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Estimates of the Financial Consequences of Nuclear Power Reactor Accidents

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ABSTRACT

This report develops preliminary techniques for estimating the financial consequences of potential nuclear power reactor accidents. Offsite cost estimates are based on CRAC2 calculations. Costs are assigned to health effects as well as property damage. Onsite costs are estimated for worker health effects, replacement power, and cleanup costs. Several classes of costs are not included, such as indirect costs, socio-economic costs, and health care costs. Present value discounting is explained and then used to calculate the life cycle cost of the risks of potential reactor accidents. Results of the financial consequence estimates for 156 reactor-site combinations are summarized, and detailed estimates are provided in an appendix. The results indicate that, in general, onsite costs dominate the consequences of potential accidents.

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1. Introduction

A number of recent developments have created an increased awareness of the need for the ability to evaluate the financial consequences of reactor accidents. Included in these is the Nuclear Regulatory Commission's current efforts to develop a set of safety goals which include an ALARA (as low as reasonably achievable) criterion, which defines the nature of cost-effective improvements, and therefore requires the ability to measure the degree of improvement. Even before such a criterion is adopted, financial risk analysis tools are valuable additions to the decision making process for evaluating cost-benefit tradeoffs for proposed design requirements or backfit proposals. In addition, recent experience at Three Mile Island has focused attention on the potential for tremendous financial consequences in even minor accidents (at least when minor is defined in terms of health effects). In a recent paper, Starr and Whipple [1] explore the possibility of using the utilities' financial self-interest as a basis for increased cooperation with the NRC and a less adversarial relationship with the regulatory body.

In order to further explore the potential role of financial risks in the regulatory process, it is necessary to have a better understanding of what these risks are. In this report we will examine the financial consequences of potential accidents at existing nuclear power plants. The estimates of health consequences and offsite financial consequences will be based on CRAC2 (Calculation of Reactor Accident Consequences, Version 2) predictions which were made to support a recent project which evaluated the impact of alternative siting criteria [2]. Costs for replacement power are based on studies ongoing now at Argonne National Laboratories.

The methods developed in this project, and the results presented in this report have a number of potential applications. Value/impact analyses are playing an increasingly visible role in decision making in the regulatory process, and there is a specific, immediate need for simple value/impact analysis tools for support of the decision making processes in the Severe Accident Rulemaking. In addition, a means of value/impact analysis is critical to the practical implementation of an ALARA criterion based on cost, such as the one proposed in the ACRS (Advisory Committee on Reactor Safeguards) safety goals [3]. The results presented in this report can be used to gain a better understanding of the relative importance of the contributors to financial consequences. In addition, the information on the range of consequences can be useful in a reevaluation of the liability limits of the Price-Anderson Act.

As in all studies of this nature, it is important to point out the large uncertainties in all results. The uncertainties in the CRAC2 code have been discussed at length in other places [2,4]. In addition, source terms, which play a significant role in determining the consequences predicted with the CRAC2 model, are the subject of considerable discussion [5]. Studies examining the sensitivity of results to changes of the magnitude proposed by Rahn and Levenson [2] indicate that offsite consequence predictions could change considerably if the current source terms are discarded in favor of the new, smaller ones proposed. In addition to the uncertainties in the CRAC2 predictions, additional uncertainty is added in the estimates of onsite effects, such as cleanup and replacement power costs. These uncertainties will be quantified to the extent possible, and sensitivity studies will be included to help judge the impact of the uncertainty.

We begin in the next section with an overview of the CRAC2 code and the prediction of offsite consequences. The following section will discuss the methods used for converting the CRAC2 results into the form appropriate for use in this study. Section 4 explains the use of present value discounting and presents the formulæ for discounting used in this study. The next section discusses the assignment of dollar values to health effects. In section 6 we discuss the estimation of onsite consequences. Section 7 is a summary of the results. In section 8 we examine the sensitivity of the results to assumptions made in the course of the calculations. This section is followed by an appendix containing estimates of the financial consequences at all sites which are currently operating or hold construction permits.

