate for government decision-making. Therefore, the sensitivity of projected costs to discount rate is studied using 0% (i.e., no discounting) and 10% rates along with the recommended 4% societal discount rate.

3.3 REPLACEMENT POWER COSTS

One of the most important cost components over much of the spectrum of LWR events is the incremental cost of replacement power, or the production cost increase for supplying power to the associated electric utility system during a nuclear plant outage. The net societal costs resulting from the need to replace power which had been produced by a previously operating reactor can be very substantial. The net cost is incurred because power produced by operating nuclear plants is cheaper than that available from sources used for replacement power.

The methods available for compensating for the generating capacity lost due to a nuclear reactor forced outage depend on the duration and timing of the forced outage event [Bu82]. For shorter duration outages it is possible that a utility would not have to purchase replacement power but through short-term generation increases and load management methods could meet the needs of its service area. This has been identified in a recent study of the loss of benefits from nuclear plant outages [Bu82]. Typical utility emergency operating procedures for short-term outages (~1 month to 1 year) are shown in Table 3.1. The fourth item in Table 3.1 is the purchase of emergency power from other utilities.

For longer-term nuclear plant outages or permanent plant shutdowns, there exists an alternate set of options to offset the need for generating capacity lost due to the plant outage. These options include long-term purchase agreements with neighboring utilities, load management and conservation programs, deferment of planned power plant retirements, acceleration of existing construction schedules, addition of new capacity to the utility construction schedule, additional interconnections in the power grid, and the imposition of restructured electricity usage rates.

All of the available options for compensating for nuclear plant forced outage time have associated societal costs. This cost is incurred because nuclear power plants in operation have very low operating and fuel-cycle costs relative to fossil-fueled units. Because large operating nuclear generating units produce low marginal cost power, they are normally employed in base-load generation of electricity and higher marginal cost non-nuclear generating units are used to handle variations in power requirements on a daily or seasonal basis. The loss of power generation from a nuclear generating unit normally results in the need to employ higher cost generating units, and a net cost results from the use of a more expensive energy source. Therefore, because of the low marginal power production costs of operating nuclear units, and their use in meeting base load requirements, any forced outage is likely to result in some net power production cost increase.

Table 3.1 - Typical utility operating procedures for short duration outages [Bu82].

Utility Action[a]	Typical Effect
Bypass plant pollution control equipment	Increase available generating capacity by a small amount
Switch from economic dispatch to critical fuel conservation dispatch	Prolong time before more serious emergency actions are necessary
Purchase excess industrial generation	Add generating capacity
Purchase emergency power from other utilities	Often make substantial power available, but at high cost
Reduce standby reserves	Increase generating capacity by 50-100% of the capacity of a large unit
Direct load control (customer load management)	Reduce load
Reduce voltage by 5%	Reduce load by 3%
Appeal to industry	Reduce load by 1-2%
Appeal to public	Reduce load by 1-2%
Interrupt interruptible service	Reduce load
Run generating units at extreme outputs	Increase generating capacity by 1-3%
Reduce spinning reserve to zero	Increase generating capacity by the capacity of a large unit
Reduce voltage 8% (an additional 3%)	Reduce load by 1%
Shed load (rotating blackouts)	Reduce load by amount necessary to balance with supply

[a] Actions are listed in the approximate order in which they would be implemented.

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The methods available for compensating for the generating capacity lost due to a nuclear reactor forced outage depend on the duration and timing of the forced outage event [Bu82]. For shorter duration outages it is possible that a utility would not have to purchase replacement power but through short-term generation increases and load management methods could meet the needs of its service area. This has been identified in a recent study of the loss of benefits from nuclear plant outages [Bu82]. Typical utility emergency operating procedures for short-term outages (~1 month to 1 year) are shown in Table 3.1. The fourth item in Table 3.1 is the purchase of emergency power from other utilities.

For longer-term nuclear plant outages or permanent plant shutdowns, there exists an alternate set of options to offset the need for generating capacity lost due to the plant outage. These options include long-term purchase agreements with neighboring utilities, load management and conservation programs, deferment of planned power plant retirements, acceleration of existing construction schedules, addition of new capacity to the utility construction schedule, additional interconnections in the power grid, and the imposition of restructured electricity usage rates.

All of the available options for compensating for nuclear plant forced outage time have associated societal costs. This cost is incurred because nuclear power plants in operation have very low operating and fuel-cycle costs relative to fossil-fueled units. Because large operating nuclear generating units produce low marginal cost power, they are normally employed in base-load generation of electricity and higher marginal cost non-nuclear generating units are used to handle variations in power requirements on a daily or seasonal basis. The loss of power generation from a nuclear generating unit normally results in the need to employ higher cost generating units, and a net cost results from the use of a more expensive energy source. Therefore, because of the low marginal power production costs of operating nuclear units, and their use in meeting base load requirements, any forced outage is likely to result in some net power production cost increase.

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Reduce voltage 8% (an additional 3%)	Reduce load by 1%
Shed load (rotating blackouts)	Reduce load by amount necessary to balance with supply

[a] Actions are listed in the approximate order in which they would be implemented.

Because of the variation in methods and fuels used for generating replacement power in different parts of the U.S., the costs of replacement power for nuclear plant outages will vary depending on plant location. In estimating the losses from a nuclear plant forced outage event, the plant location and likely mix of units to be used for generation of replacement power must be accounted for. Also, the availability of interconnections and power transfer must be considered along with the availability of excess capacity to be used for replacement power generation.

In this study it is assumed that excess capacity exists for generation of replacement power for a given reactor plant or site forced outage. This assumption is justified given the current state of power productive capacity in the U.S. [Bu82]. However, if in some specific case replacement power for a nuclear unit outage was not available, then the societal costs of decreased power system reliability and supply shortages must be considered. This is discussed in the study of the loss of benefits from nuclear plant outages [Bu82].

There are other potential costs resulting from the production of replacement power for nuclear plant outages which are not estimated in this report. Increased mining, shipment, and burning of replacement fuels may result in impacts on human health and safety. Also, the increased use of fossil fuels could result in environmental effects such as acid rain or CO_2 global climate effects. These potential losses are treated as externalities and are not included in the estimation of replacement power costs from nuclear plant outages in this study.

3.3.1 SIMPLIFIED MODEL FOR NUCLEAR PLANT OUTAGE POWER PRODUCTION COST INCREASES

A simplified method for estimating the societal costs resulting from nuclear power plant outages has been developed in a previous study [Bu82]. A detailed loss of benefits analysis requires data-intensive models that simulate the characteristics of a particular utility affected by a plant outage. These detailed models include regional load growth, expansion plans, mix of generating units, and emergency options which might be available for a particular utility. The simplified method for estimating reactor outage costs is intended to provide rough estimates of the production cost increases for a specific plant outage.

The simplified model relates first year power production cost increases to the fraction of replacement power from oil-fired power plants and non-economy* power purchases. The simple model

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* Non-economy power purchases refer to power generated by higher marginal cost fuel sources (e.g., gas turbines).

relationship between oil-fired and non-economy replacement power fraction and the power production cost increase due to a full year of reactor outage time is shown in Figure 3.1. Also shown is the range of results from detailed loss of benefits case studies from which the simple model is derived. The data from the analyses are not sufficient to develop a detailed relationship, but the data do provide an estimate of the importance of the fraction of replacement power from non-economy sources in determining production cost increases. Beyond the first year of forced outage duration, the yearly power production cost increase can be modified for real cost escalation to estimate the total power production cost increase for long-duration plant outages.

In order to use the relationship in Figure 3.1, it is necessary to estimate the fraction of non-economy purchases for a specific plant outage. For the purpose of this study the average fraction of replacement power from non-economy purchases within each of the National Electric Reliability Council (NERC) regions is employed. The NERC regions in the U.S. are shown in Figure 3.2, along with the average fraction of non-economy replacement power purchases for each region in Table 3.2 [Bu82]. The average fraction of non-economy purchases varies widely across the NERC regions.

Given an estimate of the fraction of oil-fired and non-economy replacement power purchases for an outage, the present discounted value of the production cost increase for a given forced outage can be calculated by integrating over the outage duration:

$$D_p = \frac{MC}{65} \int_{t_1}^{t_2} F(t) e^{-rt} dt \tag{3.2}$$

where

D_p = present discounted value of production cost increases over the outage period (1982 \$),

$F(t)$ = unit production cost increases of outage versus time (\$/MWe-year),

M = electrical generation rating of reactor involved in outage (MWe),

C = assumed capacity factor of plant had outage not occurred (%),

r = real discount rate (per year),

t_1, t_2 = start, end time of reactor plant outage.

Figure 3.1 - Relationship between power production cost increase and non-economy power fraction [Bu82].

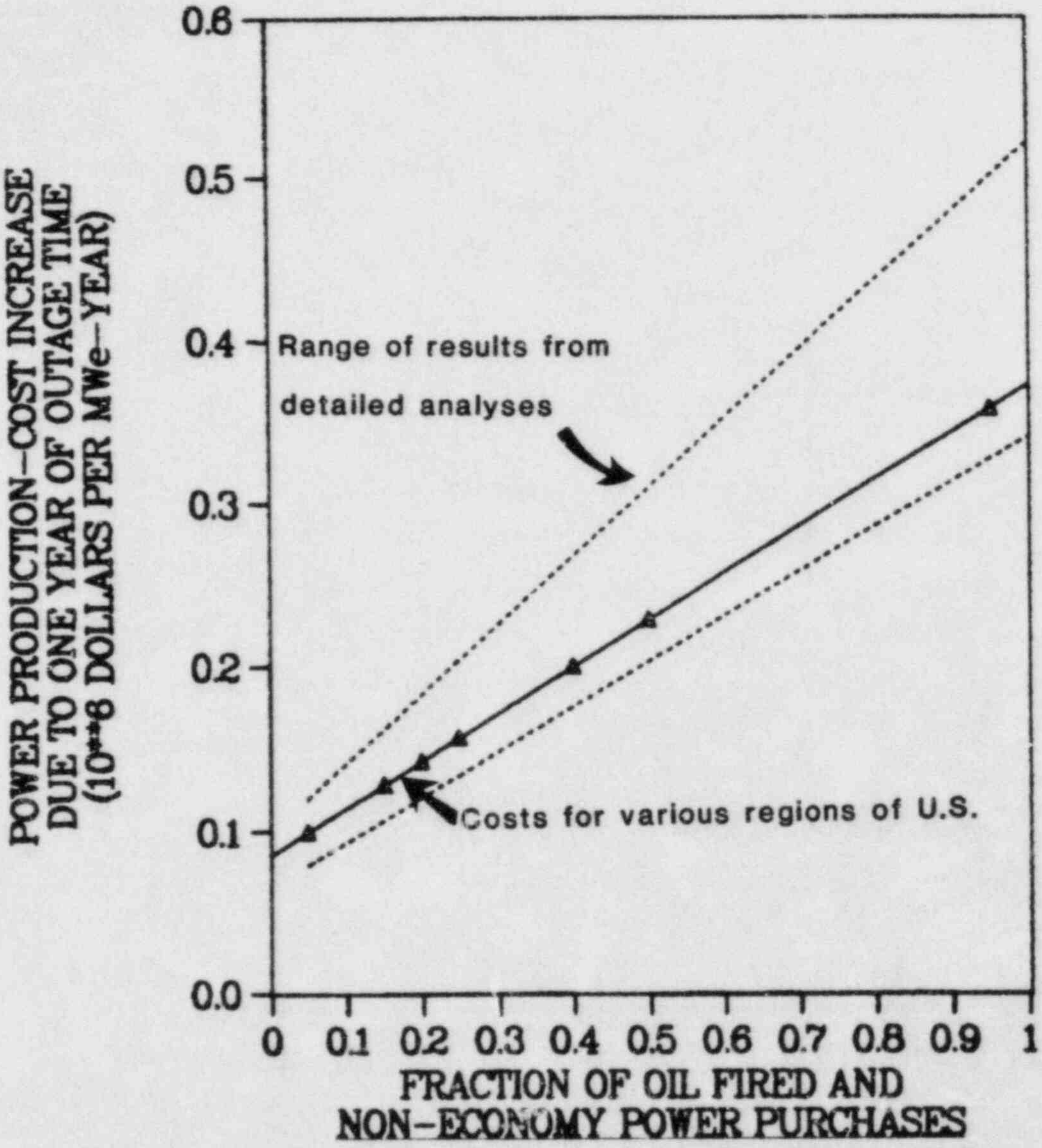


Figure 3.2 - Regional Electric Reliability Councils of the National Electric Reliability Council [Na81].

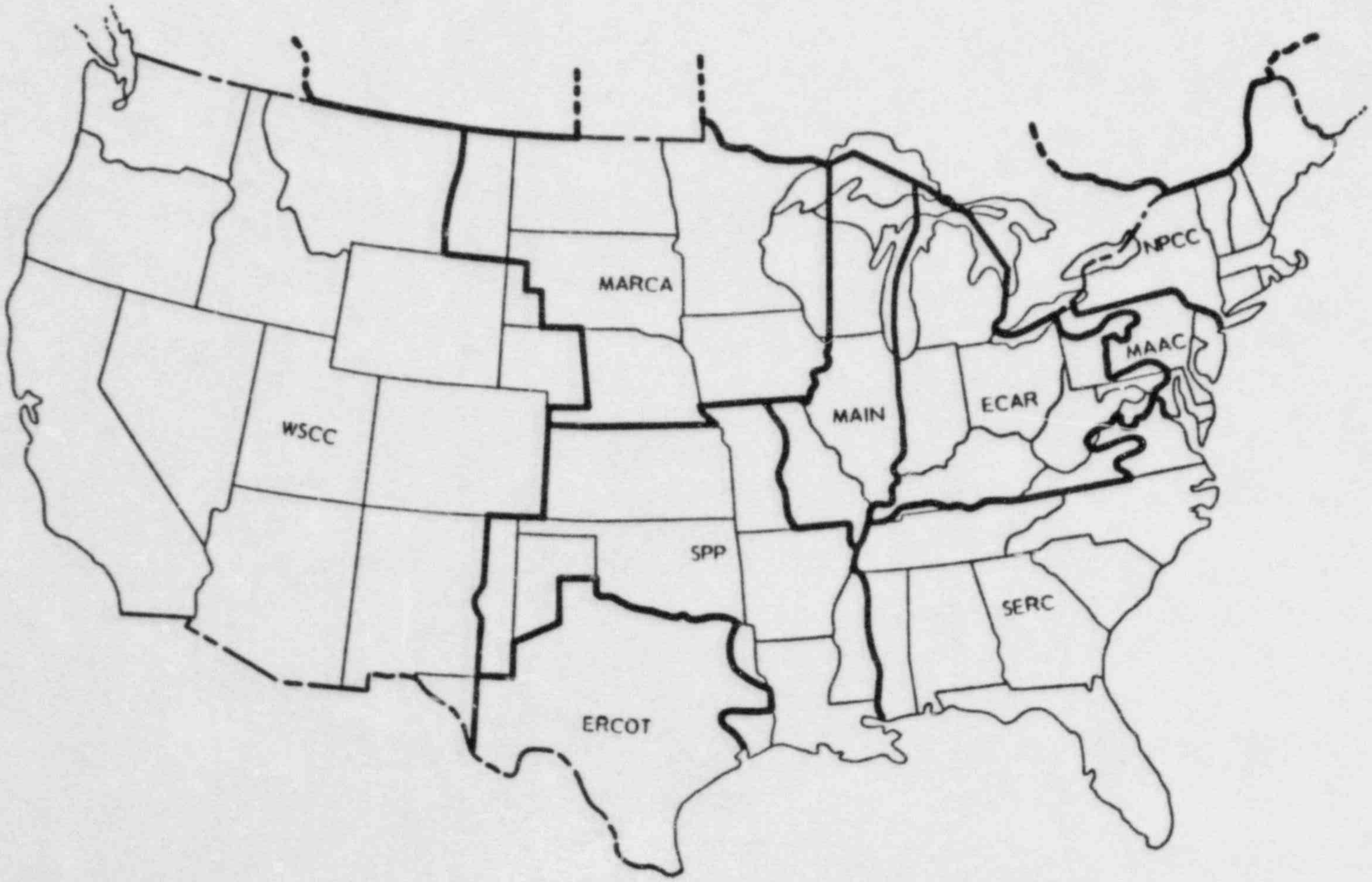


Table 3.2
Average Fraction of Oil-Fired and Non-Economy Replacement Energy by NERC Region** [Bu82]

National Electric Reliability Council Region	Percent of Replacement Energy from Oil-Fired Power Plants and Non-Economy Power Purchases
MARCA	20*
NPCC	95*
MAAC	50
MAIN	15*
ERCOT	50
SPP	40
WSCC(California)	95
WSCC(non-California)	25
SERC	15*
ECAR	5

* Based on ANL loss-of-benefit studies [Bu82]. Data from other regions derived from [NA81,DE81].

** Over a ten year outage period, the replacement fuel for a known outage would change as utilities make firm arrangements for power transfers. The regions having the highest dependence on high-priced fuels would be the most likely to change over time. In general, replacement capacity would not be available in less than 10 years.

The simple model was derived in the loss of benefits study on the assumption that the plant would have operated at an average capacity factor of 65% had the outage not occurred.

The real power production cost increase as a function of time can be specified. Two cases of importance include the assumption of zero growth in real power production costs ($F(t)$ = constant in equation 3.2), and a constant real escalation rate of power production cost. For the latter case the production cost model becomes:

$$D_p = \frac{MC}{65} \int_{t_1}^{t_2} F_o e^{-(r-g)t} dt \qquad (3.3)$$

or,

$$D_p = \frac{MCF_o}{65} \left[\frac{e^{-(r-g)t_1} - e^{-(r-g)t_2}}{(r-g)} \right] \qquad (3.4)$$

where

F_o = power production cost increase at time zero (\$/MWe-year),

g = real escalation rate of replacement power costs (per year).

This is the form of the model which is used in this study, with F_o estimated from the average fraction of replacement power supplied from non-economy purchases (Table 3.2).

It is important to recognize the limitations and assumptions which underlie the simple model for estimating power production cost increases due to reactor outages:

1. The model is intended to provide estimates of the power production cost increases for long-duration outages at nuclear power plants.

2. The model does not account for utility-specific characteristics such as fuel mix, excess capacity, load curves, and alternative options which could be employed during plant outages.

3. The correlation between replacement energy from non-economy purchases and the production cost increase due to the first year of outage time is based only on a range of values observed in detailed case studies.

4. The average (non utility-specific) fraction of non-economy replacement power purchases for an NERC region is used in this study.

5. The cost estimates are based on studies performed at a time when fossil fuel prices were high relative to nuclear generation costs. Drastic changes in world oil prices or other fossil fuel prices relative to nuclear generation costs could change the basis for the model.

6. External replacement power costs such as environmental effects are not included in the model.

The simple replacement power cost model is used for outages of less than 10 years duration in this study. The model is also used to estimate the costs of short duration outage events (<1 year). This is an extension of the intended use of the model since it was developed for use in modeling production cost increases for long duration outages. The model does not account for daily or seasonal effects which might have important impacts on the costs of short outages, or alternative measures to alleviate the need for replacement power purchases [Bu82]. Therefore, the simple model could significantly overestimate the costs for very short duration outages. However, the model is appropriate based on other uncertainties in the event cost analysis performed in this study. For plant outages lasting more than 10 years or permanent plant shutdowns, the power production cost increase for the first 10 years is combined with the capital cost model discussed in the following section. The replacement power cost model is also used to estimate power purchase costs for multiple unit plant shutdowns at a single site.

3.4 REACTOR PLANT CAPITAL INVESTMENT LOSS AFTER SEVERE ACCIDENTS

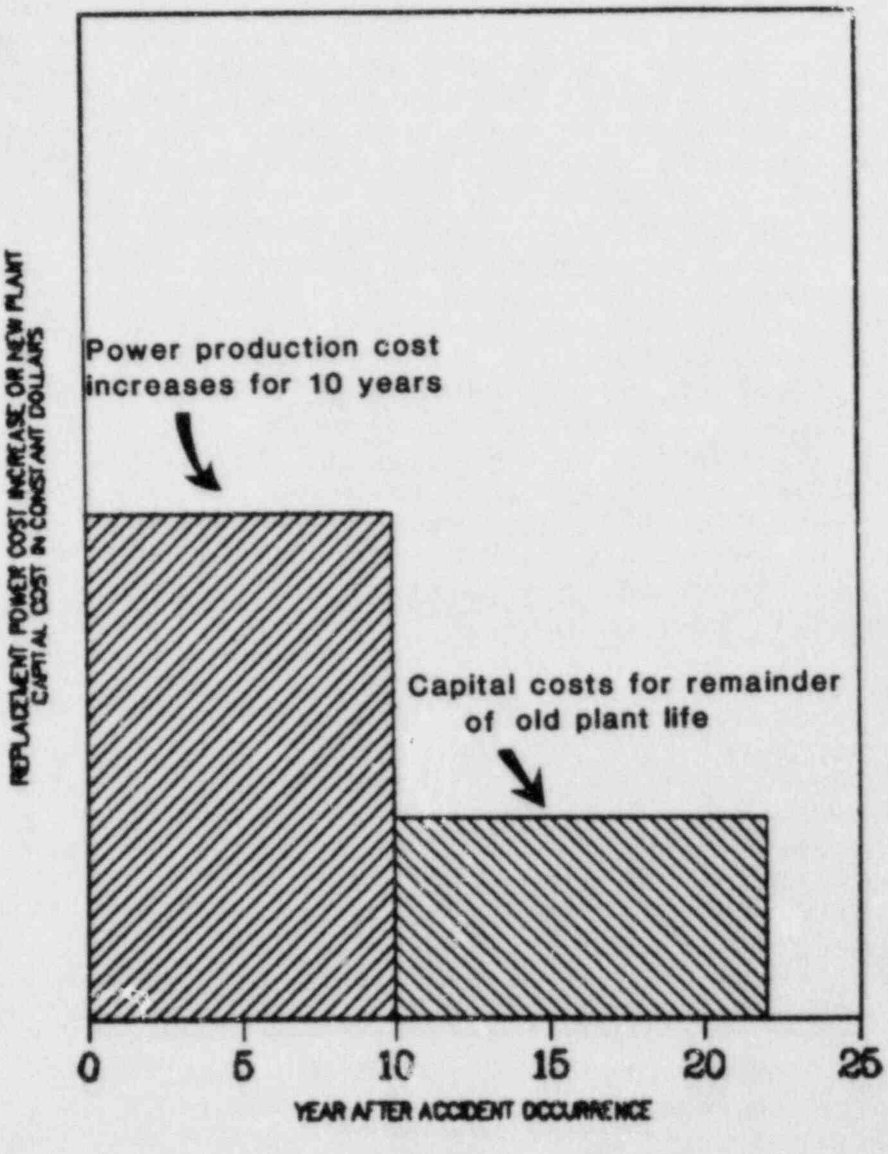
For some LWR events, plant damage may be so severe that the reactor would be permanently shut down sooner than originally planned, thus shortening the productive lifetime of the reactor plant. In these cases, the entire capital investment in the plant may not have been recovered, so some part of the capital cost of the plant represents investment lost. The normal method for accounting for this loss would be to calculate the depreciated value of the reactor plant at the time of the event. The remaining book value of the plant is a loss after an event which results in early permanent shutdown.

For example, if a nuclear plant is 18 years old when an event causing permanent plant shutdown occurs, and the anticipated plant service lifetime is 40 years, 22 years of societal benefits from plant operation are lost due to the event. To account for this physical plant loss using traditional methods, the initial capital investment in the plant would be depreciated over 18 years using a specified depreciation schedule (e.g., straight line, sum-of-the-years digits, double declining balance). This depreciated value should represent the remaining value of the initial capital investment. Unfortunately, standard accounting depreciation and plant lifetime schedules are accelerated and shortened to allow for earlier capital depreciation tax deductions. Therefore, the depreciated capital value estimated using this method may be zero. Also, the possibility of investment appreciation is not accounted for in estimates of book value using depreciation schedules. Therefore, the standard accounting book value does not truly represent the potential future societal benefits of plant operation which are lost due to the accident.

The net societal cost of permanent plant shutdown is estimated in this study by including replacement power cost increases and capital costs necessary to replace the lost productive capacity of the plant. Power production cost increases are integrated for a period of 10 years in which new productive capacity could be built to replace the shutdown plant. After the new replacement plant is constructed and brought on line, the capital costs of the new plant are integrated for the remaining lifetime of the original plant at which the accident occurred. In the example, the annualized capital costs of the new plant are integrated for 12 years after completion of the new plant. This cost is added to the 10-year integrated cost of replacement power purchases necessary while the new plant was under construction and non-productive (Figure 3.3). Thus, the net societal cost of the plant shutdown includes 10 years of replacement power purchases, and 12 years of new plant capital amortization. Costs beyond the projected productive lifetime of the damaged plant are assumed to be similar to those incurred had the accident not taken place. Therefore, the time horizon of concern with this approach is limited to the remaining productive lifetime of the original plant. It is assumed that a nuclear plant would be built to replace the damaged plant for ease of cost estimation.

The present value of the capital costs of a new 1000 MWe nuclear power plant at the time of plant startup is assumed in

Figure 3.3 - Replacement power cost increases and new replacement plant capital costs in example problem.



this study to be ~3 billion 1982 dollars . This cost estimate is used to estimate an annualized capital charge over the 40-year plant life using standard present value discounting. It is assumed that plant capital costs are linearly dependent on plant electrical output rating in the analysis. No capital costs are included for accidents which result in replacement power purchase periods of less than 10 years. Capital costs are only estimated for severe reactor accidents (category II and III events) which might result in early permanent plant shutdown.

The present discounted cost calculated using the above method includes the value of the physical plant loss and power production cost increases assuming that excess capacity exists which can be used for replacement electric power generation during new plant construction. The cost reflects the use of a non-optimal fuel for electric power generation for the 10 year period in which new capacity is not available to replace the damaged plant. However, if for some reason sufficient excess capacity does not exist for replacement of the lost generation capacity, then the above method must be modified to account for the costs of potential electric power supply shortages (i.e., brownouts, blackouts) which are not included in the simple replacement power cost model.

3.5 PLANT DECONTAMINATION COSTS

After a serious accident at an LWR facility (medium or large consequence event) it may be necessary to decontaminate areas within the power plant which have become contaminated with radioactive material released from the reactor core. Cost estimates for the decontamination of areas within the reactor plant after serious accidents are reviewed in this section. These costs are negligible for routine forced outage events.

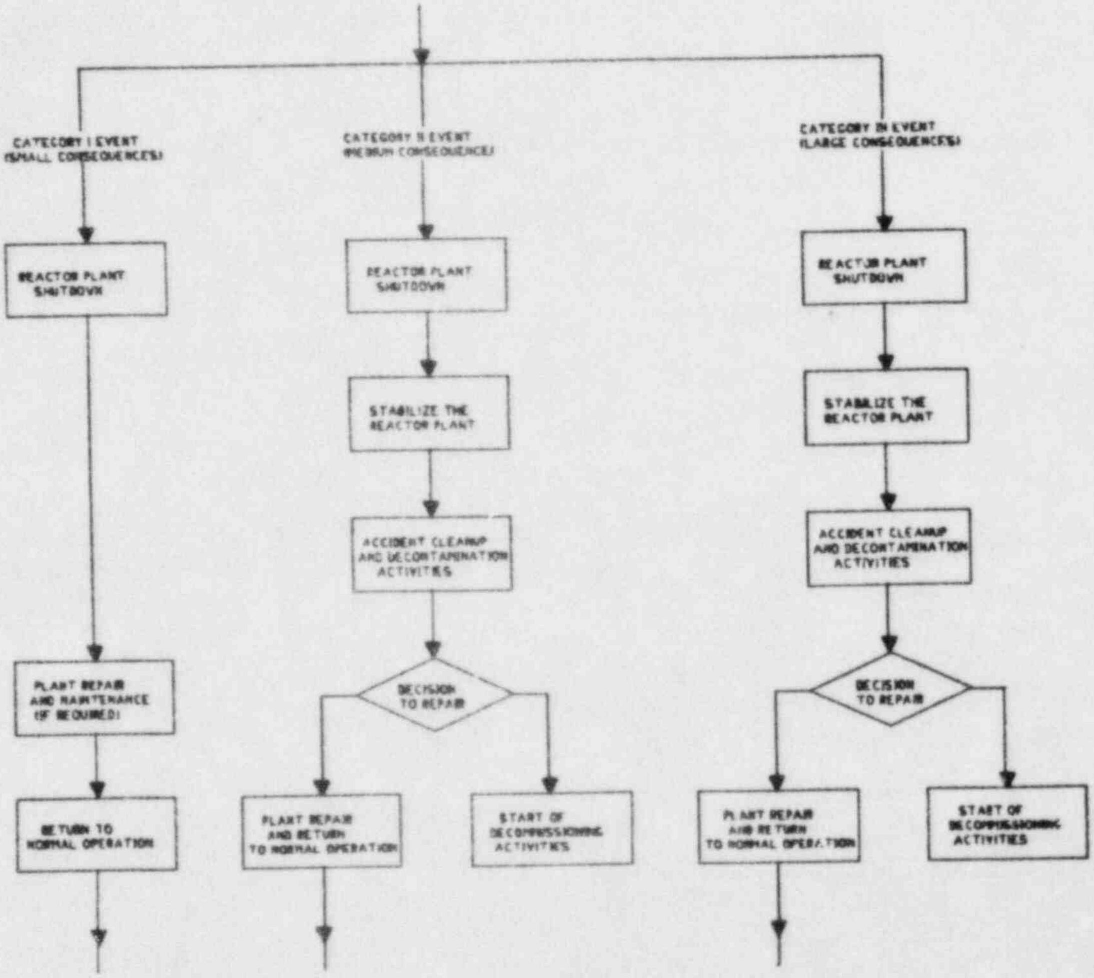
3.5.1 PLANT DECONTAMINATION COSTS FOR CATEGORY II EVENTS (MEDIUM CONSEQUENCES)

A flowchart for post-accident actions following LWR events of different severities is presented in Figure 3.4. After any severe LWR accident the facility must be brought to a stable condition. The stabilization of plant systems would result in small incremental costs relative to the costs of cleanup and repair or decommissioning. The costs of post-accident plant decontamination are discussed in this section.

3.5.1.1 TMI-2 Accident Experience

The experience gained to date with the cleanup of the accident at Three Mile Island Unit 2 provides a source of

Figure 3.4 - Flowchart of post-accident actions for LWR event categories.



information regarding medium consequence reactor accident cleanup/decontamination costs. The accident on March 28, 1979, resulted in significant fuel cladding failure and perhaps some fuel melting in the reactor core region. The auxiliary and containment buildings for Unit 2 were contaminated with radioactive material released from the reactor core during the accident.

Several time and cost estimates for the TMI-2 recovery program have been developed as the cleanup process continues. Because the process is a learning experience, cost estimates and program plans must be continually updated to reflect new information. The cost estimates presented in this section are based on Revision 1 of the TMI-2 Recovery Program Estimate dated July, 1981 [GP81]. Updated recovery program plans and cost estimates have been prepared but the cost estimates are not significantly different from the 1981 estimates.

The estimates of the cleanup costs for the TMI-2 unit contain allowances for delays resulting from problems in financing plant cleanup and regulatory concerns. Revision 1 of the recovery program plan includes a longer time for plant cleanup due to the lack of available funding for the recovery program. The extended cleanup program plan incorporates higher cost estimates for base plant operations and maintenance which must be performed throughout the entire cleanup process regardless of the total program duration. There are distinct cost advantages to completion of the cleanup program in the shortest possible time period.

The cash flow diagram for the estimated costs of the TMI-2 decontamination and cleanup program is shown in Figure 3.5. The cash flows represent total undiscounted costs in 1980 dollars for each year measured from the time of accident occurrence*. The estimates include costs for disposal of radioactive waste, except for the reactor core which is to be stored in the Spent Fuel Storage Pool. The estimates do not include allowances for reconstruction or decommissioning of the reactor after cleanup. The costs for man-rem incurred during the cleanup process are also not included in the total cost estimates. However, the projected cleanup effort is predicted to result in ~30,000 man-rem to workers, which is a small contribution to the total estimated cleanup cost.

The net present value of the TMI-2 decontamination and cleanup costs per Revision 1 of the program plan is estimated

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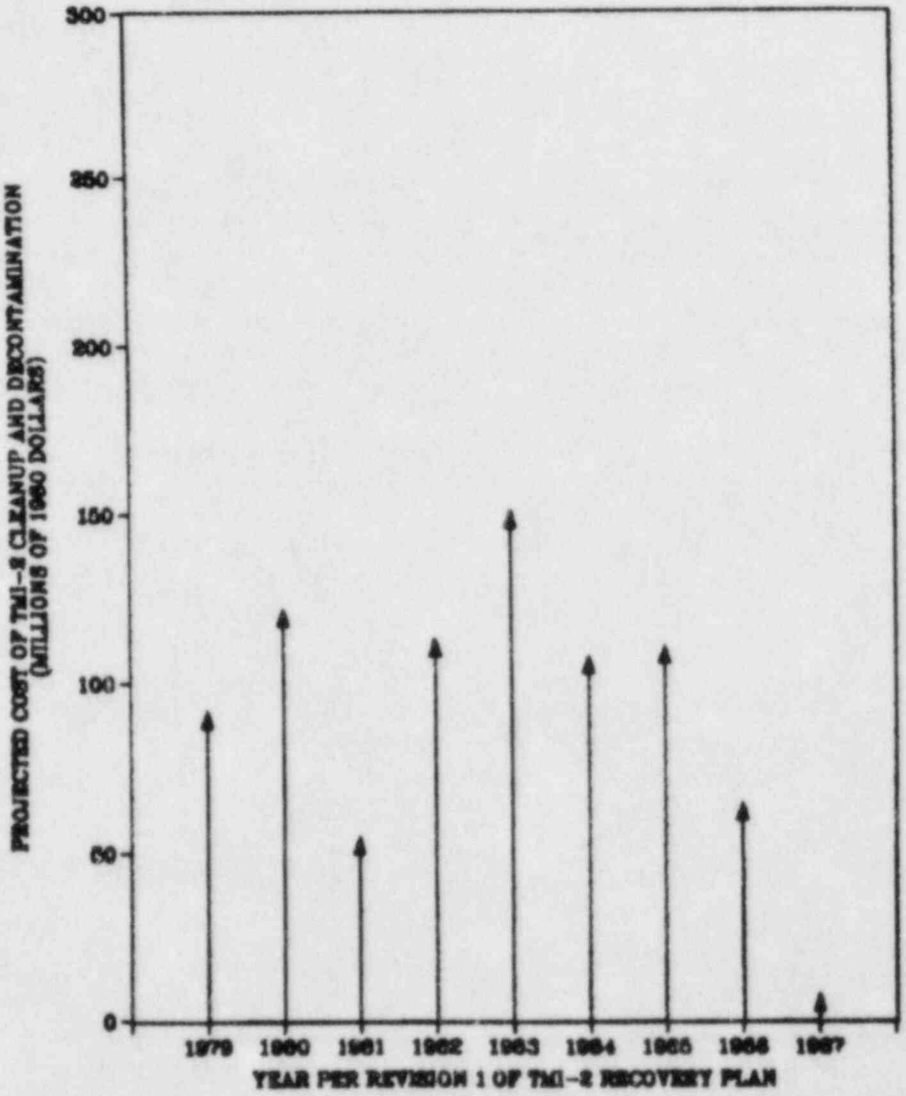
* Cost estimates for the 1979-1980 period are combined in Revision 1 of the TMI-2 Recovery Program Plan. The total cost for 1979-1980 has been scaled by the actual duration of the recovery program in 1979 and 1980 to estimate expenditures in these years.

Figure 3.5 - Projected expenditures on TMI-2 decontamination program versus time [GP81].



using discrete escalation and discounting:

$$D_C = \sum_{n=0}^{m} C_n \left[\frac{(1+g)}{(1+r)}\right]^n \qquad (3.5)$$

where

D_C = the net present value of decontamination costs at the time of accident occurrence,

n = the year measured from the year of accident occurrence,

m = the year of the completion of the cleanup program,

C_n = unescalated, undiscounted program cost estimate for year n after accident occurrence,

g = real escalation rate for program costs (assumed constant and uniform for all costs),

r = real discount rate for program costs.

General Public Utilities (GPU) estimates of total program costs are computed using then-current dollars (i.e., not in constant dollars). The GPU estimates of the costs include cost escalation on Bechtel work of 9% per year, and cost escalation on GPU work of 8% per year. This leads to the GPU estimate of total undiscounted decontamination program costs of approximately $\$1.0 \times 10^9$ dollars.

The cost projections used in this study are based on constant dollars. The net discounted cost of the decontamination and cleanup program for the TMI-2 accident versus the real discount rate is shown in Figure 3.6. The discounted cost is sensitive to the discount rate chosen because the program is planned to cover an 8 year time period.

The constant-dollar discounted and escalated cost of the TMI-2 decontamination and cleanup program is shown versus the parameter (1+g)/(1+r) in Figure 3.7. If the discount rate chosen is equivalent to the escalation rate chosen, the discounted cost is the same as the total unescalated, undiscounted constant-dollar cost estimate. For a 4% real discount rate, and a 0% real escalation rate (i.e., no real growth in costs), the net present cost of the program as planned is ~750 million 1980 dollars (~850 million 1982 dollars).

Finally, the sensitivity of the total cleanup cost estimate

Figure 3.6 - Total projected cost of TMI-2 decontamination program versus discount rate.

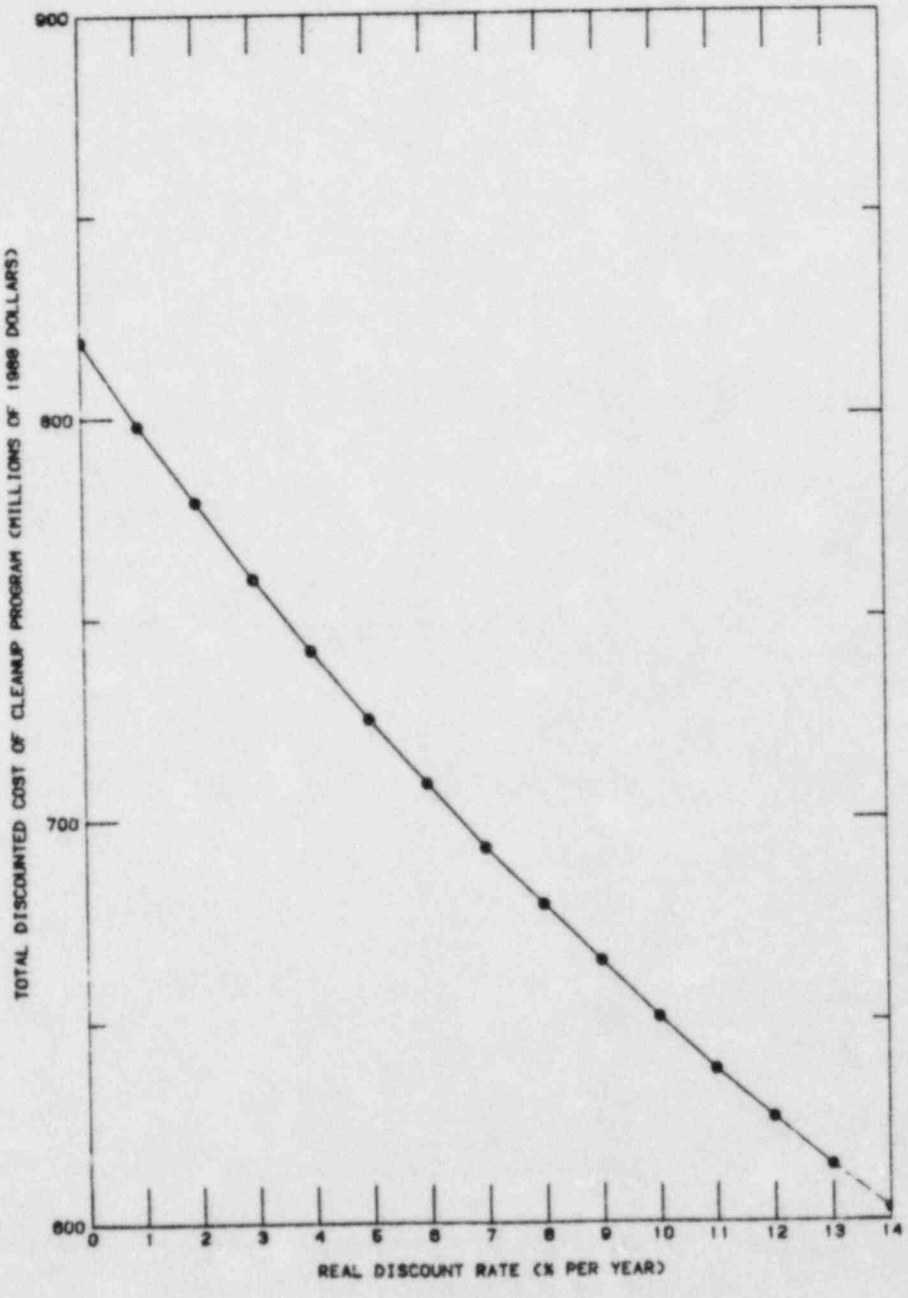
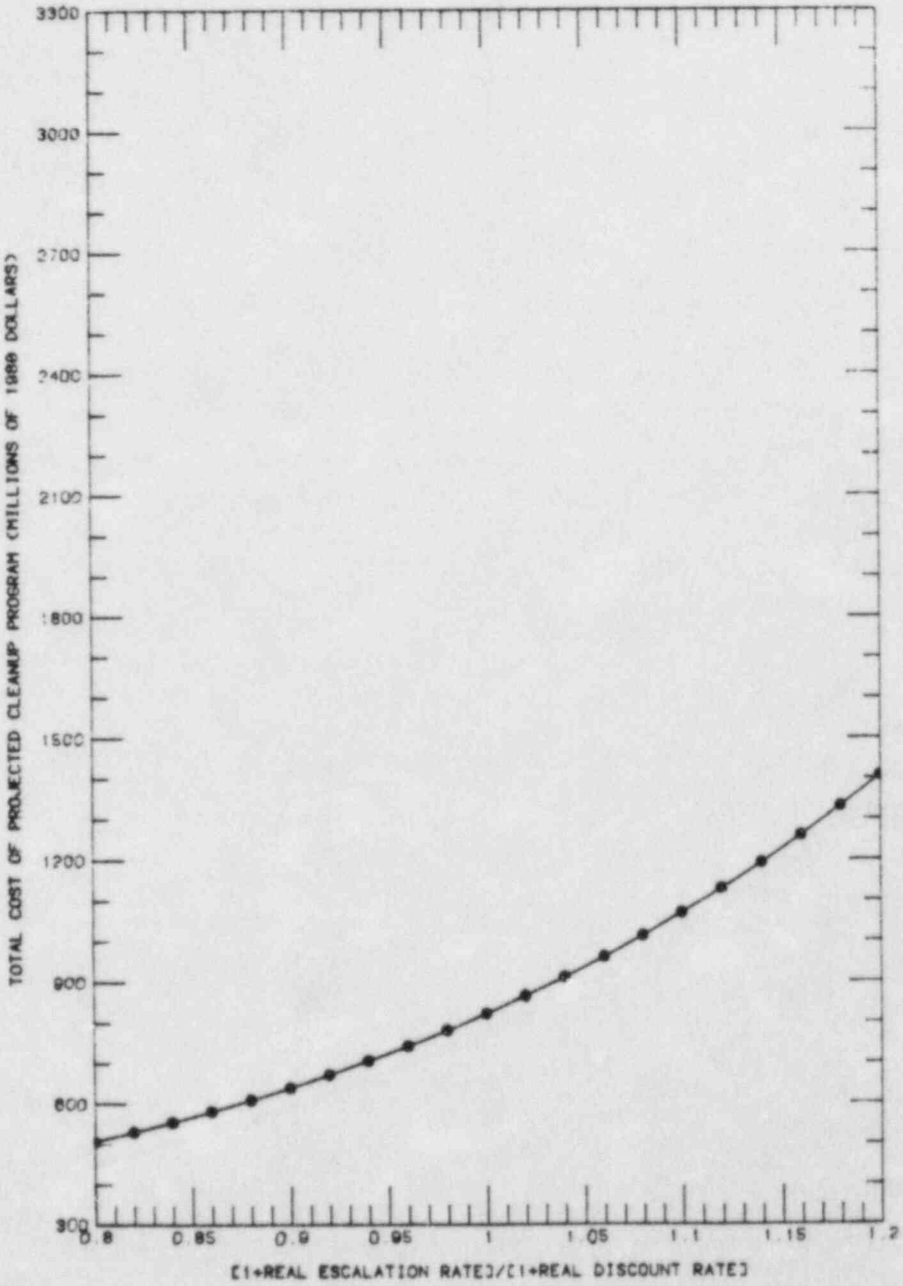


Figure 3.7 - Total projected cost of TMI-2 decontamination program including escalation and discounting.



for the TMI-2 accident to the time period of the cleanup process is shown in Figure 3.8. The "cold iron" cost of maintaining the plant in a stable condition without any decontamination activities was assumed to be ~40 million dollars per year [Ra83]. The amount estimated to be spent above this amount was scaled to estimate costs for a 4 year and a 12 year program duration. Discounted cost estimates for the 4, 8, and 12 year decontamination program durations are shown in Figure 3.8. This figure shows that a rapid, efficient program could reduce the decontamination costs substantially. However, given the regulatory and financial constraints which would exist after any severe accident it is unlikely that a rapid cleanup program could ever be carried out.

3.5.1.2 PNL Post-Accident Cleanup Study

A study performed to estimate the post-accident cleanup and decommissioning costs for a reference PWR provides a source of information regarding severe accident cleanup costs [Mu82a, Mu82b]. The reference accidents, estimated manpower requirements for cleanup, and estimated costs for cleanup from the study are shown in Table 3.3. The reactor core is assumed to stay within the reactor vessel in all of the reference accidents. Core-melt accidents with reactor vessel melt-through are not considered. The cost estimates for cleanup of the accidents are based on the assumption that a rapid, efficient cleanup program is possible using available technology without financial or regulatory constraints. The cleanup cost estimates for the severe accidents considered range from $78-378 million 1981 dollars and total preparation and cleanup periods of 3-8 years. The cost estimates do not include estimates for research and development program expenditures which have added to the costs of the TMI-2 recovery program. The TMI-2 accident is similar to a scenario 2 or 3 accident as defined in the study. The study predicts that the cost of cleanup of the TMI-2 accident could be less than half of current GPU program estimates. However, it is unlikely that these optimistic cost estimates could be achieved based on regulatory and financial considerations.

3.5.2 PLANT DECONTAMINATION COSTS FOR CATEGORY III (LARGE CONSEQUENCE) EVENTS

It is necessary to estimate accident cleanup and decontamination costs for an accident which results in full-scale core melting and subsequent breach of the reactor vessel. No historical data or projected cost estimates for onsite decontamination exist for such events. The dominant cost contributor for cleanup of these events is likely to be the cost of working in high radiation environments. Experience at TMI has shown that each man-hour spent in high radiation environments requires

Figure 3.8 - Estimated TMI-2 decontamination program costs for various program durations.

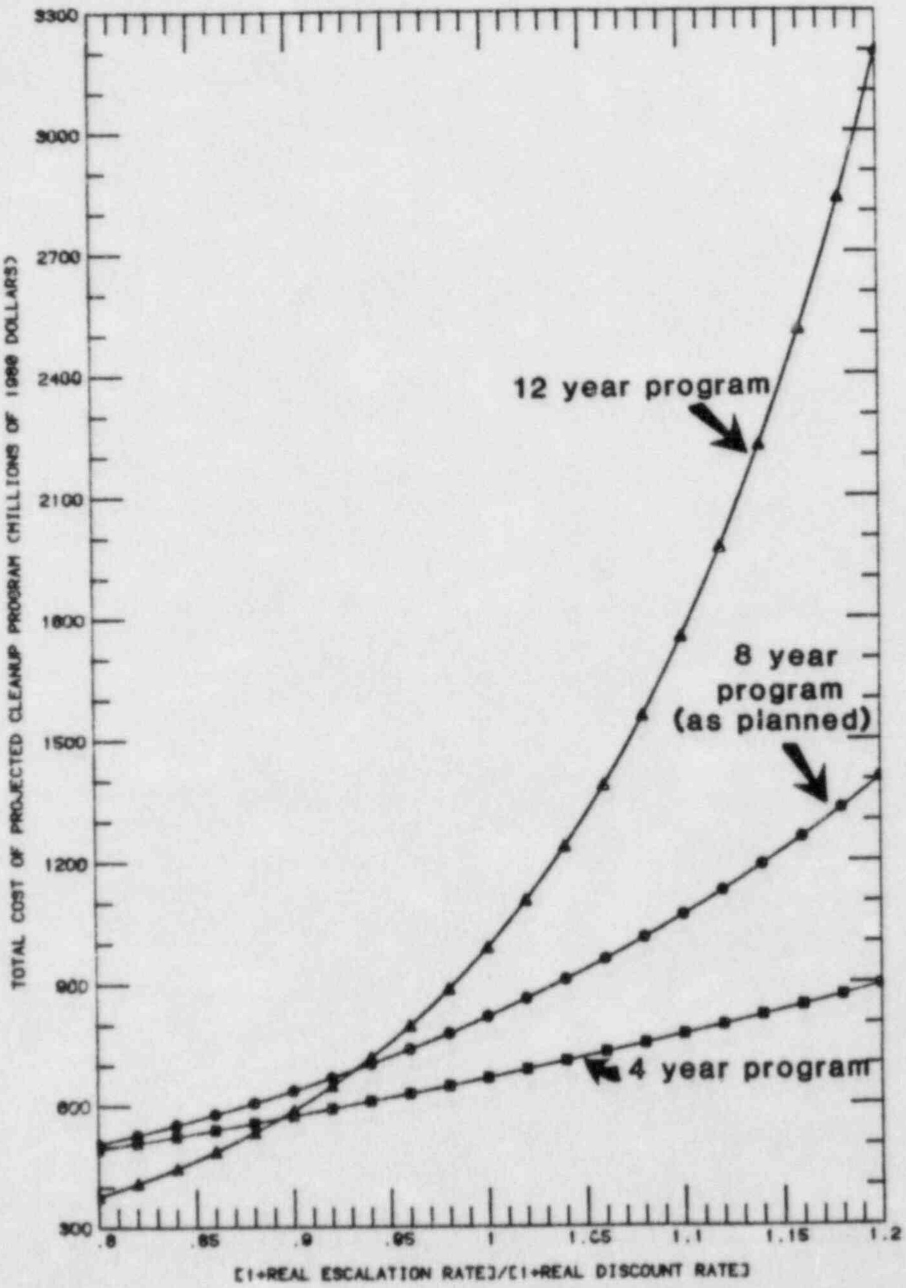


Table 3.3
Results of PNL Study of Post-Accident Cleanup Costs [Mu82b]

Estimated Parameters	Scenario 1 Accident	Scenario 2 Accident	Scenario 3 Accident
Accident Description	An accident which results in 10% fuel cladding failure, no fuel melting, moderate contamination of the containment building, and no significant physical damage to buildings and equipment.	An accident which results in 50% fuel cladding failure, some fuel melting, extensive radioactive contamination of the building, moderate contamination of the auxiliary and fuel buildings, and only minor physical damage to buildings and equipment.	An accident which results in 100% fuel cladding failure, significant fuel melting and core damage, severe radioactive contamination of the containment building, moderate contamination of the auxiliary and fuel buildings, and major physical damage to structures and equipment.
Total Manpower Required for Cleanup Program	465 man-years	1323 man-years	3564 man-years
Preparation Period for Cleanup Program	1.5 years	2.5 years	3.0 years
Cleanup Program Duration	1.5 years	2.8 years	5.0 years
Total Time to Completion	3.0 years	5.3 years	8.0 years
Estimated Total Accident Cleanup Costs (1981 dollars)	$78.9 million	$200.2 million	$378.2 million
Estimated Decommissioning Costs Following Accident Cleanup	$38.6-$58.3 million*	$52.4-$72.2 million*	$79.3-$105.8 million*

* Range is based on alternative decommissioning methods of dismantlement, safe storage, or entombment of reactor plant.

an additional 10-100 man hours in preparation, regulatory, and related activities. After a core-melt accident with reactor vessel melt-through, the radiation fields within the plant containment could be much higher than those observed within the TMI plant.

Based on these considerations and experience with severe accident cleanup costs, it is almost certain that cleanup costs would be greater after a core-melt event than after a degraded core accident confined to the reactor vessel. This is based on the assumption that permanent entombment of the plant in place after the accident would be an unacceptable cleanup alternative. As a lower bound, twice the optimistic estimate of ~400 million dollars for cleanup of a degraded core accident is used for cleanup of a core-melt accident with subsequent vessel breach. As an upper bound, it is assumed that the core-melt accident could result in a factor of 3 greater cleanup costs than the accident at TMI-2. Thus, an upper bound of ~2500 million dollars will be assumed. A best-estimate of 2 times the TMI-2 accident cleanup costs, or ~1700 million dollars, is used for core-melt accidents with reactor vessel breach. As with the TMI-2 accident, the total man-rem incurred in the cleanup process is likely to be a small contributor to overall cleanup program costs.

These estimates of core-melt accident onsite decontamination costs contain large uncertainties due to the lack of understanding of severe accident physical processes and post-accident cleanup methods and effectiveness. Estimates of the costs of the cleanup program for the TMI-2 accident are uncertain due to a lack of available information concerning the state of the reactor plant. Future information gained from experience should be incorporated into updated cleanup cost estimates.

3.6 PLANT REPAIR COSTS

Some events at LWR facilities which occur during operation may result in damage to plant components which would require repair before the continuation of plant operation. The magnitude of plant repair costs for various ranges of accidents are discussed in this section. Only marginal repair costs are included in the analysis, not those costs which would have been borne if an accident did not occur.

The magnitude of plant repair costs is difficult to quantify for the majority of LWR forced outages or accidents. The major reason for this is the difficulty in distinguishing between normal maintenance of plant equipment and repairs which are forced by an event. In many cases repairs after an event can be performed by the normal plant operations crew, and outside contractors are not employed. Also, for most routine operating events, replacement parts for repairs have relatively small costs. Moreover, the costs of repairs after routine forced outages are normally not distinguished on financial records. Thus, it is difficult to obtain any data on the repair cost (if any cost was incurred) for routine outages.

More severe LWR operational events obviously might involve significant plant repair costs. For the purpose of this report, repair costs are distinguished from the costs of decontamination of plant equipment after a severe accident at an LWR facility. Repair costs for events which cause severe plant contamination are defined to include only the work necessary to restore the plant to operational status after decontamination has been completed (see Figure 3.4).

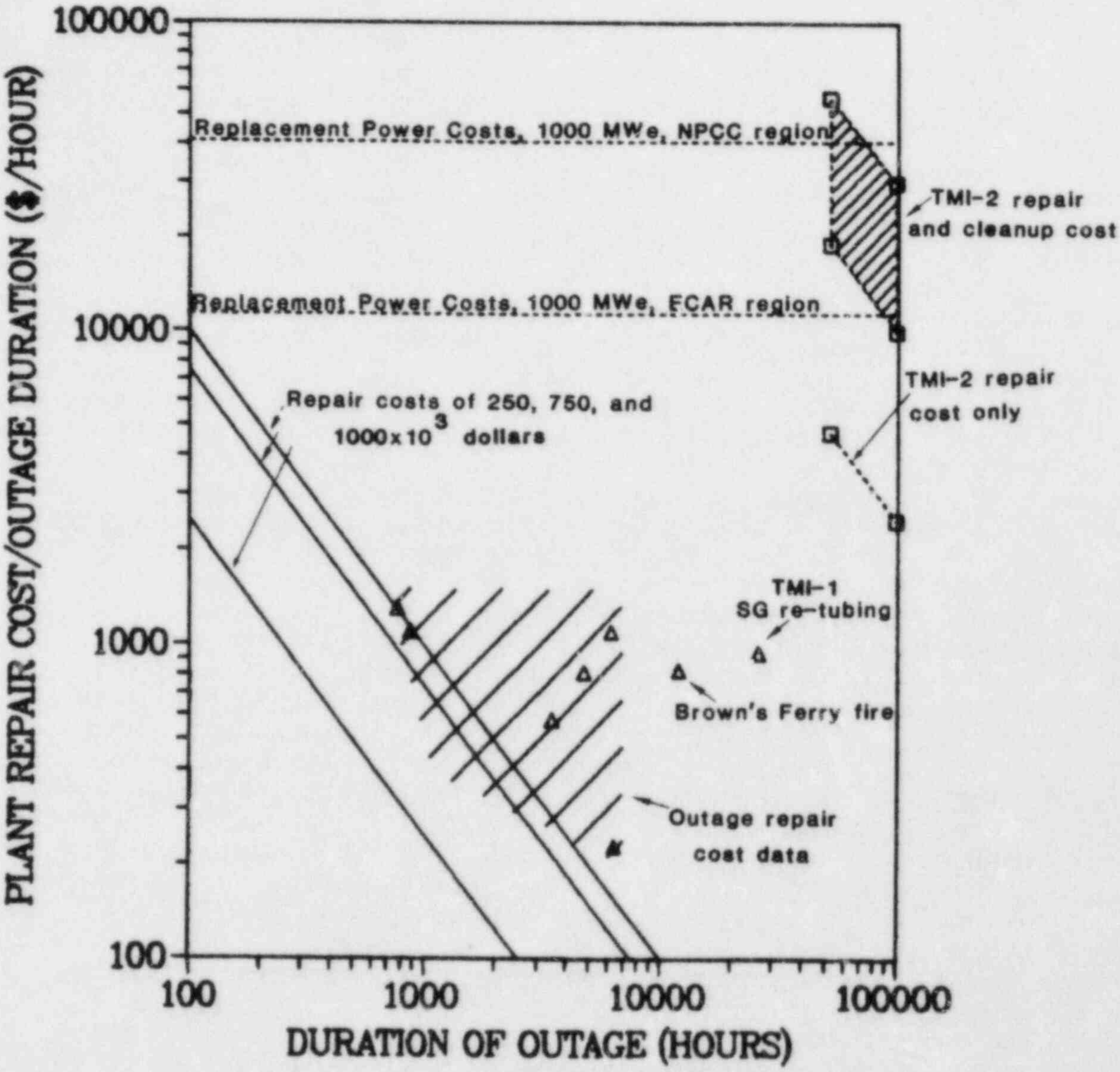
3.6.1 REPAIR COSTS FOR CATEGORY I EVENTS

To estimate the cost of plant repair after forced outage events, historical plant operational data was combined with onsite property damage data for LWR outage events [Ho82]. Plant repair costs are compared with the magnitude of other costs for routine LWR events. The data for plant repair cost versus the duration of the resulting forced outage event are shown in Figure 3.9. This graph shows the plant repair cost per hour of plant outage as a function of outage duration for the available data. Replacement power costs are shown for a 1000 Mwe plant in two NERC regions based on the replacement power cost model discussed in Section 3.3.1. Lines corresponding to $250,000, $750,000, and $1,000,000 total repair costs are also shown in Figure 3.9. These lines correspond to commonly chosen deductible limits in onsite property damage insurance policies [Lo82].

If the total repair cost for an outage event is less than the deductible limit for the plant under consideration, then data for the total repair costs resulting from the outage were unavailable. This is the reason for the general lack of data within the deductible limits. Many LWR outages result in total repair costs within the deductible limits. Of the ~70 LWR long-duration forced outage events analyzed, only 9 events resulted in repair costs which were above the deductible limits. These data points are shown in Figure 3.9.

The repair cost data in Figure 3.9 show that for all LWR events which do not result in significant plant contamination, repair cost (per hour) is predicted to be less than 20% of the replacement power cost (per hour) for a 1000 MWe plant. This data includes repair cost estimates for the Brown's Ferry fire and the steam generator re-tubing outage at TMI-1. The data represent the upper limits of plant repair costs for routine outages, since many events resulted in repair costs lower than the deductible limits. The data indicate that typical plant

Figure 3.9 - Plant repair cost for LWR forced outage events from historical data.



repair costs are in the range of ~$1000 per hour of outage duration.

Based on the analyses of repair costs for LWR plant outages, it is likely that plant repair costs would be small compared to replacement power costs incurred after a routine forced outage event. As a lower bound, plant damage repair costs are assumed to be negligible compared to replacement power costs for routine forced outage events. A best estimate of plant repair costs of $1000 per hour of outage duration is used in the analysis of small consequence event costs. Finally, as an upper bound plant repair costs for routine LWR outages are estimated to be 20% of replacement power costs.

3.6.2 REPAIR COSTS FOR CATEGORY II EVENTS

Estimates of the repair and the sum of repair and decontamination costs for the accident at TMI-2 are shown in Figure 3.9. The estimates for repair costs per hour are higher than those for routine forced outage events. The repair costs represent about 20% of the total decontamination and repair costs. Also, the estimates of the total recovery costs for TMI-2 are comparable to the estimates of replacement power costs for the accident. Thus, for events which result in significant plant contamination, it is likely that repair and decontamination costs will be significant in relation to replacement power costs. However, in the case of the accident at TMI-2, repair costs alone would only represent about 10% of the total estimated accident cost (including replacement power costs).

The accident at TMI-2 is used to estimate the cost of plant repair for medium consequence (category II) events after plant decontamination has been carried out. The estimates are based on the assumption that repair of the reactor plant is chosen over decommissioning after cleanup. Reconstruction and restoration of the TMI-2 unit to pre-accident status is estimated to cost between $190 and $260 million 1982 dollars, depending on the costs included in reconstruction. These estimates are preliminary, and the final costs will not be known until the plant has been decontaminated and repair is undertaken.

A minimum repair cost is estimated for category II events assuming that only the core must be replaced (~80 million 1982 dollars) and refueling and startup tests must be conducted (~22 million 1982 dollars). This results in a lower bound repair cost estimate of $100 million 1982 dollars for these events. As an upper bound on repair cost estimates for category II events, it is assumed that the core must be replaced (~80 million 1982 dollars) and plant reconstruction and associated site support, operations, and refueling services would require 3 times the effort currently projected for TMI-2 (~520 million dollars). This leads to an upper bound estimate of ~600 million 1982 dollars for plant repair costs. A best-estimate of ~275 million 1982 dollars as projected for the repair of TMI-2 after cleanup is used in the analysis [GP81].

3.6.3 REPAIR COSTS FOR CATEGORY III EVENTS

Repair costs after severe LWR accidents involving core-melt and reactor vessel breach would be substantially higher than those for an event like the TMI-2 accident in the event that plant repair is chosen over immediate decommissioning. A large contributor to the difference in repair costs for a core-melt accident would be the replacement of the reactor vessel after such an event. Also, very significant containment system damage might exist after core-melt accidents. The repair and requalification of the plant is expected to be very costly because current LWR designs do not include plans for reactor vessel replacement. Because of the large decontamination costs and the potential severity of plant damage after core-melt accidents with reactor vessel breach, it is likely that immediate decommissioning will be the most cost-effective action. Even if repair is undertaken and the plant is returned to operation, it is estimated that costs will be close to those for immediate decommissioning. Thus, all large consequence (Category III) events are treated as though repair is not performed and early decommissioning is begun immediately after plant cleanup. This should lead to small errors in cost estimation for these events.

3.7 EARLY DECOMMISSIONING COSTS FOR CATEGORY II AND III EVENTS

After accidents at LWR facilities resulting in plant contamination, an alternative to plant repair and restoration to pre-accident condition is immediate decommissioning. This results not only in the need to replace the power which would have been generated over the remaining plant life, but also incurring costs for decommissioning earlier than anticipated. Because of present value discounting, incurring decommissioning costs sooner results in real costs. It is assumed that the decommissioning cost incurred after plant decontamination would be roughly the same as that which is anticipated at the normal end of plant life. This assumption is validated in studies of post-accident cleanup and decommissioning [Mu82a,Mu82b].

Much study has been done on the costs of decommissioning LWRs. Most studies examine alternatives of mothballing, dismantling, or entombing reactors and estimate costs for each alternative. Table 3.4 shows a comparison of decommissioning cost estimates of different organizations over a range of studies. The costs represent the total undiscounted summation of all decommissioning costs at the time of plant shutdown.

Table 3.4
Summary of Cost Estimates for Decommissioning Large LWR Facilities

Costs for Immediate Dismantlement of a Large PWR

Source of Estimate	Reported Esimate (Millions of Dollars)	Year of Report	1978 Dollar Cost (Millions of Dollars)	1981 Dollar Cost (Millions of Dollars)
[Br76]	44	1975	57	75
[Ba78]	79	1976	88	103
[Ma76]	34	1975	43	56
[St77]	51	1976	57	67
[Sm78]	43	1978	43	56
[Mu82a] (Post-Accident)	49.3-105.8	1982	–	49-106
Costs for Immediate Dismantlement of a Large BWR				
[Br76]	60	1975	77	101
[Ba78]	95	1976	100	131
[Ma76]	31	1975	40	52
[Ca80]	67	1978	67	87
[KB79]	115	1979	–	133.5

* Range is based on alternative decommissioning methods of dismantlement, safe storage, or entombment of reactor plant.

Most studies include a contingency in the cost estimate of ~25% [Sm78, Mu76]. All cost estimates have been updated to 1981 dollars using simple price indexes [Pr83]. An undiscounted decommissioning cost estimate of $100 million 1982 dollars is used in this study, based on immediate dismantlement of the reactor plant.

The real cost incurred due to accelerated decommissioning of a reactor facility is dependent upon the time during the life of the reactor at which decommissioning occurs. The real cost due to accelerated decommissioning is calculated using:

$$D_d = S\ 1.0 - e^{-(l-t_d)r} \qquad (3.6)$$

where

D_d = real cost incurred due to acceleration of decommissioning activities,

S = cost of decommissioning at end of plant life (~$100 million 1982 dollars),

r = real discount rate,

l = plant service life (40 years),

t_d = time at which decommissioning starts, measured from the start of plant commercial operation.

For severe reactor accidents involving plant contamination, a long time period may be necessary for plant cleanup before decommissioning activities begin. This is accounted for in the cost analyses.

Sensitivity studies were performed to determine the importance of early decommissioning costs to total costs for medium and large consequence accidents. For accidents which occur very early during plant life, the cost due to accelerated decommissioning can be a substantial fraction of the $100 million dollar end-of-life decommissioning cost. However, accelerated decommissioning costs are generally small compared to total costs for medium and large consequence events.

3.8 WORKER HEALTH EFFECT AND MEDICAL CARE COSTS

Any event at an LWR facility has the potential for causing plant worker health impacts. These impacts may have costs ranging from minimal health care costs to costs for worker fatalities caused by an event. A review of standard methods for accounting for health care and health effects costs is included in section 4.4.6 on offsite health effects and medical care costs.

3.8.1 HEALTH COSTS FOR CATEGORY I EVENTS

Plant worker health effects resulting from routine LWR forced outage events are extremely rare. These health effects are incurred as part of the risk of operating an LWR facility and are not included in the cost estimates for routine forced outage events. Because of the low probability of worker health effects, and the small costs of such effects, other costs associated with routine forced outage events will dominate expected worker health effect costs.

3.8.2 HEALTH COSTS FOR CATEGORY II EVENTS

Accidents involving significant contamination of the LWR facility result in an increased potential for worker health effects because of the radioactive material released within the plant. Plant workers in areas of the plant where serious system failures occur may also sustain injuries induced by causes other than radiation.

Because very little data exists for category II accidents, any estimation of the likelihood of resulting worker health effects is highly uncertain. Because the accidents in this category do not result in reactor vessel failure or large releases of radioactive material to the environment around the plant, it is likely that any resulting injuries in the plant area will be highly localized. Therefore, the accidents are not expected to be significantly different from normal plant operation for the possibility of worker injuries, and no significant worker health effect costs are assumed to result from accidents in this category. This is consistent with the historical experience of TMI-2. Even if some of the plant work crew were injured during an accident of this type, cost estimates for this impact would be small compared to other accident costs (if reasonable dollar values are used for health effect costs).

3.8.3 HEALTH COSTS FOR CATEGORY III EVENTS

The most serious core-melt accidents at LWR facilities may result in significant injuries or fatalities among workers at the facility. Failure of the reactor vessel and possible release of radioactive material to the environment could lead to contamination of equipment and exposure of workers in many areas of the plant.

An upper-bound estimate of the costs of worker health effects after a category III accident has been evaluated and included in the financial risk estimates of Strip [St82]. Estimated dollar values for worker injuries ($100,000/injury) and fatalities ($1,000,000/fatality) were used in the analysis. A typical work shift for a single plant includes approximately 40 workers, and it was conservatively assumed that a core-melt accident would result in 10 early fatalities and 30 early injuries. This results in an upper estimate of worker health effects cost of ~13 million dollars. This cost is small compared to other cost components for core-melt accidents.

3.8.4 CONCLUSION-WORKER HEALTH EFFECTS AND HEALTH CARE COSTS

For routine outage events or severe accidents which do not breach the reactor vessel, it is assumed that no significant onsite worker health impacts are incurred. Even if a large fraction of the onsite workers incurred health effects after a severe accident, the contribution to total accident costs is small if reasonable values for personnel injuries and fatalities are used. For core-melt accidents with reactor vessel failure, an upper-bound of 10 early fatalities and 30 injuries is used to estimate the costs of onsite worker health effects. Even this worst-case assumption of worker health effects contributes negligibly to total accident losses. Onsite costs for these accidents are dominated by other cost components. Methods used for estimating the costs of offsite health effects from severe accidents are discussed in section 4.4.6.

3.9 ELECTRIC UTILITY "BUSINESS COSTS" AND NUCLEAR POWER INDUSTRY IMPACTS

It is possible that a plant licensee or electric utilities in general might incur higher costs for borrowing capital and continuing to provide adequate electricity to service areas after severe accidents at LWR facilities. These costs are incremental "business costs" which are discussed in this section. Another possible impact of severe LWR accidents may be future policy decisions which lead to the rapid shutdown, phasing out, or slowed growth of the nuclear electricity generating industry in the U.S. These potential nuclear power industry impacts are also discussed in this section.

3.9.1 ELECTRIC UTILITY "BUSINESS COSTS"

"Business costs" have been addressed in studies which estimate the costs of closing currently operating nuclear generating facilities [St81b]. These costs might result from altered risk perceptions in financial markets combined with the need for the plant licensee to replace the income once generated by the operating plant. These costs mainly would affect the licensee of a damaged plant, but could also affect the electric utility industry in general through the financial markets.

Business costs originate in the increased cost of capital to an electric utility caused by increased borrowing costs in financial markets or limitations on access to financial markets. Increased borrowing costs result from altered perceptions of risk in investment in a specific utility which results in a higher demanded return on capital. Limitations on access to financial markets can result from the plant licensee's loss of income which results in insufficient coverage on existing financial security commitments. This occurred after the TMI-2 accident, as Metropolitan Edison's interest coverage ratio fell below 2.0, which prohibited the issuance of new bonds. Capital borrowing costs and/or market access limitations can have serious impacts on construction programs, financing options, and dividend policies, all of which did occur after the TMI-2 accident [GA80].

In discussing business costs it is important to distinguish between increased capital borrowing costs due to improved information provided by an accident, and possible increases in borrowing costs due to mis-information or falsely perceived risks. The portion of increased capital costs due to improved information provided by an accident represents only a redistribution of benefits within society through financial markets which efficiently value the benefits of nuclear power utilities as an investment. An accident which results in an incorrect perception of nuclear power risks can result in increased electric utility capital borrowing costs which are true societal costs. To the extent that increased risk perceptions are not supported by new accident information, business costs do result in a net societal loss due to impacts on construction and maintenance programs which may be significantly altered due to cash flow limitations. It is likely that market access limitations result in an increased cost for a societal necessity, electricity, in future years.

Previous estimates of the business costs which may be incurred due to the loss or shutdown of a nuclear generating facility have been large. Studies of the costs of closing the Indian Point nuclear power plant have estimated business costs to be between $1 and $6 billion 1981 dollars, or ~15-30% of the total estimated costs [St81b]. The range of estimates shows the large uncertainties in these estimates.

Unfortunately, estimation of business costs due to an accident requires separation of impacts due to improved information and those due to false risk perceptions. Limitations on access to capital markets which result after an accident are likely to result in significant business costs which represent net societal losses. Obviously, the electric utility industry and nuclear plant licensees should be very concerned with the potential business costs caused by an accident because they can influence the stature of companies within financial markets.

Because of the difficulties in estimation and the specific nature of business costs after a serious accident, these costs are not explicitly estimated in this study. However, particularly in electric utility financial risk analyses, these costs can be important in estimating the impacts of serious accident events (Categories II and III) and should be considered in some way in making decisions. This area requires more investigation regarding the ultimate distribution, magnitude, and specific characteristics which can influence net societal costs.

3.9.2 NUCLEAR POWER INDUSTRY COSTS

Another potential impact of severe LWR accidents is that policy decisions or risk perceptions could cause the elimination of or slowed growth in the U.S. nuclear power industry. It has been argued that the accident at TMI-2 has caused losses in the U.S. nuclear power industry since no new plant orders have been placed and many plant cancellations have occurred since the accident. It has also been argued that severe accidents with offsite consequences could result in societal overreaction and a forced shutdown of all or many operating nuclear power reactors effectively eliminating nuclear power as an alternative for electricity generation.

Several studies have investigated the consequences of closing commercial nuclear power reactors in the U.S. [St81b,Bu82]. Table 3.5 shows the electrical generating capacities and actual loads for each NERC region in 1980 and projections for 1990 [Bu82]. The reserve margin with and without nuclear power plant operation is shown for each NERC region. The reserve margin is the total installed capacity minus the peak load for each region. A typical reserve margin used for electric utility planning purposes is in the range 15-30% to allow for scheduled and unscheduled refueling and maintenance shutdowns for each generating unit. The table shows that reserve margins without nuclear power plants were under 15% in many regions in 1980. By 1990, almost all regions are predicted to have reserve margins without nuclear units less than 15%, and some areas would not have sufficient capacity to meet the predicted peak load requirements. A forced shutdown of all nuclear units would result in a marked decrease in the reliability of electric power supply in some NERC regions along with very large power production cost increases.

Currently, five NERC regions depend on nuclear units for ~20% of total power generation (nuclear representing ~15% of total generation capacity), and by 1990 four regions are predicted to depend on nuclear power units for 40% of electricity generation (and nuclear is predicted to represent ~30% of total generation capacity) [Bu82]. A shutdown of all nuclear units would result in the need to replace a large fraction of

Table 3.5 - Loads and generating capacities of NERC regions in 1980 and projections for 1990 [Bu82].

Actual Loads and Generating Capacities for National Electric Reliability Council Regions in 1980

NERC Region	Peak Load (GWe)	Installed Capacity (GWe)	Regional Reserve Margin (%)	Installed Nuclear Capacity (GWe)	Nuclear % of Total Capacity	Regional Reserve Margin Without Nuclear (%)
ECAR	63.0	88.2	40	4.5	5.1	33
ERCOT	31.7	42.5	34	0.0	0.0	34
MAAC	34.5	45.0	30	7.1	15.8	10
MAIN	33.9	41.7	23	6.3	15.1	4
MARCA-U.S.	19.4	25.6	32	3.7	14.5	13
NPCC-U.S.	36.8	51.1	39	7.8	15.3	18
SERC	90.4[a]	115.9[a]	28	15.5	13.4	11
SPP	45.0	50.6	12	1.7	3.4	9
WSCC-U.S.	72.9	102.3	40	2.6	2.5	37
NERC-U.S.	427.6[b]	562.9	32[b]	49.2	8.7	20[b]

Projected Loads and Capacities for National Electric Reliability Council Regions in 1990

NERC Region	Peak Load (GWe)	Installed Capacity (GWe)	Regional Reserve Margin (%)	Installed Nuclear Capacity (GWe)	Nuclear % of Total Capacity	Regional Reserve Margin Without Nuclear (%)
ECAR	89.4[a]	119.2	33	14.1	11.8	18
ERCOT	48.9	59.1	21	5.9	10.0	9
MAAC	41.8	54.2	30	14.5	26.8	-5
MAIN	45.3	54.1	19	16.2	29.9	-16
MARCA-U.S.	27.8	32.5	17	3.7	11.4	4
NPCC-U.S.	43.2[a]	62.5	45	14.6	23.4	11
SERC	122.7	158.1	29	41.1	26.0	-5
SPP	62.5	74.9	20	6.9	9.2	9
WSCC-U.S.	104.4	140.2	34	16.9	12.1	18
NERC-U.S.	586.0[b]	754.8	29[b]	133.9	17.7	6[b]

[a] Winter loads and capacities -- all unmarked loads and capacities are summer.

[b] Based on noncoincident peak loads.

the electricity generated in the U.S. with higher-cost power from alternative sources. A forced shutdown of all nuclear units in 1990 is predicted to result in the need to replace 813X10^9 kWhre with electricity generated from other sources during the first year of the shutdown.

The large magnitude of the cost of replacing this power can be estimated using the simplified power production cost increase model. Assuming an average 65% nuclear generating unit capacity factor, and an average non-economy replacement power fraction of 0.5, the estimated cost of the first-year power production cost increase for closing all nuclear units in 1990 (assuming no escalation of replacement power costs relative to nuclear generation costs through 1990) is ~$33 billion 1982 dollars. This calculation is based on the assumption that sufficient capacity and interconnections are available to replace all of the power generated by the closed nuclear units (a very optimistic assumption). The replacement of power over the remaining nuclear plant service lives would result in estimated societal direct costs between ~$500 billion and ~$2 trillion 1982 dollars due to plant closings. This is an estimate of the cost society would be forced to pay assuming the decision is made to close all operating nuclear units after an event which occurs in 1990.

Any severe accident at an LWR facility will result in new information concerning the risks of nuclear power reactor accidents which should be incorporated rationally into the societal decision-making process. It is difficult to determine what societal reaction to new information would be. There is no evidence to prove that societal overreaction would take place after a serious nuclear reactor accident. Other industries such as commercial airlines, chemical manufacturing, and coal mining have experienced devastating accidents and continue operations with only minor safety modifications. Even the U.S. nuclear industry has survived a serious accident without immediate and complete shutdown. The loss of benefits to society from an immediate, complete shutdown of any large industry after a severe accident would be too large to allow societal overreaction to force this action.

For the purpose of this study, it is assumed that society would make rational policy decisions based on new information which is obtained after reactor accidents. These decisions may have serious impacts on the U.S. and world nuclear power industries. Therefore, from the nuclear power industry and electric utility perspectives these decisions could result in significant direct costs. However, from the societal perspective it is anticipated that these costs would be balanced by benefits considered in the societal decision-making process.

Other potential nuclear power industry costs of severe reactor accidents have been investigated since the accident at TMI-2. A study has used the observed drop in the performance of PWRs in the western world to estimate a total cost of replacement power due to increased plant outage time as a result of the TMI-2 accident [Ev82]. The lower bound estimate of the total cost due to increased PWR outage time resulting from the accident is $700 million dollars. However, the study does not estimate the potential benefits of increased plant safety and confidence which have resulted from the increased forced outage time. The increased forced outage time after TMI-2 has largely resulted from decisions to improve the safety of some PWRs in light of information gained from the accident. Therefore, no significant societal cost is assumed to result from the increased plant outage time resulting from regulatory concerns after severe accidents.

Finally, studies have been performed to estimate the decrease in the valuation of nuclear power in the period following the TMI-2 accident [Zi82a,Zi82b,Ne82]. Studies of stock prices of utilities owning nuclear power plants showed no significant decrease in the valuation of the investment one year after the accident occurred. The only exception to this is for plants under construction in states where CWIP (Construction Work in Progress) funding is not allowed. The stock of these utilities showed some drop in valuation, probably due to increased uncertainty in the time required to obtain an operating license for plants under construction. Studies of nuclear utility bond prices showed some decrease in valuation occurred after the accident at TMI-2, but this may have been due to a general trend in the valuation of the electric utility industry as an investment. The results of these studies indicate that the nuclear utility industry was beginning to slow before the accident at TMI-2. Much of the industry depression attributed to the TMI-2 accident can actually be explained by economic and regulatory forces which began before the accident occurred.

Serious accidents at LWR facilities could result in large impacts on the nuclear power industry and electric utilities in the U.S. because of societal decisions based on new information and risk perceptions. Therefore, from the perspective of particular interest groups it is important to consider the potential direct losses resulting from these impacts. From the societal perspective, any direct losses to nuclear power industries should be balanced by benefits considered in the societal decision-making process. If societal overreaction does not occur and decisions are made on a rational basis, then significant societal costs should not be incurred for nuclear power and electric utility industry impacts.

3.10 ONSITE LITIGATION COSTS

After very severe accidents at nuclear power reactors, issues of liability and compensation for losses incurred can be settled through litigation. The U.S. legal system has previously and would in the future play a major role in assigning liability for the risk associated with nuclear power reactor accidents to individual parties. The transfer payments resulting from legal settlements and the legal fees associated with the litigation process are discussed in this section.

The legal awards for damages incurred as a result of an LWR accident are transfer payments which result in the distribution of net costs. The societal costs of LWR accidents are estimated directly within this study without regard for the ultimate distribution resulting from transfer payments. Most of the transfer payments resulting from the litigation process do not result in additional net societal costs. It is possible that compensation could be awarded for costs which are not quantified directly in this study. The dollar costs estimated in this study could be augmented to reflect the additional costs of accidents quantified through litigation awards, but the contribution to total societal accident costs is likely to be small.

The legal fees for the time and efforts of those individuals involved in the litigation process do represent societal costs since efforts could have been expended on other problems if an accident had not occurred. Studies have shown that the costs of corporate lawyers are very high, particularly in those cases where outside counsel is required [IC78]. Legal fees can be substantial to an individual group but are unlikely to be significant accident costs from the societal perspective.

Most legal compensation awarded after a reactor accident represents transfers of net societal costs which are estimated in other sections of this study. Cost estimates could be augmented to account for effects like "pain and suffering" which have not been included in the societal cost estimates presented. The legal fees incurred by parties involved in the litigation process do result in a net cost, but the contribution to total societal costs is likely to be small. Therefore, no direct cost estimates are included for onsite litigation resulting after severe accidents.

3.11 SUMMARY-ONSITE CONSEQUENCES OF LWR EVENTS

A summary of the models and estimates to be used in the analysis of the economic risk from onsite consequences of LWR events is presented in Table 3.6. Lower-bound, upper-bound, and best-estimates are shown for those cost components where subjective judgments have been combined with historical data and

Table 3.6
Summary of Estimates and Models for Onsite Costs of LWR Events$^+$

Onsite Cost Components		**Category I Events (Routine Forced Outages, No Plant Contamination)**	**Category II Events (Degraded Core Accidents, No Reactor Vessel Breach)**	**Category III Events (Core-Melt Accidents, With Reactor Vessel Breach)**
Power Production Cost Increase		Simplified ANL model	Simplified ANL model	Simplified ANL model
Loss of Plant Capital Investment		NA	Annualized capital costs discounted over remaining life (for no repair case)	Annualized capital costs discounted over remaining life (assuming no repair)
Cost due to early Decommissioning		NA	100×10^6 discounted to completion of cleanup (for no repair case)	100×10^6 discounted to completion of cleanup
Worker Health Impacts	Upper Bound	SM	SM	(13×10^6)
Electric Utility "Business" Costs		SM	EX	EX
Plant Cleanup and Decontamination Costs	Lower Bound	NA	80×10^6	800×10^6
	Best-Estimate	NA	850×10^6	1700×10^6
	Upper Bound	NA	1400×10^6	2500×10^6
Plant Repair Costs	Lower Bound	SM	100×10^6	NA
	Best-Estimate	$1000/hour outage duration	275×10^6	NA
	Upper Bound	20% of power production cost increases	600×10^6 (for repair case)	NA
Nuclear Power Industry Costs		SM	SM*	SM*
Onsite Litigation Costs		SM	SM*	SM*

NA Cost component is not applicable for accident category.

SM Cost is small relative to other cost components for accident category from societal view.

SM* Cost is small relative to other cost components for accident category from societal view. However, these impacts may result in significant transfers, and consideration of these costs is important for decison-making by specific interest groups.

EX Estimation of cost is explicitly excluded in this study. However, these impacts could be important for societal and interest group consideration.

$^+$ Cost estimates represent purely economic losses from LWR accidents and outages. Other impacts or attributes of impacts which could be important in societal decision-making are not included in this study (i.e., individual preferences).

available studies of potential costs. For some accident categories specific cost components may be negligible or not quantified in this study.

3.11.1 CATEGORY I FORCED OUTAGE EVENTS (SMALL CONSEQUENCES)

The LWR events in category I include routine forced outage events of up to a few years duration which do not result in significant plant contamination. The outage duration for these events is estimated from historical nuclear plant operating experience. Power production cost increases for these outages are estimated using the simplified replacement power cost model discussed in Section 3.3.1. Upper and lower bound estimates for replacement power costs are obtained from the range of values upon which the simple model is based. Estimates of repair costs after routine forced outages show that in some cases these costs are negligible. A best-estimate for repair costs of ~$1000 per hour of outage duration is used in the analyses. As an upper bound on repair costs, 20% of the replacement power costs are included for the entire outage duration.

The remaining onsite cost components are negligible for all events in category I. It is assumed that the plant is repaired and returned to operation after all category I events. Therefore, it is not appropriate to estimate capital value losses, decommissioning costs, and electric utility and plant licensee "business costs" for these events. Marginal worker health effects and health care costs are negligible for these events. Because little or no radioactive material is released from the core in these events, any plant decontamination costs incurred would be small. Also, nuclear power industry and onsite litigation costs are not important for these events.

3.11.2 CATEGORY II EVENTS (MEDIUM CONSEQUENCES)

Category II LWR events include accidents which lead to core-damage but do not result in reactor vessel breach or a release of radioactive material to the environment. Some radioactive material is released from the reactor core in these accidents. The forced outage duration is estimated for these events in cases where plant repair is chosen rather than immediate decommissioning. Based on studies of post-accident cleanup and decontamination, a lower bound estimate of 4 years for cleanup is assumed. A best-estimate of 8 years for plant cleanup time is based on the projected TMI-2 decontamination program and estimates from post-accident cleanup studies. An upper bound estimate of 12 years is used for plant cleanup following the worst category II accidents. Plant repair, if elected, is predicted to require much shorter time periods than the cleanup operations. Lower, best, and upper bound estimates of 1, 2, and 3 year repair periods after decontamination are used. This results in total outage duration estimates of 5, 10, and 15 years before the possible return to operation after a category II event. The option of immediate decommissioning after cleanup is also included in the analyses.

The models and estimates used for replacement power costs, plant capital costs, decontamination and cleanup costs, and possible repair or decommissioning costs for category II events are shown in Table 3.6. The only cost component which is assumed to be negligible for these events is worker health effect and health care costs. Electric utility and plant licensee business costs, onsite litigation costs, and nuclear power industry costs are small from the societal perspective, but could be very important to these specific groups after severe accidents.

3.11.3 CATEGORY III EVENTS (LARGE CONSEQUENCES)

Category III accidents include full scale core-melt accidents which breach the reactor vessel, and possibly result in a significant release of radioactive material to the environment around the reactor plant. These accidents are very low probability events which are included in plant specific probabilistic risk analyses. No historical data exist for these events, and very little information is available concerning recovery costs. Because of the likely extent of plant damage after category III events, costs are estimated based on the assumption that immediate plant decommissioning would be chosen over repair for these accidents. It [illegible] sible that the plant would be repaired and returned [illegible] operation, but costs are estimated to be close to those for immediate decommissioning after events in this accident severity category.

The onsite cost components estimated for a category III accident are outlined in Table 3.6. The cost of plant repair is not explicitly estimated since immediate decommissioning is assumed to occur. The onsite decontamination and cleanup cost estimates for category III events are based largely on extrapolation of the results of studies and historical data for category II events. It is assumed that plant cleanup would be mandated, and permanent entombment of the contaminated plant at the site location would not be an acceptable option (although possibly technically feasible and less costly). The estimates of plant cleanup costs are uncertain because of options which would be available and the lack of information concerning cleanup costs. Electric utility and plant licensee business costs which could be important after events in this severity category are explicitly excluded from quantification in this study but should be considered in decision-making. Nuclear power industry and onsite litigation costs are assumed to be small from the societal perspective but could be important to particular groups, particularly if societal overreaction occurs after severe accidents.

3.11.4 ESTIMATION OF LWR ECONOMIC RISKS

The cost estimates developed in this section are used in the estimation of societal economic risk from the onsite consequences of LWR events. Models are developed in Chapter 4 to estimate the magnitude of offsite costs of LWR accidents. Chapters 5 and 6 combine the onsite and offsite costs with frequency estimates for LWR events to estimate the economic risks from small, medium, and large consequence events. Conclusions concerning the contribution of specific cost components to economic risks from accidents of various severities are discussed in these chapters.

CHAPTER 4

OFFSITE ECONOMIC CONSEQUENCES OF LWR EVENTS

The offsite economic consequences of severe LWR accidents are discussed in this section. Conclusions from previous studies of post-accident population radiation exposure pathways are reviewed for use in the offsite economic consequence model. The offsite economic consequence models developed for eventual incorporation into the MELCOR series of risk assessment codes are described. Potential offsite economic impacts of severe LWR accidents not included in the new model are discussed. The major differences between the new economic models and those in the CRAC2 code are reviewed. Finally, assumptions used to develop a prototype offsite economic consequence model for use in the calculations in this study are outlined.

4.1 LWR ACCIDENT OFFSITE COSTS DISCUSSED

The LWR accident offsite population protective measure costs discussed in this section include population evacuation costs, temporary relocation costs, agricultural product disposal costs, land and property decontamination costs, land interdiction (or condemnation) costs, and permanent relocation costs which may be incurred after severe accidents involving releases of radioactive material to the environment. These cost components are associated with population protective measures to avoid radiation exposure after contaminating events. The economic impacts of radiation-induced human health effects which result from population exposure after an event are also discussed. Other impacts such as litigation costs (for offsite damages) and secondary economic effects (outside of directly contaminated areas) are discussed in this section. Offsite impacts explicitly excluded from the estimation of economic consequences in this study are outlined.

4.1.1 DEFINITION OF TERMS USED IN DISCUSSION

Unfortunately, organizations involved with offsite emergency response and public protection have used many terms to describe various countermeasures which might be implemented after reactor accidents. The terms used to describe LWR accident offsite emergency response are defined in this section to eliminate confusion which may otherwise exist. The definitions used are in close agreement with those used in the RSS [Nu75b].

The term "evacuation" is used to refer to the immediate movement of individuals out of an area at the time of an accident. Evacuation may be implemented before any release of radioactive material occurs as a precautionary measure based on in-plant conditions which could worsen. This is distinguished from "temporary relocation" which is the movement of a population from an area based on monitored levels of radioactive contamination. "Agricultural product disposal" refers to the disposal of milk or crops which are contaminated with radioactive material until projected individual and population doses from ingestion are acceptable. "Decontamination" refers to the process of cleanup and restoration of land and property in an area through measures which reduce dose rates by removing surface-deposited radioactive material. "Land interdiction" refers to the prohibition of inhabitation or use of areas for a protracted period of time (~years), and is therefore a long-term exposure reduction measure. "Permanent relocation costs" refer to lost income, productivity, and moving costs incurred in the transition period of population relocation from interdicted land areas.

4.2 REVIEW OF POPULATION RADIATION EXPOSURE PATHWAYS FOLLOWING LWR ACCIDENTS

Detailed studies on the importance of radiation exposure pathways for LWR accidents were performed as part of the RSS [Nu75b]. The studies included consideration of both acute and chronic exposure pathways following severe LWR accidents. The projected doses from important exposure pathways are used in both the CRAC2 and new economic models to determine the need for population protective measure implementation.

The acute exposure pathways include groundshine, cloudshine, and inhalation of radionuclides which may be deposited by or contained in a passing cloud of radioactive material. Acute doses are incurred within a short time period (~1 to a few days) after the release of radioactive material to the environment. The population protective measures which are effective in reducing acute exposures include evacuation and sheltering followed by short-term relocation.

The chronic exposure pathways of concern after serious LWR accidents include the milk ingestion, food ingestion, and the groundshine exposure pathways. Studies performed in the RSS concluded that these are the most important chronic exposure pathways for LWR accidents. This conclusion is based on the radionuclide inventory of an LWR reactor core, the estimated release fractions of each element group, and the limiting body organs and health effects of concern for each radionuclide. The CRAC2 code projects chronic doses from these exposure pathways for the maximum exposed individual to determine the need for population protective measure implementation in each area affected by a release of radioactive material. The RSS concluded that milk ingestion dose criteria are the most limiting for LWR accidents. The criteria for individual doses from crop ingestion are the next most limiting, and the criterion for the groundshine exposure pathway is the least limiting of these three pathways in terms of areas that would be affected.

A simplified diagram of the CRAC2 population protective measure model is shown in Figure 4.1. Milk disposal is implemented in the largest area following most accidents, with crop disposal necessary in a smaller area, and decontamination of land and property to reduce groundshine exposure in a still smaller area. Land area interdiction is required in the smallest area where decontamination efforts cannot reduce groundshine dose rates to acceptable levels.

Protective action implementation criteria are defined for the milk ingestion, food ingestion, and chronic groundshine exposure pathways in the new offsite economic models. This approach, which is the same as that used in CRAC2, is based on detailed studies of the importance of exposure pathways after LWR accidents which result in releases of radioactive material to the environment. Other chronic exposure pathways are predicted to be less important and therefore do not need to be considered in determining the need for population protective measures in an area.

4.3 MODELING OF STAGED OFFSITE PROTECTIVE MEASURE IMPLEMENTATION

The new economic models are based on staged implementation of offsite population protective measures in post-accident situations. A time chart of protective measure implementation after the start of a severe LWR accident sequence is shown in Figure 4.2.

Individuals living in areas near the reactor plant may begin evacuation after the start of an accident sequence but prior to any release of radioactive material to the environment. If a release of radioactive material to the environment takes place, radiation monitoring teams will begin the task of collecting dose rate information at offsite locations from surface-deposited radionuclides. This action is likely to occur within hours of any significant release of radioactive material to the environment. The new economic model allows projection of individual doses during this "emergency phase" period to account for the costs of temporarily relocating individuals in addition to those initially evacuated. The "emergency phase" relocation criterion is based on dose rate or projections of short-term individual doses from exposure to surface-deposited materials. The model assumes that monitoring of milk and crops begins immediately after any release of radioactive material to

Figure 4.1 - Example of protective action implementation areas for severe LWR accidents [Nu75b].

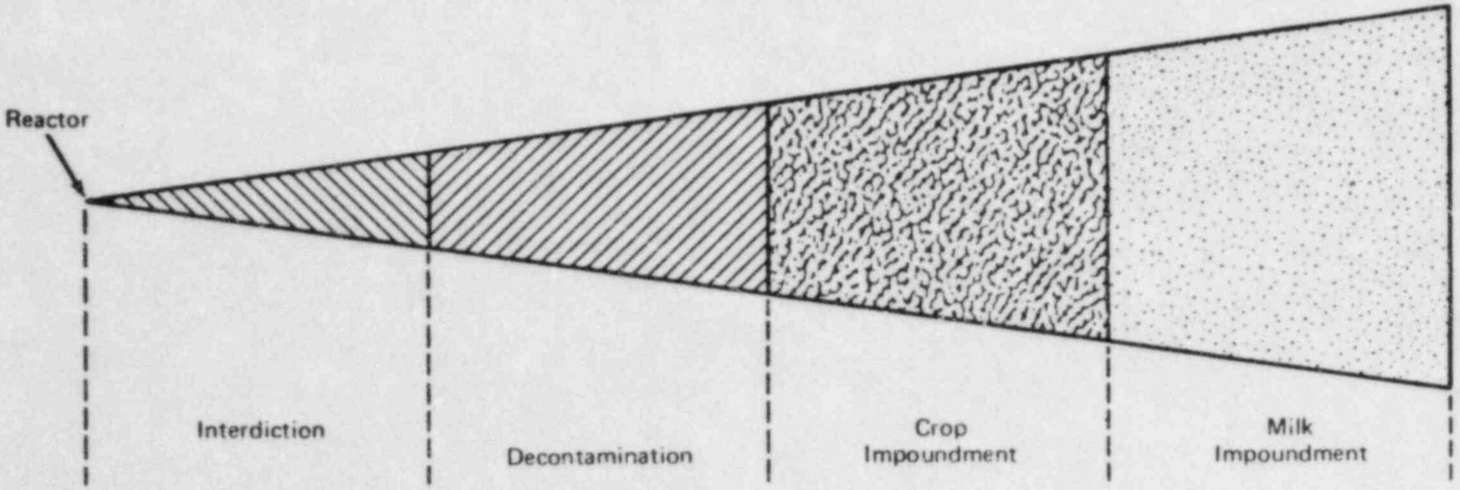
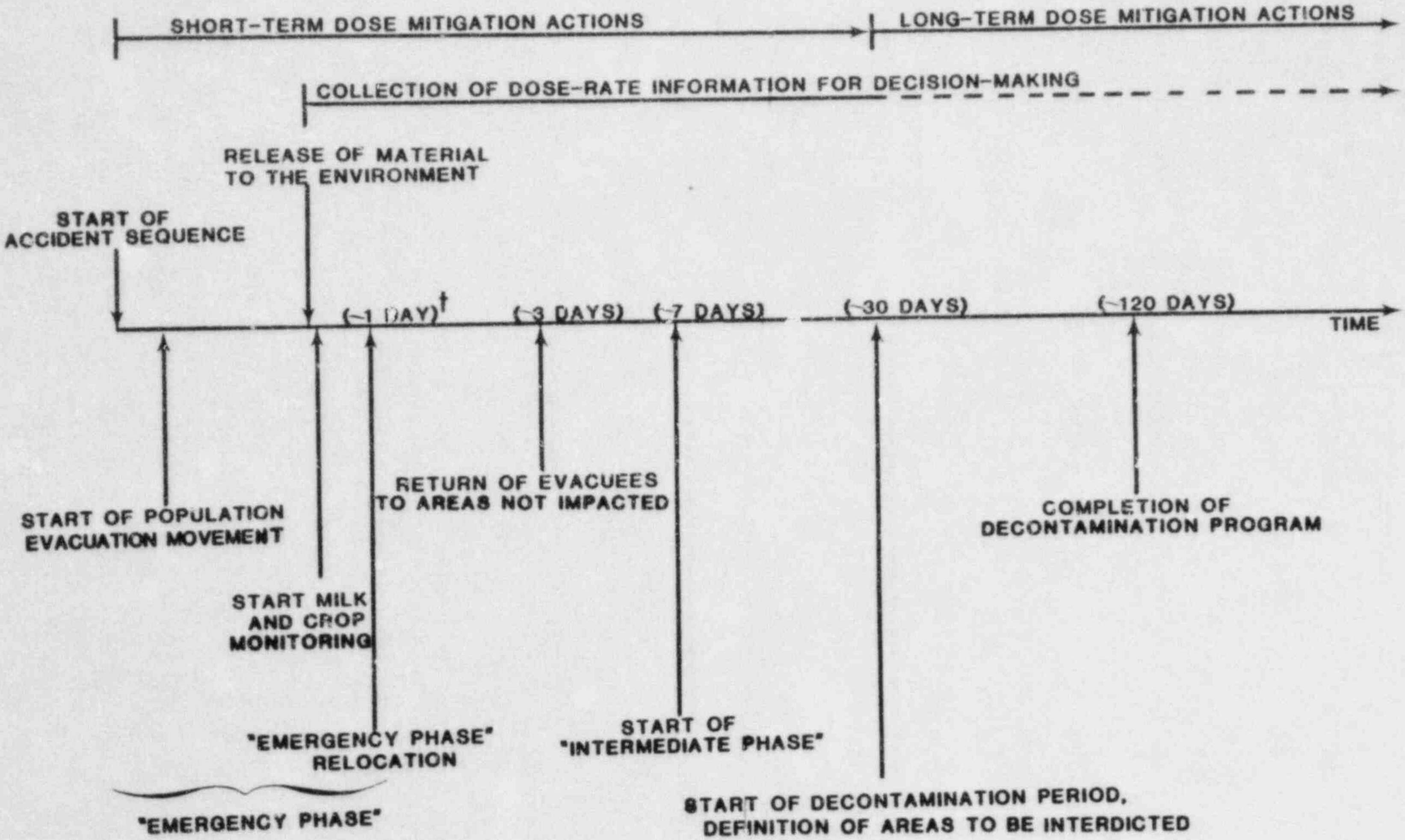


Figure 4.2 - Staged protective action implementation model used for estimating offsite costs.