2. Offsite Consequences

The offsite consequence analyses presented in this report were calculated using the CRAC2 [4] code, an improved version of the code originally developed for the United States Reactor Safety Study

(RSS). CRAC2 employs a straightline Gaussian plume model to represent the transport and dispersion of radionuclides released in reactor accidents. The model allows for changes in weather (based on hourly observations) during the transport of the plume; however, it assumes that wind direction remains constant (hence, straightline). Radiation dose to the public is based on both external exposure from airborne and deposited radionuclides and internal exposure from inhaled and ingested radionuclides. Duration of external dose is determined by the evacuation scenario defined by the user, which allows specification of both evacuation and sheltering zones, as well as unprotected areas. Internal dose duration is the remainder of the life of the exposed individual.The manner in which health effects are calculated from dose will be described in detail in a later section.

In addition to calculating health effects, the CRAC2 model also provides estimates of offsite economic consequences. The data on which the economic consequence estimates are based are generally detailed only down to the state level. Thus, particular industries or areas of economic activity in the vicinity of a plant are not taken into consideration. All costs are expressed in 1980 dollars [2, Appendix A]. Economic consequences not included in the CRAC2 code are all onsite costs (capital loss, replacement power, cleanup), economic costs of health effects, costs of litigation, and indirect costs (such as shut down of adjacent or other reactors, loss of industrial capacity and jobs, etc).

CRAC2 results are based on the simulation of a number of weather sequences sampled according to a statistical model. (A comparison of the effectiveness of the CRAC2 sampling procedure with the sampling procedure used in the RSS version of CRAC can be found in [6]). The results from these sequences are combined to generate a distribution of results, which is frequently presented as a complementary cumulative distribution function (CCDF). In this report we will present all results as means (averages) of the distributions estimated by CRAC2.

The CRAC2 results presented in this report are from calculations performed as part of a project to support NRC activity on reactor siting criteria [2]. Calculations were performed for 91 sites in the United States which had reactors with operating licenses or construction permits. Many of these sites have more than one reactor, and therefore the results presented in the appendix to this report show 156 reactor-site combinations. The CRAC2 runs used the actual population distributions surrounding the sites, based on the 1970 census, and a wind rose recorded at the site over a one-year period. All persons within 10 miles of the reactor were assumed to evacuate to 15 miles (at which point they are assumed to receive no additional exposure) at a speed of 10 miles per hour after a delay of either 1, 3, or 5 hours (with weights on the delay times of 30%, 40%, and 30% respectively). Because of the difficulty in obtaining consistently high quality hourly weather observations for all the selected reactor sites, a surrogate meteorological record was derived from data collected by the National Weather Service at a station with meteorological conditions similar to those at the plant [7]. Since the objective of the project for which these CRAC2 runs were performed was to provide guidance in siting, all CRAC2 runs assumed an 1120 MWe PWR reactor, not the reactor existing at the site. Thus, the results calculated in these CRAC2 runs are not directly representative of the actual potential consequences of an accident at the site. In a following section we discuss how we scaled these results to derive an approximation of potential consequences for the actual site reactor.

An accident spectrum consisting of five accident groups, ranging from a gap activity release to a large scale fuel melt with large atmospheric release, was developed by the NRC to represent the range of fission product release in potentail accidents [8]. These groups are:

- Group 1—Severe core damage. Essentially involves loss of all installed safety features. Severe direct breach of containment. (similar to PWR2)
- Group 2—Severe core damage. Containment fails to isolate. Fission product release mitigating systems (e.g., sprays, supression pool, fan coolers) operate to reduce release. (similar to PWR5)
- Group 3—Severe core damage. Containment fails by basemat melt-through. All other release mitigation systems have funtioned as designed. (similar to PWR6)
- Group 4—Limited to moderate core damage. Containment systems operate but in a somewhat degraded mode. (similar to PWR9)

- Group 5—Limited core damage. No failures of engineered safety features beyond those postulated by the various design basis accidents are assumed. The most severe accident in this group includes substantial core melt, but containment functions as designed. (an order of magnitude smaller than PWR9)

For the purpose of decision making such as in siting and emergency response, the NRC has defined five releases, denoted SST1–SST5 (Siting Source Term), to represent the five accident groups [2]. By assigning appropriate probabilities to the five source terms, this set of releases can be used to represent the risk from any current LWR design.

CRAC2 calculates three major classes of public health effects. These are: early fatalities, early injuries, and latent cancer fatalities. In addition, CRAC2 also calculates thyroid and genetic effects, which will not be discussed in this report. Early fatalities are estimated on the basis of exposure to the bone marrow, lung, and gastrointestinal tract, and are observed within one year of exposure. Bone marrow damage is the major contributor. The risk of early fatalities for a given dose is determined by a **dose-response curve**. The dose-response curve used for the calculations presented here is taken from the RSS, and is called Curve B, which assumes supportive treatment of exposed individuals. (Supportive treatment indicates procedures such as reverse isolation, large doses of antibiotics, and transfusions of whole-blood packed cells or platelets.) Dose-response curves are defined for both greater and lesser degrees of treatment. However, it is believed that adequate facilities do not exist to supply the greater level of treatment required to justify the "heroic effort" response curve, while the minimal effort response curve assumes thst only standard hospitilization techniques are used to treat the exposed population. Curve B has an $LD_{50/60}$ (dose to bone marrow at which 50% of the exposed population is expected to die within 60 days) of 510 rads. All persons exposed to greater than 615 rads are assumed to have a 100% mortality rate, and no deaths are assumed for persons receiving less than 320 rads.

Persons receiving large doses who do not die are subject to early injuries, which are defined as non-fatal radiation induced illnesses requiring medical attention or hospitalization, and include prodromal vomiting, skin illnesses, and immunological system impairment. These early health effects are estimated on the basis of early dose to the whole body, lung, and gastrointestinal tract. Whole body dose dominates the effect. Rate of effects is determined from dose by means of dose-response curves, as were early fatalities. The dose-response curves for early injuries were also drawn from the RSS.

The final health effect we are concerned with is latent cancer fatalities. Latent cancers are based on early and chronic dose, and are assumed to have a ten-year latency period followed by a period at risk for the remainder of the individual's life (except leukemia which has a 30 year plateau). The dose-response curve for latent cancer fatalities is taken from the BEIR I report, and is linear in dose. Dose effectiveness factors are used to reduce the effect of low doses in a manner similar to the linear-quadratic model of dose response.

Two other CRAC2 results will be presented for each reactor-site combination in the tables accompanying this report. These are person-rem and property damage. Person-rem is the total population dose commitment, expressed in rem, from the postulated accident. Property damage, which is measured in 1980 dollars, is a measure of the economic consequences of an accident. Economic effects taken into account include lost wages, relocation expenses of the evacuated population, decontamination costs, lost public and private property, and interdicted land and farm crop costs, all calculated on the basis of statewide landuse and land value data, and the population distribution surrounding the specific site. Further details on the treatment of economic consequences can be found in references [2,9]. Economic consequences which are not included are the cost of providing health care to the affected population, all onsite costs, litigation costs, and indirect costs. In addition, no dollar value is assigned to health effects. The manner in which these factors are treated in this report will be detailed in the following sections.

Table 1 below lists the means of the selected effects for the five releases at the Indian Point site, (which is located in the Hudson Valley approximately 40 miles north of New York City), conditional on the stated release and an 1120 MWe PWR. This table shows that even at one of the most densely populated sites in the United States, SST4 and SST5 lead to essentially no offsite consequences. Because of this lack of offsite consequences, results from SST4 and SST5 will not be presented in the tables for each of the 156 reactor-site combinations. Treatment of onsite consequences for SST4 and SST5 will be discussed in the section on onsite consequences.