†APPROXIMATE TIME AFTER DEPOSITION OF MATERIAL IN AN AREA

determine the need for agricultural product disposal.

As improved information becomes available concerning areas affected by a release of radioactive material, individuals initially evacuated should be allowed to return to areas not impacted. This is accounted for in the cost estimates in the new models. After improved information becomes available concerning dose-rates in affected areas and the decay of surface-deposited radionuclides with time, a second projected individual dose may be used to determine those areas where high dose-rates prohibit reentry of the population. This time period is referred to as the "intermediate phase" of protective action implementation in the model. A projected individual dose from groundshine exposure during this period is compared to a criterion for continued relocation from impacted areas.

After time is available to accurately determine the dose rates in affected areas, a projected long-term individual dose from exposure to surface-deposited materials is used to determine those areas which require decontamination or interdiction. Interdiction costs are estimated for those areas where decontamination efforts cannot reduce dose rates to acceptable levels. Costs of decontamination and doses to workers are estimated in those areas where decontamination efforts can reduce dose-rates to acceptable levels. The cost of population relocation as necessary during the decontamination process is accounted for.

The modeling of staged protective measure implementation is used to provide realistic estimates of the costs of post-accident population protective measures. The projection of doses over multiple time periods accounts for the durations of protective measures which may be necessary for short- and long-lived radionuclide releases. The staged implementation of offsite protective measures after severe LWR accidents is considered to be realistic because perfect information would not be immediately available in post-accident situations, and dose-rates may change rapidly with time.

4.4 NEW OFFSITE COST MODELS

New models have been developed for estimating the costs of offsite protective actions and radiation-induced health effects after severe LWR accidents. The models will be incorporated into the consequence model in the MELCOR series of risk assessment codes to estimate the offsite economic impacts of accidents. The cost of population evacuation, temporary relocation, agricultural product disposal, land and property decontamination, land interdiction, permanent population relocation, and health impacts which may be incurred after an accident are included in the models. The models developed for estimating each of these cost components are described in this section. The symbols used in the discussion of the new offsite cost models are defined in Table 4.1.

4.4.1 POPULATION EVACUATION COSTS

Two important protective measures which may be implemented during a serious reactor accident are evacuation or sheltering of the population in the immediate vicinity of the plant. The costs of sheltering individuals in preparation for and during the passage of a cloud of radioactive material are assumed to be negligible. Sheltering in homes or in places of work is a relatively non-disruptive measure which can be rapidly implemented and lasts for very short time periods. The costs of possible relocation following the sheltering period are included in the discussion of "emergency phase" relocation costs.

The costs of immediate evacuation are estimated in the new model using:

$$C_{ev} = P_{ev} \bullet t_{ev} \bullet [E+(I \bullet R)] \qquad (4.1)$$

where

C_{ev} = the cost of the evacuation ($).

P_{ev} = population in the user specified area to be evacuated (number of persons).

t_{ev} = duration of evacuation, measured in the number of days for individuals to return to unaffected areas (days).

E = cost of food, lodging, and transportation for each evacuee ($/evacuee-day).

I = national average per-capita personal and corporate income ($/person-day).

R = ratio of region-specific to national average personal incomes.

The evacuation costs per person (E) include the costs of housing, food, and transportation using commercial or mass care facilities, and the cost of evacuation personnel to supervise the process. These costs were estimated using a 1974 study of evacuation risks [Ha74]. The costs from this report have been updated to 1982 dollars in Table 4.2 using housing, food, transportation, and military pay indexes for evacuation super-

Table 4.1

Symbols Used in Offsite Model Discussion

Symbol	Units	Definition
A	[acres]	Area affected by protective action
C_c	[$]	Cost of crop disposal
C_d	[$]	Cost of decontamination program
C_{dl}	[$]	Portion of decontamination program costs for labor
C_{dr}	[$]	Cost of population relocation during decontamination
C_{ep}	[$]	Cost of population relocation during "emergency phase"
C_{ev}	[$]	Cost of population evacuation
C_h	[$]	Cost of population health effects of type j
C_i	[$]	Cost of land interdiction
C_{ip}	[$]	Cost of population relocation during "intermediate phase"
C_m	[$]	Cost of milk product disposal
DD	[man-rem]	Whole-body groundshine dose to decontamination workers
DF_f	[$/acre]	Cost of farm area decontamination by factor f
DMY	[man-years]	Man-years of labor required in decontamination program
DR_f	[$/person]	Cost of residential, business, and public property decontamination by factor f
DT	[rem]	Individual dose from constant exposure during the decontamination period
DW	[$/man-year]	Decontamination worker salary
DY	[dimensionless]	Fraction of farm sales from dairy products
E	[$/person-day]	Cost of food, lodging, and transportation for relocated individuals

Table 4.1 (cont.)

Symbol	Units	Definition
FF	[dimensionless]	Fraction of area used for farmland
FI_f	[dimensionless]	Fraction of farm value in improvements
FI_r	[dimensionless]	Fraction of non-farm value in improvements
FL_f	[dimensionless]	Fraction of farm decontamination cost for labor
FP	[$/acre]	Annual farm product sales
FV	[$/acre]	Value of farm land and improvements
HC_j	[$/health effect]	Cost of health effect j
I	[$/person-day]	National average personal and corporate income per-capita
N_d	[# of workers]	Decontamination workers required for program
N_{h_j}	[# of health effects]	Number of population health effects from radiation exposure
ρ	[/year]	Depreciation rate for improvements in interdicted areas
P_d	[# of persons]	Population in area to be decontaminated
P_{dr}	[# of persons]	Population relocated during decontamination
P_{ep}	[# of persons]	Population relocated during the "emergency phase"
P_{ev}	[# of persons]	Population initially evacuated
P_{in}	[# of persons]	Population in area to be interdicted
P_{ip}	[# of persons]	Population relocated during "intermediate phase"
r	[/year]	Societal discount rate
R, RV_r	[dimensionless]	Ration of region-specific to national average per-capita personel income
RL_f	[dimensionless]	Fraction of non-farm area decontamination costs for labor

Table 4.1 (cont.)

Symbol	Units	Definition
RV_f	[dimensionless]	Ratio of region-specific to national average farm values
S	[dimensionless]	Season factor
t_d	[years]	Duration of decontamination program
t_{1ep}	[days]	Start of "emergency phase" relocation period
t_{2ep}	[days]	End of "emergency phase" relocation period
t_{ev}	[days]	Duration of evacuation for areas not impacted
t_{2ev}	[days]	End of evacuation period for areas not impacted
t_i	[years]	Duration of land area interdiction
t_{1ip}	[days]	Start of "intermediate phase"
t_{2ip}	[days]	End of "intermediate phase"
t_m	[years]	Duration of milk disposal
WF_f	[dimensionless]	Decontamination worker dose reduction factor for farm areas
WR_f	[dimensionless]	Decontamination worker dose reduction factor non-farm areas
V_f	[$]	Tangible wealth contained in farm areas
V_r	[$]	Tangible wealth contained in non-farm areas
VR	[$/person]	National average non-farm tangible wealth per-capita

Table 4.2

Costs of Evacuation Per Evacuee-Day (1982 $) [Ha74]

Commercial Care Facilities:

Housing	$ 16.90
Food	5.30
Transportation (Private)	2.40
	$ 24.60/evacuee-day

Mass Care Facilities:

Housing	$ 6.90
Food	3.70
Transportation (Mass)	1.30
	$ 11.90/evacuee-day

Evacuation Personnel (~2% of total # of evacuees)

Compensation	$58.00/day
Food, Housing, and Transportation	Same as evacuees

Total Weighted Cost - (E) (Based on 80% commercial care, 20% mass care facilities)	= $23.70/evacuee-day

vision personnel [Pr83,SA83]. The costs are weighted assuming 80% of evacuated individuals use commercial care facilities (motels, restaurants, and private cars), and 20% use mass care facilities [Nu75b]. Using these assumptions the average food, housing, and transportation cost per evacuee-day is approximately $24.

The lost wages of evacuees and the corporate income losses due to the evacuation of an area may be included in evacuation costs. This cost component is modeled by accounting for lost personal income (not including interest, dividends, and transfer payments) and corporate income and profits during an evacuation period. All income loss estimates are weighted by region-specific factors which are defined for each grid element to account for variations in population incomes. The national average personal income (minus dividends, interest, and transfer payments) plus corporate profits and interest is estimated to be $26 per person-day (1982 dollars) [Pr83,SA83].

For very short evacuation periods (~1-3 days) there may be sufficient flexibility in the economy so that lost productivity, wages, and profits can be largely recovered through increased activity after the evacuation has ended. Therefore, for short evacuation periods the costs of lost income and productivity may be excluded from evacuation cost estimates.

The new evacuation cost estimates can be compared to experience with evacuation costs from the TMI-2 accident in 1979. Many individuals living near the plant evacuated at some time during the accident progression and studies have been performed to evaluate the distance, cost, and total duration of population movement. It is estimated that ~15,000 persons evacuated during the TMI-2 event, each travelling an average distance of 100 miles, and staying away from home approximately 5 days [Fl80]. The costs incurred due to population evacuation were covered by offsite liability insurance. Approximately $1.2-2.0x10^6$ dollars was paid in claims to evacuees. Based on 15,000 evacuees and a five day stay, this corresponds to an average cost of $16-$26 per evacuee-day. This is in good agreement with the values derived for use in the new cost model. The study of TMI-2 evacuation costs reported no significant loss of income from the movement [Fl80].

4.4.2 EMERGENCY PHASE RELOCATION

It may be necessary to relocate individuals away from areas in which radionuclides have deposited after a severe LWR accident These individuals may have been evacuated before the release of material, in which case it is only necessary to extend their stay out of the area, or movement of additional individuals from contaminated areas might be required. As improved information is gathered concerning the dose rates from deposited radioactive material, individuals may be permitted to reenter those areas in which projected doses do not exceed unacceptable levels.

The new economic consequence model allows specification of the time period for integration of emergency phase groundshine doses, the criterion to which projected individual doses are compared, and the time period for temporary population relocation in areas where the specified criterion is exceeded. The protective action criterion for the "emergency phase" period is defined based on projections of individual doses from surface-deposited materials.

The costs of temporary population relocation during the emergency phase period are estimated including food, housing, transportation, and income losses:

$$C_{ep} = P_{ep} \bullet [E+(I \bullet R)] \bullet [t_{2ep} - \max(t_{1ep}, t_{2ev})] \qquad (4.2)$$

where

C_{ep} = cost of emergency phase population relocation from area ($),

P_{ep} = population affected in area (number of persons),

t_{2ep} = time of end of emergency phase relocation (days),

t_{1ep} = time of start of emergency phase relocation for areas where no evacuation occurred (days),

t_{2ev} = end of evacuation period for areas where evacuation occurred (days), or 0.0 if evacuation did not occur,

and the other parameters are defined in Table 4.1. The comparison between the end of the evacuation period and the start of the emergency phase relocation avoids double-counting evacuation and temporary relocation costs. For very short emergency phase relocation periods it may be appropriate to exclude wage and income losses.

4.4.3 INTERMEDIATE PHASE RELOCATION

A time period beyond the emergency phase is modeled in which it is anticipated that better information concerning dose fields would be available, the decision process for long-term protective actions would be started, and preparations for long-term actions would be made. Like the emergency phase, an individual dose projection is compared to the criterion for temporary population relocation from an area. All previously relocated individuals in areas not exceeding the intermediate phase criterion are assumed to resume normal activities in this period.

The cost of intermediate phase relocation from an area is estimated in a manner similar to emergency phase relocation costs:

$$C_{ip} = P_{ip} \bullet [E+(I \bullet R)] \bullet [t_{2ip}-t_{1ip}] \qquad (4.3)$$

where

C_{ip} = cost of intermediate phase relocation from an area (\$),

P_{ip} = population to be relocated from the area (number of persons),

t_{1ip} = time of start of intermediate phase relocation (days),

t_{2ip} = time of end of intermediate phase relocation (days),

and the other parameters are defined in Table 4.1. It is assumed that the intermediate phase relocation period does not overlap with the emergency phase relocation period in the model ($t_{1ip} \geq t_{2ep}$). As in the emergency phase period, it is likely that relocated individuals cannot continue normal productivity patterns and income is assumed to be lost during this relocation period. The parameter R can be defined for each spatial interval to estimate region-specific relocation costs.

4.4.4 AGRICULTURAL PRODUCT DISPOSAL

A model very similar to that employed in CRAC2 is used to estimate the costs of milk and crop disposal which may be necessary after severe LWR accidents. The method of projecting maximum individual doses from ingestion of crops and milk is discussed in the RSS [Nu75b]. The disposal criteria for milk and crops used in this study are identical with those used in the RSS.

4.4.4.1 Food (Crop) Product Disposal

Direct deposition of radionuclides on crops from releases which occur during the growing season can result in the need to dispose of the agricultural harvest which is affected. The cost of crop disposal in these cases is estimated using:

$$C_c = FF \bullet A \bullet FP \bullet (1.0 - DY) \bullet S \qquad (4.4)$$

where

C_c = cost of crop disposal ($).

FF = fraction of region which is farmland.

A = area where doses from ingestion of foods would be unacceptable (acres).

FP = average annual farm production (sales) in area ($/acre).

DY = fraction of farm sales from dairy products.

S = season factor, = 1.0 in growing season, = 0.0 outside of growing season.

It is assumed that crops in growth are disposed of in all areas which require the long-term protective measures of decontamination or land interdiction. Accidents which occur outside of the growing season result in no crop disposal costs. The parameters FF, FP, and DY are defined for each grid element in the consequence calculations. Dairy products are considered separately in the milk disposal cost calculations.

4.4.4.2 Milk And Dairy Product Disposal

Population dose levels from ingestion of milk could exceed protective action criteria after a release of radionuclides because dairy cows are extremely efficient collectors of radionuclides deposited on pastureland. The dose projection models and criterion used for projecting maximum individual doses from ingestion of milk are the same as those described in the RSS [Nu75b].

The cost of milk disposal when necessary is estimated using the following equation:

$$C_m = FF \bullet A \bullet FP \bullet DY \bullet S \bullet t_m \qquad (4.5)$$

where

C_m = cost of milk disposal ($).

t_m = time for radioactivity levels in milk to reach
acceptable levels for ingestion (years),

and all other parameters are defined in Table 4.1. The value of one year of dairy product production is assumed to be lost in all areas requiring the long-term protective actions of decontamination or land interdiction. For areas requiring only food pathway protective actions, the duration of milk interdiction is normally less than 90 days (.25 years). The parameters FF, FP, and DY can be defined for each spatial grid element. Iodine levels in milk and projected thyroid doses are normally limiting considerations for milk interdiction. Because cows are assumed to be fed with stored feed outside of the growing season, accidents occurring during this period result in no milk disposal costs.

4.4.5 LONG-TERM PROTECTIVE ACTIONS

After assessments of dose rates in various areas have been completed, it would be necessary to make decisions concerning acceptable doses over long periods of time (~years) and the return of populations to contaminated areas. The dominant long-term chronic exposure pathway is likely to be groundshine from surface-deposited radionuclides. Two effective methods of reducing long-term population exposure via this pathway are decontamination and/or land interdiction with permanent population relocation. Modeling techniques and equations used in estimating costs of these two population protective measures are discussed in this section.

The need for long-term protective actions is determined by projecting a long-term individual dose from exposure to surface-deposited materials and comparing this dose to a specified criterion for the implementation of population protective countermeasures. The time period for dose projection and the protective action criterion are flexible in the new economic model.

4.4.5.1 Decontamination Of Land And Property

Decontamination is a less disruptive measure than long-term interdiction of areas because after the cleanup process is completed normal activities can resume in the affected areas. Decontamination can restore much of the initial wealth and economic activity in an area without the need for permanently moving the population to new locations.

Recently much attention has been given to the potential effectiveness and costs of decontamination techniques after LWR accident releases [Wa82,Li83,Os83]. The experimental data which exist concerning the effectiveness of decontamination techniques are dependent on radionuclides, particle sizes, and the chemical forms characteristic of deposited materials. Little data exist which are directly applicable to the small particle sizes (~0.1-10 µm) and soluble materials which are anticipated in releases from most severe LWR accidents. The cost and effectiveness estimates for decontamination contain large uncertainties, and results of future experimentation with decontamination techniques should be used to update models for decontamination.

The cost estimates used in this study for various levels of decontamination effort in an area are taken from a detailed review of decontamination effectiveness and costs performed at Sandia National Laboratories (SNL) [Os84]. Cleanup cost estimates were provided for farmland and residential, business, and public property based on decontamination techniques which are currently feasible. The study also considered the large areas which may require decontamination after the worst accidents in defining the variety of decontamination techniques which could be employed.

The study estimated decontamination costs in farm areas based on low and high level efforts. The cost estimates for low level effort are based on plowing of grassland and cropland areas and reseeding of all grassland areas. Costs for high level efforts are based on deep plowing of grasslands and scraping and burial of contaminated cropland areas (deep plowing could do damage to the quality of cropland surface soil). The farmland decontamination cost and effectiveness values employed in the economic consequence model are presented in Table 4.3. Three levels of effort are specified in the economic model with cost estimates, labor cost fractions, and decontamination effectiveness (in terms of dose rate reduction factor) specified for each level of effort. The estimated worker dose reduction factor, which is the ratio of the estimated worker dose to the total dose from constant exposure to surface-deposited radionuclides during the decontamination period, is also shown in Table 4.3 for each level of effort. The dose reduction factors are estimated based on the shielding which may be afforded by tractors and other heavy equipment used in the farmland decontamination process.

Decontamination costs for non-farm areas were estimated in the SNL study on a per-capita basis. This approach was employed in the RSS economic consequence model and is appropriate for the new offsite cost models for the following reasons:

1. Tangible assets in an area requiring decontamination should be roughly proportional to the population in the area.

Table 4.3

Decontamination Cost and Effectiveness Values for Farm Areas [Os84]

Dose Rate Reduction Factor After Decontamination (f)	Approximate Costs ($/acre) ($DF_f$)	Fraction of Cost for Paid Labor (FL_f)	Worker Dose Reduction Factor (Estimated Worker Dose/Dose From Continuous Exposure) (WF_f)
3	160	.30	.10
15	440	.35	.25
20	480	.35	.33

2. The costs of decontamination should be roughly proportional to the total tangible assets requiring cleanup or disposal in an area.

3. Detailed analyses of decontamination costs based on land usage mapping and estimation of decontamination costs for specific area types is not justified for risk models because areas requiring decontamination are large enough that average values provide reasonable cost estimates. The large uncertainties inherent in estimates of reactor accident radionuclide release processes (source terms), atmospheric transport and deposition, decontamination effectiveness, and decontamination costs limit the usefulness of more detailed analyses.

The non-farm area decontamination costs and effectiveness values used in the new economic model are shown in Table 4.4. The decontamination cost estimates incorporate information on a multitude of possible methods to be used in the decontamination of non-farm areas, and have been weighted to account for residential, commercial and industrial, and public use land areas based on national average statistics. The methods to be employed for each level of effort and each type of area include combinations of decontamination techniques. However, dose rate reduction factors for decontamination techniques cannot generally be multiplied to account for combinations or repeated applications of cleanup techniques. The estimated factors for combinations of methods will generally be less than the product of factors for each individual decontamination method.

The total cost of the necessary decontamination program in an area is estimated by weighting farm and non-farm costs for the appropriate decontamination factor by the farm acreage and population in an area:

$$C_d = (FF \bullet A \bullet DF_f) + (P_d \bullet DR_f) \tag{4.6}$$

where

C_d = cost of decontamination program in an area (\$),

A = total area to be decontaminated in interval (acres),

DF_f = cost of decontamination of farmland by appropriate decontamination factor f (\$/acre),

P_d = population living in area before accident occurrence (persons),

Table 4.4

Decontamination Cost and Effectiveness Values for Non-Farm Areas [Os84]

Dose Rate Reduction Factor After Decontamination (f)	Approximate Costs (\$/person) (DR_f)	Fraction of Cost for Paid Labor (RL_f)	Worker Dose Reduction Factor (Estimated Worker Dose/Dose From Continuous Exposure) (WR_f)
3	2600	.7	.33
15	6900	.5	.33
20	7400	.5	.33

DR_f = cost of decontamination of residential, business, and public property by appropriate decontamination factor f (\$/person),

and the other parameters are defined in Table 4.1. Decontamination costs are not discounted because it is assumed that the program would be implemented as quickly as possible after accident occurrence. Although weathering and decay of radionuclides would provide incentives to delay the decontamination process, it is likely that migration and fixation of radionuclides onto surfaces in an area with time would make decontamination more difficult and costly. Also, delay of decontamination in an area prolongs the societal and economic disruption caused by the process. Therefore, the most effective approach is to complete decontamination of those areas which can be restored to acceptable levels as quickly as possible.

The portion of the decontamination program costs due to labor is estimated using the following equation:

$$Cd_l = (FF \bullet A \bullet DF_f \bullet FL_f) + (P_d \bullet DR_f \bullet RLf) \qquad (4.7)$$

where

Cd_l = the labor cost for the decontamination program in each area (\$),

FL_f = the fraction of farm decontamination cost for the appropriate factor f which is estimated to be paid labor,

RLf = the fraction of residential, business, and public property decontamination cost for the appropriate factor f which is estimated to be paid labor,

and the other parameters are defined in Table 4.1. The estimated labor cost fractions for each level of decontamination effort in both farm and non-farm areas are presented in Tables 4.3 and 4.4. These values are estimated based on average decontamination labor costs of ~\$10/man-hour [Os84]. The remainder of decontamination costs are based on necessary cleanup equipment and building materials.

The total man-years of effort required for the decontamination program in each area is estimated using:

$$DMY = \frac{C_{dl}}{DW} \qquad (4.8)$$

where

DMY = the total man-years of effort required in area,

DW = the average cost of decontamination labor (\$/man-year),

and the other parameters are defined in Table 4.1. The average cost of decontamination labor is estimated to be ~\$30,000 per man-year in this study (~\$10/hour for a 56 hour work week). This cost is estimated based on costs for military and disaster relief personnel. The total man-years of effort required is used to estimate the number of decontamination workers required to complete the decontamination program in a specified program duration:

$$N_d = \frac{DMY}{t_d} \tag{4.9}$$

where

N_d = the number of decontamination workers required to complete program in the estimated program duration (number of workers),

t_d = specified average time required to complete the decontamination effort (years),

and the other parameters are defined in Table 4.1. For severe accidents involving large areas to be decontaminated, many workers would be required to complete the decontamination program in a short time. Costs and time periods estimated for decontamination assume that combinations of military personnel, disaster relief agencies, and commercial personnel would be employed.

Doses incurred by decontamination workers during the decontamination effort are estimated in the model by accounting for the time workers will be in contaminated areas and possible shielding which could be afforded for various levels of decontamination effort:

$$DD = \frac{DT}{DW \bullet t_d}[(FF \bullet A \bullet DF_f \bullet FL_f \bullet WF_f) + (P_d \bullet DR_f \bullet RL_f \bullet WR_f)] \tag{4.10}$$

where

DD = the total dose incurred by decontamination workers in an area due to exposure to surface-deposited radionuclides (Man-Rem),

DT = the dose which would be incurred by an individual from constant exposure to surface-deposited radionuclides for the entire decontamination period (Rem),

WF_f = ratio of decontamination worker dose for appropriate level of effort in farm areas to individual dose from constant exposure during decontamination period,

WR_f = ratio of decontamination worker dose for appropriate level of effort in residential, business, and public areas to individual dose from constant exposure during decontamination period,

and the other parameters are defined in Table 4.1.

The dose ratios for decontamination workers in residential, business, and public areas (WR_f) are estimated for all levels of effort assuming that workers work 8 hour days, are constantly working in areas yet to be decontaminated, and leave the impacted area at the end of each day. No dose reduction is afforded by machinery shielding in non-farm areas since much of the effort is likely to be manual labor and the radionuclides of concern are hard gamma emitters. The farm area dose ratios for decontamination are slightly reduced because the machinery involved in the cleanup adds distance and shielding between the radionuclides and the workers exposed. Worker beta doses from radionuclides deposited directly on skin and doses from worker inhalation of resuspended radionuclides are not included in the model. Worker protective measures would be taken to effectively eliminate these exposure pathways. The dose to decontamination workers is included in the estimates of total population exposure and chronic health effects. The estimated decontamination worker dose ratios for each level of effort are presented in Tables 4.3 and 4.4.

Dose rates in certain areas might warrant the temporary relocation of the population during the decontamination and cleanup process. Two options are included in the new economic model to account for costs of relocating individuals during the decontamination process. The first option includes a check to determine whether or not the long-term protective action criterion would be exceeded if individuals lived in areas decontaminated during the cleanup process. If the long-term protective action criterion is exceeded from inhabitation of the area during decontamination, then the population is relocated during the decontamination process. The second option estimates decontamination factors necessary to meet the long-term protective action criterion with the assumption that all individuals are relocated from areas to be decontaminated during the cleanup process. The number of individuals to be relocated during decontamination can be significantly different for the two assumptions.

The cost of relocating individuals during the decontamination process is estimated using:

$$C_{dr} = P_{dr} \bullet [E + (I \bullet R)] \bullet t_d \bullet 365 \qquad (4.11)$$

where

C_{dr} = the cost of population relocation from an area during the period of decontamination ($).

P_{dr} = the population to be relocated from the decontamination area (number of persons).

t_d = the average time from start to completion of the decontamination process (years).

and the other parameters are defined in Table 4.1. The time from start to completion of the decontamination process is specified to represent an "average" for those areas to be decontaminated. It is assumed that normal activity resumes in an area after the decontamination program has been completed.

The new economic consequence model estimates attributes of the decontamination program which can be examined with cost estimates to identify potential resource and logistic limitations for severe LWR accidents. The model includes estimates of worker doses in chronic health effect and health effect cost calculations. A large scale decontamination program is likely to create additional employment in specific industrial sectors due to the labor, building materials, and equipment needs of the effort.

4.4.5.2 Land Area Interdiction

In those areas where surface-deposited activity levels exceed unacceptable levels and decontamination by the maximum achievable factor is not projected to reduce individual doses to acceptable levels, land interdiction is implemented as a population protective measure. The population originally inhabiting the area is assumed to be permanently moved to an alternate location. After decay, weathering, and possible future decontamination efforts, it is possible that individuals would move back to the area. Land interdiction costs are estimated using present value discounting concepts and the important assumption that some portion of the initial value of the property may be recovered if the area can be used in the future.

There are two basic methods for estimating the economic loss due to land interdiction after a release of radioactive materials. The first method measures the production rate (or rate of output) of the land and all tangible assets contained within a region, and integrates this value over the interdiction or some other specified time period. This approach is used in both the BEA economic model and the ECONO-MARC consequence model. The BEA analyses predict job losses which occur in the first year of land interdiction. The ECONO-MARC model estimates the contribution of an area to Gross Domestic Product and integrates the total production loss over the entire period of land interdiction. One problem with this approach is that all attributes of an area which contribute to societal productivity are not measured in Gross Domestic Product. For example, a parcel of land may be productive through a scenic view which it provides. This productivity is rarely measured through market transactions, and is not included in GDP. Another problem with integrating production losses to estimate interdiction cost is that production can often resume in other areas or from new capital investments. Some time period for production resumption must be specified to estimate a total cost of land interdiction. Finally, production integral approaches do not accurately account for the loss of accumulated tangible assets which may be contained in an interdicted area. Past investments in tangible goods may not be accurately reflected by integrating future production losses.

A second approach to estimating the cost of land interdiction is to use the concept of wealth to estimate the total present value of land and tangible assets in an area. Wealth provides the capability to produce output and income (including non-market output and income) over a succession of accounting periods [Ke76a,Ke76b]. The wealth of the United States has grown constantly over the lifetime of the nation due to continuous investment in tangible goods to increase productive capacity. Studies have examined both the human and non-human wealth of the nation to determine patterns of investment and wealth formation. If it were possible to measure the total productive output of an area, including output contributors like scenic views which are rarely measured directly in market transactions, then the present discounted value of all future output from all items would equal net tangible wealth. Given perfect measurement techniques and using the broad definition of production, wealth and discounted future production should be equal.

CRAC2 employs a wealth model for estimating societal costs of land interdiction. This approach is preferable to the integrated production output approach because of the better estimation of total costs of land area interdiction. Also, implicit in the wealth model is the assumption that investment can create new wealth in a different area. The wealth loss in an interdicted area can be estimated using available data for past integrated capital investments. Finally, wealth loss estimates are comparable to losses from historical events which have resulted in significant costs. Fires, auto accidents, tornadoes, and hurricanes are examples of events which result in tangible wealth losses. The costs of these events result from the costs incurred to restore the tangible property to its initial (or often an improved) condition.

Wealth and present-value concepts are used to estimate interdiction costs in the new economic model. Non-tangible financial assets such as stocks, bonds, and precious metals are not included in cost estimates since these items would generally not be affected by a reactor accident. Therefore, only land and tangible asset wealth values need to be included in the analysis.

The wealth value of land and tangible assets contained within an area can be measured using two approaches. The first approach is to estimate the market value of each item as recorded in market transactions. This approach has been used in the recent Census of Governments to estimate the average real estate values in various regions of the country [Ce77]. This approach is useful for assets which are often traded in the market, but is inappropriate for those societal assets which are seldom or never valued in market transactions (e.g., sewer systems, public transit systems, national parks). For these assets it is most appropriate to measure wealth by summing total past investment in these items and subtracting net depreciation and losses (from accidents, disasters). Possible appreciation of wealth can also be taken into account. Accounting for the net wealth stock formation using this approach is tedious because investment streams from the start of the creation of wealth in an area must be included.

The BEA is in the process of completing a multi-year study which has employed the net stock formation approach to estimate the total tangible wealth of the United States [Lo72, Mu74, Mu76, Mu76b, Mu79, Mu80, Mu82c, Yo71]. Investment streams dating back to the 1700's have been summed, depreciated, appreciated, converted to current dollars, and net losses subtracted to estimate the net tangible wealth contained in the U.S. versus time. The project has relied heavily on the National Income and Product Accounts to estimate investment in new tangible wealth. The current stocks of private and residential wealth, government wealth, consumer durables, and business inventories have been estimated in the study. Research to estimate land wealth is underway to complete the estimation of total net tangible wealth in the nation. Once these estimates are complete, net tangible wealth estimates can be easily updated in future years by using national income and product accounts. Results of a previous study performed by The Conference Board are used in estimating the wealth of land in the U.S. for this study [Ke76].

The new economic model estimates wealth contained in farm areas by using:

$$V_f = FF \bullet A \bullet FV \bullet RV_f \qquad (4.12)$$

where

V_f = total farm wealth in an area from land and improvements ($),

FV = average market value of farm land and structures in nation($/acre),

RV_f = ratio of region-specific to national average market value of farm land and structures in the area,

and the other parameters are defined in Table 4.1. The values for FF and RV can be specified for each spatial interval in the consequence calculations. Farm land and structure values are available in the 1978 Census of Agriculture and have been updated to 1982 dollars using a farm land and structure value index [Ce78,SA83].

The total tangible wealth of residential, business, and public properties in an area is estimated using:

$$V_r = P_{in} \bullet VR \bullet RV_r \qquad (4.13)$$

where

V_r = Total residential, business, and public wealth in an area ($),

P_{in} = total population in area affected (number of persons),

VR = National average tangible wealth (not including farm land or structures) per-capita ($/person),

RV_r = Ratio of region-specific to national average personal income in area.

Total tangible wealth estimates are not available on a region-specific basis. Therefore, the detailed national wealth estimates which are available from the recently completed studies of national wealth are allocated to affected areas on a per-capita basis. The wealth estimate is further weighted by region-specific personal income statistics since wealth to some extent represents income producing capacity. Areas with high incomes are likely to have more tangible wealth and more potential for wealth creation than low income areas. Interdiction cost treatment based on per-capita allocation is consistent with the level of detail treated in the consequence model. Other more complex methods of wealth allocation could be employed but are not justified in this type of analysis.

The estimates of wealth included in each interdicted area are depreciated to account for the societal cost of a period of land interdiction. It is likely that buildings and other improvements would depreciate at a faster rate than land in an interdicted area due to lack of maintenance and repairs [Nu75a]. A depreciation rate of p=.20/year is used for improvements in both farm and non-farm areas. The cost of interdiction of an area is estimated by subtracting the value of land and improvements when reclaimed after interdiction from the initial present value of the area:

$$C_i = (V_r+V_f)-e^{-rt_i}\left\{V_f\left[(1.0-FI_f)+FI_f\bullet e^{-pt_i}\right] + V_r\left[(1.0-FI_r)+FI_r\bullet e^{-pt_i}\right]\right\} \qquad (4.14)$$

where

C_i = Societal cost due to land area interdiction ($).

V_f = Initial total tangible wealth in farm land and improvements in the area affected ($).

V_r = Initial total tangible wealth in non-farm land and improvements in area ($).

FI_f = Fraction of farm wealth in improvements in area.

FI_r = Fraction of non-farm wealth in improvements in non-farm portion of area.

p = Depreciation rate for improvements during the interdiction period (/year).

r = Societal discount rate used in analysis (/year).

t_i = Total time land area is interdicted (years).

The parameters FI_f, FI_r, and t_i can be defined for each spatial interval in the new economic model. The interdiction period is estimated based on the time period necessary for radioactive decay, weathering, and decontamination efforts to reduce the integrated long-term population dose to an acceptable level. If an area is predicted to be interdicted for more than 30 years, the entire initial wealth in the area is assumed to be lost. The costs of decontamination, interdiction, or a combination of these measures is estimated for each area where long-term actions are required and the least cost alternative is included in cost and health effect estimation. Decontamination is generally predicted to be the most cost effective protective measure if the population can be returned to the area immediately after the cleanup process.

It is likely that personal and corporate incomes would be lost for some period due to permanent population relocation from interdicted areas. Permanent relocation costs are estimated based on personal income losses for a 100 day transition period and corporate income losses for a 180 day transition period [Pr83, SA83]. Costs of moving belongings to new areas should be small since all tangible property in the interdicted area is assumed to be replaced. Therefore, the cost of permanent relocation results entirely from temporary income losses in the model. This cost is estimated to be ~$4000/person in the interdiction area, which is small compared to wealth loss predictions.

4.4.6 HEALTH EFFECTS COSTS

Studies [Ac73,Co81,Ne83] have been performed to estimate the societal costs of health effects which result from various risk sources. There are two general approaches which have been used to estimate the costs of health effects. The first approach estimates individual or societal preferences for avoidance or reduction of health effect risks. Studies [Ac73, Co81] using this approach have concluded that preferences for health effect risk reduction are dependent upon the activity or circumstance which leads to the risk. Estimating health effect costs through evaluation of preferences does have the advantage that effects which cannot be quantified directly (e.g., mental anguish, pain, suffering) should be appropriately included in individual preferences. However, the interview process necessary for elicitation of risk reduction preferences can be difficult and costly.

A second approach to health effect costs evaluates the loss in human capital (or human wealth) induced by health effect occurrence. This approach values the loss in productivity of an individual caused by the incidence of a health effect. The loss in productivity can be estimated by discounting an individual's expected lifetime loss of earnings due to the incidence of a particular health effect. The advantage of this approach is that estimation of costs is straightforward. However, the estimated health effect cost from this approach includes only purely economic costs, and in no way reflects individual preferences for avoidance of pain, suffering, or anguish. Health effect values calculated using this approach are incorporated into the new economic model to represent the societal economic losses due to the incidence of radiation-induced health effects at offsite locations.

In using the human capital approach to estimate the societal losses due to health effect occurrence, it is necessary to add the direct societal costs of health care to estimate the total cost of radiation-induced health effects. A previous study has estimated the direct (medical care) and the indirect (human capital) costs of possible radiation-induced health effects after severe LWR accidents [Ne83]. The study used detailed calculations to account for the age distribution and earnings distribution of the population, average medical care costs, and health effect risk versus time after radiation exposure to estimate the costs of specific types of health effects included in the CRAC2 consequence calculation code. A computer model was developed in the study to estimate health effect costs for specific consequences and discounting assumptions. Estimates of base-case radiation injury, cancer, and genetic effects costs from the study are shown in Table 4.5. Early fatality costs were not directly estimated in the study. The cost estimates are based on a typical population exposed to radiation after an LWR accident, a 4%/year real societal discount rate, and a 1%/year real growth rate in medical costs and earnings.

The costs of radiation-induced health effects are estimated in the new economic model by multiplying the expected number of health effects by average societal costs for each type of health effect:

$$C_{h_j} = N_{h_j} \bullet HC_j \qquad (4.15)$$

where

C_{h_j} = Total medical care and human capital cost of radiation-induced health effects of type j ($),

HC_j = Average medical care and human capital cost of specific health effect j ($/effect),

N_{h_j} = Total number of health effects of type j predicted to occur in area (number of effects).

The health effect estimates included in the new economic model include early fatalities resulting from early exposure*, early injuries resulting from early exposure, latent cancer fatalities resulting from early exposure, latent cancer fatalities resulting from chronic exposure, thyroid health effects resulting from total exposure, and genetic effects resulting from total exposure. The total cancer fatality costs include leukemia, lung, gastrointestinal, breast, bone, and all other fatal cancers from exposure. The health effect costs also include the costs of non-fatal effects. All health effect cost predictions in the new economic model reflect short- and long-term protective actions which are assumed to be implemented in each area after the accident, including doses incurred by decontamination workers when appropriate.

The new economic model estimates the societal costs of radiation-induced health effects using the human capital approach with estimates of direct costs of medical care. These cost estimates have been taken from a previous study of health effect costs for severe LWR accidents (Table 4.5) [Ne83]. The values represent only societal economic losses, and do not in any way reflect true individual preferences for risk reduction from radiation-induced health effects. Therefore, the health effect costs presented in this report represent lower-bound estimates. Dollar values for health effects reflecting societal preferences for risk avoidance could be incorporated into the new economic models. However, it is questionable whether true societal preferences can be appropriately represented using constant dollar values for health effects [Ke80a, Ke80b, Ke80c].

4.5 OFFSITE COSTS NOT INCLUDED IN THE NEW ECONOMIC MODELS

4.5.1 OFFSITE LITIGATION COSTS

After any severe accident resulting in a release of radioactive material it is likely that parties affected at offsite locations will seek compensation from liable parties through litigation. As discussed in section 3.10 on onsite litigation costs, the societal costs of the litigation process itself are likely to be small. However, to individual parties involved in litigation, the costs of the litigation process could be large and should be included in analyses for these groups. Most damage rewards for offsite parties represent transfers of losses which are included in direct societal cost estimates and do not result in additional net costs. Legal awards for costs

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* Five times the average value of a radiation injury from the health effect cost study [Ne83] is used as an estimate of early fatality costs in this study (~\$500,000). The conclusions of this study are insensitive to this value.

Table 4.5

Estimates of Economic Costs of Radiation-Induced Health Effects*[Ne83]

Health Effects (j)	Medical Care and Productivity Costs (103$) HC_j
Radiation Injuries	
Prodromal	1
Bone Marrow	129
Lung	76
Gastrointestinal	100
Prenatal	281
Average	118
Cancers	
Leukemia	131
Lung	27
Gastrointestinal	25
Breast	24
Bone	118
All Others	24
Thyroid	2
Genetic Effects	52

*Cost estimates are based on 4% discount rate and 1% real growth rate in medical care costs. No estimates for early fatality costs are presented in [Ne83].

not quantified could be included by augmenting the dollar costs used in this study. No societal costs for offsite litigation cases are included in this study.

4 5.2 SECONDARY IMPACTS

It is possible that an accident could have economic impacts outside of the area directly impacted by population protective countermeasures. Also, increases in the cost of electricity in specific regions could ripple through the economy affecting prices, employment, incomes, and productivity in a region. These secondary costs or ripple effects of accidents are discussed in this section.

One problem in discussing secondary impacts is that the magnitude of impacts depends on the size of the area included in the analysis. Negative impacts in one specific impacted region are often balanced by positive impacts in another area. For example, increased labor costs on the East coast of the U.S. could lead to gradual industry relocation and increased economic activity on the West coast of the country. This type of secondary impact results in small net societal costs due to the balancing of costs and benefits in the economy. However, when viewed from a regional perspective, this secondary impact of higher labor costs could be important.

The potential secondary impacts of population protective measures such as milk disposal, crop disposal, decontamination, and land interdiction have been estimated as part of the Bureau of Economic Analysis study of reactor accident consequences using input-output analysis techniques. The results and limitations of the BEA analyses are discussed in detail in Appendix C. Analyses for various reactor sites indicate that secondary impacts of population protective measures will generally be small compared to the direct cost of measures taken in the physically affected areas. However, the BEA analyses did not estimate the potential secondary impacts (which may largely be beneficial) of a large decontamination program after severe accidents. In general, it is likely that the flexibility in the national and regional economies which is observed after most disasters would result in a lessening of the secondary impacts from population protective measures [Pe77,ED74]. It is possible that specific instances could be found where secondary impacts are important.

Another potential source of secondary impacts after accidents which result in reactor plant shutdown is the increased real cost of electricity in a particular region. This potential impact has been discussed in studies of the costs of shutting down operating reactors [St81b]. Increased electricity prices in a region can have adverse effects on employment, income, and production in the area. These effects are normally estimated using simple multipliers. The multipliers for regional impacts of higher electricity prices have ranged from negative values (indicating a net benefit to electricity price increases) to positive values of 5.5 (indicating that secondary impacts are 4.5 times as great as the direct costs). These multipliers are normally estimated using region-specific input-output or econometric models to predict the total regional impact of an energy price increase. From the societal perspective, it is likely that secondary impacts will be reduced through cancellation of costs and benefits in different regions.

Secondary impacts of severe reactor accidents are not explicitly estimated in this study because costs are estimated from the societal perspective and the level of detail and cost necessary to estimate secondary impacts for a specific event are not warranted for risk analysis applications. It is likely that secondary costs will largely be cancelled by benefits when viewed from the societal perspective. Results of input-output analyses indicate that the secondary impacts of population protective measures should be generally small. This view is supported by data from disaster experience [Pe77,ED74]. The impacts of electricity price increases due to reactor shutdown could be serious in a particular region, but are likely to be balanced somewhat by positive effects in the society viewed as a whole. Further research in estimating secondary costs should be considered to estimate the complete societal costs of severe accidents. No societal costs for secondary impacts are included in this study.

4.6 COMPARISON OF CRAC2 AND NEW ECONOMIC MODELS

A flowchart of the new offsite economic consequence model is shown in Figure 4.3. The model estimates direct costs of population protective measures and public health impacts at offsite locations after reactor accidents, and incorporates estimates from onsite cost models in the calculation of distributions of economic risks. A flowchart of the CRAC2 economic model is shown in Figure 4.4. The major differences between the new model and the CRAC2 model are:

1. The new model accounts for short-term emergency phase and intermediate phase population movement costs not included in the CRAC2 model.

2. The model accounts for population relocation which may be necessary during the decontamination and cleanup process.

Figure 4.3 - Flowchart of new economic model.

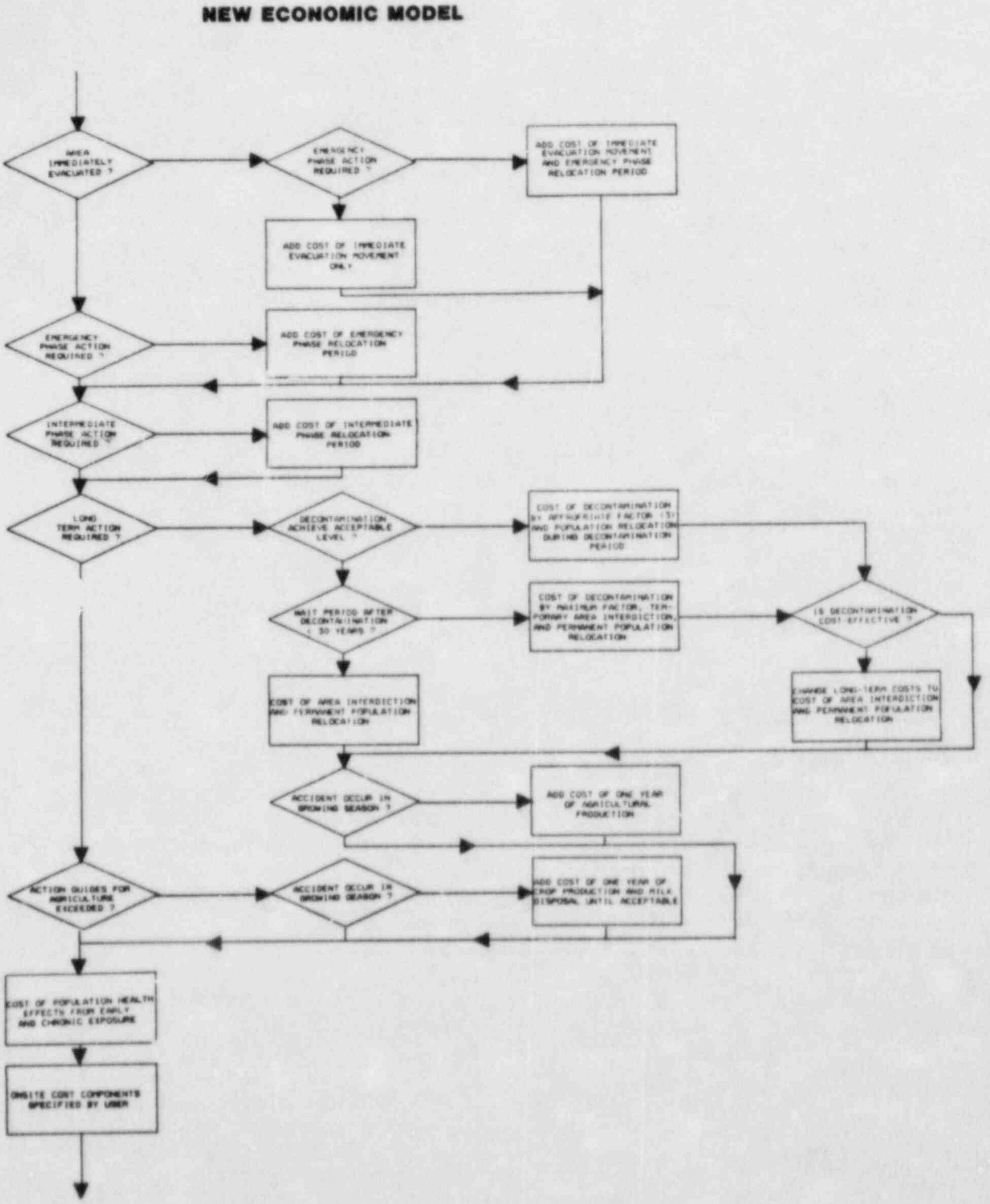
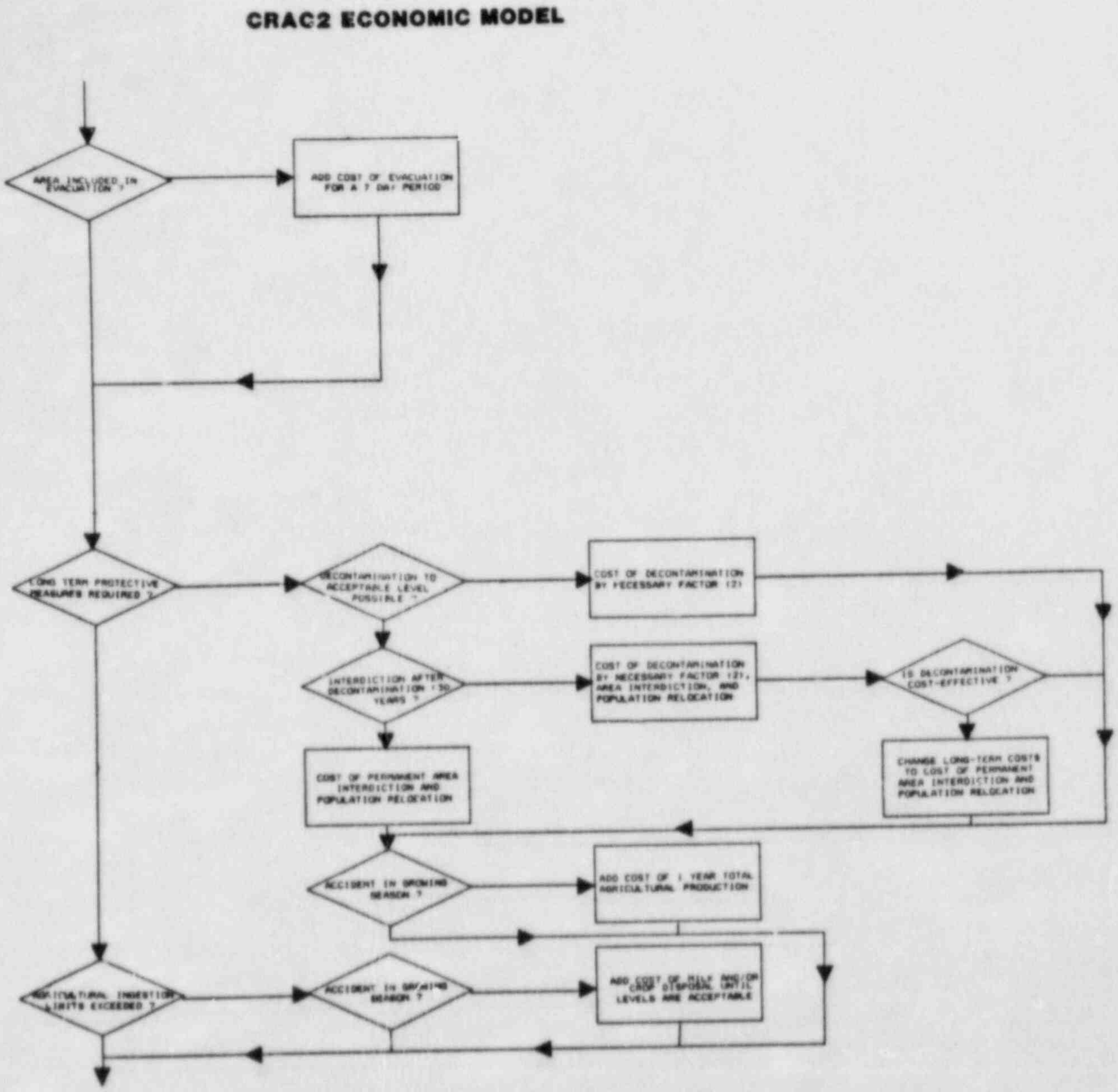


Figure 4.4 - Flowchart of CRAC2 economic model.