Indian Point
CRAC2 RESULTS: Mean Effects Conditional on Release

RELEASE CATEGORY	EARLY FATALITIES	EARLY INJURIES	LATENT CANCER FATALITIES	PERSON REM	PROPERTY DAMAGE
SST1	831.0	3640.0	8110.0	1.25E+08	1.18E+10
SST2	0.1	18.0	587.0	1.10E+07	1.46E+08
SST3	0.0	0.0	1.8	3.23E+04	1.95E+07
SST4	0.0	0.0	0.04	7.70E+02	0.0
SST5	0.0	0.0	0.003	7.70E+01	0.0

Table 1

3. Scaling to Power Level

All the CRAC2 calculations performed for the siting study, and which will be used for this project, assumed an 1120 MWe PWR at the site, rather than the actual reactor type and size. The type of reactor is not critical since the source terms were derived to represent any LWR design by appropriate selection of weights for the five releases. The power level of the reactor, and hence the core radionuclide inventory, plays a significant role in determining the magnitude of consequences. Sensitivity analyses [2] indicate that inventory scales fairly linearly with power level, and that consequences scale approximately linearly with inventory in a range surrounding 1120 MWe that includes most of the reactor sizes covered in this study. The differences between linearly scaled consequences and those calculated exactly can err in either direction, (that is, there is no systematic bias), and are within the range of values representing uncertainties due to other factors. Therefore, all results presented in this report as being representative of the true power level at the plant are derived by taking the results from CRAC2 analyses assuming an 1120 MWe power level and then scaling the result by $\frac{\text{(actual power level)}}{1120}$. Table 2 below shows the predicted consequences for Indian Point Unit 2, which has power level of 873 MWe. These mean values are the same as those in Table 1 scaled by $\frac{873}{1120} = .86$.

Indian Point Unit 2
SCALED RESULTS: Mean Effects Conditional on Release

RELEASE CATEGORY	EARLY FATALITIES	EARLY INJURIES	LATENT CANCER FATALITIES	PERSON REM	PROPERTY DAMAGE
SST1	647.7	2837.3	6321.5	9.74E+07	9.20E+09
SST2	0.1	14.0	457.5	8.57E+06	1.14E+08
SST3	0.0	0.0	1.4	2.52E+04	1.52E+07

Table 2

4. Discounting

In evaluating the economic consequences of a potential accident that can occur anytime in the life of a plant, we must sum terms for costs or risks occurring over a period of several years. This creates a problem since a dollar expended today and a dollar expended ten years in the future do not necessarily have the same value today to the recipient. This arises from the fact that the dollar received today could be put in a bank and interest collected for ten years, in addition to the flexibility of having the dollar available for use before the ten years are over. One way to compare dollars that arrive at different points in time is to find the amount of money which must be placed in a bank today to have the same amount of money at the time the other income is scheduled to arrive. The sum of money which must be put in the bank today to achieve a specified sum at a point in the future is called the discounted present value of the later sum, and the interest rate is called the discount rate. Thus, the discounted present value of \$1.00 received one year from today, assuming a 10% discount rate, is \$.91 (\$.91 × 0.1 + \$.91 = \$1.00). This type of calculation is called present value discounting. An excellent introduction to this subject can be found in an essay by Kenneth Arrow in [10] or most introductory economics texts.

In this report we have used discounting formulæ based on continuous discounting. The first formula presented here is used in calculations of the present worth of early health effects and offsite property damage. The present value of a cost C_0 which occurs with a frequency f is given by:

$$\int_{t_i}^{t_f} e^{-rt} C_0 f \, dt = C_0 f \frac{e^{-rt_i} - e^{-rt_f}}{r} \tag{1}$$

where

r = effective discount rate
f = frequency of accident costing C_0
t_i = time of onset of risk of accident
t_f = time of end of risk of accident.

For an operating plant like Indian Point Unit 2, t_i is 0. We will assume a 40 year plant life, so $t_f = 32$ for Indian Point Unit 2, which began operation in 1974 and therefore has only 32 years of remaining operational life. We will use $r = .04$ which is typical of the true discount rate experienced over the past several years. (The true, or real, discount rate is approximately the difference between the rate of inflation and the rate of interest on debt, such as the banking industry's prime rate.) In the discussion section we will examine the impact of this assumption. For these values, the multiplier of $C_0 f$ for formula (1) is 18.05.

The next formula is for calculating the present value of an expense which recurs for a number of years, such as the 10 year cleanup expense discussed in Section 6. The present value of an expense C_0 recurring for M years is given by:

$$\int_{t_i}^{t_f} f \int_{t}^{t+M} C_0 e^{-rt'} \, dt' \, dt = \frac{C_0 f e^{-rt_i}}{r^2}\left(1 - e^{-r(t_f - t_i)}\right)\left(1 - e^{-rM}\right) \tag{2}$$

Cleanup expense has t_i, t_f, and r as above, and $M = 10$. The multiplier of $C_0 f$ is therefore 148.76.

The last formula we need is for calculating the present value of an expense that will recur until a fixed date, rather than for a fixed number of years. This is the formula that applies to the replacement power costs which are charged for the remaining life of the plant (see section 6).

$$\int_{t_i}^{t_f} f \int_{t}^{t_f} C_0 e^{-rt'} \, dt' \, dt = \frac{C_0 f}{r}\left[\frac{e^{-rt_i} - e^{-rt_f}}{r} - e^{-rt_f}(t_f - t_i)\right] \tag{3}$$

For Indian Point Unit 2 the multiplier of $C_0 f$ is 228.79.

(For the reader interested in fine details, the use of the frequency f in the above formulæ implicitly allows repeat accidents at a reactor. The formulæ can be corrected to prohibit this situation. However, the correction would considerably complicate the formulæ, and for the accident frequencies under consideration the difference in results would be extremely small, appearing in the third or fourth decimal place of the answer.)

The impact of the start date on the multipliers arises from two mechanisms. As the start date moves farther into the past, the multiplier shrinks since the remaining life of the plant is reduced, and therefore t_i remains 0 while t_f gets smaller. As the start date moves farther into the future, the multiplier shrinks because there are more years of discounting intervening between the present and the onset of the risk.

Thus, the multipliers achieve their maxima for start dates in the current year, 1982. The table below shows values of the three multipliers for several start dates to give an indication of the impact of the start date on the discounted present value.

Comparison of Multipliers for Different Start Dates

START DATE	MULTIPLIER (1)	MULTIPLIER (2) M=10	MULTIPLIER (3)
1967	15.80	130.25	165.15
1974	18.05	148.76	228.79
1982	19.95	164.45	296.92
1987	16.34	134.64	243.10
1992	13.37	110.23	199.03

Table 3

The selection of the actual discount rate will have a significant impact on the predicted consequences, and to some degree on their relative magnitudes. Sensitivity to discount rate will be examined in Section 8.

5. Health Effects Costs

The assignment of a dollar value to various health effects is certain to be one of the most difficult and potentially controversial aspects of the estimation of the financial consequences of an accident. There does not appear to be any universally accepted method for assigning a value to a life, let alone a single price ascribed to the value of a life. One method that has been used is to impute a social perception of the worth of a life from the expenditures that society is willing to make in order to prevent a death. The work of Cohen [11] is an example of this technique. This approach leads to widely varying values on human lifes, from the low tens of thousands of dollars for some cancer prevention tests and highway maintenance, to hundreds of thousands of dollars per life for some auto safety features, to millions of dollars per life for some mine safety and radiological standards. A second complicating feature of assessing the value of a life is that studies have indicated that people place a different value on a lost life depending on the circumstances under which the death occurred. For example, a death in an involuntary, novel situation is perceived as being worse, or more costly, than a death from a familiar activity such as automobile driving [12]. Another confounding factor, especially for the reactor accident case, is the assessment of the difference in value for an immediate death compared to a delayed death, like a cancer fatality. One approach to dealing with this aspect is to use a concept of life shortening rather than a value for a life. Life shortening measures the number of lost years, and therefore may assign a lower value to the death of an older person than for younger person, or for a delayed death versus an immediate death.