3. The model allows user-definition of all protective action criteria to be applied in post-accident situations.

4. Most economic parameters can be specified on a spatial interval basis for site-specific calculations.

5. All cost values have been updated and expressed in 1982 dollars.

6. Additional attributes of the decontamination program are estimated in the new economic model. Dose to decontamination workers is estimated and included in the health effect calculations.

7. Dose calculations correspond closely to the protective actions which are implemented in each area. This provides the ability to estimate both costs and benefits of various protective actions.

8. Health effect costc and onsite cost components can be included in the estimation of total accident costs.

4.7 PROTOTYPE ECONOMIC MODEL USED IN THIS STUDY

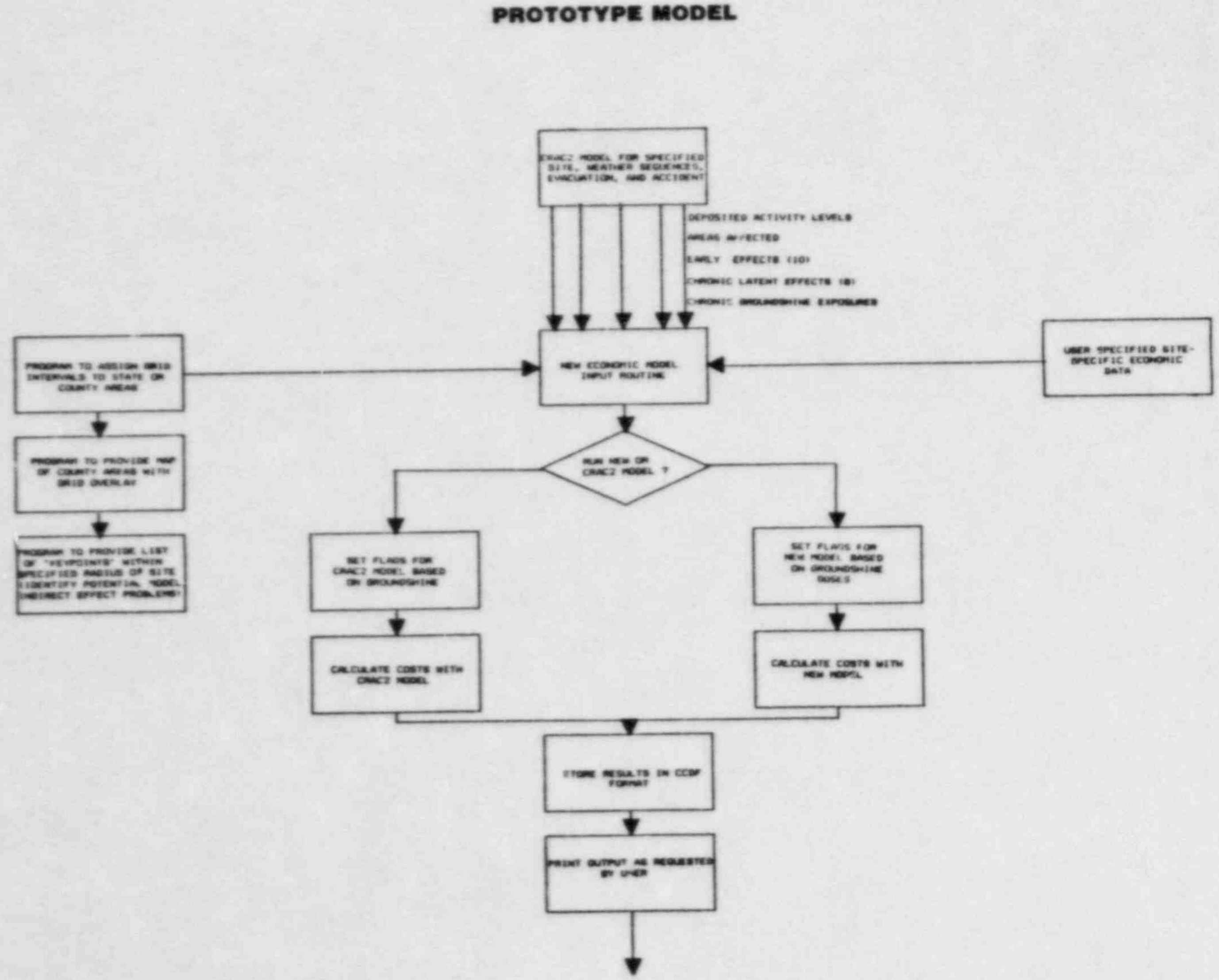
A prototype of the new economic model has been developed as part of this study for development and testing purposes. The prototype model uses radionuclide concentration data from CRAC2 analyses as input in estimating accident economic consequences. A flow diagram for the prototype model is presented in Figure 4.5. The new economic models are currently being incorporated into the MELCOR series of risk assessment codes.

The prototype economic model includes subroutines to calculate individual doses from exposure to surface-deposited materials for comparison with offsite protective action implementation criteria. Many of the dose projections necessary for the new economic models are not included in the CRAC2 code. Appendix E contains a discussion of the equations employed in the prototype model to integrate individual exposures over various time periods.

4.8 CONCLUSIONS

The new offsite economic model can be used to estimate the costs of protective actions after any accidental release of material from an LWR facility. Since routine forced outage events result in negligible offsite consequences, there is no need to employ the offsite cost models to estimate costs for

Figure 4.5 - Flowchart of prototype offsite economic consequence model.



routine forced outage events. The new offsite cost models are employed in the estimation of severe accident consequences in Chapter 6 of this report. The model predictions are compared to previous predictions from the CRAC2 economic models in Chapter 6.

CHAPTER 5

ECONOMIC RISKS FROM SMALL CONSEQUENCE LWR EVENTS

The frequencies and costs of routine LWR outage events are combined in this section to estimate the economic risks from these events. Plant outage data are used to estimate the frequency of LWR forced outage events and the severity (or duration) of forced outage events conditional upon forced outage occurrence. Onsite replacement power and repair costs for routine forced outage events are estimated using the onsite cost models described in Chapter 3. Offsite costs are negligible for this category of operational events. The possible benefits resulting from the reduction of the frequency and duration of forced outage events are discussed.

5.1 LWR FORCED OUTAGE EVENTS INCLUDED IN CATEGORY I (SMALL CONSEQUENCES)

The primary goal of this study is to estimate the economic risks posed by abnormal occurrences or unusual events which occur at U.S. nuclear power reactors. Therefore, scheduled plant events such as refueling outages are not included in estimates of LWR economic risk from plant operation. The most important contributor to onsite costs from routine forced outages is the cost of replacement power due to plant outage time. Events which do not result in plant outage time are not considered in this study. These events contribute minimally to the economic risk from plant operation. Any events which result in core-damage or radioactive contamination of plant facilities are included in event categories II and III and are discussed in Chapter 6.

5.2 DATA BASE FOR LWR FORCED OUTAGE EVENTS

A data base was formed in this study to estimate U.S. LWR forced outage frequencies by using the annual reports of nuclear plant operating experience published by the NRC [AE74, Nu77b, Nu77c, Nu79a, Nu79b, Nu81a, Nu81b]. Each NRC report presents operating statistics and data for each plant in commercial operation at the end of a given calendar year. The data base formed for this study includes calendar years 1974 through 1980.

Each individual reactor plant outage which occurred during a calendar year is summarized in the NRC data base. The plant outage data include the duration of the outage (in hours), the type of outage (forced or scheduled), a description of the nature of the outage, the cause of the outage, the reactor shutdown method, and the plant components involved for each operating U.S. LWR outage. The data are used to develop estimates of the frequency of forced outage events and outage durations for LWRs. The cause of each outage is also considered in the formation of the distribution of forced outage frequencies in this study.

Unfortunately, inclusion of all forced outage events in the formation of the outage distributions is not appropriate for the purpose of this study. Events such as regulatory forced outages resulting from NRC mandates for plant shutdown are included in the NRC data base as forced outage events. Also, the distinction between forced and scheduled outages in the NRC data base is sometimes questionable. Therefore, the cause of each individual forced outage event was reviewed and only those events which resulted from plant operation are included in the formation of distributions in this study. Judgments regarding the scheduled or non-scheduled nature of forced outage events were applied to the data base. It is necessary to take proper account of outages which extend across calendar years by summing the outage contributions into a single total outage duration. This summation is not performed in the NRC event summaries, but is included in this report. All regulatory forced outages are excluded from the estimation of economic risks from operation, but are discussed separately in Appendix B.

The nuclear plant operating experience data base formed for this study is discussed in Appendix A. The data base contains information concerning the plant name, calendar year, the date of the start of plant commercial operation, the date of plant permanent shutdown (where applicable), the reactor type, the NSSS vendor, the reactor electrical rating, the total number of forced outages occurring within each reactor-year, and the duration (in hours) of each forced outage event which occurred during each calendar year from 1974 through 1980.

5.3 DISTRIBUTION OF LWR FORCED OUTAGE FREQUENCIES

The newly developed plant operating experience data base including 367 complete reactor-years of operation is used to estimate the frequency of forced outage events at operating LWR Plants. Partial years of operation, which occur immediately after plant startup (i.e., the year of the start of commercial operation) are excluded from the analysis because of difficulty in data interpretation*. The data for the total number of

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* Some nuclear plants report outages which occur before the start of plant commercial operation. Therefore, any partial years of experience at the time of plant startup are excluded from the analysis.

forced outage events occurring in a given plant year are statistically analyzed and tests for fits of standard probability distributions are performed.

The statistical parameters of the data set used to estimate the forced outage frequency using equal weighting of all reactor-years are shown in Table 5.1. The total number of forced outage events included in the set is 3681, resulting in a mean estimate of 10.0 forced outage events per reactor-year. The minimum number of forced outage events observed in a reactor-year is 0, with a maximum of 52 forced outage events observed in a single reactor-year. The standard deviation of the data is 7.0 events per reactor-year. Statistics are also shown for PWR and BWR plants considered separately. Small differences exist in the data for the two plant types, with BWR plants on average experiencing slightly fewer forced outage events than PWR plants over the study period.

A histogram of the number of forced outage events occurring in each reactor-year of data is shown in Figure 5.1. The empirical complementary cumulative distribution functions for PWR, BWR, and all LWR plants are shown in Figure 5.2*. The distributions show small differences between BWR and PWR plants in the study period.

The data base was analyzed to estimate the distribution of plant-specific forced outage frequencies using all of the years of operational data for each plant included in the data base. The plant-average forced outage frequency for each nuclear unit in operation during the 1974-1980 period is included except those plants which experienced less than 1 full year of commercial operation during the study period. Simple statistics for the average forced outage frequency at each nuclear unit during this period are shown in Table 5.2. A total of 67 nuclear plants are included with a mean plant-average forced outage frequency of 10.6 outages per reactor-year. A histogram of the plant-average forced outage frequency data for all 67 LWRs is shown in Figure 5.3. The plant-average forced outage frequencies show less variation than the forced outage frequencies observed in each individual reactor-year of operation (Figure 5.1). This can be explained by the balancing of operational years with many and few forced outage events for each individual nuclear plant. The complementary cumulative distribution functions for plant-average forced outage frequencies for BWRs, PWRs, and all LWRs

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* Parameters were estimated for fits of the normal, lognormal, exponential, and Weibull distributions to the empirical data using a least squares estimation technique [Ch56]. A Weibull distribution was the only hypothesized distribution accepted at a .10 level of significance using a Kolmogorov-Smirnov test of the hypothesis [Gr72].

Table 5.1 - Statistical parameters of data used to estimate forced outage frequency.

Statistical Parameter	PWRs	BWRs	All LWRs
Total Reactor-Years	219	148	367
Total Forced Outage Events	2370	1311	3681
Mean Forced Outage Frequency Based on Equal Weighting of Reactor-Years (per R.-Yr.)	10.8	9.0	10.0
Median Forced Outage Frequency (per R.-Yr.)	10	8	9
Variance of Forced Outage Frequency	62.0	27.7	49.4
Standard Deviation of Forced Outage Frequency (per R.-Yr.)	7.9	5.3	7.0
Minimum Forced Outage Frequency in a Single Reactor-Year	0	0	0
Maximum Forced Outage Frequency in a Single Reactor-Year	52	31	52

Figure 5.1 - Histogram of forced outage frequency data for all LWRs, 1974-1980.

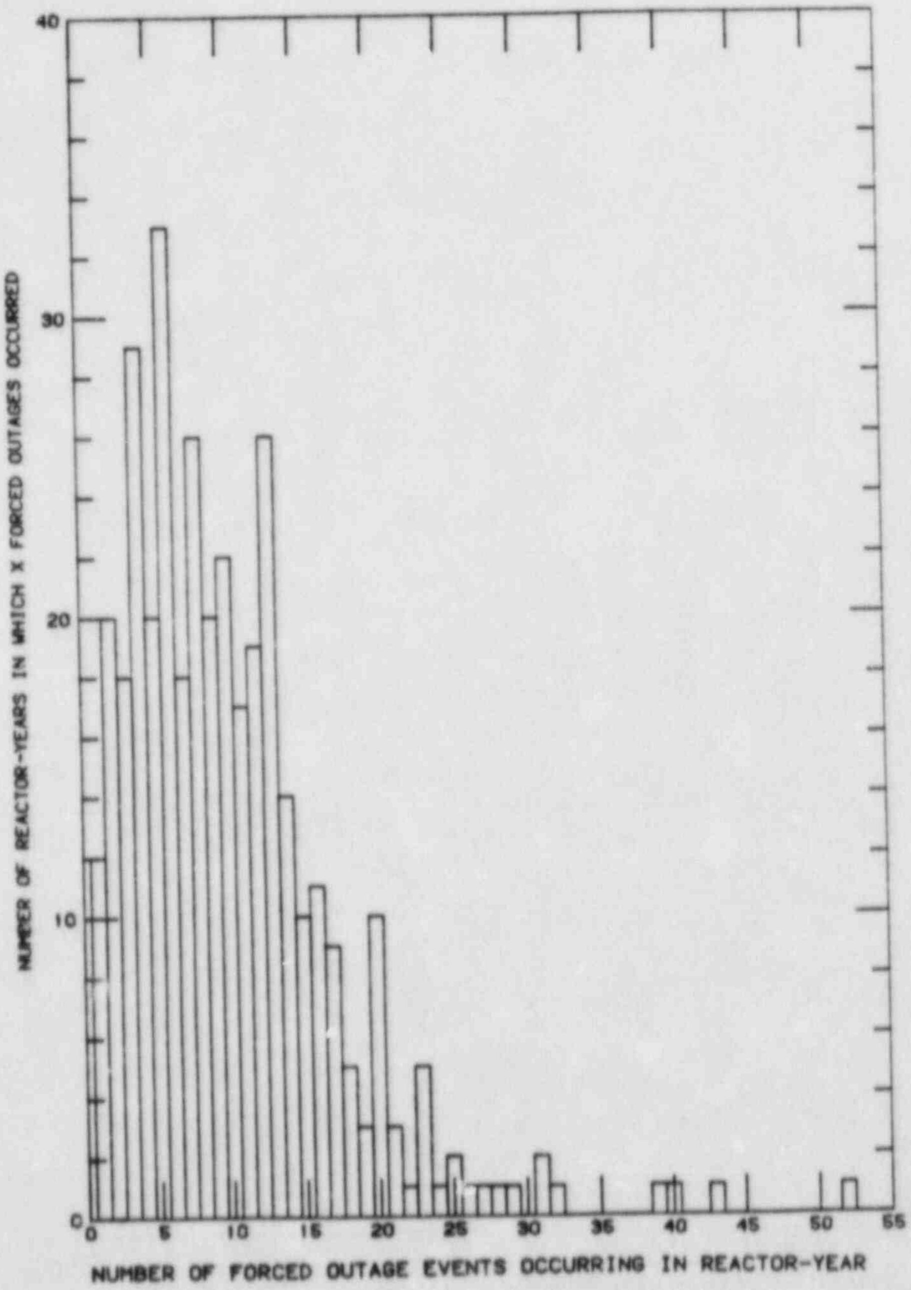


Figure 5.2 - CCDFs of forced outage frequency for BWRs, PWRs, and all LWRs, 1974-1980.

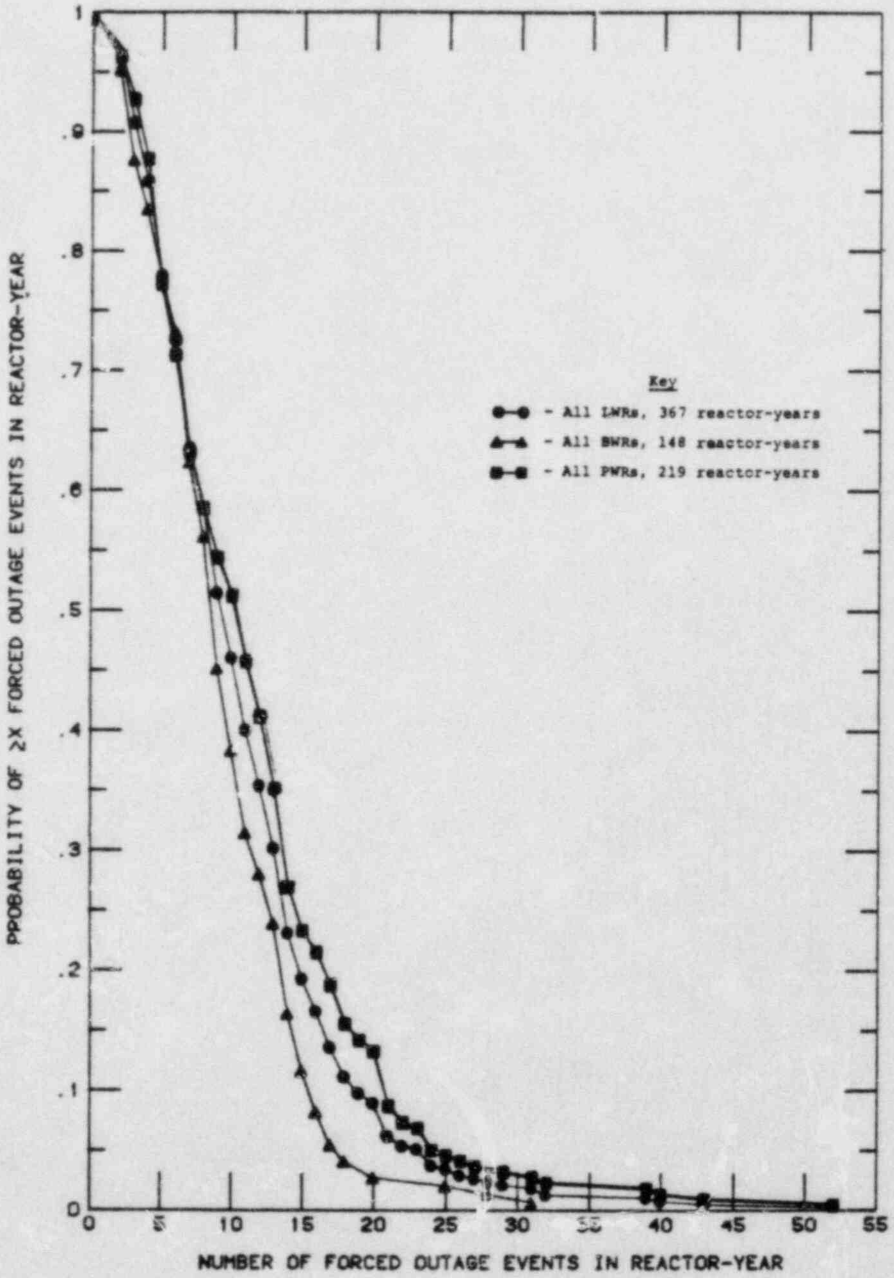
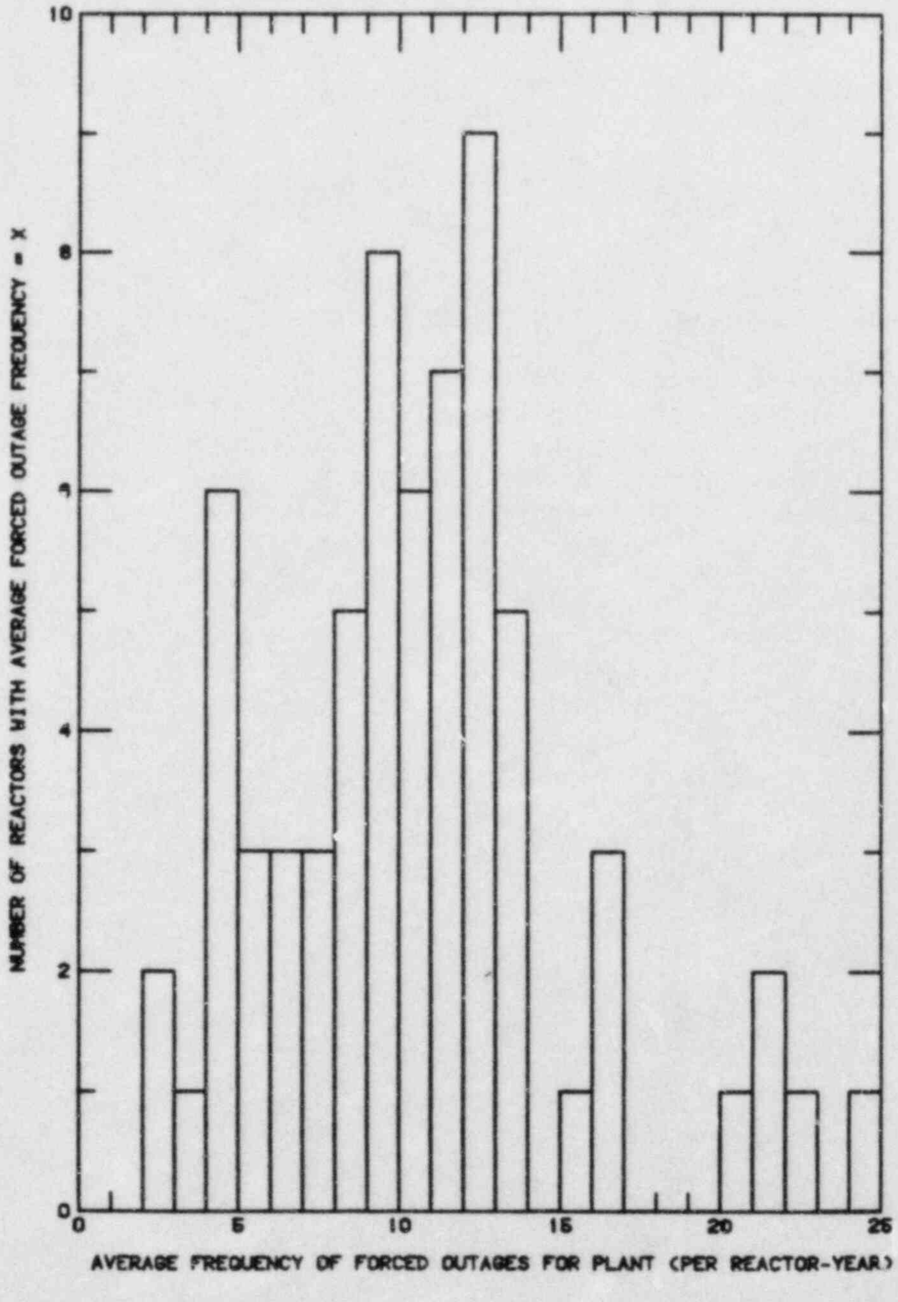


Table 5.2 - Statistical parameters of data used to estimate plant-average forced outage frequencies.

Statistical Parameter	PWRs	BWRs	All LWRs
Total Number of Plants	41	26	67
Mean Plant-Specific Forced Outage Frequency (per Reactor-Year)	11.3	9.4	10.6
Median Plant-Specific Forced Outage Frequency (per Reactor-Year)	11.2	9.6	10.4
Variance of Plant-Specific Forced Outage Frequency	24.4	17.0	22.1
Standard Deviation of Plant-Specific Forced Outage Frequency (per R.-Yr.)	4.9	4.1	4.7
Minimum Plant-Specific Forced Outage Frequency (per Reactor-Year)	2.8	2.3	2.3
Maximum Plant-Specific Forced Outage Frequency (per Reactor-Year)	24.3	21.0	24.3

Figure 5.3 - Histogram of plant-average forced outage frequency data for the years 1974-1980.



are shown in Figure 5.4. The data for plant-average forced outage frequencies are approximately normally distributed. The variation of plant-average forced outage frequency is due in part to characteristics of the portfolio of reactor plants operating during the 1974-1980 study period. Differences in the age, design, and operation and maintenance programs of each operating U.S. LWR unit contribute to the observed variation in plant-average forced outage frequency.

The data base was also used to test for correlations between the number of forced outages in each reactor-year and reactor age (during the reactor-year), reactor size, reactor type, and NSSS vendor. Significant correlations were found to exist between reactor age and the number of forced outages observed in each reactor-year of data. For nuclear units with electrical ratings larger than 500 MWe and less than 1000 MWe, significantly more forced outage events are experienced in the first few years of plant operation than in later operation years. This is consistent with standard "bathtub" failure rate behavior which is observed in most technological devices. The higher rate of forced outages in the first few years of plant life reflects "teething" and wear-in problems which often arise in engineering devices. Significant differences in the mean number of forced outage events per unit time were found for small versus large reactors. No significant correlations were found between the number of forced outages per reactor-year and the plant type or NSSS vendor.

Analyses were performed to check for correlations between the number of forced outage events in each reactor-year and the mean forced outage duration. Although it was expected that smaller numbers of forced outage events might be correlated with outages of longer duration (which result in less operating time in which forced outage events may occur), no significant correlations were found. In addition, no significant correlations were found between plant age and the mean or total forced outage duration in each reactor-year of data. Results of detailed analyses of the LWR outage data base are reviewed in Appendix D.

5.2 DISTRIBUTION OF LWR FORCED OUTAGE EVENT DURATIONS

The LWR forced outage data base is used to estimate the distribution of forced outage event durations conditional upon outage occurrence. The durations of 3681 forced outage events (in hours) are included in the analysis. No outages from partial years of reactor operation are included. The minimum outage duration in the NRC reporting system is 1 hour*. The

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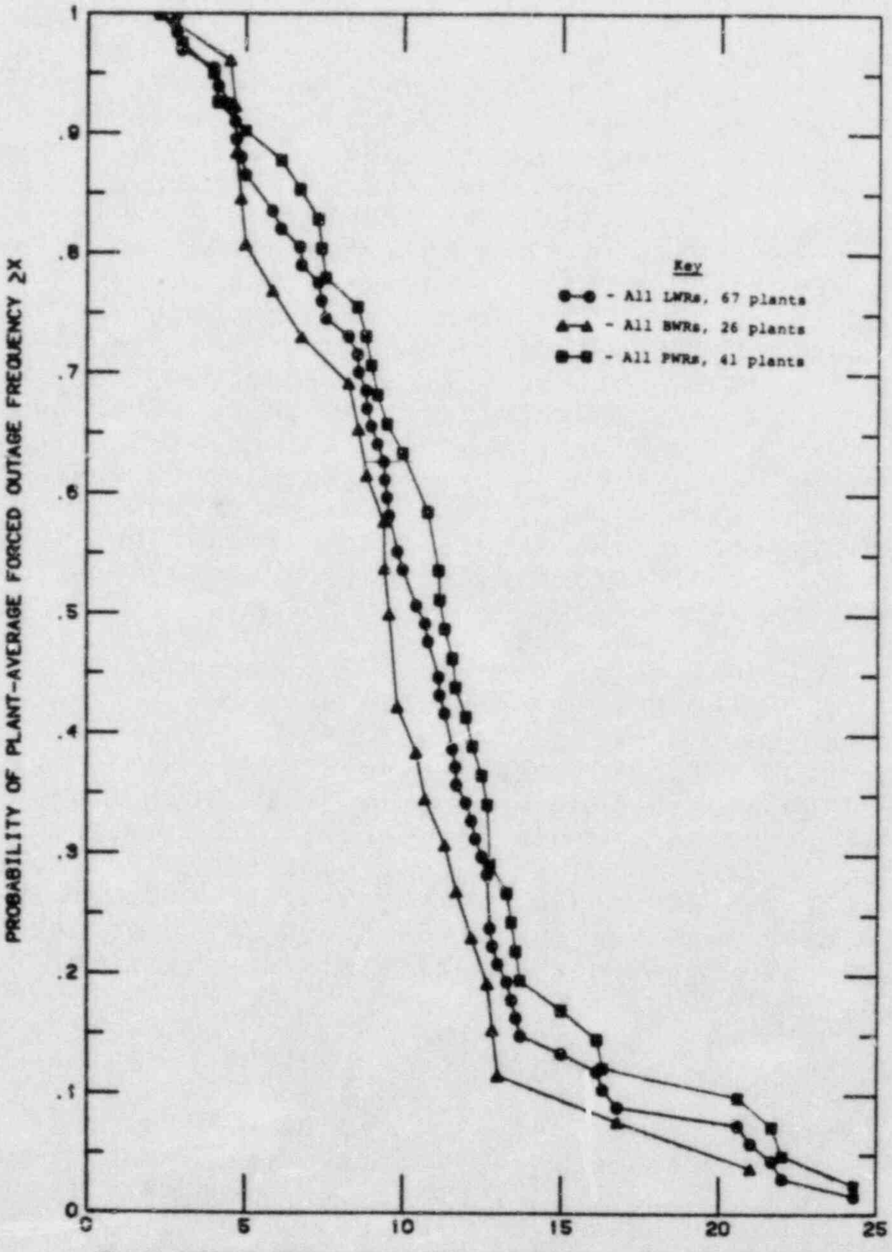
*More recent NRC reports include outage durations less than 1 hour in duration.

Figure 5.4 - CCDFs of plant-average forced outage frequency for BWRs, PWRs, and all LWRs, 1974-1980.



duration of outage events which extend across calendar years is taken to be the total summation of all plant downtime resulting from an initiating event.

The statistical parameters of the forced outage duration data set are shown in Table 5.3. The forced outages included in the data base totaled 303,754 hours of forced outage time (~35 reactor years of downtime) between calendar years 1974-1980. The mean forced outage duration during this period is approximately 82.5 hours, and the median outage duration is 15 hours. The standard deviation of the outage duration data is approximately 420 hours. A histogram and complementary cumulative distribution function of forced outage durations from the empirical data are presented in Figures 5.5 and 5.6. Relatively small differences exist in the forced outage duration distributions for PWR and BWR plants during the study period*.

5.4.1 FREQUENCY DISTRIBUTION OF FORCED OUTAGE DURATIONS

A distribution of forced outage event frequency versus outage duration is obtained by combining the frequency of forced outage event occurrence and the distribution of outage durations conditional upon event occurrence. The distribution of forced outage event durations is assumed to be independent of the total frequency of forced outage events (i.e., the distribution of event severity is independent of forced outage frequency) in the combination process. Complementary cumulative frequency distributions of outage event durations are shown in Figure 5.7 for PWRs, BWRs, and all LWRs.

5.5 DISTRIBUTION OF ECONOMIC RISK FROM CATEGORY I FORCED OUTAGES

The complementary cumulative frequency distributions of forced outage duration can easily be converted to economic risk distributions for forced outage events by correlating each forced outage duration to a cost using the models discussed in Chapter 3 of this report. As discussed in section 3.2, the real societal discount rate used in this study is 4% per year. The costs of events in this category are insensitive to discount rate because of the short duration of the cash flow streams for routine forced outage events.

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*Parameters were estimated for fits of the normal, lognormal, exponential, and Weibull distributions to the forced outage duration data for all LWRs using a least squares technique. All of the hypothesized distributions were rejected at a 0.1 level of significance using a Kolmogorov-Smirnov test.

Table 5.3 - Statistical parameters of data used to estimate forced outage event durations.

Statistical Parameter	PWRs	BWRs	All LWRs
Total Number of Forced Outage Events	2370	1311	3681
Total Outage Hours from All Forced Outage Events	184,510	119,244	303,754
Mean Forced Outage Event Duration (hours)	77.9	91.0	82.5
Median Forced Outage Event Duration (hours)	11	22	15
Variance of Forced Outage Event Duration ($hours^2$)	121,581	284,163	179,462
Standard Deviation of Forced Outage Event Duration (hours)	348.7	533.1	423.6
Minimum Forced Outage Event Duration (hours)	1	1	1
Maximum Forced Outage Event Duration (hours)	6,941	12,059	12,059

Figure 5.5 - Histogram of LWR forced outage event duration data for the years 1974-1980.

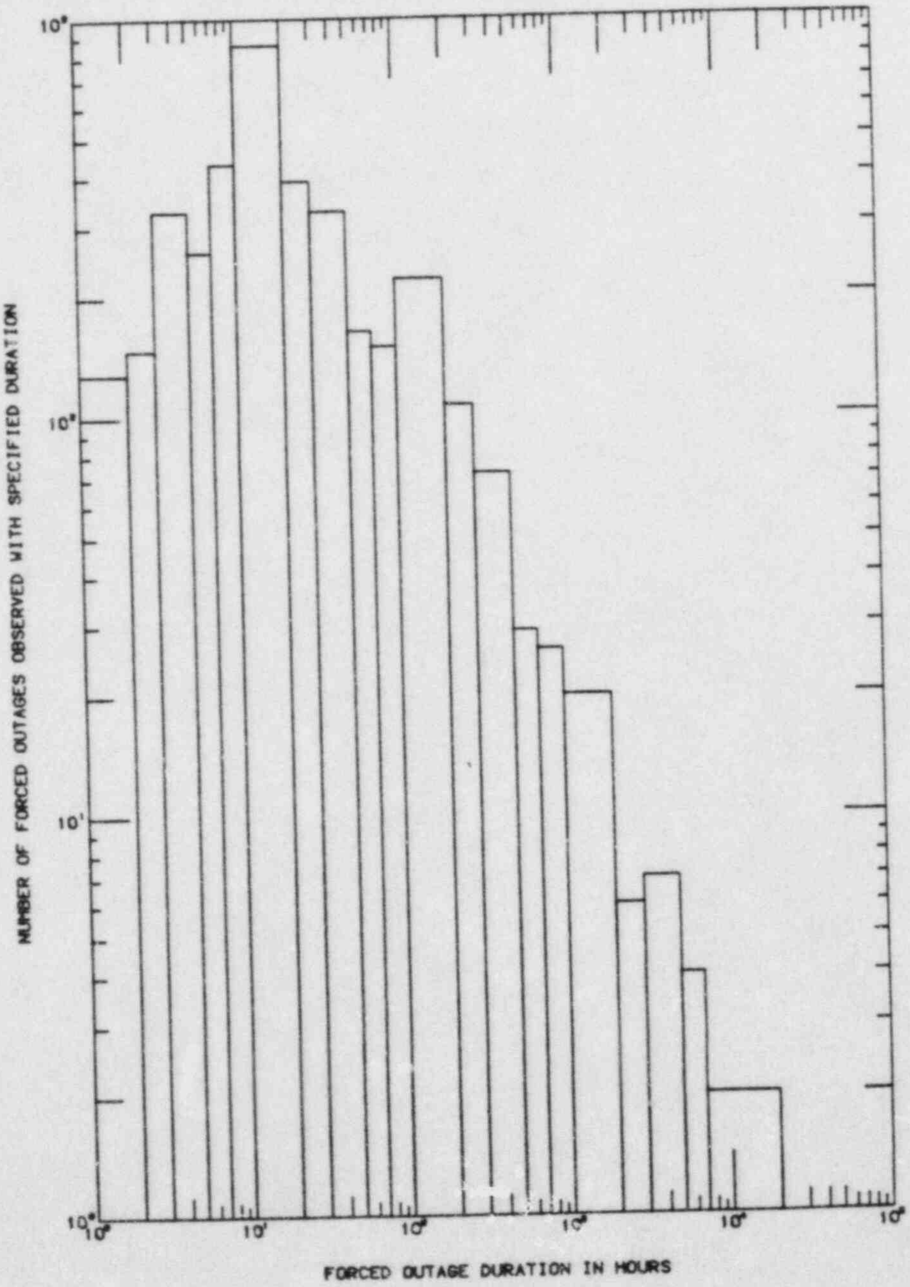


Figure 5.6 - CCDF of forced outage durations conditional upon event occurrence for BWRs, PWRs, and all LWRs, 1974-1980.

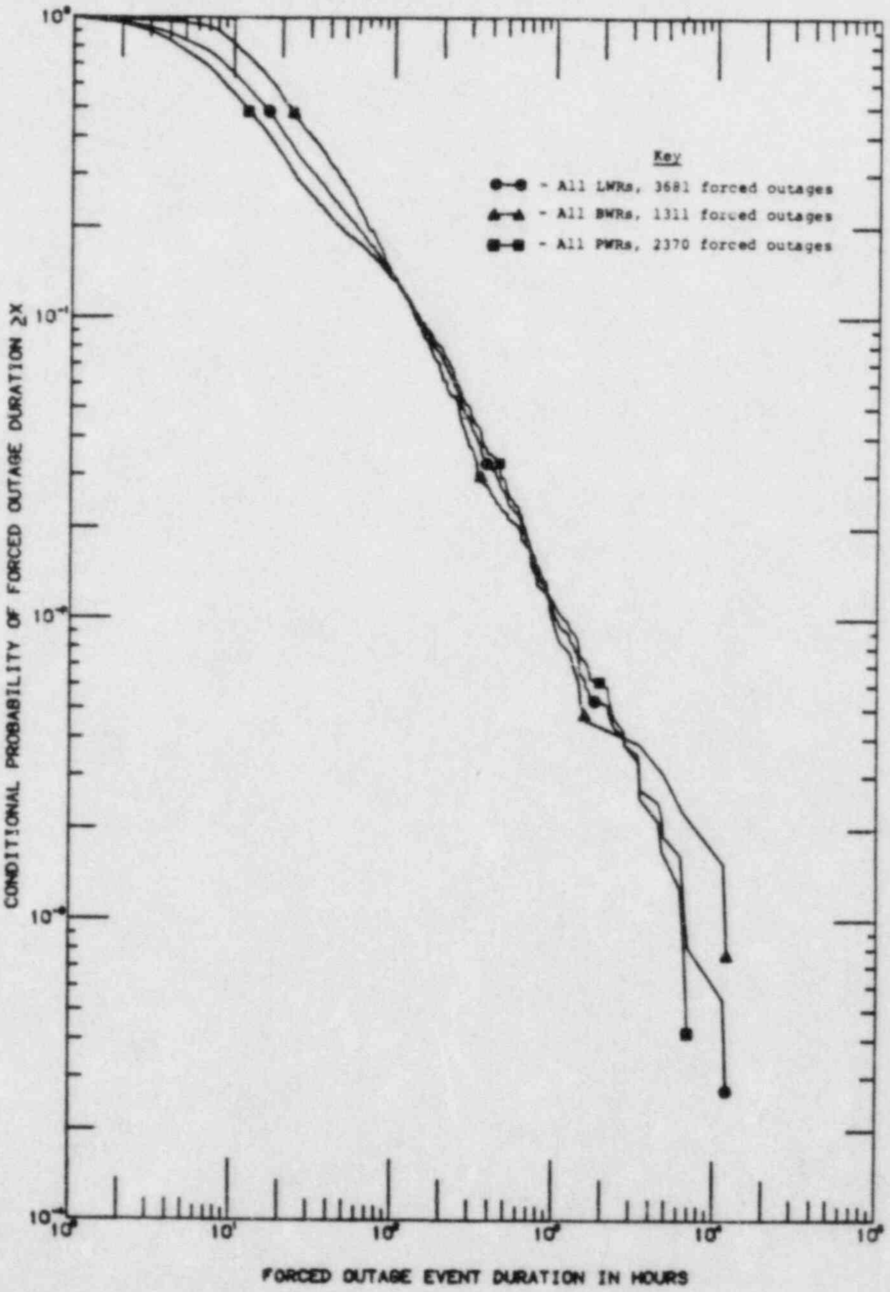
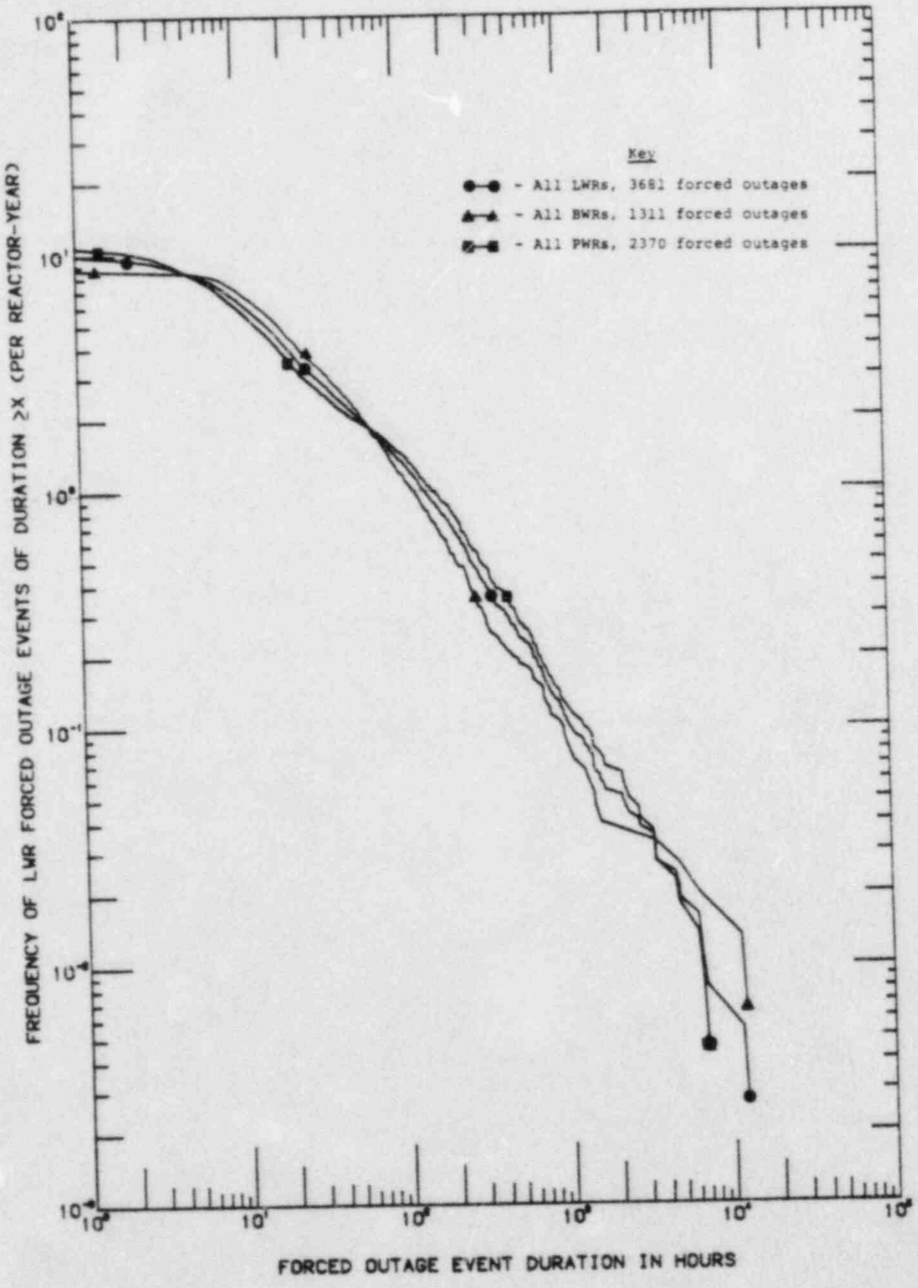


Figure 5.7 - Complementary cumulative frequency distributions of forced outage durations for BWRs, PWRs, and all LWRs, 1974-1980.



The losses for routine forced outage events in category I are dominated by replacement power costs. As discussed in section 3.6.1, plant repair costs for these events have historically been small relative to replacement power costs. The events in this category do not result in significant plant contamination, and the plant is assumed to always be repaired for return to operation. Nuclear power industry costs, litigation costs, and electric utility business costs are small for this category of events. No early decommissioning costs or offsite consequences result from this category of events. Common-mode failures which result in multiple unit forced outages at a single site are unlikely for this event category.

Using the replacement power correlation from equation 3.4, and assuming no significant escalation in real power production cost increases occurs over the short time duration associated with each outage, the discounted societal cost of a forced outage of duration h can be estimated using:

$$D_1 = \int_{t=0}^{t=h} (F + R)e^{-rt}dt \qquad (5.1)$$

where

D_1 = the discounted societal cost of a plant forced outage of duration h hours ($),

F = the power production cost increase per hour of outage duration for the plant under consideration ($/hour),

R = plant repair cost per hour of outage duration (~$1000/hour),

r = the real societal discount rate (4% per year),

h = outage duration measured in hours.

A discounted cost is calculated for each outage duration and the distribution of discounted cost versus event frequency is formed.

It is important to note that the replacement power cost model used in this section may significantly overestimate the actual societal costs due to very short duration forced outage events. The model does not account for electric utility options, seasonal effects, and other considerations which may avert the need for the purchase of replacement power. However, the model does provide a reasonable estimate of the costs due to forced outages of short duration assuming replacement power purchases or equivalent cost measures are necessary.

Complementary cumulative frequency distributions for category I forced outage costs are shown in Figure 5.8. The curves are based on frequencies estimated for a generic 1000 Mwe nuclear plant. Curves for plants located in the NPCC, MAAC, and ECAR NERC regions are shown to demonstrate the effects of replacement power cost variation on economic risks. A plant repair cost of ~$1000 per hour of outage duration is included in the analyses. The curves are based on an average total forced outage frequency of 10 events per reactor-year. The expected values of the economic risk distributions are also shown in Figure 5.8. The expected losses due to routine forced outage events vary by a factor of ~4 due to the difference in the costs of replacement power purchases across NERC regions. Table 5.4 shows the expected hours of forced outage time and dollar costs per reactor-year for an average LWR in the MAAC region for forced outage events of various durations. Outages of less than 28 days duration account for approximately half of the expected costs from category I forced outage events.

The forced outage frequency-severity data was also employed to estimate category I outage economic risks for PWRs and BWRs based on reactor-year and plant-average forced outage frequencies. The expected costs of category I forced outage events are the same for both methods of analysis. The forced outage frequency is slightly lower for BWR plants than for PWR plants in the study period, but the mean outage duration is longer for BWR plants than for PWR plants. The differences in outage frequency and severity for the two plant types tend to cancel when estimating the expected costs of category I forced outage events.

5.6 PRESENT VALUE OF LIFETIME INTEGRATED ECONOMIC RISKS

It is useful to estimate the total present value of lifetime risks for each category of reactor accidents for use in cost/benefit decisions regarding economic risk reduction measures. The total integrated economic risk over the remaining life a nuclear plant corresponds to the amount which society should be willing to spend to reduce the economic losses from events to zero, assuming expected value maximization is the decision objective (i.e., risk neutrality). Measures of risk aversion or proneness to events could be incorporated in the analysis but are not addressed in this study. The integrated economic risks reflect the present value of expected costs of events over the remaining plant productive lifetime. The sensitivity of integrated lifetime economic risks is examined using 0, 4, and 10% real discount rates. It is assumed that real fossil fuel power production costs do not escalate relative to nuclear power generation costs over the remaining lifetime of a reactor.

Figure 5.8 - Economic risk distribution for category I outages at an "average" 1000 MWe LWR in 3 NERC regions.

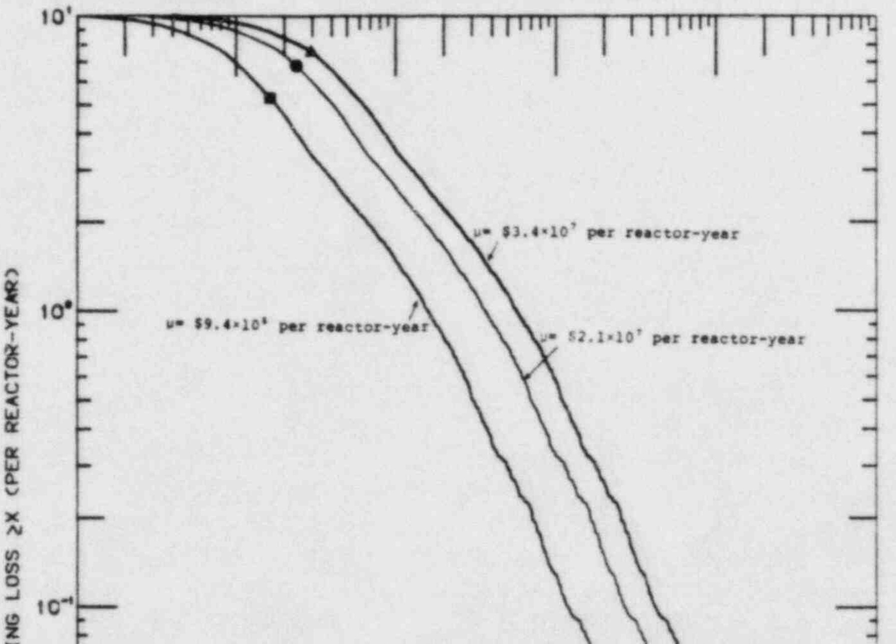


Table 5.4 - Expected costs of category I forced outage events per reactor-year of operation - "Average" LWR plant, 1000 MWe, MAAC NERC region.

Forced Outage Durations	Expected Outage Hours Per Reactor-Year	Expected Discounted Cost (4%) Per Reactor-Year
0-6 hours	8	$\$2.1\times10^5$
6-12 hours	19	$\$5.0\times10^5$
12-24 hours	37	$\$9.8\times10^5$
24-72 hours	73	$\$1.9\times10^6$
72-168 hours	96	$\$2.5\times10^6$
7-28 days	205	$\$5.4\times10^6$
28-183 days	213	$\$5.5\times10^6$
6-12 months	110	$\$2.8\times10^6$
>12 months	64	$\$1.6\times10^6$
Total Expectation Per Reactor-Year	825	$\$2.1\times10^7$

The lifetime-integrated economic risk from each category of LWR events is calculated using:

$$ER_i = \int_{t=0}^{t=L} f_i C_i(t) e^{-rt} dt \qquad (5.2)$$

where

ER_i = the present value of economic risk from category i LWR events over the remaining productive plant life (\$),

L = the remaining lifetime of the reactor plant (years),

f_i = the frequency of accident category i, (per reactor-year) assumed to be constant over remaining reactor life*

$C_i(t)$ = the cost of event i which occurs at time t discounted to the time of event occurrence (\$).

r = the real societal discount rate used in the analysis (per year).

The Surry Unit 2 nuclear power plant is used as an example for integration of lifetime economic risks in this study. The 775 Mwe plant, located in the SERC NERC region, has been in operation for approximately 10 years, with an estimated remaining productive lifetime of 30 years. The estimated integrated economic risks for category I outage events at the Surry plant are shown in Table 5.5. The estimates are based on generic forced outage frequency and duration estimates for the 1974-1980 period combined with the new onsite cost model estimates for the Surry plant. The integrated forced outage event risks vary by a factor of ~3 for the 0-10% range of discount rates. The present value of category I outage costs for the remaining lifetime of the Surry plant results from costs of replacement power during plant forced outages. The integrated values show that a significant societal benefit could be realized through reduction of forced outage time over the remaining lifetime of the plant.

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* The frequency f_i in the above formula implicitly allows repeat events at a reactor. The formula can be corrected to prohibit this situation, particularly for core-melt accidents which are likely to result in early plant shutdown. The correction would considerably complicate the formula, and because the frequencies of severe accidents resulting in early shutdown are very low, the difference in results would be extremely small.

Table 5.5 - Present value of lifetime integrated category I forced outage event economic risks for Surry #2, based on generic event frequency estimates.

Discount Rate (% per year)	Present Value of Category I Forced Outage Event Costs for Remaining Plant Lifetime*
0	$\$2.7\times10^{8}$
4	$\$1.6\times10^{8}$
10	$\$8.4\times10^{7}$

*Based on average forced outage frequency of 10 events per reactor-year over 30 year remaining plant lifetime. All costs are expressed in 1982 dollars.

5.7 PREVIOUS ESTIMATES OF FORCED OUTAGE ECONOMIC RISKS

The frequency versus outage duration spectrum for LWRs has been previously estimated as part of an EPRI study of the financial risks of reactor outages and accidents [St81]. The forced outage frequency-severity curve derived in the EPRI study is shown in Figure 5.9. The upper portion of the curve, at high frequency and small repair time, was estimated from data collected for an earlier report on nuclear component failure statistics [Ko80]. The report estimated the frequency of forced outages based on data collected for 54 U.S. commercial nuclear power reactors larger than 400 MWe and in commercial operation before June 1978. The maximum time to repair estimated from the data was approximately 500 hours, at an approximate frequency of 0.4 per reactor-year. The frequency of severe accidents with longer repair times was estimated using the median core-melt frequency and uncertainty bounds from the Reactor Safety Study [Nu75a], with the assumption that a core-melt accident would result in the equivalent of 10-30 years of outage time cost. The dashed line in Figure 5.9 is an interpolation between the historical repair time data and RSS estimates. The interpolation extends from mean repair times of ~500 to ~250,000 hours and frequencies of 0.5 to $6x10^{-5}$ per reactor-year.

The BWR, PWR, and LWR outage frequency-outage duration curves derived in this study are compared to the EPRI curves in Figure 5.9. The estimates of PWR and BWR outage frequencies for short duration outages are somewhat lower than the estimates from the EPRI study. This difference in estimates for short duration outages results from the exclusion of regulatory outages and the use of a more extensive operating experience base developed in this study. For outages longer than 500 hours in duration, historical data agrees with the EPRI interpolation very well. The maximum outage duration for which historical data exists for category I events is ~12,000 hours.

The estimated economic risk curve for category I forced outage events for a generic 1000 MWe LWR plant in the NPCC NERC region is shown in Figure 5.10. The 1000 MWe plant in the NPCC region has replacement power cost increases on the order of ~$1 million dollars per day of outage time (see section 3.2.1). This curve is compared to the economic risk curve estimated in the EPRI study for outages of greater than 10 days duration. The two estimates of the economic risk curve agree remarkably well. The expectation value for both curves for outages greater than 10 days and less than 5000 days in duration is ~$17 million dollars per reactor-year. The total expectation cost for all category I events is estimated in this study to be ~$34 million 1982 dollars per reactor-year for a 1000 MWe plant in the NPCC region.

Figure 5.9 - Comparison of forced outage duration distributions with those from EPRI study.

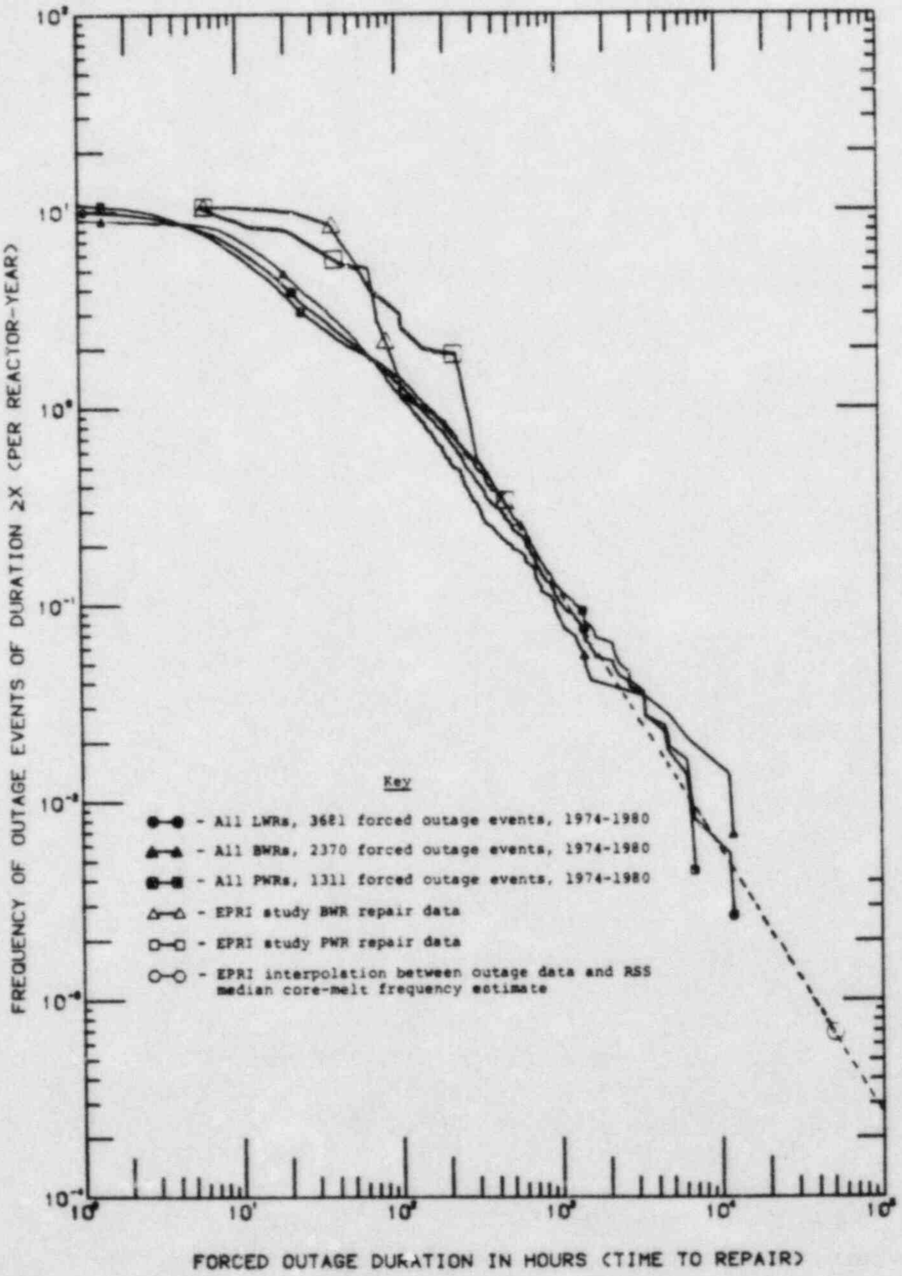
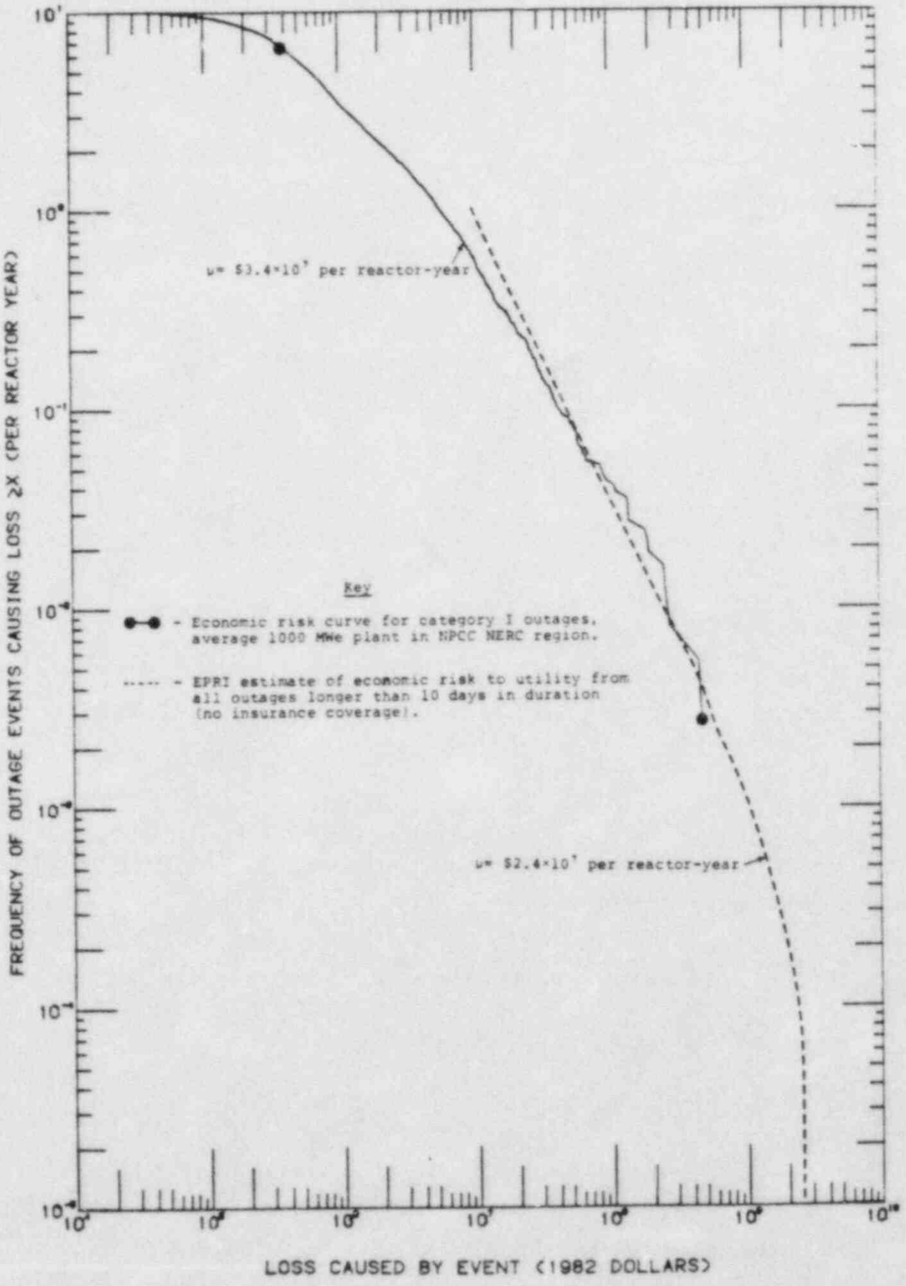


Figure 5.10 - Comparison of category I economic risk distribution to electric utility risk distribution from EPRI study.



5.8 SENSITIVITIES AND UNCERTAINTIES

The estimates of economic risks from category I forced outage events in this study blend historical frequency data and simple cost models. The economic risk values presented do not consider plant-specific attributes which may have important impacts on forced outage frequencies and costs.

The estimates of category I forced outage frequencies presented in this study are based on data for the portfolio of U.S. LWRs in commercial operation during the period 1974-1980. Based on equal weighting of all reactor-years in the data base, the average forced outage frequency during this period is 10.0 forced outage events per reactor-year. As shown in Figure 5.1, the largest number of forced outage events during a single reactor-year of operation is ~5 times greater than the mean (52 forced outage events). Some reactor-years of operation resulted in no forced outage events. The mean plant-specific forced outage frequency (based on averaging of multiple years of plant operation) from the data base is 10.6 outage events per reactor-year of operation. The highest plant-average forced outage frequency is about a factor of 2 higher than the mean, and the lowest plant-average forced outage frequency is about a factor of 3 lower than the mean value. The variation in plant-average forced outage frequency results from stochastic processes and from plant-specific attributes including plant age, design, and operations programs. The estimates of economic risk presented in this section are based on generic outage frequency estimates representative of the portfolio of operating reactors between 1974-1980.

The data base developed in this study can be used to perform detailed analyses to estimate plant-specific forced outage frequencies. A detailed analysis of forced outage frequency would consider the historical experience of a particular unit, the age of the reactor plant, and other plant attributes which may have important impacts on forced outage frequency.

The estimates of U.S. LWR forced outage costs in this section are based on simple replacement power cost and plant repair cost models. Actual replacement power costs based on detailed analyses for specific utilities have shown variations of less than a factor of 3 from the simple model results [Bu82]. The contribution of plant repair costs to total outage costs is small, and the uncertainties in plant repair cost estimates are relatively unimportant. The replacement power cost model is likely to be more uncertain for short-duration forced outage events, since a broader range of options exist for compensating for lost capacity during these outage events. The assumptions which underlie the simple replacement power cost model also become more uncertain when projecting costs into future years. In particular, the assumptions regarding the availability of generating capacity to produce replacement power and costs of fossil fuels become more uncertain when projecting costs for years in the future.

More detailed analyses of replacement power costs for a specific plant under consideration would take into account the reactor electrical rating, historical capacity factor, and utility-specific considerations regarding replacement power agreements, load variations, and excess generating capacities which might exist. Plant-specific cost analysis could substantially reduce the uncertainties associated with replacement power cost estimates.

The generic estimates of category I economic risk presented in this section contain uncertainties due to plant-specific characteristics, stochastic variations, and imperfect knowledge regarding forced outage frequencies and costs in future years. It is estimated that these variations can lead to actual plant-average category I event economic risks ranging from a factor of 10 lower to a factor of 5 higher than those presented. Most of this variation is due to the variation of forced outage frequencies based on plant-specific characteristics. More detailed analysis of plant-specific data for frequencies and costs could reduced these uncertainties to approximately factors of 3 and 1/3. This analysis can be performed within the framework presented using the forced outage data base discussed in Appendix A and detailed utility-specific replacement power cost estimates. The uncertainties are larger for future year projections due to possible changes which affect the assumptions that underlie the frequency and cost models employed.

5.9 SUMMARY AND DISCUSSION

LWR event category I is defined in this study to cover a broad range of events from short duration forced outages to severe LWR accidents which do not result in significant core-damage or radioactive contamination of plant equipment or systems. The best estimate of category I event frequencies ranges from ~10 per reactor-year for outages of any duration to ~2×10^{-3} per reactor-year for the most severe category I LWR events. The expected societal cost of events in this category is predicted to be ~\$1-\$$3\times10^{7}$ per reactor-year based on forced outage event frequencies and costs for an average 1000 MWe LWR in the U.S.

The large magnitude of the costs for category I events is important for two reasons. The expected losses result from the high-frequency of LWR forced outage events. Because of the predicted power production cost increases for LWR outages, and the use of nuclear units for base-load generation of electric power, an event which results in a period of no power production can result in significant societal costs. The prevention of forced outages should be given high priority to reduce the expected forced outage losses. The expected losses from this category of LWR events indicate that there may be significant societal (and electric utility) savings from a well organized plant maintenance program and a plan to take advantage of plant outage time as it becomes available.

There is another potential benefit to the reduction of the frequency of LWR forced outage events. Every LWR forced outage event requires that the reactor be shutdown either by nuclear plant safety systems or by operator control. Each forced outage event results in some transient of the nuclear steam supply system. Nuclear plant transients place demands on systems which are not required for normal plant operation. Probabilistic risk analyses have shown that routine plant transients can lead to system failures which result in severe accidents involving core-damage [Nu75a]. Transient-induced accidents can be important contributors to the total public health risk posed by plant operation. Thus, reduction of forced outage frequency should result in some consequent reduction in the public health risk caused by plant operation.

Analyses of forced outage frequencies versus plant age and electrical rating in Appendix D shows that large LWRs (>500 MWe) have generally experienced larger forced outage event frequencies early in plant life than in later years. This is consistent with the failure rate curve which is observed in most technological devices. There are two important consequences of this variation in forced outage frequency over plant life. First, this variation indicates that the economic risk of category I reactor accidents is not constant over the life of an LWR. Expected losses from these events would be larger during the first few years of operation than over the remainder of plant life. Secondly, public health risk posed by plant operation may not be constant over plant life. This is due to the effect of transient-induced severe accidents resulting from forced outage events. The analysis in Appendix D indicates that the frequency of forced outage events early in plant life may be factors 2-3 higher than for older plants. Experience would support this hypothesis, since the worst two accidents in U.S. nuclear power plant operation occurred at large reactors (>500 MWe) which were in the first years of commercial operation.

Finally, the potential societal costs of routine LWR outage events have received relatively minor attention compared to the losses of low probability, severe core-melt accidents. Because the events in category I are high frequency events and occur frequently during a normal year of LWR operation, the costs of these events are continually being paid, and little attention is drawn to these events by electric utilities, state rate commissions, the NRC, or consumers. The relatively minor attention given to costs of category I LWR accidents may be in large part a result of the nuclear power regulation system in the U.S.

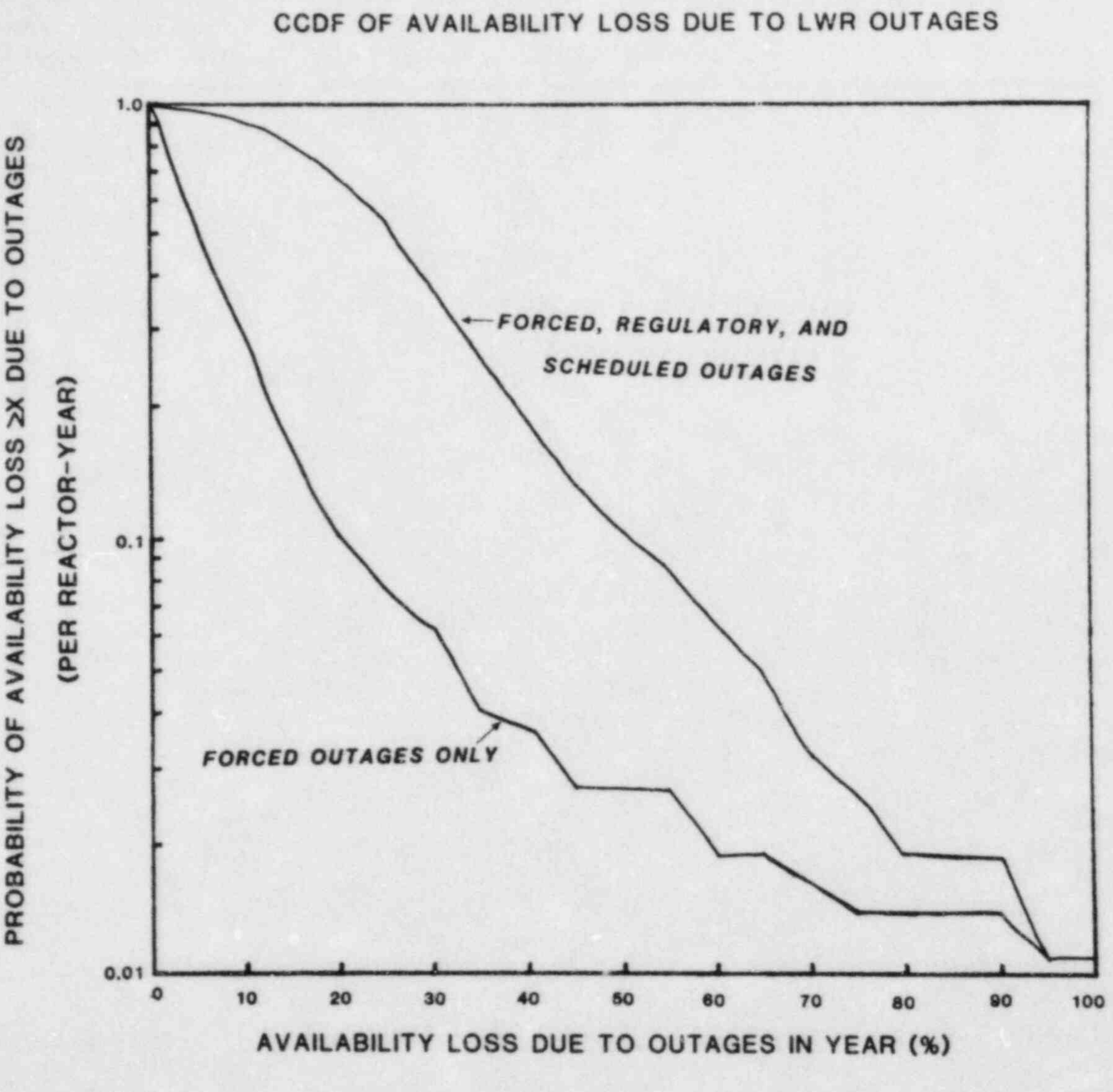
The societal costs of routine forced outage events show up in reduced availability and capacity factors for LWR plants in operation. Historically, LWRs have achieved poor capacity factors relative to the projected capacity factors for plant designs. Part of this decreased capacity factor has resulted from forced outage events which were not anticipated. Figure 5.11 shows the complementary cumulative distribution function of availability loss due to outage events of various causes from the 1974-1980 data base. This figure shows that a 10% availability loss in a reactor-year of operation caused by forced outage events was not uncommon. The availability loss due to forced outage events makes a substantial contribution to the total availability losses due to forced, regulatory, and scheduled outage events. Over time, the anticipated availability and capacity factors for LWRs have decreased based on experience with longer and more frequent plant forced outages.

The current U.S. nuclear power regulatory system provides only small incentives for reduction of the frequency of routine forced outage events. The NRC is only concerned with routine LWR forced outage events with regard to the possible contribution to public health risk from plant operation. Low probability core-melt accidents have drawn a large portion of the NRC and public attention. From the public utility commission viewpoint, routine LWR forced outage events result in decreased plant capacity factors and the need for generation of electricity from higher marginal cost plants. Normally, utilities are allowed to earn a fair return on their investments, and small percentage operating cost increases due to the increased use of higher cost fuels can often be passed on to consumers. Conversely, if a plant licensee is successful in reducing the frequency and duration of forced outage events resulting in higher plant capacity factors, public utility commissions return most of the costs avoided back to consumers so that an electric utility does not earn an excessive profit. This truncation of risks to electric utilities results in decreased incentives for the reduction of societal costs from routine LWR forced outages. Public utility commissions limit many market forces which provide incentives for plant licensees to achieve the highest possible capacity factors for societal benefit.

5.10 CONCLUSION

The economic risks of category I forced outage events are important because of the high frequency (~10 per reactor-year) of routine forced outages. A typical 1000 MWe U.S. LWR in operation is estimated to lose approximately $10-30 million dollars

Figure 5.11 - CCDF of LWR plant availability losses during the 1974-1980 period.



per reactor-year in benefits from plant operation due to the availability losses caused by routine forced outage events. The frequency of forced outage events at LWRs has shown a wide variability, and may be dependent upon reactor age, design, and plant operations programs. The variation in plant forced outage frequencies indicates that it may be possible to reduce forced outage losses through improved operation and maintenance programs for plants in operation. A reduction in the number and duration of forced outage events could result in significant societal economic benefits from increased plant availability and capacity factors. The expected costs of routine forced outage events are compared to the expected costs of more severe accidents in Chapter 6.

CHAPTER 6

ECONOMIC RISKS FROM MEDIUM AND LARGE CONSEQUENCE LWR EVENTS

6.1 INTRODUCTION

A range of economic risks from category II and III core-damage and core-melt accidents is estimated in this section. The effort is hindered to some extent by the limited understanding of severe accident physical processes and human interactions and because core-damage event frequencies have not been explicitly addressed in current probabilistic risk analyses (PRAs). Therefore, category II and III economic risks are considered jointly in this study. It is assumed that the core-melt accident frequencies from current PRAs include both core-damage and core-melt accident sequences. [illegible] range of severe accident economic risks is estimated for the Surry #2 plant using the median PWR core-melt frequency from the RSS, with the assumption that either all sequences lead only to core-damage (category II event costs) or that all sequences proceed to core-melt (category III event costs). The latter assumption is consistent with those employed in PRAs which estimate public health risks. These assumptions should bound the severe accident economic risks if the total frequency of core-melt events estimated in current PRAs includes all dominant core-damage and core-melt accident sequences. However, this range does not include the uncertainties in total severe accident frequencies. The large uncertainties in the total severe accident frequency estimates are discussed later in this section.

Estimates are developed for the Surry plant which show that total severe accident economic risks are not very sensitive to assumptions regarding the relative likelihood of core-damage versus core-melt accidents because of the large contribution of onsite costs to economic risks. Results of other probabilistic risk studies are used to estimate the variation in economic risks from medium and large consequence events at other U.S. reactor sites. Sensitivity studies of offsite core-melt accident consequences and potential applications of the newly developed offsite cost models for cost/benefit analyses of offsite emergency planning, emergency response, and post-accident countermeasure implementation are discussed. Estimated economic risks from category I forced outages and category II and III severe accidents at the Surry #2 plant are compared. The uncertainties in the estimates of core-damage and core-melt accident costs are also discussed in this section.

6.2 ESTIMATED SEVERE ACCIDENT ECONOMIC RISKS BASED ON CATEGORY II COSTS

An estimate of severe accident economic risks for the Surry #2 plant is calculated using the median core-melt frequency from the RSS with the assumption that all severe accidents result in limited core-damage and do not cause direct breach of the reactor vessel or result in a significant release of radionuclides to the environment. This assumption is clearly unrealistic and leads to a "lower bound" estimate of severe accident economic risks. The cost models from Chapters 3 and 4 are used to estimate category II accident consequences at the Surry #2 plant. The cost of precautionary offsite population evacuation for category II events is shown to be negligible compared to the expected onsite costs of core-damage events.

6.2.1 PLANT REPAIR AFTER CATEGORY II EVENTS

As discussed in section 3.5, any severe core-damage event results in the need for a plant decontamination program to remove radioactive materials which have been released from the reactor core. Following plant decontamination, a decision must be made concerning plant repair or permanent plant shutdown and decommissioning. This decision is likely to be delayed until the end of the plant decontamination process so that full knowledge of plant equipment damage from the accident is available. The decision concerning the ultimate repair of the TMI-2 unit has not been made yet. The present value of lifetime-integrated category II accident risks is relatively insensitive to assumptions regarding post-accident plant repair or decommissioning (less than a factor of 2 variation).

6.2.2 EMERGENCY RESPONSE COSTS FOR CATEGORY II EVENTS

It is anticipated that public protective measures would be implemented at offsite locations during most accident sequences which result in core-damage. The new offsite evacuation cost model is used to estimate the range of offsite emergency response costs for category II events. It is assumed that the area within 10 miles of the reactor site is evacuated for a period of 3 days as a precautionary measure during accident sequences leading to significant core-damage. This action is predicted to result in offsite protective measure costs of $\$7\times10^4$ to $\$1\times10^7$ for the range of current U.S. reactor sites. The variation in offsite costs results from differences in the number of people moved for various reactor sites. This offsite emergency response cost is small compared to onsite losses for core-damage accidents.

6.2.3 PRESENT VALUE OF LIFETIME-INTEGRATED ECONOMIC RISKS FOR SURRY #2

The societal costs of category II accidents are dependent upon the time during the life of an LWR plant when the accident occurs. An accident which occurs early in plant life results in a larger societal cost than one which occurs near the end of an LWR plant's productive lifetime because little of the capital value of the plant is recovered early in the plant life. This variation of accident economic risk is accounted for in the integration of economic risk over the remaining lifetime of the reactor plant (Eq. 5.2).

Estimates of the present value of lifetime-integrated severe accident economic risks at Surry #2 are shown in Table 6.1. The estimates are based on the bounding assumption that all severe accidents result in only in limited core-damage (i.e., P{Category II Events} = P{Core-Melt from RSS}, and P{Category III Events = 0}). The risk estimates are based on category II event costs and an assumed core-damage accident frequency of $6x10^{-5}$ per reactor-year of operation. The core-damage frequency is assumed to be constant over the reactor lifetime in the economic risk integration. The integrated economic risks are shown for real discount rates of 0, 4, and 10%. The present value of offsite evacuation costs is estimated to be ~$2-8x10^{3}$ dollars over the 30 year remaining plant lifetime. The present value of onsite economic risks including plant decontamination, replacement power, and plant repair or capital costs is predicted to be ~$1-4x10^{6}$ dollars over the remaining plant lifetime for the 0-10% range of discount rates. The integrated onsite costs are 2-3 orders of magnitude higher than integrated offsite losses for category II accidents. Most of the onsite costs result from replacement power and plant capital losses, with about one fourth of the lifetime risk from category II accidents resulting from plant decontamination and cleanup costs for these accidents. The total present value of lifetime risks varies by a factor of ~4 for real discount rates of 0%-10%.

The potential loss of multiple reactor units at a site due to a single core-damage accident is an important consideration for category II events. The TMI-2 accident resulted in the need to cleanup and restore shared plant systems to operation before TMI-1 restart. This operation could have been completed within months of the accident. Unrelated plant equipment problems and regulatory concerns after the accident have forced continued shutdown of the TMI-1 plant for nearly 5 years. The cost of replacement power for the undamaged TMI-1 unit has been an important contributor to the total cost of the TMI-2 accident. For identical units at the same site (like Surry #1 and #2), shutdown of both units after all category II events for an equivalent time period results in a lifetime-integrated economic risk ~60% higher than that for single unit shutdown.

Table 6.1 - Present value of severe accident economic risks based on category II event costs, remaining lifetime of Surry #2 plant.

Assumed Core-Damage Accident Frequency = 6×10^{-5}/reactor-year*

Discount Rate	Present Value of Lifetime Economic Risks Offsite Costs (Evacuation)	Onsite Costs
0%	$\$8.4\times10^{3}$	$\$3.9\times10^{6}$
4%	$\$4.8\times10^{3}$	$\$2.1\times10^{6}$
10%	$\$2.6\times10^{3}$	$\$1.0\times10^{6}$

All costs are expressed in 1982 dollars.

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*Estimates based on the median core-melt frequency from the RSS with the assumption that all severe accident sequences result only in limited core-damage (category II event consequences). This assumption is clearly unrealistic and is used to provide lower bound estimates of severe accident (category II and III event) economic risks.

Because category II accidents are limited in scope to exclude core-melt accidents which breach the reactor vessel, and most multiple unit reactor sites have some separation of plant systems, forced shutdown of multiple units caused by plant equipment problems should be unusual. It is more likely that regulatory concerns could result in multiple unit shutdowns after category II core-damage accidents. The large cost of multiple unit shutdowns like that which occurred after the TMI-2 accident should be considered in post-accident regulatory decision-making.

6.3 ESTIMATED SEVERE ACCIDENT ECONOMIC RISKS BASED ON CATEGORY III COSTS

An estimate of severe accident economic risks for the Surry #2 plant is calculated in this section using the source terms defined for PWR core-melt accidents in the RSS. It is assumed that all core-melt accident sequences cause direct breach of the reactor vessel and possibly result in a significant release of radionuclides to the environment (i.e., P{Category III Events} = P{Core-Melt from RSS}, and P{Category II Events} = 0}). This is consistent with the assumption used in the RSS for estimating public health risks from plant operation.

The events in category III may impact public health and safety at offsite locations. The costs of countermeasures to protect the public from radiation exposure after severe accidents with environmental releases of radioactive material are estimated using the new offsite cost models. The offsite consequence estimates for an accident are dependent on the site-specific demographic characteristics of the areas surrounding the reactor. Also, the meteorological conditions, wind direction, and emergency response measures implemented during a severe accident have important impacts on the public health effects from a release of radioactive material to the environment. These considerations are incorporated probabilistically using the prototype offsite economic consequence model. The prototype model interfaces with the CRAC2 consequence model for input to the economic calculations (see Fig. 4.5).

6.3.1 RSS PWR CORE-MELT ACCIDENT SOURCE TERMS

The source terms defined in the RSS based on analysis of the Surry plant are shown in Table 6.2. Seven categories of PWR core-melt accidents were defined in the RSS for input to the offsite consequence analysis. Specific core-melt accident sequences were assigned to one of the seven release categories. Two categories of accidents less severe than core-melt events were defined in the RSS (PWR8-PWR9) to estimate the potential

Table 6.2 - Summary of RSS PWR accident source terms [Nu75b].

Release Category	Probability (reactor-yr^{-1})	Time of Release (hr)	Duration of Release (hr)	Warning Time for Evacuation (hr)	Elevation of Release(g) (meters)	Energy Release (10^6 Btu/hr)	Fraction of Core Inventory Released(a)							
							Xe-Kr	Organic I(b)	I(b)	Cs-Rb	Te-Sb	Ba-Sr	Ru(c)	La(d)
PWR 1	9×10^{-7}(a)	2.5	0.5	1.0	25	20 and 520(e)	0.9	6×10^{-3}	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR 2	8×10^{-6}	2.5	0.5	1.0	0	170	0.9	7×10^{-3}	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR 3	4×10^{-6}	5.0	1.5	2.0	0	6	0.8	6×10^{-3}	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR 4	5×10^{-7}	2.0	3.0	2.0	0	1	0.6	2×10^{-3}	0.09	0.04	0.03	5×10^{-3}	1×10^{-3}	4×10^{-4}
PWR 5	7×10^{-7}	2.0	4.0	1.0	0	0.3	0.3	2×10^{-3}	0.03	9×10^{-3}	[illegible] $\times 10^{-3}$	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR 6	6×10^{-6}	12.0	10.0	1.0	0	N/A	0.3	2×10^{-3}	8×10^{-4}	8×10^{-4}	1×10^{-3}	9×10^{-5}	7×10^{-5}	1×10^{-5}
PWR 7	4×10^{-5}	10.0	10.0	1.0	0	N/A	6×10^{-3}	2×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-6}	1×10^{-6}	2×10^{-7}
PWR 8	4×10^{-5}	0.5	0.5	N/A(f)	0	N/A	2×10^{-3}	5×10^{-6}	1×10^{-4}	5×10^{-4}	1×10^{-6}	1×10^{-8}	0	0
PWR 9	4×10^{-4}	0.5	0.5	N/A	0	N/A	3×10^{-6}	7×10^{-9}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0

(a) Background on the isotope groups and release mechanisms is presented in Appendix VII.
(b) Organic iodine is combined with elemental iodines in the calculations. Any error is negligible since its release fraction is relatively small for all large release categories.
(c) Includes Ru, Rh, Co, Mo, Tc.
(d) Includes Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am, Cm.
(e) Accident sequences within PWR 1 category have two distinct energy releases that affect consequences. PWR 1 category is subdivided into PWR 1A with a probability of 4×10^{-7} per reactor-year and 20×10^6 Btu/hr and PWR 1B with a probability of 5×10^{-7} per reactor-year and 520×10^6 Btu/hr.
(f) Not applicable.
(g) A 10 meter elevation is used in place of zero representing the mid-point of a potential containment break. Any impact on the results would be slight and conservative.

impacts of design basis accidents. Because the offsite economic consequences of the PWR8-PWR9 event categories are dominated by initial evacuation costs*, and since these events are predicted to result in very limited damage to the reactor plant (fuel cladding failure), these accidents are not included in the discussion of category II and III accidents.

The RSS PWR source terms are used in the offsite economic risk calculations in this study. Recently, there has been concern that these source terms may be conservative or non-realistic for most LWR accident sequences [Le81,Nu81c]. Research is underway to redefine LWR accident source terms based on detailed accident phenomonology studies for LWRs [SN83,Sp83]. The new economic model has been designed to incorporate any new source term definitions with minimum effort without invalidating the assumptions which underlie the model. Economic risks from core-melt accidents can be reevaluated when new source term definitions are available. The sensitivity of offsite economic consequences to source term definition is discussed in section 6.6.

6.3.2 SITE-SPECIFIC DATA USED IN THE OFFSITE ECONOMIC CONSEQUENCE CALCULATIONS

The new offsite economic consequence model provides the capability to use site-specific economic data in estimating the costs of emergency response and population protective countermeasures after an accident. County economic data for annual farm product sales, the fraction of each area used in farmland, market values of farmland and improvements, and the fraction of farm sales from dairy products are used in the offsite economic consequence calculations for the Surry reactor site. These data are taken from the 1978 Census of Agriculture and updated to 1982 dollars (where appropriate) using cost inflators [Ce78a,SA83]. County data for per-capita personal income are taken from the Bureau of Economic Analysis Local Area Personal Income Series for 1982 [BE83a].

County economic data are allocated to a 16x34 interval polar grid which is normally used for consequence calculations with

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* Calculations performed with the prototype economic model indicate that ~90% of PWR8 offsite costs and ~99% of PWR9 offsite costs result from population evacuation. Although these events have higher frequencies than core-melt accidents, they contribute minimally to the total economic risks because the onsite and offsite costs of these accidents are small relative to category II and III accidents resulting in severe plant damage.

the CRAC2 code [Ri83]. A computer code was developed to allocate county economic data to each polar grid element based on the nearest centroid of county population to the geometric center of each polar grid element. The locations of county population centroids are taken from the Bureau of the Census PICADAD data base [CE78c]. This data allocation scheme leads to slight errors in the assignment of county economic data to consequence model grid elements. However, this allocation scheme is appropriate since economic data generally vary smoothly around small counties, and much averaging is performed to allocate Census population data to the consequence model grid. County-average economic data are assigned to grid elements within 100 miles of the reactor site for the calculations in this study. National-average economic data are used in areas beyond 100 miles from the reactor site due to the large size of grid elements, the large uncertainties associated with atmospheric transport and deposition calculations at these distances, and since accident economic consequences are generally small in these areas.

A graphics display code was developed in this study to provide a map of county boundaries surrounding a reactor site with an overlay of the consequence model calculation grid. The code employs county boundary data from the Bureau of the Census DIME data base along with the county centroid population data from the PICADAD data base to map the area surrounding a reactor site [Ce78b,Ce78c]. The scale of a map is user-specified, allowing detailed mapping of the area immediately surrounding a site, or mapping of the entire consequence calculation grid. Maps of the Surry reactor site with the 16x34 consequence calculation grid overlay are shown in Figures 6.1 and 6.2. The graphics routine is used to clearly identify those grid elements which cover ocean areas only. The economic data for ocean intervals are set equal to zero since only small economic consequences occur in these areas.

6.3.3 POPULATION PROTECTIVE MEASURE ASSUMPTIONS

The offsite economic consequences of any large accident at a nuclear power reactor are strongly dependent on the population protective measures which are assumed to be taken. Based on current guidance, the calculations in this section assume that the entire population within 10 miles of the reactor site is evacuated during all core-melt accidents [Nu80b]. Individuals are returned to areas not impacted by a release of radioactive material 3 days after the initiation of evacuation. An integrated groundshine exposure of 1 Rem in the time period 1-7 days after deposition of radionuclides in an area is used as a criterion for emergency phase relocation from contaminated areas. An integrated groundshine exposure of 2 Rem in the time period 7-30 days after deposition of materials in an area is used as

Figure 6.1 - Map of counties and consequence calculation grid within 500 mile radius of Surry site.

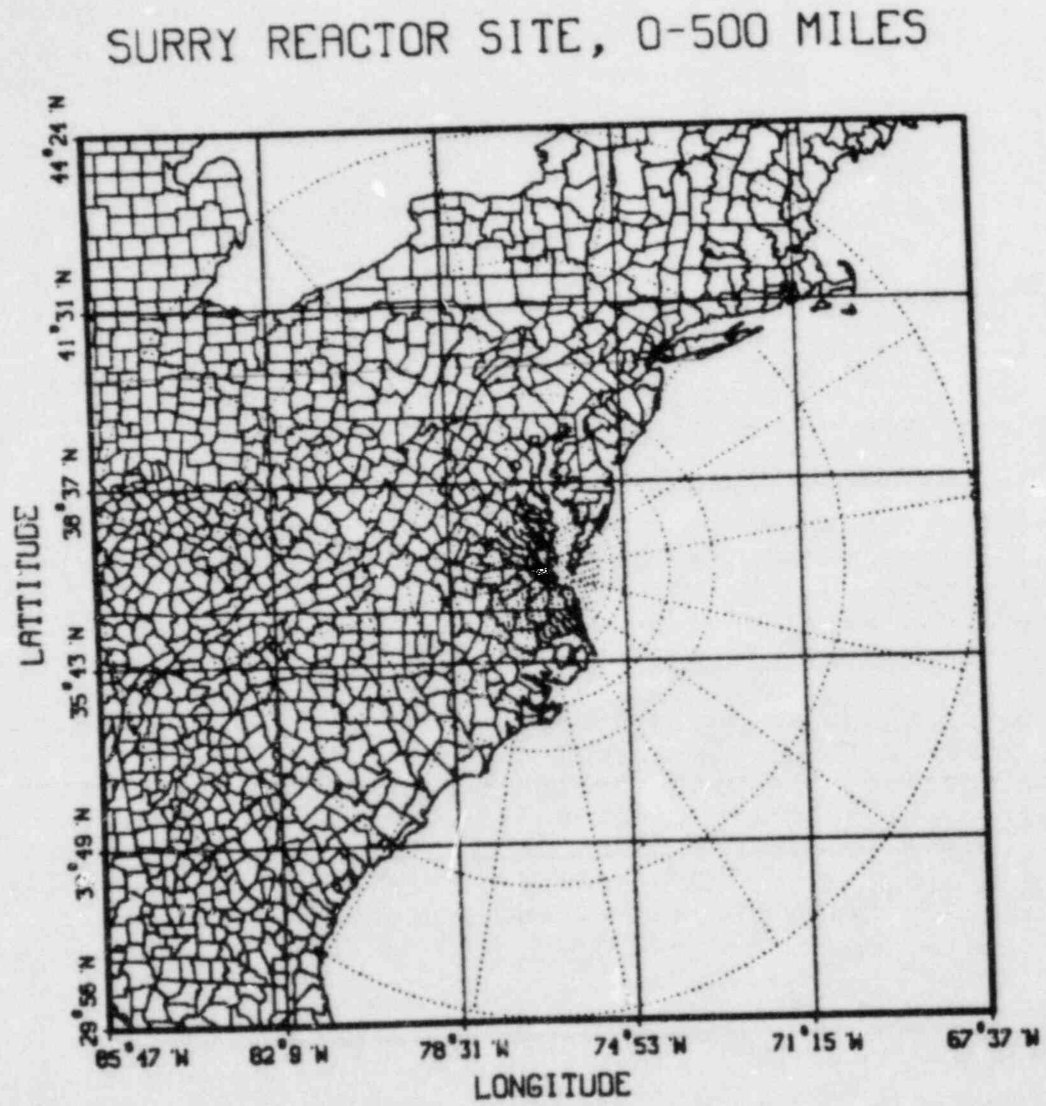
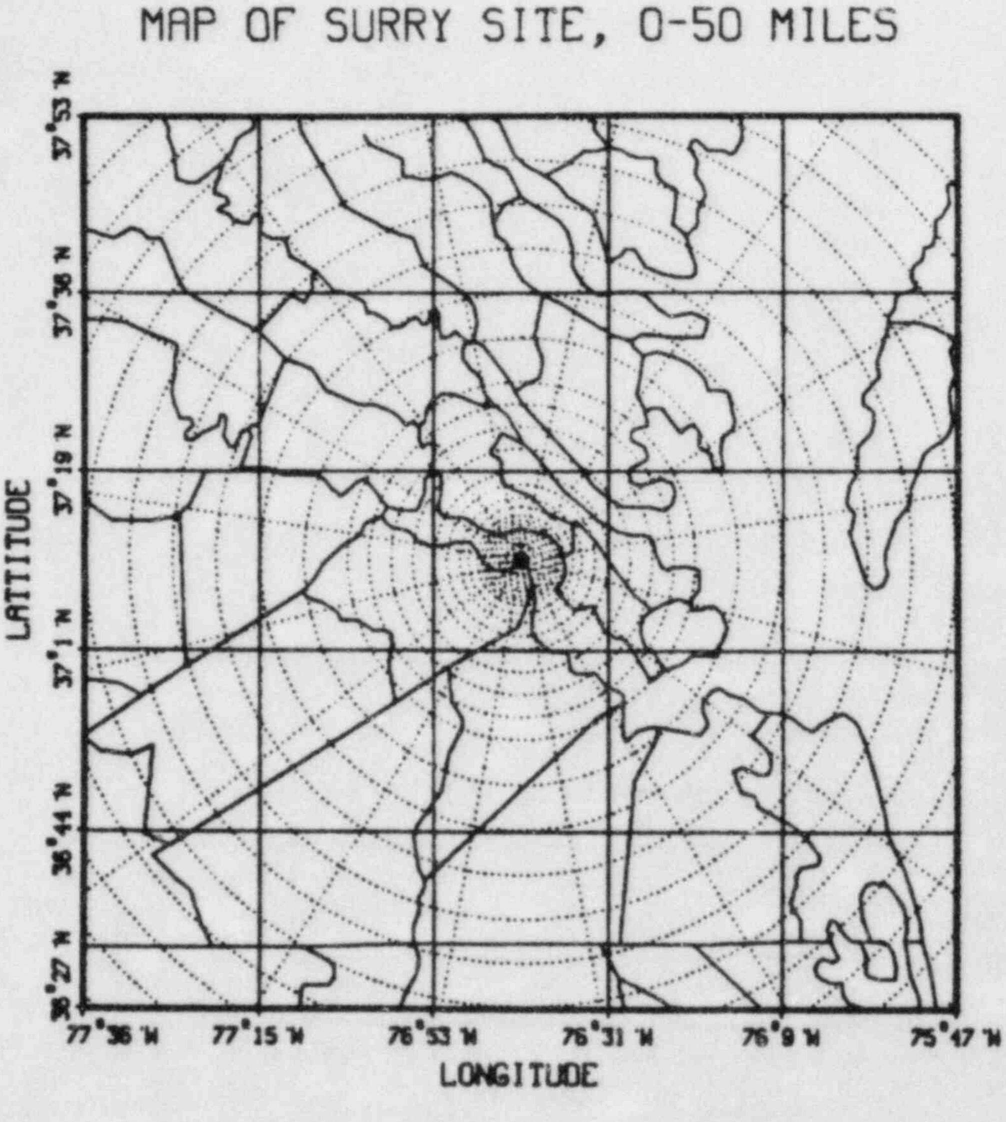


Figure 6.2 - Map of counties and consequence calculation grid within 50 mile radius of Surry site.



the criterion for intermediate phase relocation. A long-term protective action criterion of 25 Rem integrated groundshine exposure during the period 30 days - 30 years after deposition of radioactive materials is used in the calculations. The dose levels and organs considered for disposal of contaminated agricultural products are the same as those used in the RSS [Nu75b].

The economic consequences and public health impacts of an accident are strongly affected by the user-specified protective action implementation criteria. The criteria chosen in this study are based on sensitivity studies performed with the new economic model, and guidance provided by the Environmental Protection Agency, the Federal Radiation Council, and the RSS [EP75,FR64,Nu75b]. The sensitivity of offsite economic consequences to offsite protective action implementation criteria is examined in section 6.6.

6.3.4 DISTRIBUTIONS OF CORE-MELT ACCIDENT ECONOMIC CONSEQUENCES AT SURRY #2

The new onsite and offsite economic consequence models are employed to estimate risks using the RSS source terms for the Surry reactor. The consequence calculations are based on 100 samples of Washington, D.C. meterological data using the metbin sampling technique [Ri81] and the yearly average wind rose for the Surry reactor site. All economic data have been updated and results are presented in 1982 dollars.

The complementary cumulative distribution function for core-melt accident economic consequences over the remaining lifetime (~30 years) of the Surry plant is shown in Figure 6.3. The figure shows the probability of occurrence of core-melt accidents with economic consequences greater than specified magnitudes over the remaining lifetime of the Surry plant. The lowest probability accident consequences shown have an estimated chance of one in a million of occurring during the entire remaining life of the reactor plant. Consequences with probabilities lower than one in a million over the remaining plant life have a negligible contribution to expected costs. The expected values of all of the cost component curves for lifetime core-melt accident risk are also shown in Figure 6.3. The cost estimates presented are discounted to the time of accident occurrence at 4% per year. The economic risks in future years are not discounted to the present in the economic consequence distributions in Figure 6.3. Discounting of future accident risks is appropriate for calculating the total present value for risk-reduction expenditure decisions; however this leads to difficulty in interpretation of economic consequence distributions.

The economic risk distributions and means presented in

Figure 6.3 - Distributions of core-melt accident economic risks for remaining lifetime of Surry #2 plant (based on loss of single unit).

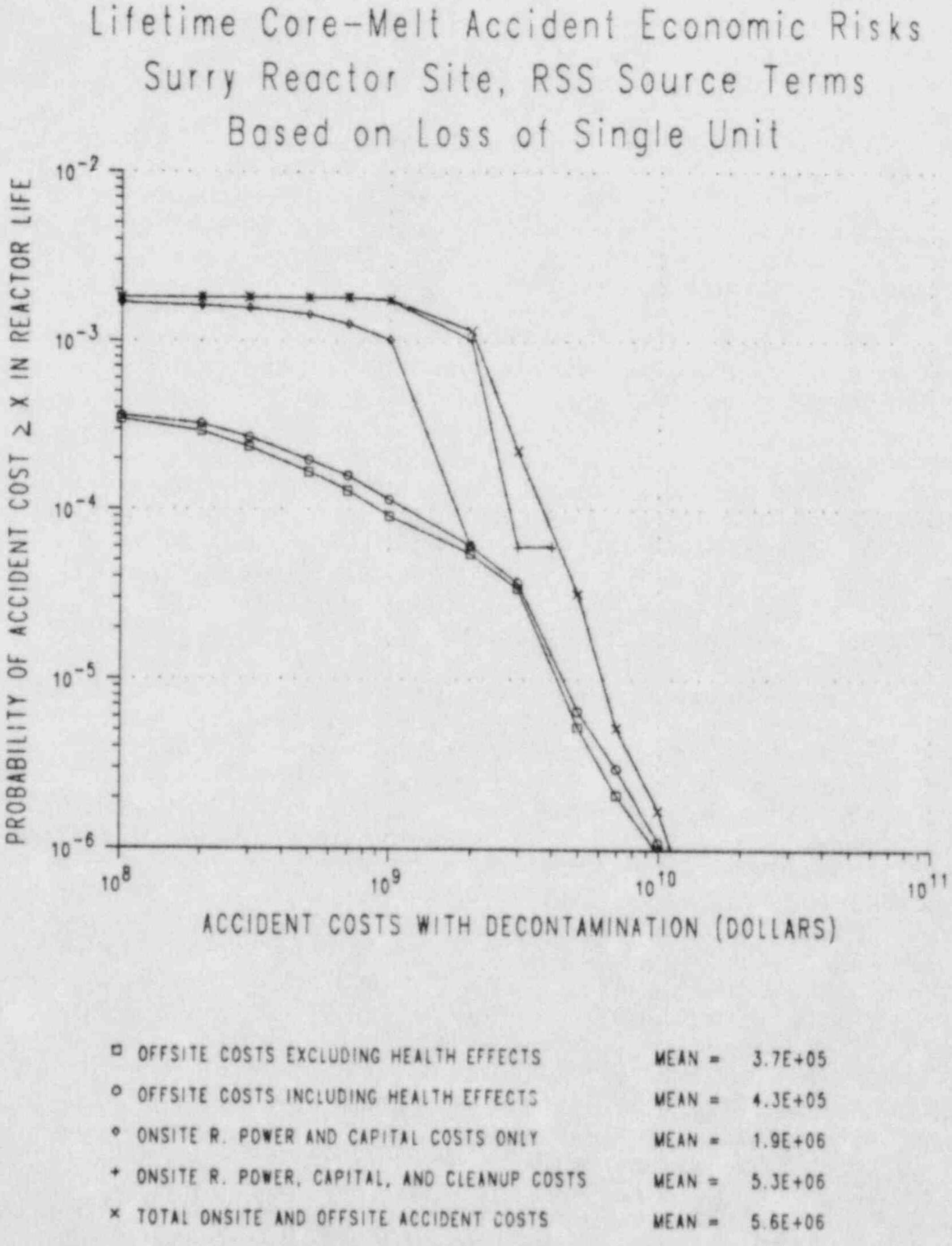


Figure 6.3 show some important characteristics of the core-melt economic risks at the Surry plant. The onsite costs of replacement power, plant capital losses, and plant decontamination after a core-melt event dominate the offsite property damage and public health effects costs except for very low probability accidents at this site. The economic consequence distributions show that the most likely core-melt accidents would result in small offsite consequences relative to the onsite costs of plant loss and cleanup. Expected offsite property damage and health effect costs of core-melt accidents are a factor of 10 lower than expected onsite losses.

The economic risk distributions in Figure 6.3 are based on the loss of a single 775 Mwe unit at the Surry site after a core-melt accident. Because of the severity of core-melt accidents with reactor vessel breach, and the potential for large releases of radioactive material contaminating the site to high levels, it is possible that the generation capacity of both units at the Surry site would be lost in the event of a core-melt accident. Figure 6.4 shows the economic risk distributions based on the assumption that both units of the Surry reactor site are forced out of service after a core-melt accident at Unit 2. The figure includes replacement power and capital losses for both units of the Surry site after a core-melt accident at Unit #2. The total expected core-melt accident costs over the remaining lifetime of the Surry Unit 2 plant are approximately 1/3 higher assuming both units 1 and 2 are lost after a single core-melt accident. The risk distributions in Figure 6.4 show an even larger dominance of onsite costs over offsite cost components for the Surry #2 plant.

The contribution of each of the RSS PWR1A-PWR7 core-melt accident release categories to expected costs over the lifetime of the Surry plant is shown in Table 6.3. The contribution of each release category to onsite costs is directly proportional to the accident category frequency since the onsite cleanup, replacement power, and capital losses are approximately the same for all core-melt accident categories. The high-frequency core-melt accidents resulting in small releases of radioactive material to the environment are the largest contributors to expected onsite costs. In contrast, ~90% of expected offsite costs result from low probability PWR2 and PWR3 release categories. The offsite core-melt accident economic risks are dominated by low frequency, large consequence accidents. The expected onsite accident costs are larger than expected offsite accident costs for all release categories.

The RSS estimate of offsite costs for the PWR1A-PWR7 release categories for a "composite" reactor site is also shown in Table 6.3. Although the "composite" site estimate is not directly comparable to the results presented for the Surry reactor site, the rough comparison in Table 6.3 shows that the new model predictions are similar in magnitude to those from the RSS.

Figure 6.4 - Distributions of core-melt accident economic risks for remaining lifetime of Surry #2 plant (based on loss of both units).

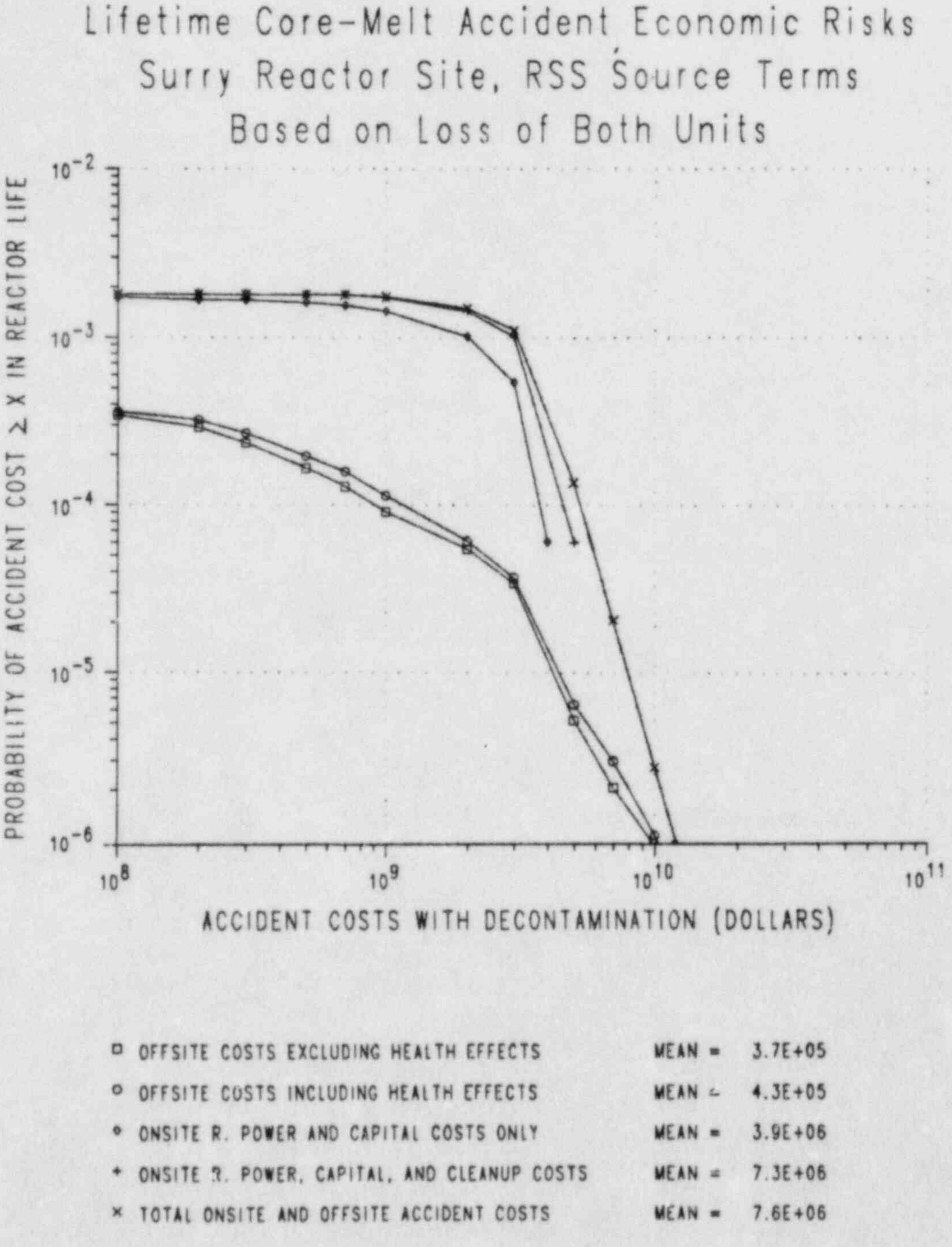


Table 6.3 - Contribution of PWR1A-PWR7 core-melt accident categories to lifetime-integrated economic risks, Surry #2, single unit loss.

Release Category	RSS Frequency (per r.-yr.)	Contribution to Expected Onsite Costs	Contribution to Expected Offsite Costs
PWR1A	4×10^{-7}	$\$3.5\times10^{4}$	$\$1.6\times10^{4}$
PWR1B	5×10^{-7}	$\$4.4\times10^{4}$	$\$2.1\times10^{4}$
PWR2	8×10^{-6}	$\$7.1\times10^{5}$	$\$3.1\times10^{5}$
PWR3	4×10^{-6}	$\$3.5\times10^{5}$	$\$6.8\times10^{4}$
PWR4	5×10^{-7}	$\$4.4\times10^{4}$	$\$1.2\times10^{3}$
PWR5	7×10^{-7}	$\$6.2\times10^{4}$	$\$5.3\times10^{2}$
PWR6	6×10^{-6}	$\$5.3\times10^{5}$	$\$9.5\times10^{2}$
PWR7	4×10^{-5}	$\$3.5\times10^{6}$	$\$5.3\times10^{3}$
Total (Core-Melt)	6×10^{-5}	$\$5.3\times10^{6}$	$\$4.3\times10^{5}$

Expected Offsite Core-Melt Accident Costs per Reactor-Year:

RSS - "Composite" Site	$\$1.3\times10^{4}$ (1974 \$)
New Model - Surry Site	$\$1.4\times10^{4}$ (1982 \$)

Table 6.4 summarizes the expected costs of core-melt accidents over the remaining Surry plant lifetime based on the RSS source terms. The expected offsite costs from core-melt events at this site are small compared to the expected costs of replacement power, capital losses, and plant cleanup after core-melt accidents. However, offsite impacts of core-melt accidents could be much higher for more densely populated sites. As discussed in section 4.4.6, the public health effect dollar values used in the analysis are based on purely economic costs, and do not include societal preferences for avoiding health risks. Larger health effect costs which reflect preferences for risk avoidance could easily be incorporated into the new offsite economic consequence model if desired. The dollar values for offsite health effects must be increased by factors of 50-100 to make them important contributors to the expected costs of core-melt accidents at the Surry site. This supports the conclusions of earlier studies which found the total costs of core-melt accidents to be relatively insensitive to health effect dollar values even including preferences for health effect risk reduction [St82].

6.3.5 PRESENT VALUE OF LIFETIME-INTEGRATED CORE-MELT ECONOMIC RISKS FOR SURRY #2

Estimates of the present value of lifetime-integrated economic risks of core-melt accident costs for the Surry #2 plant are shown in Table 6.5. The economic risk estimates are based on the core-melt accident frequencies and source terms defined in the RSS. The integrated onsite and offsite economic risks are shown for real discount rates of 0, 4, and 10%. The frequency of each core-melt accident category is assumed to be constant over the reactor lifetime in the economic risk integration. The present value of total offsite core-melt accident costs is estimated to be ~\$1-4x10^5 dollars over the 30 year remaining plant lifetime. The present value of onsite economic risks including plant decontamination, replacement power, and plant repair or new plant capital costs are predicted to be ~\$2-6x10^6 dollars over the remaining plant lifetime for the 0-10% range of discount rates. The integrated onsite costs are approximately a factor of 10 higher than integrated offsite costs for core-melt accidents at the Surry site. Most of the onsite costs result from plant decontamination and cleanup costs, replacement power cost increases, and plant capital losses for these accidents. The total present value of lifetime risks varies by a factor of ~4 for real discount rates of 0%-10%.

The estimates of total severe accident economic risks based on category III costs (Table 6.5) are about a factor of 2 higher than the estimates based on category II event costs (Table 6.1). This factor results from the assumption that all

Table 6.4 - Lifetime core-melt accident economic risks for Surry #2 based on loss of single generating unit.

Cost Component	Expected Costs Over Plant Lifetime Due to Core-Melt Accidents
Onsite Replacement Power, Capital Costs	$\$1.9\times10^6$
Onsite Decontamination/Cleanup Costs	$\$3.4\times10^6$
Offsite Property Damage	$\$3.7\times10^5$
Offsite Public Health Impacts*	$\$6.0\times10^4$
Total	$\$5.7\times10^6$

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*Based on purely economic costs of medical care and productivity losses due to early fatalities, early injuries, and latent health effects.

Table 6.5 - Present value of severe accident economic risks based on category III event costs, remaining lifetime of Surry #2 plant.

Core-Melt Accident Frequency = 6×10^{-5}/reactor-year*

Discount Rate	Present Value of Lifetime Economic Risks Offsite Costs	Onsite Costs
0%	$\$4.4\times10^{5}$	$\$5.5\times10^{6}$
4%	$\$2.5\times10^{5}$	$\$3.3\times10^{6}$
10%	$\$1.3\times10^{5}$	$\$1.7\times10^{6}$

All costs are expressed in 1982 dollars.

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*Estimates based on the median PWR core-melt accident frequencies and source terms defined in the RSS with consequence calculations for the Surry site (category III events).

category III accidents would result in early plant shutdown, and the higher plant decontamination cost estimates for category III accidents. The costs of offsite property damage and health effects for core-melt accidents also contribute to the difference in economic risk estimates.

6.4 UNCERTAINTIES IN ECONOMIC RISK ESTIMATES

Uncertainties in the category II and III event economic risk estimates are dominated by uncertainties in event frequencies. The event frequency estimates from probabilistic risk studies are highly uncertain due to imperfect information regarding severe LWR accident initiators and physical processes. The uncertainties in the RSS core-melt frequencies were estimated to be factors of 5 and 1/5 [Nu75a]. However, a critical review of the RSS concluded that uncertainties were significantly underestimated in the study [Le78]. Uncertainties in the relative frequencies of core-damage versus core-melt accidents are also large. However, these uncertainties result in only a factor of 2 variation in severe accident economic risk estimates. Thus, uncertainties in the total LWR severe accident frequencies are more important in determining the uncertainties in severe accident economic risks.

Uncertainties in onsite costs for category II accidents are dominated by uncertainties in replacement power cost increases, plant decontamination costs, and the duration of plant outages after category II accidents. For the entire range of core-damage accidents, it is estimated that the total onsite costs could range from a factor of 3 higher to a factor of 5 lower than those presented. This range is dominated by uncertainties in plant outage duration and plant decontamination costs for core-damage accidents. Because offsite costs of category II events are small relative to onsite costs, the uncertainties in offsite costs contribute negligibly to the total uncertainties in total category II accident costs.

Uncertainties in onsite costs for category III accidents are dominated by uncertainties in plant decontamination costs, replacement power cost increases, and replacement generating capacity capital costs. The total onsite costs are estimated to range from a factor of 3 higher to a factor of 5 lower than those presented for core-melt accidents. The uncertainties in offsite costs of core-melt accidents are dominated by uncertainties in offsite property decontamination costs and the criteria chosen for implementation of long-term population protective measures after contaminating events. The total offsite cost for core-melt accidents are estimated to range from a factor of 5 higher to a factor of 5 lower than those presented for a defined release of radioactive material. The uncertainties in onsite costs are the most important contributor to uncertainty in total societal core-melt accident costs for the Surry #2 plant.

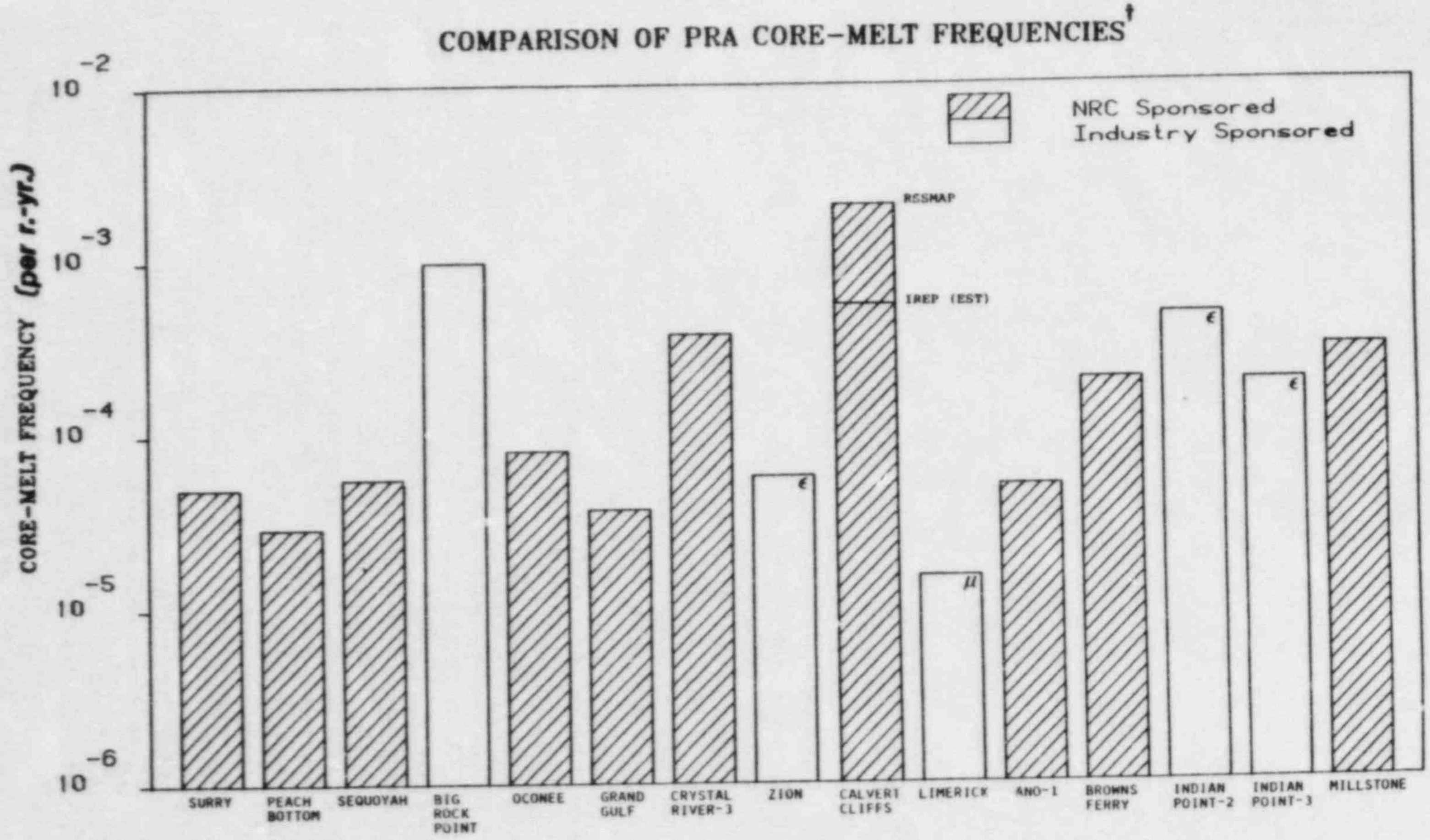
6.4.1 RANGE OF RISKS FOR OTHER PLANTS

The range of severe accident economic risks at other plants is largely determined by plant-specific accident frequencies. Many plant-specific probabilistic risk studies have been performed to estimate the core-melt frequency and/or the public health risk from plant operation. A comparison of the plant specific core-melt frequencies from probabilistic safety studies performed since the RSS is shown in Figure 6.5 [Ha83]. The values presented represent median or "point" estimates of core-melt accident frequencies at each plant unless otherwise indicated in the figure. Comparison of the plant-specific frequency estimates can be misleading because the studies have not been performed using consistent methodologies and assumptions. The predicted range of core-melt frequencies spans approximately two orders of magnitude from $\sim 2\times10^{-3}$-10^{-5} per reactor-year. This range is consistent with the best-estimate of core-damage event frequency from the TMI-2 accident and U.S. LWR experience ($\sim 2\times10^{-3}$ per reactor-year). Some variation in core-melt frequencies results from the use of different techniques and assumptions in the risk studies for each plant. Plant-specific design characteristics also contribute significantly to the variation in core-melt frequency estimates.

Calculations were performed to examine the importance of site demographic characteristics in determining offsite economic risks from core-melt accidents. The new offsite cost models were employed to estimate core-melt risks for the Surry #2 plant (RSS PWR source terms) at the Indian Point site. The expected offsite consequences of each of the PWR1A-PWR7 accident categories at the Indian Point site are approximately a factor of 10 greater than for the equivalent plant at the Surry site. This results in comparable offsite and onsite economic risks for core-melt accidents at the Indian Point site. The total estimated onsite and offsite economic risks at the Indian Point site are approximately a factor of 2 greater than those for an equivalent plant at the Surry site. Site demographic characteristics significantly impact offsite economic risks, but have less impact on total economic risks because they do not influence onsite accident consequences.

Based on the range of core-melt accident frequencies from plant-specific probabilistic risk studies, historical experience, and U.S. LWR site demographic characteristics, crude estimates of category II and III economic risks at other U.S. LWR plants might range from ~6 times lower to ~30 times higher than those presented for Surry #2. The variation in core-damage event frequency is likely to be the dominant contributor to the total variation in core-damage event economic risk estimates for specific plants. Site-specific demographic characteristics are also important for determining the total offsite economic risks from core-melt accidents at other U.S. LWR sites.

Figure 6.5 - Comparison of PRA core-melt frequencies [Ha83].



COMPARISON OF PRA CORE-MELT FREQUENCIES†

† All values are median or "point" estimates unless otherwise indicated. There are large uncertainties in the values presented. Also, PRAs were not performed using consistent methodologies and assumptions.

μ Mean estimate.

ϵ Includes detailed external event analysis.

Calculations have been performed to estimate the lifetime severe accident economic risks for other reactor sites using the new onsite and offsite economic consequence models. Economic risks for the Peach Bottom reactor site based on the RSS release categories BWR1-BWR4 are similar to those presented for the Surry reactor site. Results for sites with higher population densities show higher offsite costs for core-melt accidents than those presented for the Surry site. However, for all sites which have been examined, the offsite costs of severe accidents are predicted to be small relative to onsite costs except for low-probability core-melt accidents which result in large releases of radioactive material.

6.5 COMPARISON OF CORE-MELT ECONOMIC CONSEQUENCE ESTIMATES WITH RESULTS OF PREVIOUS STUDIES

The results of previous studies of core-melt accident economic consequences are compared to results calculated with the new economic model in this section. Results of offsite costs predictions from the CRAC2 economic model are compared to results from the new economic model. Differences in the results calculated with the two models are discussed.

CRAC2 estimates the economic consequences of post-accident population protective measures which are implemented after a release of radioactive material to the environment. The CRAC2 code has recently been employed in a study of the financial consequences of core-melt accidents (NUREG/CR-2723) [St82] which used the Sandia Siting Study Source terms SST1-SST3 [Al82] to explore the lifetime integrated costs of core-melt accidents. Simple models were employed in the study to estimate onsite cleanup and replacement power costs. A comparison of lifetime integrated SST1 accident cost estimates from that study [St82] and the new economic models is presented in Table 6.6. The table shows that the total cost estimates for the Surry reactor site are very similar. Significant differences exist in health effect costs due to the use of health effect dollar values which include preferences for risk reduction in NUREG/CR-2723. The new economic model includes genetic effect and thyroid health effect costs which were not included in the previous estimates. The estimate of onsite cleanup costs in this study is higher than the estimate from NUREG/CR-2723. However, the total estimated lifetime SST1 accident financial consequences are very similar as shown in Table 6.6.

A comparison of the mean offsite cost components for an SST1 release at the Surry plant from the CRAC2 and new economic consequence models is shown in Table 6.7. The CRAC2 model does not have the capability of estimating emergency phase relocation costs, intermediate phase relocation costs, or costs for population relocation during the decontamination period. The

Table 6.6 - Comparison of new model predictions and results from NUREG/CR-2723 for the SST1 release, Surry reactor.

NEW MODEL RESULTS VS. NUREG/CR-2723

Expected Value of Accident Costs for Plant Life*

Economic Risks for SST1 Release Category, Surry Reactor

Cost Component Considered	**NUREG/CR-2723**	**New Economic Models**
Offsite Health Effects	$1.0 \times 10^{10} \times f_1$	$0.6 \times 10^{10} \times f_1$
Offsite Property Costs	$3.2 \times 10^{10} \times f_1$	$3.5 \times 10^{10} \times f_1$
Onsite Cleanup	$2.5 \times 10^{10} \times f_1$	$5.4 \times 10^{10} \times f_1$
Onsite Total Costs	$5.7 \times 10^{10} \times f_1$	$8.6 \times 10^{10} \times f_1$
Total Costs	$9.9 \times 10^{10} \times f_1$	$1.3 \times 10^{11} \times f_1$

*** f_1 is defined to be the SST1 release category frequency (per reactor-year). Multiplication by f_1 in the table yields the total expected costs of SST1 accidents over the remaining plant lifetime in dollars.**

Table 6.7 - Comparison of offsite cost estimates from CRAC2 and new models, conditional on SST1 accident release, Surry #2 plant.

Cost Component	CRAC2 Mean Costs	New Model Mean Costs
Evacuation	$\$3.0\times10^{6}$	$\$4.5\times10^{6}$
Emergency Phase Relocation	-	$\$2.3\times10^{7}$
Intermediate Phase Relocation	-	$\$8.6\times10^{7}$
Agricultural Product Disposal	$\$8.0\times10^{7}$	$\$9.1\times10^{7}$
Population Relocation During Decontamination	-	$\$9.3\times10^{7}$
Land and Property Decontamination	$\$4.2\times10^{8}$	$\$6.6\times10^{8}$
Land and Property Interdiction	$\$1.9\times10^{8}$	$\$1.6\times10^{8}$
Interdicted Population Relocation	$\$4.9\times10^{7}$	$\$2.6\times10^{7}$
Offsite Health Effects	-	$\$1.5\times10^{8}$
Total Offsite Costs	$\$7.4\times10^{8}$	$\$1.1\times10^{9}$

Other Attributes Estimated in New Model	
Total Population Dose Incurred, 0-100 Years	1.4×10^{7} Person-Rem
Total Population Dose Avoided by Protective Measures	4.1×10^{7} Person-Rem
Decontamination Worker Dose	2.8×10^{5} Person-Rem
Labor Required for Decontamination Program	1.1×10^{4} Person-Years
Number of Decontamination Workers Required for Completion of Program in 90 Days	4.6×10^{4} Persons

results of both models indicate that the cost of property decontamination is the most important contributor to total offsite costs for an SST1 release at the Surry plant. The cost of property interdiction in areas where decontamination cannot reduce dose rates to acceptable levels is the second most important contributor to offsite costs for this large release of radioactive material. The costs of offsite health effects are also predicted to be relatively important for this large source term. The emergency phase relocation, intermediate phase relocation, and decontamination period relocation costs are relatively small for this accident release category. However, these costs dominate the initial evacuation costs which are the only population relocation costs included in the CRAC2 models. Updated costs of decontamination, interdiction, and relocation in the new economic model result in total cost estimates less than a factor of 2 higher than those from the CRAC2 model.

Additional attributes of SST1 accident consequences estimated in the new economic model are shown in Table 6.7. The implementation of population protective measures (including decontamination, interdiction, and relocation) results in a factor of four reduction in total population dose incurred in the first 100 years after accident occurrence. The dose to decontamination workers during the decontamination period is estimated to be about 2% of the total population dose incurred in this period. A total of ~11,000 man-years of effort is involved in the decontamination program to reduce population exposure from the accident. Based on a mean time to completion of 90 days for the decontamination efforts, this program would require a work force of ~46,000 men. Clearly, a large decontamination program after a severe reactor accident would have some important beneficial economic impacts in an affected area. However, manpower limitations may force an extended period for completion of the offsite decontamination program after large releases of radioactive material.

Calculations performed for various U.S. LWR sites have shown that the new offsite economic model predictions of offsite costs are generally factors of ~2-4 higher than those predicted by the CRAC2 code. This difference results from more accurate accounting for costs, inclusion of more cost components, indexing of costs to 1982 dollars, improved estimates of decontamination costs and effectiveness, and the use of county-level economic data with the new economic models. One important difference between CRAC2 and the new model is that the new model provides direct estimates of the benefits of population protective measures in terms of population dose avoided. These benefit estimates can be used in cost/benefit analysis of protective measure implementation as discussed in the following section.

6.6 SENSITIVITY STUDIES OF CORE-MELT ACCIDENT OFFSITE ECONOMIC CONSEQUENCES

The new offsite economic consequence models have been used to evaluate the sensitivity of offsite costs to assumptions regarding source terms and offsite public protective measure implementation criteria. An example cost/benefit analysis of offsite protective measure implementation is also presented.

6.6.1 SENSITIVITY OF OFFSITE COSTS TO SOURCE TERMS

There has been concern expressed recently that the source terms defined in probabilistic safety studies may overestimate the releases of radioactive material to the environment from severe LWR accidents [Le81]. The conclusions of research aimed at defining new source term values based on detailed accident physical progression studies can be incorporated into future economic risk studies [SN83,Sp83]. The reduction of source term values would result in small or no changes in onsite cost estimates for severe LWR accidents. The offsite costs of necessary protective measures and public health effects could be substantially impacted by significant source term reductions.

The sensitivity of core-melt accident offsite costs to source term magnitude is examined for the SST1 release category at the Surry reactor site. Table 6.8 shows the results of offsite economic consequence calculations for the Surry reactor site conditional on the SST1 source term, and for the SST1 source term with release fractions for all elements except noble gases reduced by factors of 10 and 100. The table shows that the mean total offsite economic consequences vary approximately linearly with the source term release fractions. Property interdiction costs and interdicted population relocation costs vary non-linearly due to the threshold nature of these effects. The cost of evacuation is independent of source term and becomes more important relative to total costs for small source terms.

The sensitivity of offsite costs to source term magnitude is important for consideration of offsite economic risks. However, since onsite costs contribute significantly to the economic risks from core-melt accidents, and these costs are not sensitive to source term values, the total economic risk from core-melt accidents is less sensitive to source term definition.

6.6.2 SENSITIVITY OF OFFSITE COSTS TO PROTECTIVE MEASURE IMPLEMENTATION CRITERIA

The offsite costs of a release of radioactive material from an LWR accident are dependent upon post-accident decisions regarding population protective measure implementation in each

Table 6.8 - Sensitivity of offsite economic consequences to source term definition, Surry #2, SST1 release category.

	Mean Offsite Costs		
Offsite Cost Component	SST1	SST1/10*	SST1/100**
Evacuation	$\$4.5\times10^{6}$	$\$4.5\times10^{6}$	$\$4.5\times10^{6}$
Emergency Phase Relocation	$\$2.3\times10^{7}$	$\$3.4\times10^{6}$	$\$1.4\times10^{5}$
Intermediate Phase Relocation	$\$8.6\times10^{7}$	$\$1.2\times10^{7}$	$\$6.3\times10^{5}$
Agricultural Product Disposal	$\$9.1\times10^{7}$	$\$1.5\times10^{7}$	$\$1.4\times10^{6}$
Population Relocation During Decontamination	$\$9.3\times10^{7}$	$\$6.6\times10^{6}$	$\$1.1\times10^{5}$
Land and Property Decontamination	$\$6.6\times10^{8}$	$\$1.0\times10^{8}$	$\$5.3\times10^{6}$
Land and Property Interdiction	$\$1.6\times10^{8}$	$\$5.8\times10^{6}$	$\$7.1\times10^{4}$
Interdicted Population Relocation	$\$2.6\times10^{7}$	$\$1.3\times10^{6}$	$\$2.6\times10^{2}$
Offsite Health Effects	$\$1.5\times10^{8}$	$\$2.8\times10^{7}$	$\$4.9\times10^{6}$
Total Offsite Costs	$\$1.1\times10^{9}$	$\$1.5\times10^{8}$	$\$1.6\times10^{7}$

*SST1 source term with all release fractions except the noble gases reduced by a factor of 10.

**SST1 source term with all release fractions except the noble gases reduced by a factor of 100.

area impacted by the release. The post-accident decision-making process is modeled in the offsite economic consequence model by comparing projected individual doses to criteria specified for protective measure implementation. The sensitivity of offsite economic consequences to the long-term protective action implementation criterion is examined in this section.

The dependence of the mean offsite costs for the SST1 release category at the Surry reactor on the long-term protective action criterion is presented in Table 6.9. The long-term protective action criterion is based on individual doses integrated from 30 days to 30 years after deposition of radioactive materials. The Surry economic risks presented are based on the 25 Rem criterion in this period. Results are shown in Table 6.9 for criteria ranging from 5-500 rem individual whole-body exposure during this period. The total offsite accident costs vary by approximately a factor of 5 for the range of protective action criteria examined. As more stringent criteria are applied, the costs of population protective measures increase because larger areas and populations are affected. However, the costs of offsite public health effects decrease as the population exposure to radioactive material is reduced. The new economic model is useful for performing sensitivity studies regarding population protective measure implementation criteria because both costs and benefits of countermeasure implementation are estimated.

The offsite economic consequences of LWR accidents are strongly dependent upon the population protective measure implementation criteria defined in the new offsite economic consequence model. Offsite cost estimates could be increased by large factors based on the assumption that very stringent criteria are applied in post-accident decision-making. However, this assumption may be unrealistic given the limited benefits and potential resource limitations which would result from such actions.

6.6.3 COST/BENEFIT ANALYSIS OF POST-ACCIDENT COUNTERMEASURES

The new economic consequence model can be applied to cost/benefit studies of post-accident public protective action implementation criteria. An example of this application of the model is presented in this section.

The prototype economic model estimates the population exposure avoided (man-rem) in the emergency phase, intermediate phase, and long-term periods. The costs of protective measures implemented in each post-accident period are calculated in the model. For exposure beyond the acute time period, each population man-rem incurred has approximately an equivalent impact on predicted radiation-induced public health effects.

Table 6.9 - Sensitivity of offsite costs to long-term protective action implementation criterion, SST1 release, Surry #2 plant.

Protective Action Criterion for Period 30 days - 30 years After Material Deposition (Individual Whole-Body Dose)	Mean Costs of Long-Term* Offsite Protective Actions	Mean Costs of Offsite Health Effects	Mean Total Offsite Costs
5 Rem	$\$4.1\times10$[illegible]	$\$9.8\times10^{7}$	$\$4.1\times10^{9}$
10 Rem	$\$2.3\times1$[illegible]	$\$1.3\times10^{8}$	$\$2.4\times10^{9}$
25 Rem	$\$1.1\times$[illegible]	$\$1.5\times10^{8}$	$\$1.3\times10^{9}$
50 Rem	$\$7.5\times10^{8}$	$\$1.8\times10^{8}$	$\$9.3\times10^{8}$
100 Rem	$\$5.0\times10^{8}$	$\$2.2\times10^{8}$	$\$7.7\times10^{8}$
500 Rem	$\$2.5\times10^{8}$	$\$5.8\times10^{8}$	$\$8.3\times10^{8}$

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*Long-term protective action costs include all costs associated with decontamination and/or interdiction of land and property in those areas where required.

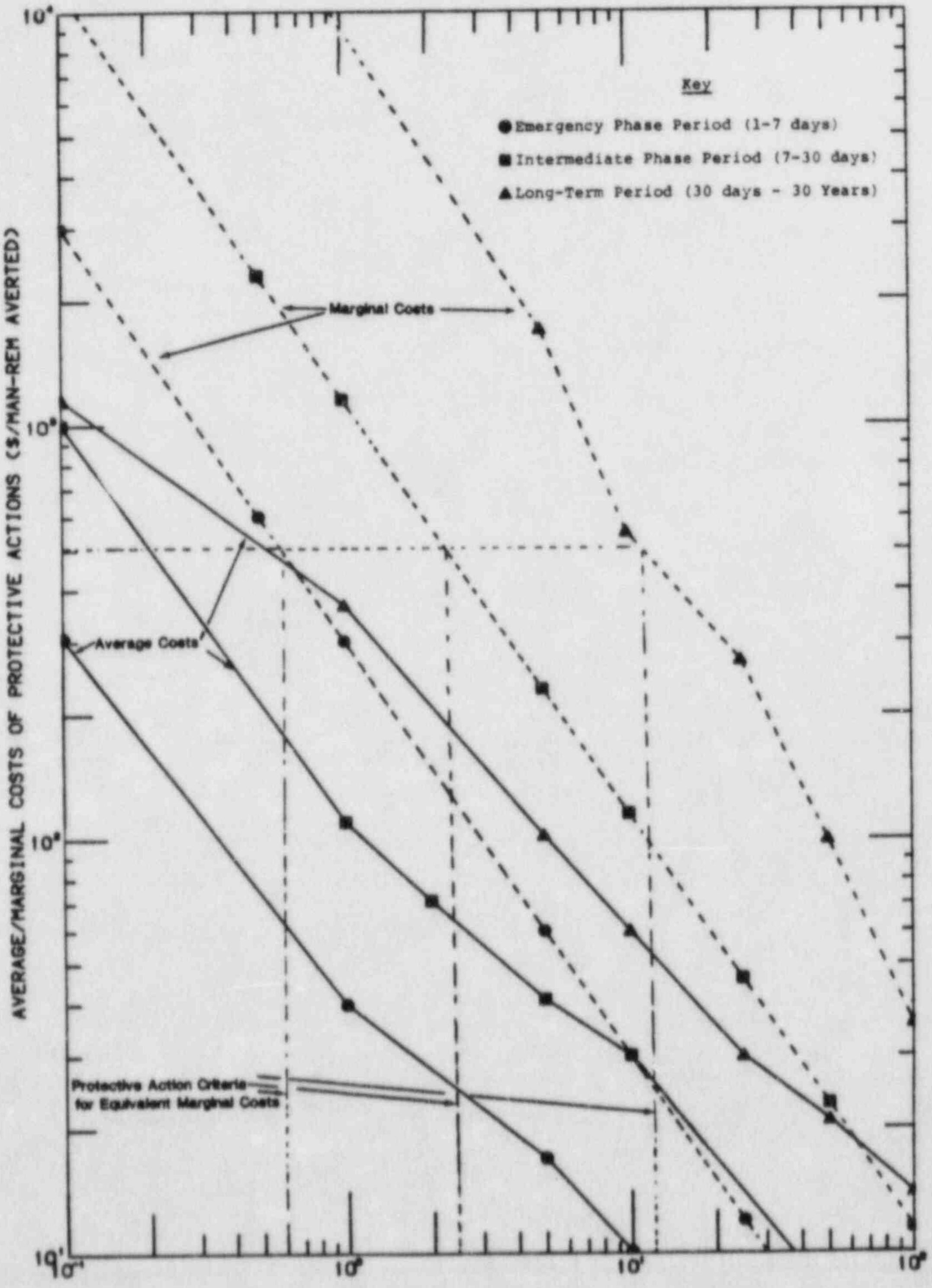
Therefore, for population protective measures beyond the acute time period, man-rem avoided is a useful measure of the benefit of implementing population protective measures.

Results of sensitivity studies of protective measure implementation criteria are presented in Figure 6.6. The figure is based on results of calculations performed conditional on an SST1 release at the Surry site. The emergency phase period is defined to extend from 1-7 days, the intermediate phase from 7-30 days, and the long-term phase from 30 days-30 years after the deposition of materials. The figure shows the mean cost/benefit ratio in terms of dollars per man-rem averted during each of these protective measure periods for a wide range of protective measure implementation criteria. Curves are shown for both the average and marginal cost per man-rem averted for protective action criteria in each defined time period. The figure shows that the cost/benefit ratios based on average cost are smaller than those based on marginal cost. This behavior is observed because a large portion of protective measure costs and benefits are incurred in areas where dose rates are high. As more restrictive criteria are applied, additional costs and additional man-rem averted are small relative to total costs and benefits.

A more useful measure of costs and benefits for decision-making is the marginal cost/benefit ratio. This ratio is the cost of avoiding an additional man-rem (at the margin) by applying a more restrictive criterion for population protective measure implementation. Unlike the average cost per man-rem averted, the marginal cost per man-rem averted is determined exclusively by costs and benefits in those areas which only marginally exceed a protective action criterion. This ratio explicitly demonstrates the costs and benefits of avoiding each additional man-rem as the protective action implementation criterion is decreased.

Cost/benefit studies of protective action criteria can be useful for decision-making regarding recommended individual exposure limits for different time periods. For post-accident response beyond the acute time period the marginal cost incurred to avoid population exposures should be roughly equivalent for efficient use of societal financial resources. The dotted lines in Figure 6.6 demonstrate the protective action criteria in each time period which lead to an equivalent marginal cost of ~$500 per man-rem averted. The new economic model can be employed in the future to develop consistent, efficient population protective measure implementation criteria for use in post-accident situations. The costs and effectiveness of evacuation plans for severe LWR accidents could also be evaluated on a site-specific basis using the new models.

Figure 6.6 - Mean cost/benefit ratios for offsite protective measures after an SST1 release at the Surry site.



6.7 COMPARISON OF ROUTINE OUTAGE AND SEVERE ACCIDENT ECONOMIC RISKS FOR SURRY #2

The present values of lifetime economic risks from category I and category II and III events for Surry #2 are compared in Table 6.10. The risk estimates for category I outages are based on the generic frequency estimates from Chapter 5 combined with outage costs for the Surry plant estimated with the new onsite cost models. The economic risks for category II and III events are based on the PWR core-melt frequencies and source terms from the RSS with offsite consequence calculations for the Surry site. The large uncertainties in the RSS core-melt accident frequencies are not reflected in the economic risk estimates in Table 6.10. Results are shown for societal discount rates of 0, 4, and 10%. Societal economic risk is predicted to be dominated by category I forced outage events. The contribution of category II and III accidents to economic risk is predicted to be a factor of 50-80 lower than the risks from routine forced outage events. The expected offsite economic risks of severe accidents are predicted to be a factor of ~500 lower than the onsite risks from all event categories. In contrast to public health risk which is dominated by low frequency, large consequence events, economic risks from LWR operation are dominated by high frequency, low consequence events. This cost has been paid historically through reduced LWR plant availability and capacity factors.

The uncertainties in estimated category I event risks are relatively small (~factors of 3 and 1/5) because of the high frequency of these events (~10 per reactor-year) and the data availability for routine outage costs. The estimates of category II and III economic risks are highly uncertain because of the large uncertainties in the estimates of total core-damage and core-melt accident frequencies and the limited understanding of severe accident physical processes. Results of probabilistic risk studies predict that core-melt accident frequencies range from ~2x10^{-3} to ~10^{-5} per reactor-year for U.S. LWR plants. The uncertainties in plant decontamination costs, replacement power cost increases, and new plant capital costs are the most important contributors to the uncertainties in total severe accident cost estimates.

Uncertainties in core-melt accident source term definition are extremely large and have important impacts on offsite accident consequence projections. Changes in source term definitions would have smaller impacts on total cost estimates for core-melt accidents because onsite losses are not significantly influenced by source term definitions. Uncertainties in offsite cost estimates for a given source term are dominated by uncertainties in decontamination costs, which are factors of approximately 5 and 1/5. A detailed uncertainty analysis of offsite core-melt accident economic consequences is planned as part of

Table 6.10 - Present value of category I and category II & III event economic risks for remaining life of Surry #2 plant.

Discount Rate	Category I Events ($\approx$10/reactor-year)	Category II & III Events* ($\approx 6\times10^{-5}$/reactor-year) Offsite	Onsite	Total
0%	$\$2.7\times10^{8}$	$\$4.4\times10^{5}$	$\$5.5\times10^{6}$	$\$5.9\times10^{6}$
4%	$\$1.6\times10^{8}$	$\$2.5\times10^{5}$	$\$3.3\times10^{6}$	$\$3.6\times10^{6}$
10%	$\$8.4\times10^{7}$	$\$1.3\times10^{5}$	$\$1.7\times10^{6}$	$\$1.8\times10^{6}$

*Estimated risks for category II & III events based on RSS PWR core-melt accident frequencies and source terms with consequence calculations performed for the Surry #2 plant.

the MELCOR program. The new economic consequence model is structured for ease of implementation of uncertainty analysis techniques.

The comparison of economic risks from the entire spectrum of LWR events indicates that societal economic risks are dominated by high frequency, low consequence forced outage events. Also, the offsite economic risks from severe LWR accidents are predicted to be small relative to onsite risks. These conclusions are not significantly influenced by uncertainties in severe accident frequencies and source terms.

6.8 SUMMARY AND CONCLUSIONS

Calculations performed with the new economic consequence models indicate that the expected costs of category II and III accidents at the Surry site are dominated by onsite costs of post-accident decontamination, replacement power cost increases, and plant capital losses. For all sites which have been examined, the offsite costs of severe accidents are predicted to be small relative to onsite costs except for low-probability core-melt accidents which result in large releases of radioactive material. The offsite costs of population protective measures are dominated by land and property decontamination costs. The costs of offsite public health effects are small based on purely economic costing of health care and health effects. Calculations performed for various U.S. LWR sites indicate that offsite cost predictions from the new model are generally factors of 2-4 larger than those from the CRAC2 code.

The new offsite models have been used to examine the sensitivity of offsite economic consequences to source-term and population protective measure assumptions. The offsite cost predictions are sensitive to source term definition. Offsite costs can also be significantly affected by offsite protective measure implementation criteria. The new economic models have been used in example cost/benefit analyses which demonstrate the usefulness of marginal cost/benefit ratios in planning for post-accident population protective measures. It is recommended that the newly developed offsite economic models be exercised in further studies of costs and benefits of LWR accident population protective measures.

The new onsite and offsite cost models have been used to estimate the economic risks at the Surry #2 plant with frequency estimates from generic outage data and the RSS. The example economic risk calculations for the Surry Unit 2 plant result in the following conclusions:

1. Unlike public health risks, economic risks from LWR operation are dominated by high frequency, small consequence forced outage events. The societal costs of these events result from reduced availability and capacity factors and the need for use of higher marginal cost fuel sources for generation of electricity.

2. The economic risks from LWR operation are dominated by onsite losses, specifically replacement power cost increases for short duration outages. Severe accident economic risks are also dominated by onsite losses including plant decontamination costs, replacement power costs, and plant capital losses. Only very low probability core-melt accidents with large releases of radioactive material are predicted to result in offsite costs as large as onsite plant costs.

These conclusions result from the comparison of economic risks from various categories of operational events at the Surry #2 plant, with the assumption that society is risk-neutral to all economic losses. The conclusions are not sensitive to the large uncertainties inherent in the estimates of the economic risks from severe LWR accidents.

CHAPTER 7

SUMMARY AND CONCLUSIONS

The primary goal of this study was to develop models to be used for analyses of economic risks from events which occur during U.S. LWR plant operation. These models have been developed for potential use by both the nuclear power industry and regulatory agencies in cost/benefit analyses for decision-making purposes. The newly developed models include capabilities to estimate both onsite and offsite costs of LWR events ranging from routine plant forced outages to severe core-melt accidents resulting in large releases of radioactive material to the environment. The models developed are useful for estimating societal economic risks based on either generic or plant-specific economic data. The models can easily be modified for use in economic risk studies for particular interest groups in the U.S. nuclear power industry.

The new onsite cost models estimate societal losses from power production cost increases, plant capital losses, plant decontamination costs, and plant repair costs which may be incurred after LWR operational events. Early decommissioning costs and plant worker health impact costs are included but do not contribute significantly to the onsite losses from LWR events. The dominant cost for most LWR outage events is the power production cost increase caused by the need for using generating facilities with higher fuel-cycle costs. Replacement power purchase cost increases are estimated based on the mix of units available in each region of the U.S. Plant repair costs for routine forced outage events have historically been small relative to replacement power cost increases. Plant decontamination costs and capital costs of replacement power generation facilities are important for severe LWR accidents resulting in core-damage or core-melt. Electric utility business costs, nuclear power industry costs, and litigation costs for severe LWR accidents are likely to be small from the societal perspective. However, these costs may be important and warrant careful consideration for specific groups within the U.S. nuclear power industry.

The newly developed offsite economic models estimate the costs of post-accident population protective measures and public health impacts. The costs of population evacuation and temporary relocation, agricultural product disposal, land and property decontamination, and land interdiction are included in the economic models for population protective measures. Costs of health impacts including medical care costs are also included in the new offsite economic consequence models. The new offsite models offer several advantages over the CRAC2 economic models.

including more accurate accounting of short-term population relocation costs, accounting for population relocation costs during land and property decontamination, flexibility of all time periods and protective action implementation criteria, incorporation of site-specific economic data, estimation of additional decontamination program attributes, calculation of both costs and benefits (in terms of population exposure avoided) of population protective measures at offsite locations, and estimation of medical care and health effects costs. A prototype model was developed in this study for development and testing of the new offsite economic models. The new models will be incorporated into the MELCOR consequence calculation code which is currently under development.

A computer data base of LWR experience from 1974-1980 was developed to estimate the frequency-severity spectrum of unscheduled, non-regulatory forced outage events at U.S. LWRs. The data base was combined with the new onsite economic cost models to estimate the expected losses from routine forced outage events. The losses from routine LWR forced outage events are large due to the high frequency (~10 per reactor-year) and power production cost increases for these events (see Table 6.10). The costs of LWR forced outage events are paid through reduced availability and capacity factors for plants in operation. During the 1974-1980 study period, forced outage events caused an average 10% availability loss per reactor-year of U.S. LWR operation. Forced outage events caused by regulatory concerns showed a consistently increasing trend during the 1974-1980 study period. The average availability loss due to regulatory forced outage events increased by roughly a factor of 5 to approximately 6% in 1980. The total plant availability losses due to forced outage events result in significant societal costs from the use of higher cost fuel sources.

Detailed analyses of the forced outage data base showed that forced outage events occur more frequently at LWR plants in the first years of operation than later in plant life. This trend is consistent with "bathtub" failure rate behavior observed in most technological devices. This behavior is important because it indicates that economic risk from forced outage events and transient-induced core-melt accident risks are not constant over the life of LWR plants. Risk management programs in the U.S. LWR industry should direct special attention to plants in the first few years of commercial operation. Historical accident experience supports the hypothesis that risks are increased in the first years of LWR commercial operation. Wear-out related increases in forced outage frequency were not apparent in the 1974-1980 operation data.

The new onsite and offsite economic consequence models have been applied in an example calculation to estimate the economic risks from core-damage and core-melt accidents at the Surry #2 plant. The analysis included the assumption that the median core-melt accident frequency from the RSS included all accident sequences resulting in either limited core-damage or full scale core-melt. The present value of expected costs of severe accidents over the remaining life of the Surry #2 plant is less than 6 million dollars, based on the RSS median core-melt accident frequencies (see Table 6.10). The dominant contributors to expected core-damage or core-melt accident costs are plant decontamination costs, power production cost increases, and new generation facility capital costs. The expected offsite property damage and health effects costs are an order of magnitude lower than expected onsite costs for the RSS PWR source terms. The economic costs of offsite health effects are small for most core-melt accident categories. The dominant offsite cost for large accident release categories is the cost of land and property decontamination. The total expected offsite costs of core-melt accidents for the remaining Surry plant life are predicted to be less than $1 million dollars. Only for extremely low probability events are offsite costs equal to or greater than onsite costs. The expected core-melt accident costs are small compared to the expected losses from high frequency routine forced outage events. The uncertainties in the economic risk estimates are large and are dominated by the uncertainties in event frequencies for severe accidents, and by replacement power cost uncertainties for routine forced outage events.

The example applications of the new onsite and offsite economic risk models in this study lead to some important conclusions concerning LWR economic risks. Current probabilistic risk analyses predict core-melt frequencies ranging from ~2X10-3 per reactor-year to ~1X10-5 per reactor-year for U.S. LWR plants in operation. The general conclusions from the analysis are not sensitive to this range of core-melt frequencies. In contrast to public health risks from LWR operation which are dominated by low frequency core-melt accidents, societal economic risks from plant operation are dominated by high frequency routine forced outage events. From an economic perspective, assuming society is risk-neutral to economic losses, the maximum economic benefit could be achieved through reduction of routine forced outage frequencies and durations. The economic risk calcula- tions performed in this study indicate that reduction of core-melt accident frequencies should result in smaller economic benefits. Thus, although reduction of core-melt accident frequencies and consequences is important for controlling public health risks, economic analyses indicate that limited societal financial resources might be more productively used in controlling routine forced outage losses.

Reduction of routine outage frequencies would also reduce the frequency of plant transients and would thus have some impact on core-melt accident frequency and public health risks as well.

The analysis of LWR economic risks indicates that focusing U.S. nuclear power regulation completely on severe accidents may be economically inefficient, and that the most productive expenditures for plant improvements might be made to increase the availability and capacity factors of operating LWR units by reducing forced outage frequencies and costs. Expenditures for core-melt accident prevention are likely to produce larger benefits than expenditures for systems which mitigate the offsite consequences of core-melt accidents since a large portion of the expected costs of core-melt accidents result from the loss of physical plant.

The newly developed onsite and offsite economic consequence models have many applications beyond the example calculations presented in this report. The new models will be used in detailed sensitivity and uncertainty analyses as part of the MELCOR severe accident risk assessment program to more accurately quantify the range of economic risks from severe accidents. The LWR forced outage data base has already been used in support of actuarial analyses within the nuclear insurance industry. It is recommended that the new offsite economic consequence models be used to perform cost/benefit analyses to assess post-accident population protective measure implementation criteria in the future. The newly developed models represent flexible tools to be used in support of decision-making in both regulatory and nuclear industry agencies.

CHAPTER 8

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APPENDIX A

U.S. LWR OPERATION EXPERIENCE DATA BASE

The data base of LWR operating experience developed in this study to estimate the frequency of LWR forced outage events is discussed in this section. The data base for 1974-1980 is available on magnetic tape in either ASCII or binary data formats.

The data base was formed from annual publications of forced outage data from the U.S. Nuclear Regulatory Commission [AE74, Nu77b, Nu77c, Nu79a, Nu79b, Nu81a, Nu81b]. Only forced outage events (not scheduled) have been included in the new data base. Also, all regulatory outages have been excluded from the data base for the purpose of this study. Finally, the total duration of a single forced outage event is recorded in the calendar year in which the forced outage event was initiated. Only those outage hours which occurred between January 1, 1974 and December 31, 1980 are included in the data. The plant ~~name, plant type, NSSS vender, plant~~ electric rating, startup and shutdown year*, and the number of forced outage events observed are tabulated for each recorded plant year of data. An example of the data base format for a single reactor-year of operation is presented on the following page.

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*The plant start and end of operation are reported to the nearest 0.1 year. The shutdown year is reported as 0.0 for plants still in commercial operation.

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*************************************************************
 ASCII FORCED OUTAGE DATA, ALL PLANTS, 1974-1980 4203 PTS.
              CALENDAR YEARS 1974 THROUGH 1980
************************************************************


    PLANT NAME = BIG ROCK POINT 1     CALENDAR YEAR = 1974
    PLANT TYPE = BWR        NSSS VENDOR = GENERAL ELECTRIC
    PLANT RATING (MWe) = 00072
    PLANT STARTUP, SHUTDOWN YEAR = 1963.3, 0.0
    FORCED OUTAGE EVENTS IN CALENDAR YEAR = 2
    FORCED OUTAGE EVENT DURATIONS (IN HOURS):  253 792
```

APPENDIX B

ANALYSIS OF REGULATORY FORCED OUTAGES FROM 1974-1980

Nuclear plant outages caused by regulatory orders are explicitly excluded in the forced outage data base developed in this study. The economic risk profile presented in this report includes only losses from those events resulting from plant operation, not risks which result directly from regulatory policies or mandates. The regulatory outages which occurred during the calendar years 1974-1980 are discussed in this section.

Figure B.1 shows the total number of U.S. commercial LWR reactor years of experience which were recorded in each calendar year from 1973-1980 inclusive. The number of U.S. operating reactors more than doubled during this period of study, beginning with under 30 in 1973 and concluding with nearly 70 operational LWRs at the end of 1980. This period of rapid growth is also marked with fundamental changes in the character of U.S. LWRs. The size (in terms of electrical power rating) of new reactors grew throughout this period finally peaking at ~1000 MWe per unit at the end of the study period Thus, the portfolio of U.S. LWRs was constantly changing with time during the study period.

The average availability (the percentage of the year each power plant is available for electricity generation) of U.S. LWRs in each calendar year during the study period is shown in Figure B.2. From the years 1973-1977, the average availability fluctuated between approximately 68-73%, averaging about 70% during this period. U.S. LWRs experienced a very good year in 1978 averaging a 75% availability during the calendar year. In 1979, regulatory impacts of the TMI-2 event and other unrelated regulatory impacts sent the average availability down nearly 9 percentage points to about 67%. Finally, in 1980, regulatory and industry changes resulting from the accident were instituted and the drop in availability continued. The average availability of U.S. LWRs dropped nearly 11% in the two years between 1978-1980.

The LWR regulatory outages recorded between 1974-1980 were analyzed to determine the impact of changing regulatory policies and standards on the availability of U.S. LWRs. Figure B.3 shows the approximate decrease in reactor availability due to regulatory forced outage events in each calendar year*.

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* This is only approximately correct since if fewer regulatory outages did occur, it is likely that outage hours from other causes may have increased.

Figure B.1 - Total number of commercially operating U.S. nuclear power plants versus time.

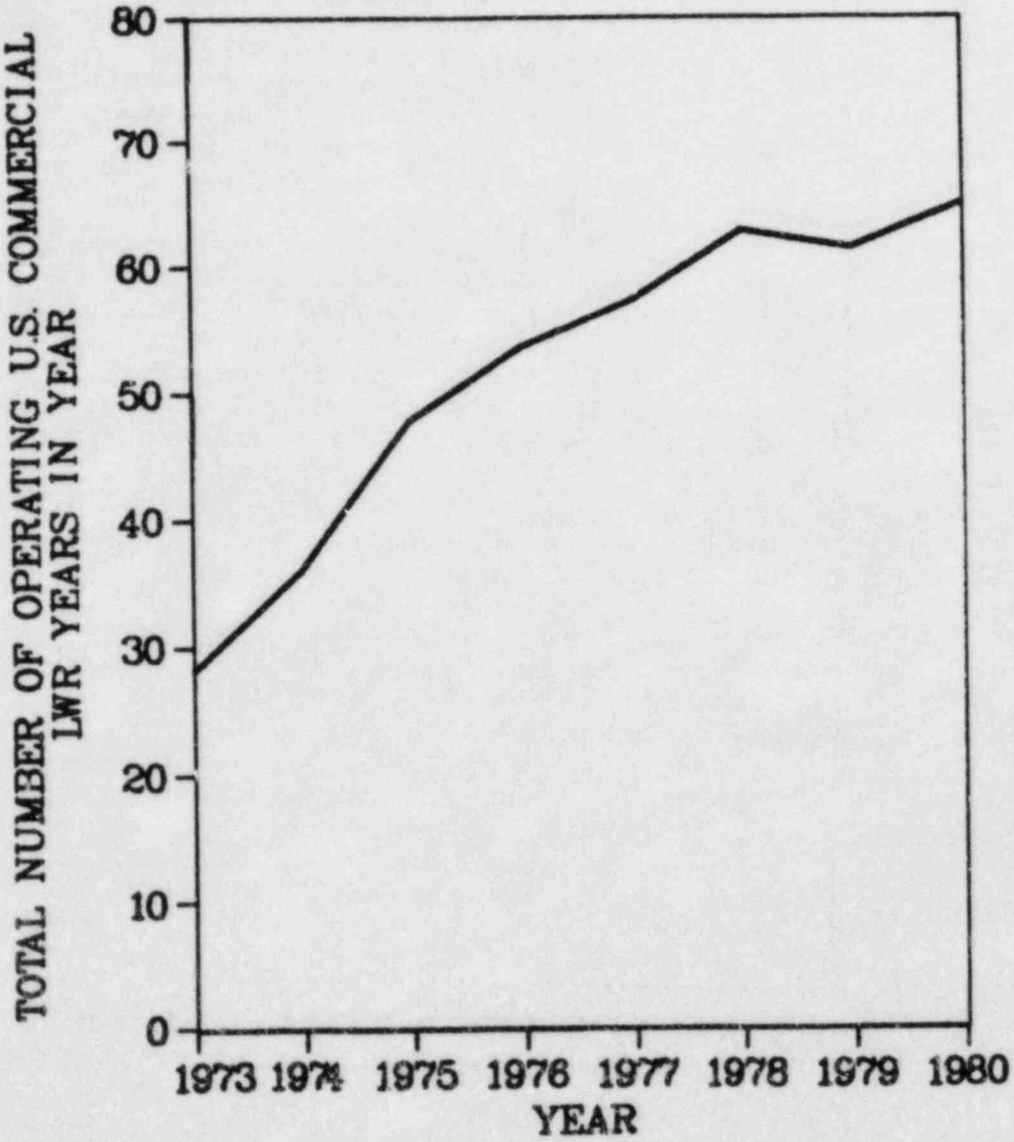


Figure B.2 - Average U.S. LWR availability versus time.

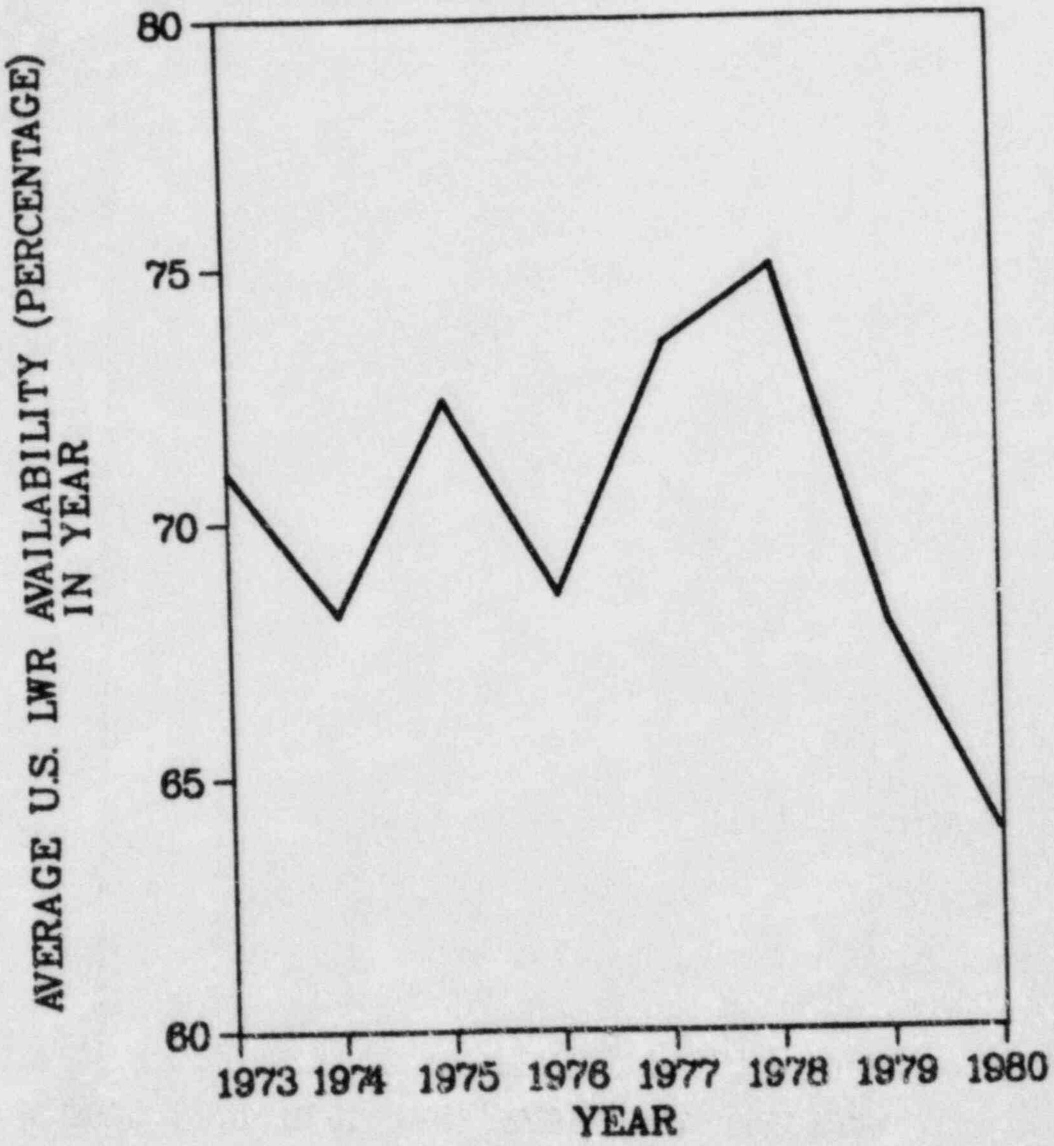
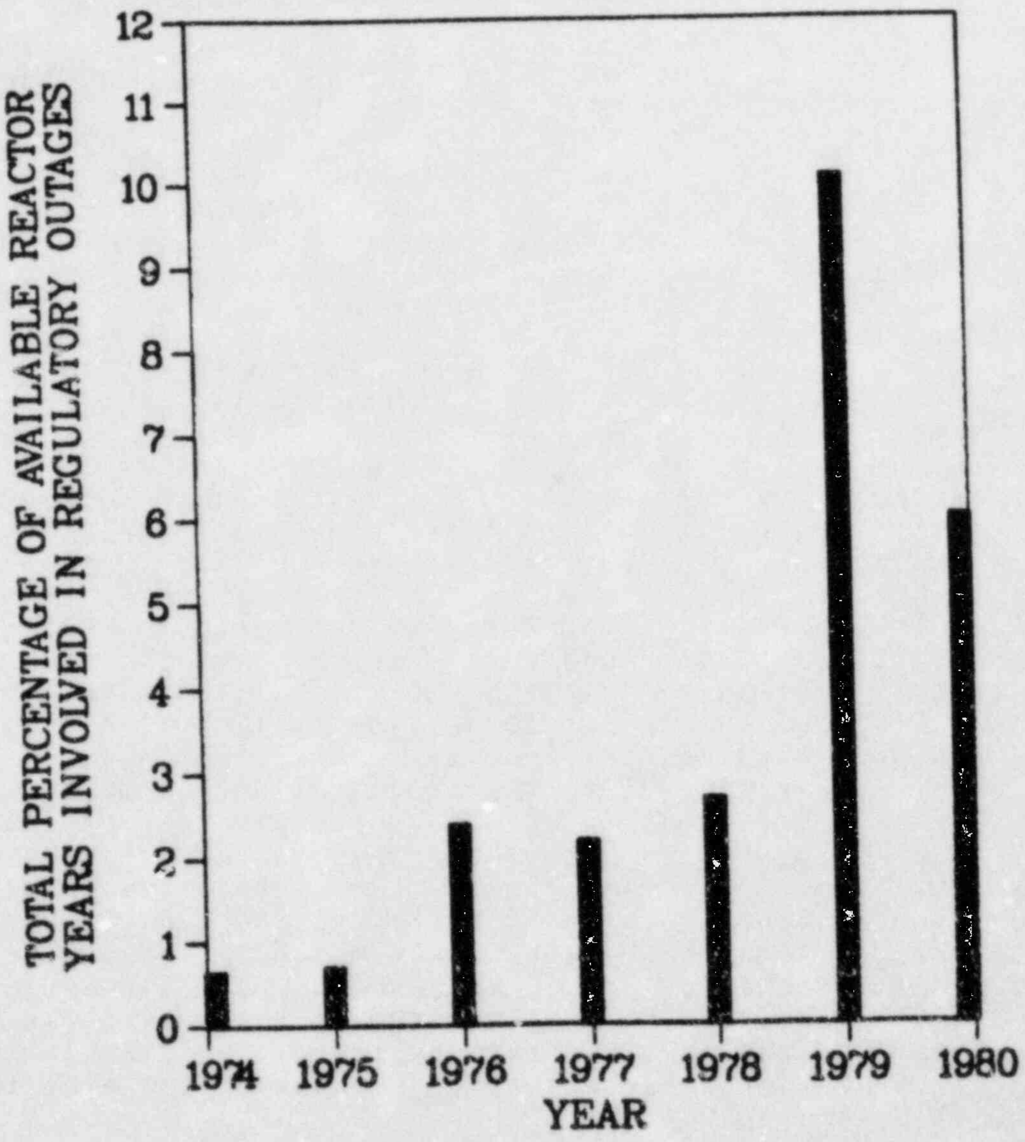


Figure B.3 - Total percentage of reactor-years lost in regulatory outages.



This figure shows a striking increase in the impact of regulatory forced outages throughout the study period. In 1974-1975, less than 1% of the available commercial reactor years were lost due to regulatory causes. From 1976-1978, regulatory outages accounted for a 2-3% loss in average plant availability. Finally, due to the regulatory impacts of the TMI-2 accident and other concerns, nearly 11% of all available reactor years were lost due to outage events in 1979. Regulatory outages decreased somewhat in 1980, but the loss of availability was still higher than in pre-TMI years.

The total number of hours of reactor operation removed by regulatory outages in each calendar year is shown in Figure B.4. Since the total number of reactors operating increased throughout the study period, this data shows an even larger increasing trend than the average availability loss data. In 1980, approximately 30,000 reactor hours were involved in regulatory outages (nearly 4 full reactor years). Assuming the reactors involved would have operated at an average 70% capacity factor had the regulatory outages not taken place, and using the simple replacement power cost model discussed in Chapter 3, the societal cost of these outages in 1980 is estimated to be between 0.4 and 0.9 billion dollars. The large number of regulatory outage events in recent years resulted in very large costs.

Finally, the average U.S. LWR forced and scheduled outage percentage throughout the study period is shown in Figure B.5. Again a general increasing trend in the time lost due to scheduled outages (outages which can be delayed until at least the start of the next weekend) is observed in the study period. Part of this increase is due to the increase in regulatory outages in the period, most of which are reported as "scheduled" outages. The annual forced outage percentage shows signs of inverse correlation to the scheduled outage percentage. This is to be expected since more downtime is available during scheduled outages to perform maintenance which may otherwise have required a forced outage for completion. The forced and scheduled downtime percentages in a given calendar year can be added to determine the total average availability loss due to all outages. The average availability decreased from ~70% in 1973 to ~65% at the end of 1980.

Figure B.4 - Total reactor hours involved in regulatory outages.

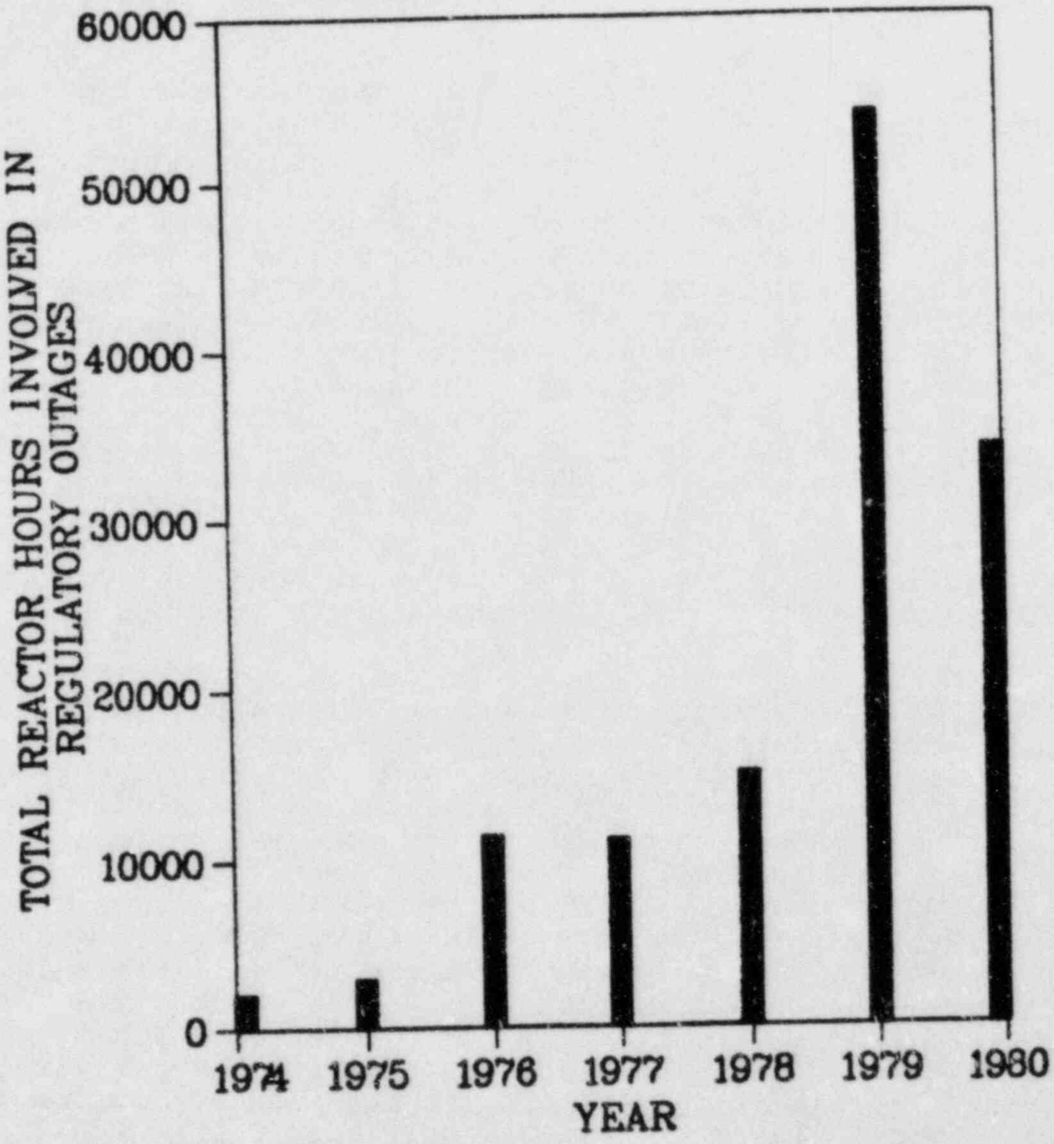
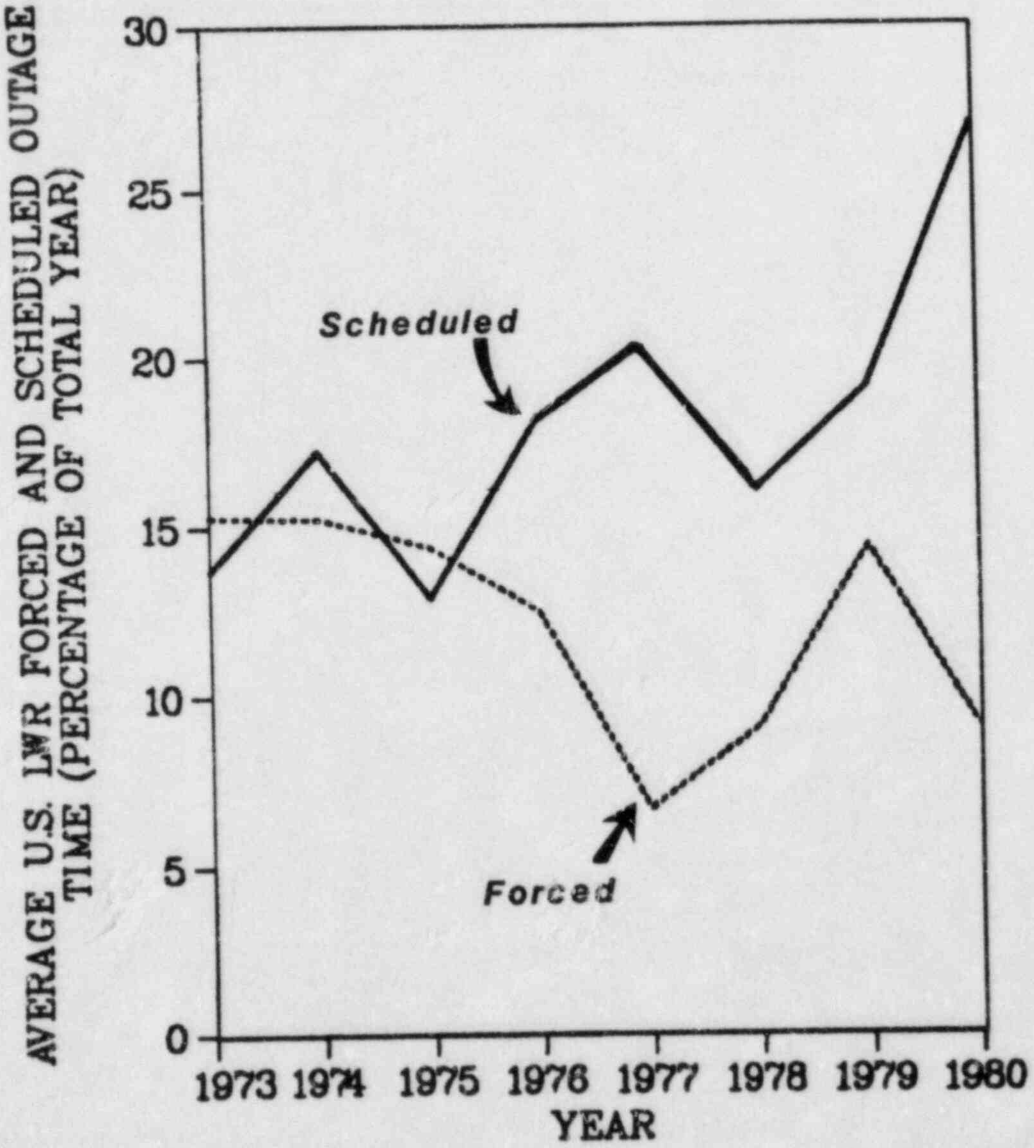


Figure B.5 - Average forced and scheduled outage time of U.S. LWRs.



The analysis of regulatory outages over the study period shows a consistent increasing trend in the number of plant downtime hours attributable to regulatory actions. In recent years, regulatory actions have become increasingly important in determining the average LWR performance in the U.S. The inclusion of regulatory forced outages in the analysis of LWR performance can significantly bias results downward. Regulatory outages are excluded in the estimation of event frequencies in this report to remove the influence of past regulatory policies. Therefore, the outage frequency and severity estimates contained in Chapter 5 include only events which result from plant operation, not those resulting from regulatory mandates or policies.

APPENDIX C

BEA ECONOMIC ANALYSIS METHODOLOGY AND RESULTS

Recently the Bureau of Economic Analysis (BEA) within the U.S. Department of Commerce has applied an input-output economic model, RIMS II*, to estimate the potential impacts of severe nuclear reactor accidents. The basic conceptual methodology and the results of the BEA analyses are reviewed in this section.

C.1 BASIC INPUT-OUTPUT METHODOLOGY

The essential principles of the input-output method of economic analysis are most easily understood through a transaction table, which summarizes the transactions which occur in an economy during some period of time. Table C.1 shows a hypothetical transaction table for the economy in a particular region. The horizontal rows of figures show how the output of each sector of the economy is distributed among other economy sectors. The vertical columns show how each sector obtains needed inputs of goods and services from other sectors. Each entry in a horizontal row is also an entry in a vertical row, thus the table shows the fabric of the economy, the flows of trade and services by which all of the sectors are linked together. The composition of the transaction table is based on transfers of goods and services in a region, and may be constructed using available industrial transaction statistics. The transaction table used in the RIMS-II model is based on the 1972 BEA national I-O table which contains 496 individual industrial sectors (a 496 X 496 matrix).

Input-Output economic analysis is most often used to show the effect on a regional economy of a change in demand for goods in one sector of the economy. For example, using Table C.1 one can see that an increase in the final demand for agricultural output would affect the demand for construction, manufacturing, trade, and service sector outputs which are used as inputs in the production of agricultural output. A change in one industrial sector inevitably affects the entire economy, each sector appropriately adjusting to approach a new equilibrium in the region. Because I-O analysis does reflect the fabric-like nature of the economy, it is a very powerful tool for predicting economy-wide effects of changes in demand for goods in one economic sector (demand-driven analysis). The I-O methodology can

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* Regional Input-Output Modeling System II

Table C.1 - Example of a regional transaction table [Ca82].

		Purchasing industry						Final demand				
		Agriculture (1)	Construction (2)	Manufacturing (3)	Trade (4)	Services (5)	Total intermediate sales (local)	Household expenditures	Other final demand	Exports	Total final demand	Total outputs
Selling industry	Agriculture (1)	10	5	5	2	0	22	10	10	28	48	70
	Construction (2)	5	20	15	5	5	50	0	40	0	40	90
	Manufacturing (3)	10	30	30	10	10	90	5	5	5	15	105
	Trade (4)	5	10	10	15	10	50	10	7	5	22	72
	Services (5)	15	5	5	20	5	50	15	5	0	20	70
	Total intermediate purchases (local)	45	70	65	52	30	262	40	67	38	145	407
Final payments	Household earnings	15	15	25	5	15	75	2	1	0	3	78
	Other value added	5	1	3	4	5	18	0	0	0	0	18
	Imports	5	4	12	11	20	52	1	0	0	1	53
	Total final payments	25	20	40	20	40	145	3	1	0	4	149
	Total inputs	70	90	105	72	70	407	43	68	38	149	556

also be modified to predict economy-wide effects of input shortages in specific economic sectors (supply-constrained analysis). The basic mathematics used in these forms of regional I-O analysis are discussed in BEA reports [Ca82].

In order to use the I-O methodology in modeling severe LWR accident impacts, it is necessary to specify the areas which are affected and the impact on industrial output in each area affected. The BEA analyses divide the entire region considered into the "physically affected" area which is contaminated by the accident, and the "physically unaffected" area, which is the area immediately surrounding the contaminated area. The physically affected area is divided into the interdicted, decontamination, crop interdiction, and milk interdiction areas based on the mean results of CRAC2 analyses for a given accident source term. The assumptions used in the analyses for the percentage of annual output lost due to post-accident countermeasures in each area are defined in Table C.2. These estimates of output lost are used to drive the I-O analyses for each region. The analyses are intended to account only for the first year after accident occurrence, therefore the maximum output loss in any region is defined to be 100% of annual production.

One problem with the RIMS-II analysis of post-accident countermeasure impacts is that the areas affected are defined at the county level. Only entire counties are included in each area specification and no sub-county land areas are included. The assignment of counties to production loss categories for the St. Lucie reactor site, conditional upon an SST1 release and a WNW wind direction, is shown in Table C.3. A map of the St. Lucie site, with an overlay of a typical straight line Gaussian plume coverage area as predicted by CRAC2 for the WNW wind direction is shown in Figure C.1. The inclusion of the entire area in each affected county leads to large differences in the basic problem for the BEA versus the CRAC2 economic analyses. Even for the widest plume coverage areas predicted by CRAC2 (~70°), the areas specified in the BEA St. Lucie site analyses are much larger as shown in Figure C.2. Thus, the BEA analyses may overpredict impacts due to the inclusion of entire counties in specification of the affected areas. Further work is underway using RIMS-II to more accurately model the areas affected after an accident [BE82c]. Comparison of results to CRAC2 predictions is currently difficult because the specifications of affected areas differ substantially.

C.2 ANALYSIS OF BEA RESULTS

Although the BEA analyses do not exactly correspond to predicted areas of contamination for specific accident sequences, the results are useful for analysis because they provide estimates of impacts based on a detailed economic analysis

Table C.2 - Definition of protective measure output effects in BEA analyses [Ca82].

Industry affected	Percent of annual output loss				Percent of annual output loss
	Interdicted	Decontamination	Crop interdicted	Milk interdicted	Physically unaffected
Dairy	100	25	16	16	0
Crops	100	100	100	0	0
Forestry and greenhouse	100	0	0	0	0
Livestock and poultry	100	50	0	0	0
Nonagriculture, excluding tourist avoidance	100	25	0	0	0
Hotels and lodging places, additional effects due to tourist avoidance	0	56	45	45	10

Table C.3 - Definition of counties included in BEA analysis for SST1 release, St. Lucie site, WNW wind direction [Ca82].

Type of production loss	Counties	Length of production loss	Extent of tourist avoidance
Physical contamination: All industries	Physically affected: Interdicted (27 miles) Indian River, FL St. Lucie, FL (host county) Martin, FL	More than 1 year, all industries including agricultural production	100% for more than 1 year
All industries, except agriculture	Decontamination (86 miles) Okeechobee, FL Highlands, FL	Three months loss in nonagricultural output; one year loss in all crop output, except no loss in greenhouse, nursery, and forestry output; three months loss in dairy output; and six months loss in livestock and poultry output	100% for 3 months, then 75% for 9 months
Agriculture, including dairy milk	Crop-interdicted (199 miles) All of the above, and Hernando, FL Pasco, FL Hillsborough, FL Hardee, FL Polk, FL No further contamination; the Gulf of Mexico is 160 miles from the reactor site.	No loss in nonagricultural output; one year loss in agricultural output, except no loss in greenhouse, nursery, and forestry output; no loss in livestock and poultry output; and two months loss in dairy output	45% for 1 year; except in the interdicted and contaminated areas as noted above
Indirect economic effects:	Physically unaffected: BEA Economic Areas* 42-44, less above counties	First year only, based on RIMS II	10% for 1 year

*For component counties, see BEA Economic Areas (Revised 1977), BEA, U.S. Department of Commerce, Washington,

Figure C.1 - Comparison of BEA affected areas versus typical Gaussian plume predictions.

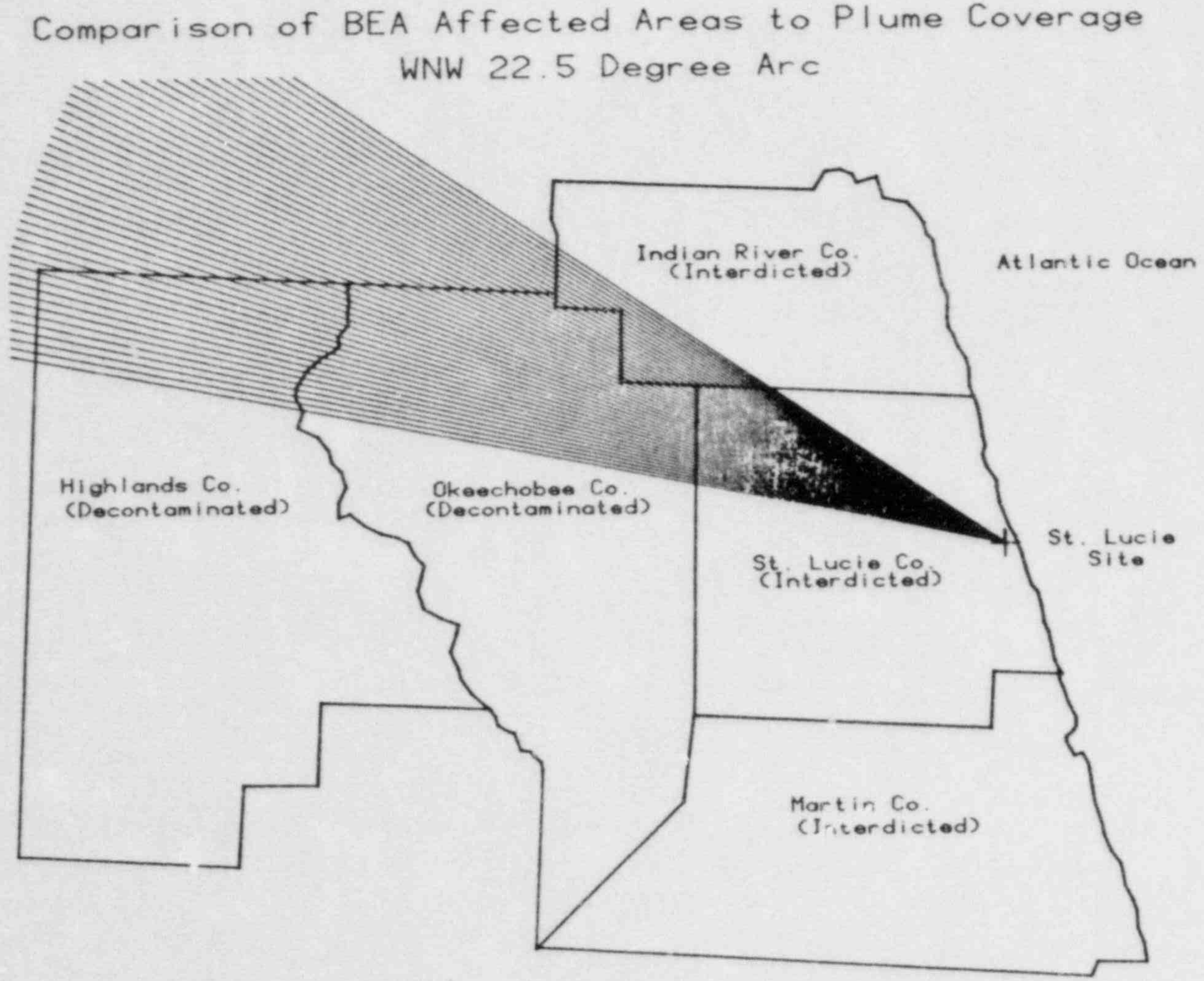
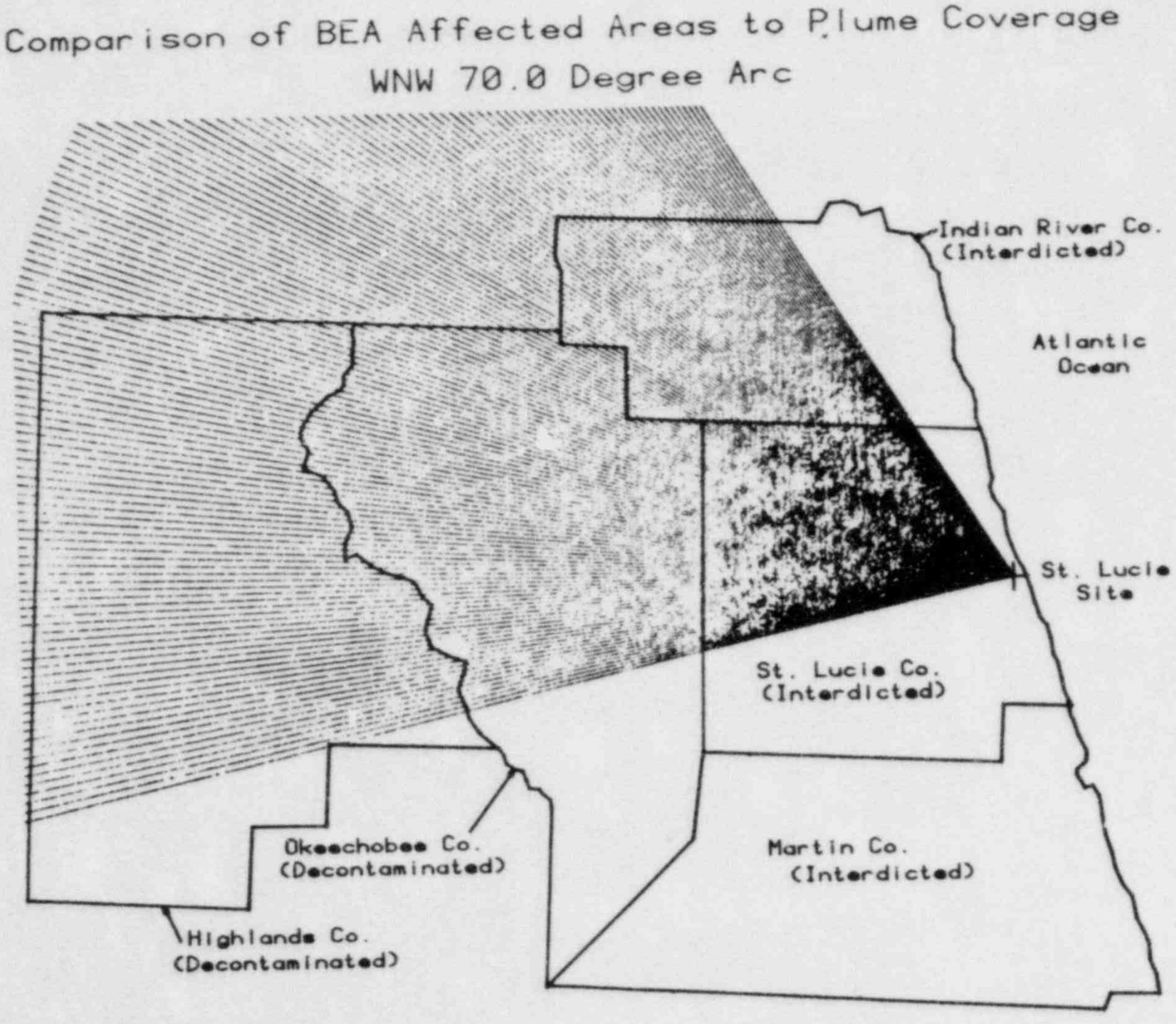


Figure C.2 - Comparison of BEA affected areas versus widest Gaussian plume predictions.



technique. The BEA analyses estimate secondary impacts, or impacts which occur outside of the physically affected area. The results of the BEA analyses predict the secondary impacts to be small relative to effects in the contaminated area. This result, which seems intuitive based on economic principles, is useful because secondary effects are not accounted for in the CRAC2 or new economic models.

The BEA predictions of jobs lost after accidents at different sites were checked for correlation with the population within the counties assumed to be interdicted. This correlation would be important because the CRAC2 and new economic models assume that interdiction and decontamination costs will be directly proportional to the population in a given area. Studies performed with the British ECONO-MARC economic impact model indicated that per-capita interdiction cost models provide reasonable estimates when compared with more detailed analyses based on land usage maps [Cl82].

BEA analyses have been performed for a variety of reactor sites with a wide range of affected populations. Figure C.3 shows the total employment in each of the study areas which were available for analysis. The total employment in the study areas ranged from under 1 million to over 12 million persons.

Three predictions of accident area employment impacts are presented in the BEA analyses based on different assumptions used in the I-O analyses. The maximum direct job losses predicted include all jobs lost in the physically affected area, assuming no output increase in the physically unaffected area and that all affected households do not resume normal consumption expenditures. Partially compensated job loss predictions are based on the assumption that output increased to the maximum desired capacity in the physically unaffected area, but directly affected households do not resume normal consumption expenditures. Finally, fully compensated job loss predictions are based on the assumption that output increases to the desired capacity in the physically unaffected area, and that affected households resume normal consumption expenditures. Each of these predicted results was correlated to the population in the area assumed to be interdicted. Figures C.4-C.6 show the maximum direct, partially compensated, and fully compensated job losses predicted for each reactor site, accident, and wind direction considered in the BEA studies [Ca82,BE82b,Ne82b]. The results of linear regression performed on the results are also shown in the figures. The predicted job losses from the BEA analyses are remarkably linear with the interdicted area population, all three correlation coefficients being in the range of ~0.95. The results of the BEA studies predict the losses in the directly affected area to vary approximately linearly with the population in the area.

Figure C.3 - Total study area employment for sites considered in BEA studies.

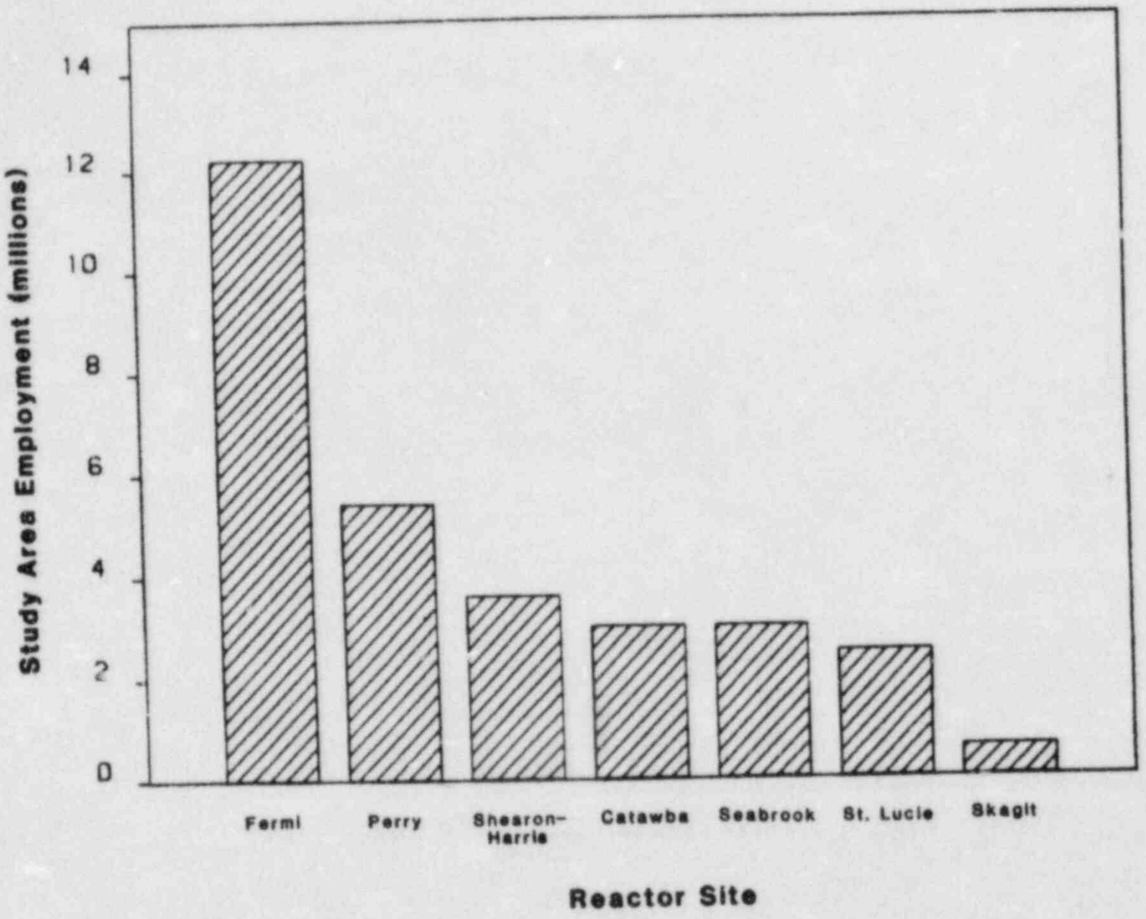


Figure C.4 - BEA non-compensated direct job loss predictions versus interdicted area population.

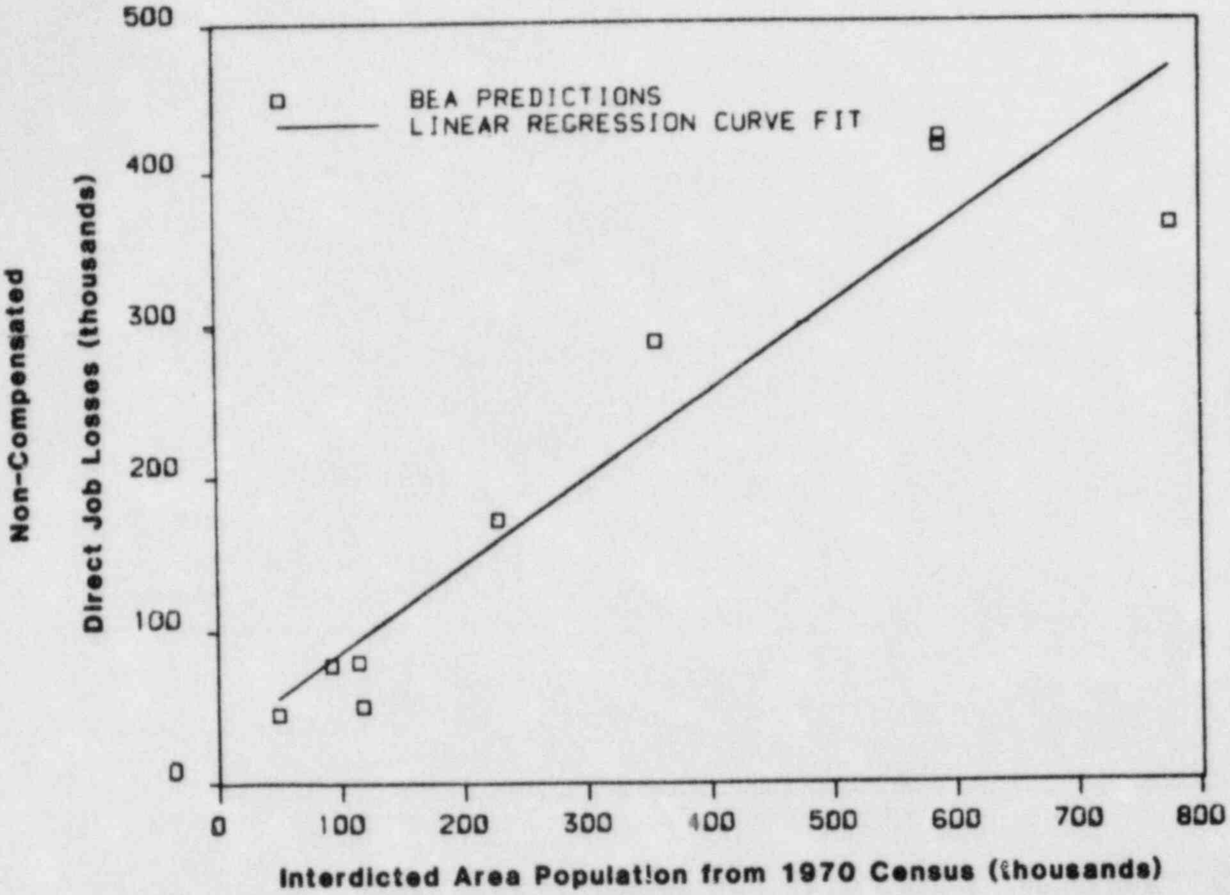


Figure C.5 - BEA partially compensated direct job loss predictions versus interdicted area population.

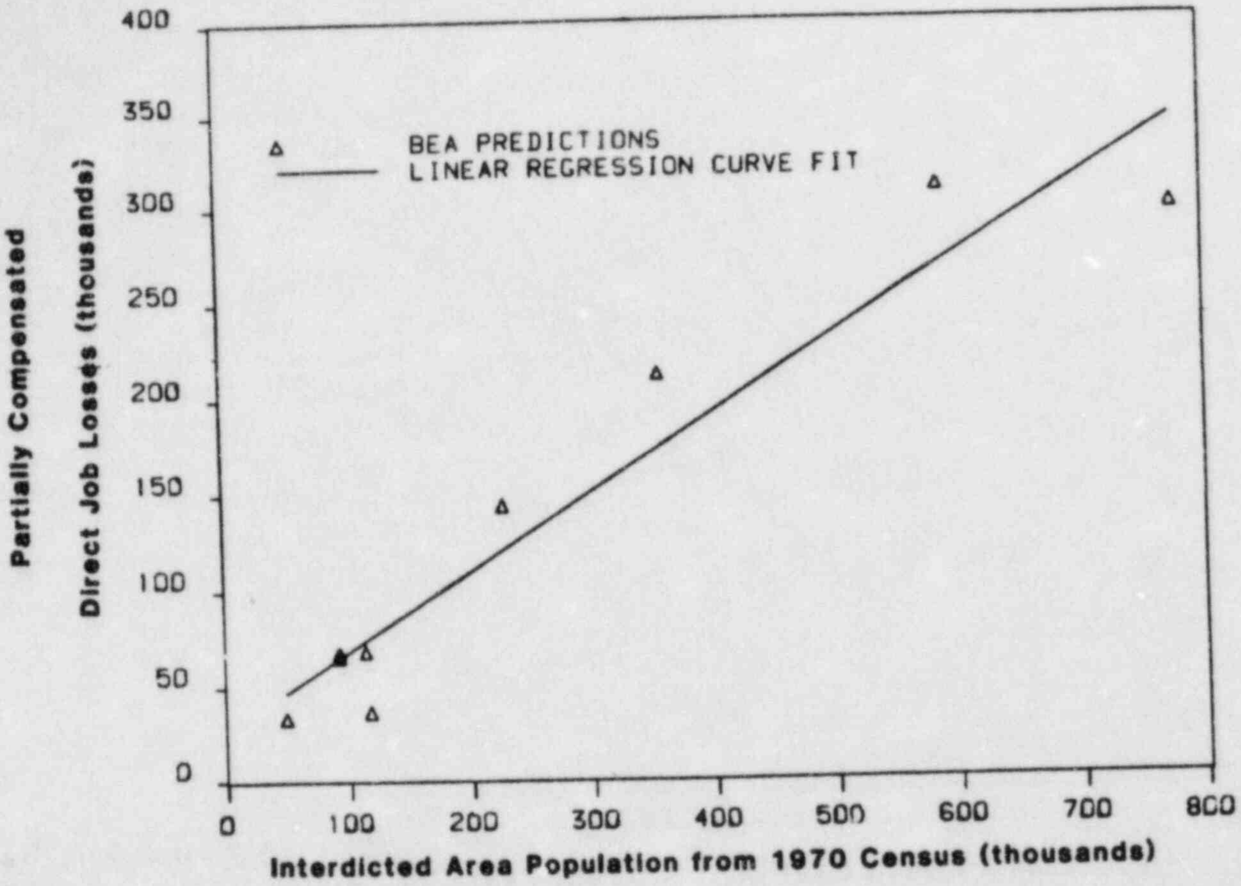
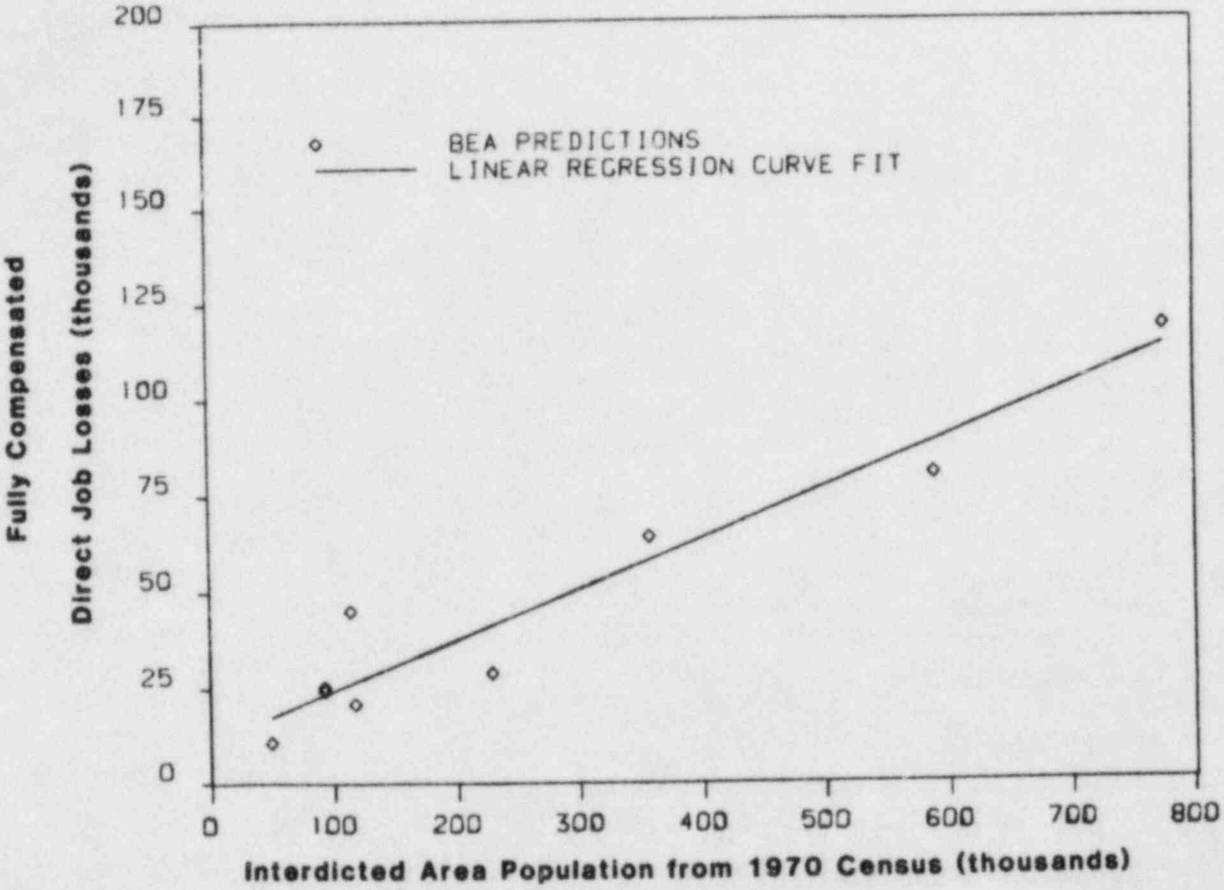


Figure C.6 - BEA fully compensated direct job loss predictions versus interdicted area population.



The BEA reactor accident economic impact studies are useful because of the application of a different economic modeling technique to the estimation of reactor accident economic impacts. The I-O modeling technique is very data intensive and computationally expensive and is therefore inappropriate for use in risk-analysis applications requiring analysis of hundreds of accident sequences, weather scenarios, and wind directions. The RIMS-II model has also been used with areas defined at the county level which results in large differences from CRAC2 predictions. Since the CRAC2 code employs a simple Gaussian plume atmospheric dispersion model, the areas defined in the BEA analyses should be considered carefully in interpreting impact predictions.

The BEA results indicate that secondary or spillover effects will generally be small relative to the direct effects in physically contaminated areas. Also, the BEA results indicate that losses will generally be a linear function of the population living in the affected area. This result agrees with the comparisons of land-usage based and per-capita based interdiction losses predicted by the ECONO-MARC model. The use of per-capita cost estimates and the exclusion of secondary or spillover effects in the CRAC2 and newly developed economic consequence models is supported by results obtained using different modeling techniques. Future research and assessments of indirect effects and population based loss predictions should be analyzed for verification of the assumptions underlying the new offsite impact model.

APPENDIX D

ANALYSIS OF LWR FORCED OUTAGE DATA BASE

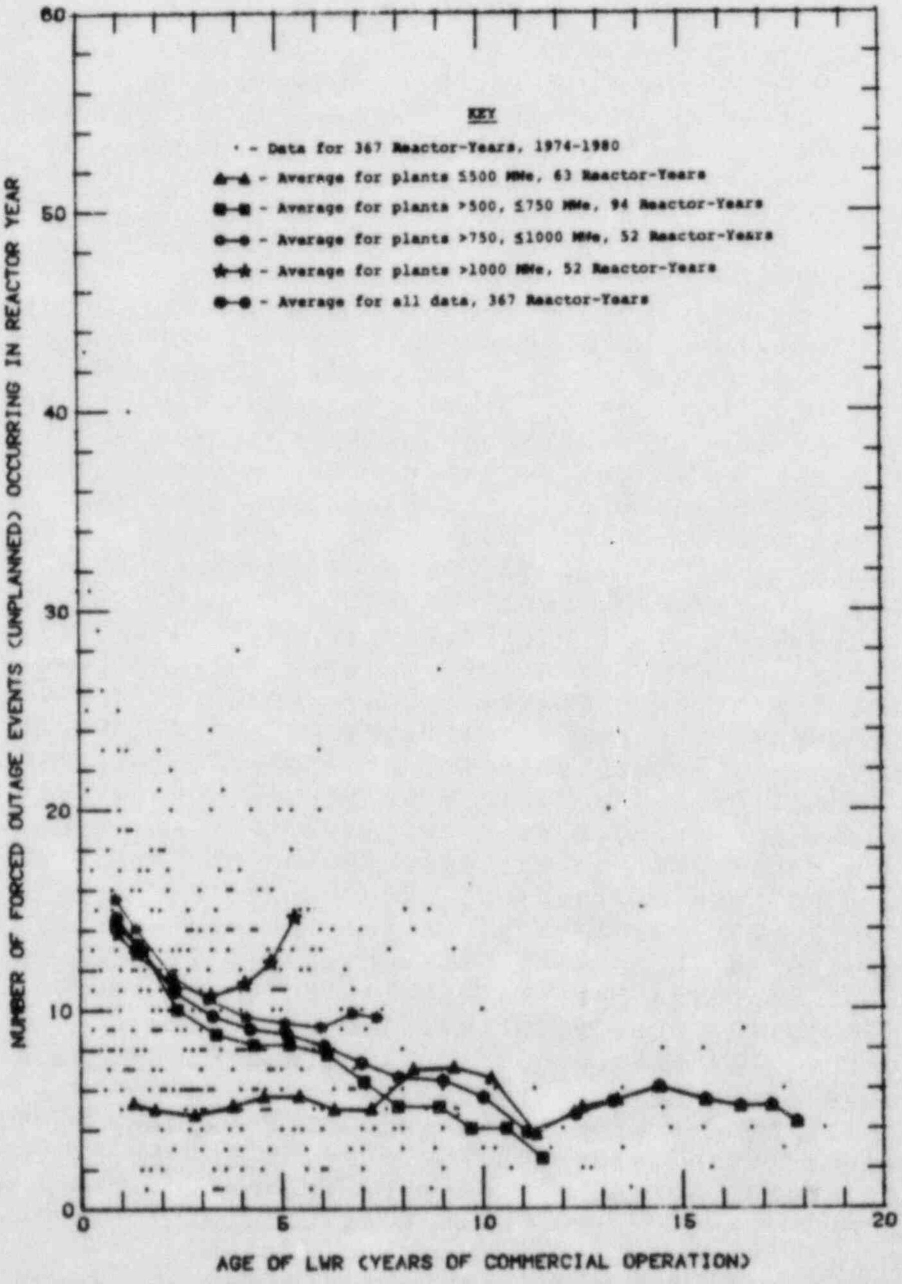
This appendix reviews the results of detailed analyses performed on the LWR forced outage data base developed in this study. The data were analyzed to determine impact of reactor size (electrical rating), age, NSSS vendor, and reactor type (BWR vs. PWR) on the forced outage frequency observed in each calendar year. Regression analyses were performed to check for possible correlations between forced outage event durations, forced outage event frequencies, and reactor age. Regulatory forced outages are excluded from all analyses in this section.

D.1 FORCED OUTAGE FREQUENCY VERSUS REACTOR PLANT AGE

Figure D.1 shows the number of forced outage events occurring in each reactor-year versus the age of the LWR during the year. The raw data include 367 U.S. commercial reactor years of operation between 1974-1980. The high density of raw data points for small reactor ages reflects the large number of plants which began commercial operation during the study period. The raw data points also show a trend towards larger numbers of forced outage events in the first few years of reactor operation. A moving average of plants in 3-year age groups, including all of the raw data points, is shown in Figure D.1. Collectively, all plants averaged about 15 forced outage events in the first year of operation, dropping steadily to about 10 forced outage events in the fifth year of plant operation. After 10 years of plant operation the plants included in the 1974-1980 data averaged about 5 forced outage events per reactor year. Thus, the initial years of plant operation show an average forced outage frequency approximately three times as large as the forced outage frequency for older plants.

The curve for the number of forced outage events versus reactor age is consistent with a "bathtub" failure rate curve and the learning curve observed in many technological devices [Gr72]. The high incidence of forced outage events for new reactors is caused by "teething" or wear-in problems with the system. As the reactor becomes older, wear-in problems become less important, and the base forced outage rate is approached. As the reactor plant nears the end of its productive lifetime (projected to be ~40 years from startup), an increase in the forced outage rate would be expected due to wear-out failures. Since none of the reactors included in the data sample are more than 20 years old, the lack of wear-out related effects is not unexpected. Also, regular maintenance work may be effective in

Figure D.1 - Forced outage frequency versus plant age for plant size groups.



correcting wear-out related problems before forced outage events occur.

Figure D.1 also shows curves for the yearly forced outage rate versus LWR age based on various size categories of plants. The curve including all plants under 500 MWe differs significantly from the curve for all plants considered collectively, exhibiting a relatively constant forced outage rate of ~7 forced outage events per reactor year over all LWR ages. The curves for plants between 500 MWe and 1000 MWe in size show significant wear-in forced outage rate effects. Finally, large LWRs (> 1000 MWe) have not shown significant wear-in effects, and the forced outage rate has remained relatively constant at ~12 per reactor year. However, no large reactors in the data base were more than 5 years old.

Figure D.2 shows the forced outage rate versus LWR age for PWR and BWR plants considered separately. Only very small differences can be seen between the average PWR and BWR forced outage frequencies for a given plant age group. Both types of LWRs do show significant wear-in or learning curve effects during the first few years of plant operation. Figure D.3 shows the forced outage frequency versus LWR plant age for plants based on the NSSS vendor. The curves for all four U.S. NSSS vendors show similar wear-in or learning curve effects.

The results of the above analyses indicate that for LWRs larger than 500 MWe and smaller than 1000 MWe, the plant forced outage frequency is a function of plant age measured from the date of start of commercial operation. During the study period 1974-1980, the average forced outage frequency for these plants decreased during the first few years of operation, leveling off after about 8 years of operation at approximately 1/3 of its initial value. This trend in mean forced outage frequency is observed for LWRs independent of plant type and NSSS vendor, except for those plants smaller than 500 MWe or larger than 1000 MWe. For the smallest plants, the forced outage frequency was approximately constant for all plant ages. Possible explanations for this small plant behavior include small system simplicity, improved system reliability, or extensive operations experience in the U.S. with small reactor startup and operation. For large plants, the forced outage frequency did not show a significant decrease with reactor age. This could be explained by the small amount of data included for large plants, a lack of experience with large reactor startup and operation, or decreased system reliability due to increased size and complexity.

The decrease of forced outage frequency observed with longer commercial operation of an LWR plant may have important implications on the economic and public health risks posed U.S. LWR operation. Many safety analyses performed on LWRs to date

Figure D.2 - Forced outage frequency versus LWR age for plant type groups.

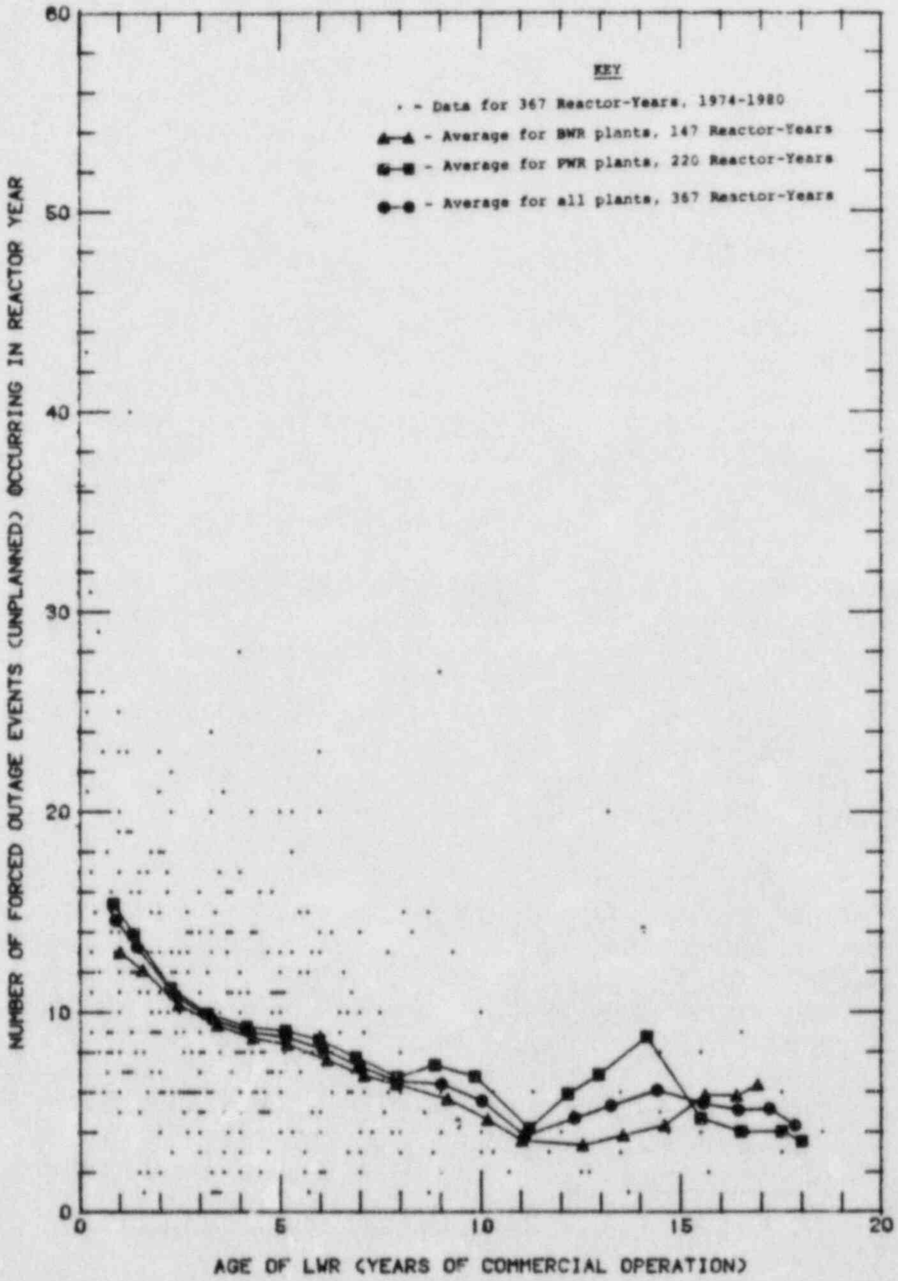
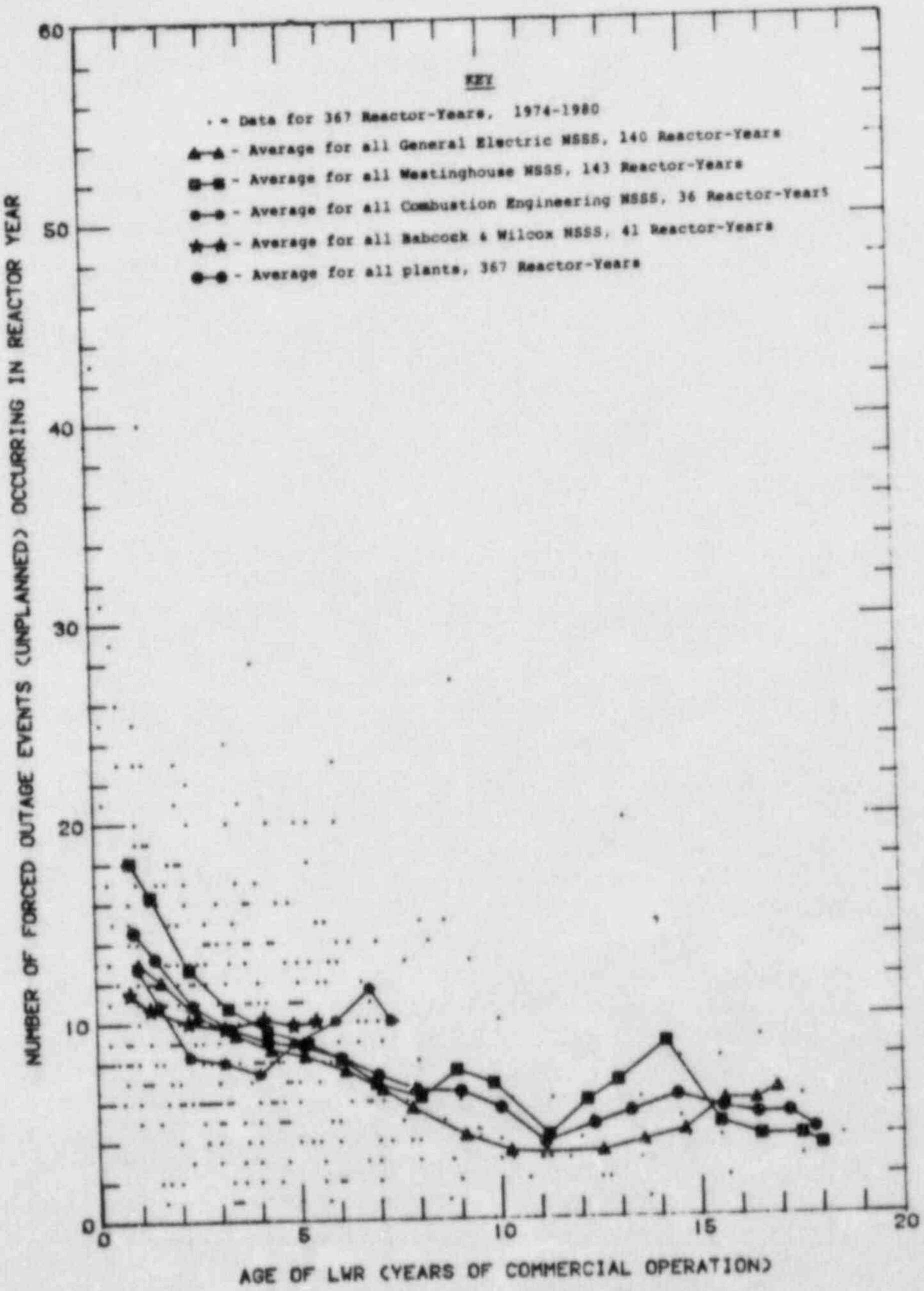


Figure D.3 - Forced outage frequency versus LWR age for plant NSSS vendor groups.



have found transient-induced accident sequences to be an important contributor to risk from LWR operation [Nu75a]. Each forced outage event at an LWR facility results in at least some transient of the reactor system to achieve either a hot or cold shutdown condition. Each forced outage event results in demands placed on systems required for transient operation, and possible demands for engineered safety systems if normal systems fail to operate correctly. Since transient frequency can be important in determining the risk from plant operation, the risk from plant operation may reflect a "bathtub" curve over plant life. Risk reduction or control programs should focus efforts on very new and very old (if LWR system wear-out is indeed an observed effect) plants in operation. This conclusion is supported by historical experience with the worst two U.S. commercial reactor incidents* occurring at reactor facilities in commercial operation less than 1 year. The dependence of risks on reactor age should be seriously explored. The maximum potential for economic losses exists in the first years of plant operation since little of the capital value of the plant has been recovered in this period.

D.2 POSSIBLE CORRELATIONS BETWEEN FORCED OUTAGE DURATION, FREQUENCY, AND PLANT AGE

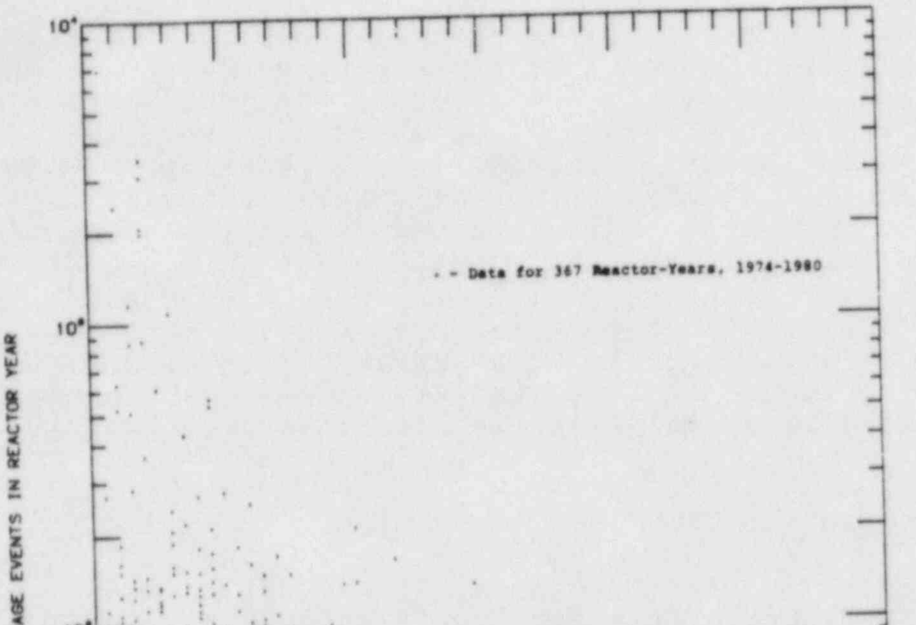
It may be expected that some correlation would exist between the number of forced outage events in a reactor year and the duration of each individual forced outage event. The occurrence of fewer forced outage events may be the result of very long outage durations in which the plant is not operating. Large numbers of forced outage events might be in part due to the short duration of each individual outage event allowing increased operating time for more forced outage events to occur. Also, forced outage durations may be dependent on plant age, older plants requiring longer outages for major system repairs. The operations data base developed in this study is checked for such correlations in this section.

Figure D.4 shows the mean duration of forced outage events versus the total number of forced outage events observed in each reactor year included in the data base. The data shows much variation and no clear correlation is observed in the raw data. Using standard linear regression the correlation coefficient between the two parameters (R^2) is less than 0.20. The duration of forced outage events shows little consistent variation with the total number of forced outage events which occur in a reactor year. This result supports the basic assumption which underlies the calculations in Chapters 3 and 5, that the

---

*The worst two U.S. commercial reactor incidents are considered to be the TMI-2 accident in March, 1979 and the Brown's Ferry Fire in March, 1974.

Figure D.4 - Mean duration of forced outages versus number of forced outage events in each reactor-year.



distribution of forced outage severity (or duration) is independent of the observed forced outage frequency. The assumption that the distribution of severity is independent of frequency is used in performing actuarial analyses for many types of insurance (i.e., fire, floods, auto accidents).

As discussed, the frequency of LWR forced outage events shows a strong dependence on reactor age for most LWRs. Analyses were performed to check for possible correlations between reactor age and forced outage event severity (or duration). Figure D.5 shows the mean duration of forced outage events in a reactor year versus the age of the LWR at the time the data were recorded. The data show very little consistent variation and the R^2 of a linear regression is very small (< 0.10). Figure D.6 shows the total duration of forced outage events in each reactor year versus the age of the reactor plant. Again, no correlation is shown and linear regression results in a very low regression coefficient. Thus, the total duration of forced outage events appears to be independent of LWR age.

D.3 CONCLUSIONS

Based on the results of detailed analyses of forced outage frequencies and durations from the LWR data base, forced outage frequency shows some dependence on LWR age and LWR electrical rating. However, there is no significant difference between forced outage frequencies based on reactor type (BWR vs. PWR) or NSSS vendor. The variation of forced outage frequency with reactor age is consistent with a "bathtub" shape due to wear-in effects, but increases in forced outage frequency due to wear-out effects are not observed in the data base. The data base should be continually updated in the future and analyses performed to check for wear-out induced effects.

The increase in forced outage frequency due to wear-in effects for large LWRs (> 500 MWe) has important implications for the variation of risk from reactor operation with time. Based on the analyses performed it is expected that risk from transient-induced accidents would be approximately three times as large in the first years of operation as in the middle of reactor plant life. This hypothesis is supported by historical experience with two serious U.S. LWR accidents occurring in the first years of reactor operation. The variation of transient-induced accident risk with reactor age could have important implications for risk reduction and risk mitigation programs.

The analysis of the data base to check for correlations between forced outage durations and forced outage frequency showed that no significant correlation exists. This supports the assumption of forced outage severity distribution and frequency independence which is used in Chapters 3 and 5. The

Figure D.5 - Mean duration of forced outage events versus LWR age.

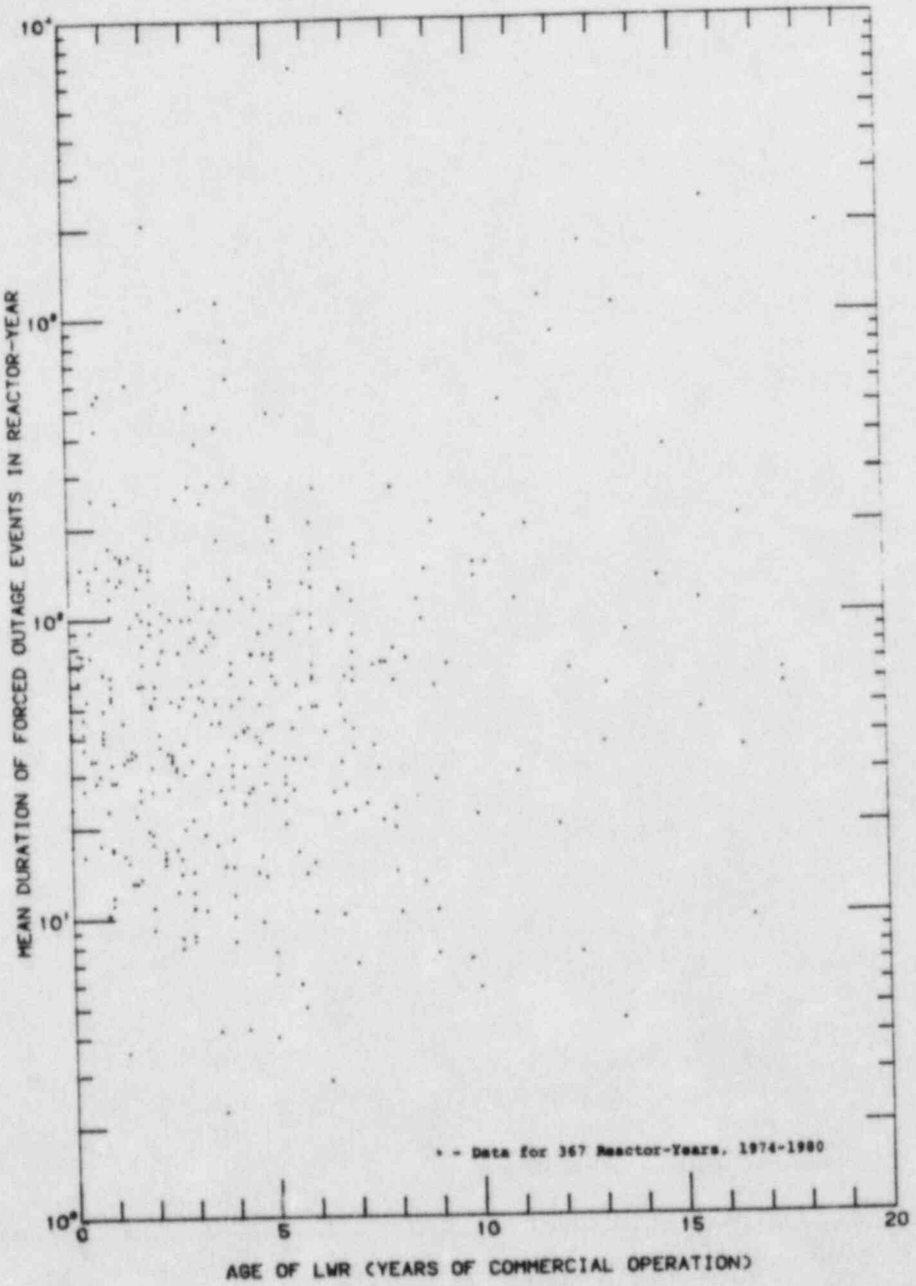
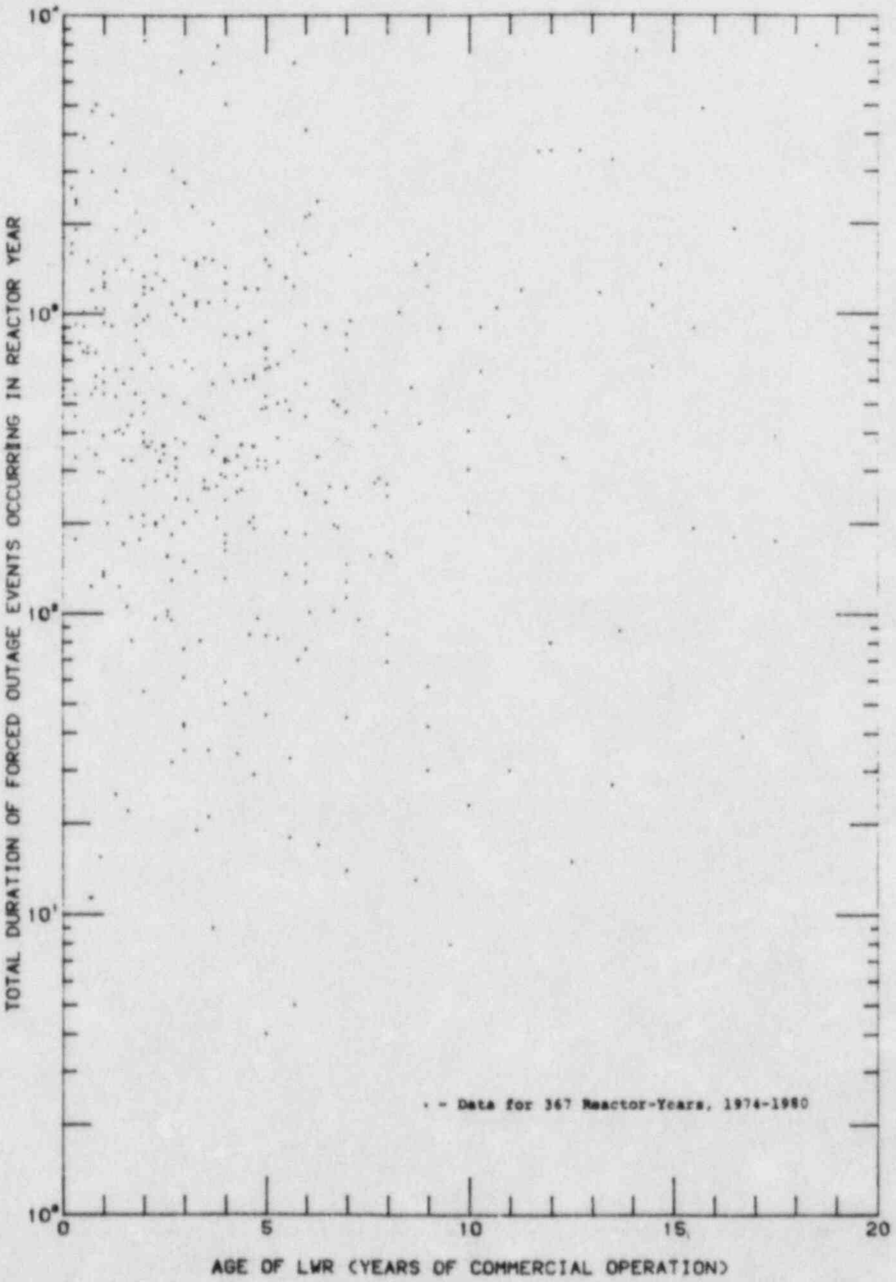


Figure D.6 - Total duration of forced outage events in year versus LWR age.



mean and total duration of forced outage events also showed no significant correlation with reactor age. Thus, the assumption of frequency and severity distribution independence is used in all actuarial analyses contained in this report.

APPENDIX E

DOSE PROJECTIONS IN THE PROTOTYPE OFFSITE ECONOMIC MODEL

Dose rates from surface-deposited radioactive materials are projected in the prototype economic model by accounting for radioactive decay, weathering, and shielding provided by structures and geometry using the RSS model:

$$RD_i(t) = SF \bullet DC_i \bullet SD_i^\circ \bullet \left[a_1 e^{-\lambda_{w_1} t} + a_2 e^{-\lambda_{w_2} t} \right] e^{-\lambda_i t} \qquad \text{(E.1)}$$

where

$RD_i(t)$ = the dose rate from isotope i as a function of time after deposition (Rem/Year).

SF = the shielding factor to account for dose rate reduction afforded by buildings, etc. (dimensionless).

DC_i = dose conversion factor which relates deposited activity levels for isotope i to whole-body doses ({Rem/year}/{Ci/m**2}).

SD_i° = initial surface deposition level of isotope i (Ci/m**2).

λ_i = radioactive decay constant of nuclide i (/year).

a_1 = weathering constant from RSS (0.63).

a_2 = weathering constant from RSS (0.37).

λ_{w_1} = weathering coefficient from RSS (1.13/year).

λ_{w_2} = weathering coefficient from RSS (0.0075/year).

This model is based on data collected for dose rates from cesium-137 versus time but is employed for all deposited radionuclides in the RSS model [Nu75b]. This equation is integrated between two points in time, t_1 and t_2, to project a maximum individual dose from constant exposure to deposited radionuclides during a specified time period:

$$D_i^{t_1-t_2} = SF \cdot DC_i \cdot SD_i^o \left\{ \frac{a_1}{\lambda_{w1} + \frac{0.693}{T_i^{1/2}}} \left[exp\left(-\lambda_{w1} t_1 - \frac{0.693}{T_i^{1/2}} t_1 \right) - exp\left(-\lambda_{w1} t_2 - \frac{0.693}{T_i^{1/2}} t_2 \right) \right] + \frac{a_2}{\lambda_{w2} + \frac{0.693}{T_i^{1/2}}} \left[exp\left(-\lambda_{w2} t_1 - \frac{0.693}{T_i^{1/2}} t_1 \right) - exp\left(-\lambda_{w2} t_2 - \frac{0.693}{T_i^{1/2}} t_2 \right) \right] \right\} \tag{E.2}$$

where

$D_i^{t_1-t_2}$ = integrated dose commitment during period t_1-t_2 for isotope i (Rem),

$T_i^{1/2}$ = half-life of isotope i (years),

t_1, t_2 = beginning and end of dose integration period (years),

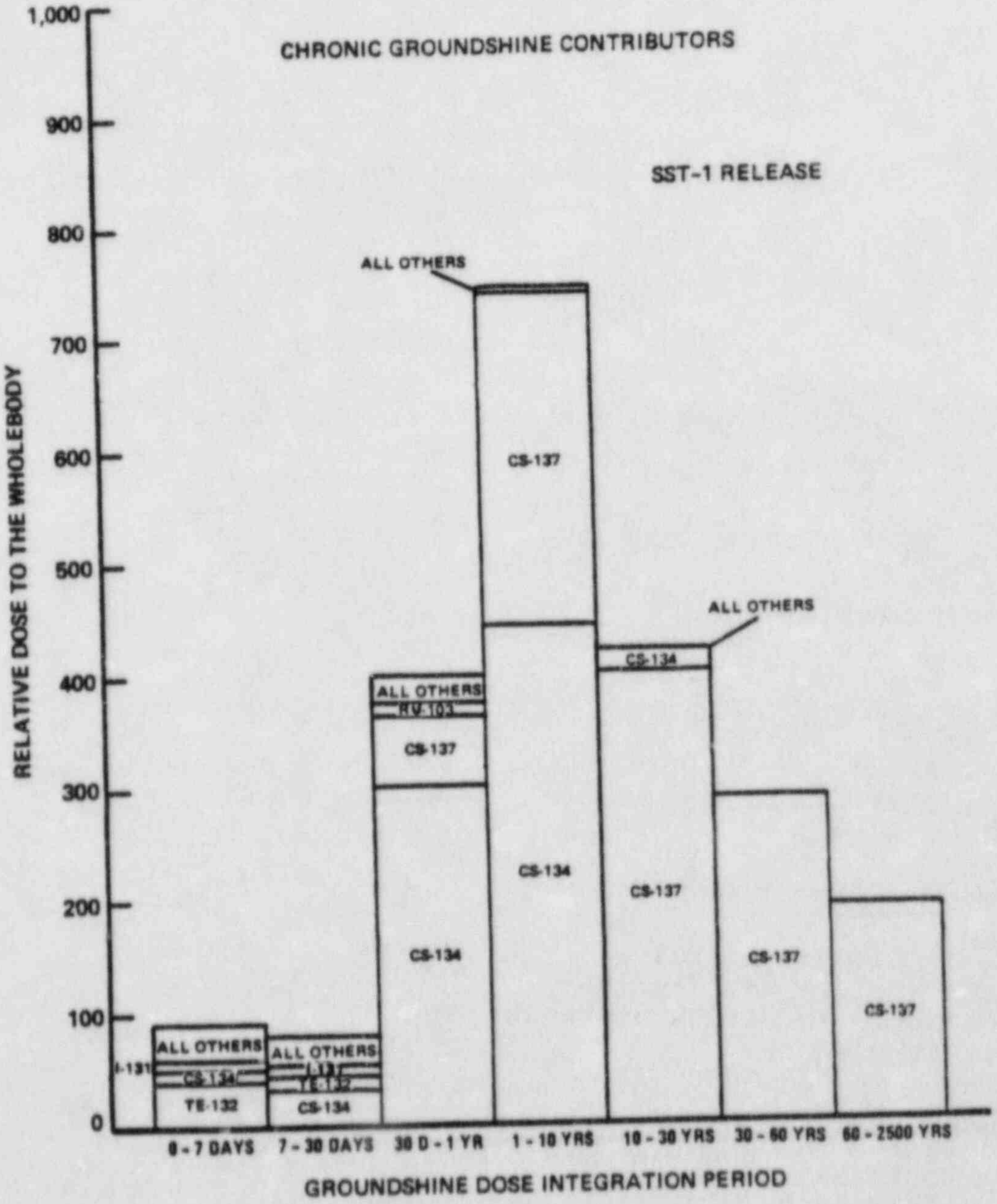
where all other parameters have been defined. This equation is used to project individual doses from exposure to surface-deposited materials in the emergency phase, intermediate phase, and long-term protective actions periods. The equation is summed over all deposited isotopes in an area to estimate total dose to an individual during each period. Details on the derivation of this equation are provided in the RSS [Nu75b].

Calculations were performed to identify the isotopes which must be considered to accurately project doses from groundshine exposure in different time periods. Reduction of the number of isotopes which must be considered can considerably reduce the computational expense using Equation E.2. Figure E.1 shows the contribution of important isotopes to integrated groundshine exposures in various time periods after deposition for the SST1 source term [Al82]. Over a period of many years, the cesium isotopes dominate the projected groundshine doses for this source term. The same is true for other LWR severe accident source terms. The CRAC2 model includes 10 isotopes in the projection of 0-30 year groundshine doses. The prototype economic model considers 54 isotopes in the projection of groundshine exposures for the following reasons:

1. The prototype model allows user specification of the integration periods for projecting doses for protective action implementation. These integration periods may be only a few hours or many years, therefore consideration of both short- and long-lived isotopes may be necessary.

2. Future changes in source terms may change the relative contributions of short and long-lived isotopes to groundshine doses.

Figure E.1 - Contributions of isotopes to whole-body groundshine doses for the SST1 release category.



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Models to be used for analyses of economic risks from events which occur during U.S. LWR plant operation are developed in this study. The models include capabilities to estimate both onsite and offsite costs of LWR events ranging from routine plant forced outages to severe core-melt accidents resulting in large releases of radioactive material to the environment. The models have been developed for potential use by both the nuclear power industry and regulatory agencies in cost/benefit analyses for decision-making purposes.

The newly developed economic consequence models are applied in an example to estimate the economic risks from operation of the Surry #2 plant. The analyses indicate that economic risks from LWR operation, in contrast to public health risks, are dominated by relatively high-frequency forced outage events. The implications of this conclusion for U.S. nuclear power plant operation and regulation are discussed. The sensitivities and uncertainties in economic risk estimates are also addressed.

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