A recent report by a subcommittee of the ACRS [3] proposes values for early deaths and delayed deaths. The values are $5 million and $1 million respectively. (The value for early deaths was proposed in combination with a risk aversion criterion, and therefore is actually expressed in "equivalent deaths". Equivalent deaths are calculated for a given accident by raising the consequences of the accident to the 1.2 power, and therefore for accidents with large consequences the effective valuation on life will be larger than $5 million.) The values were proposed in the context of an ALARA (as low as reasonably achievable) criterion to require improvements to a reactor facility. The Nuclear Regulatory Commission has proposed, in NUREG-0880 [13], the use of a value of $1000 per man rem averted. This extrapolates to approximately $10 million per latent cancer fatality. In neither of these cases has a rationale for selecting these figures been given, and therefore there is no basis for discussing their merit in this report.

Rather than enter the controversy by attempting to place a value on human life, we will treat the issue by using empirical values of society's willingness to expend resources to avert a death. This approach is useful in the context of this report since we are trying to develop techniques which can be used to develop a value/impact approach for potential regulatory application. Therefore, the use of empirical societal values from life-saving technological "fixes" in comparable circumstances is an appropriate approach in this context. We have chosen a value of $1 million for early fatalities and $100,000 for early injuries and latent cancers. The choice of these values is only a starting point for discussion; a later section on sensitivities will examine the impact of the selection of these particular values, and provide insight into the results if other values are selected. The lower figure is in the range (although slightly larger) of imputed life values based on various medical treatments or screening techniques, mostly related to cancers, which are comparable to the delayed deaths caused by radiological accidents. The higher figure is larger than most values for traffic safety programs or equipment, which are used to prevent prompt deaths, comparable to the early death as defined for our purposes. In addition, it is in the range of the imputed life values based on other considerations such as aircraft safety. (These comparisons are based on the imputed values in [11].) For the purposes of accounting for cost, it is assumed that effects are charged for when the accident occurs. While these particular values may cause controversy, the discussion of sensitivities in Section 8 shows that these assumptions have relatively little impact on the overall conclusions. Thus, while the actual values used are important in many areas of application, the conclusions of this report are relatively unaffected by values within the range of general discussion. Note that these costs are used to represent the expenditure that society is willing to make to avert a loss of life, and do not include the costs for medical care. Table 4 below shows the mean (average) costs for the offsite consequences conditional on the stated release.

Indian Point Unit 2

OFFSITE COSTS: Conditional on Release

RELEASE CATEGORY	EARLY FATALITIES ($'s)	EARLY INJURIES ($'s)	LATENT CANCER FATALITIES ($'s)	PROPERTY DAMAGE ($'s)
SST1	6.47E+08	2.84E+08	6.32E+08	9.20E+09
3ST2	1.00E+05	1.40E+06	4.58E+07	1.14E+08
SST3	0.0	0.0	1.40E+05	1.52E+07

Table 4

Table 5 below shows the discounted present value of the costs in Table 4 summed over the life of Indian Point Unit 2, assuming frequency f_i (expresssed per year) for release i. Thus, early fatality, early injury, latent cancer fatality, and property damage values are discounted to the present using discounting formula (1). The values in the tables have units of dollars and represent the discounted present value of the risks summed over the plant life; they are not the cost of any single accident. Thus, if one were to assign a value of 10^{-5} to f_1, (this value is selected for illustrative purposes only), the expected mean lifetime risk due to property damage would be $\$1.66 \times 10^6$. This does not imply, however, that accidents with larger consequences could not occur.

Indian Point Unit 2

DISCOUNTED PRESENT VALUE OF OFFSITE COSTS (times frequency f_i)

RELEASE CATEGORY	EARLY FATALITIES ($'s)	EARLY INJURIES ($'s)	LATENT CANCER FATALITIES ($'s)	PROPERTY DAMAGE ($'s)
SST1	$1.17E+10 \times f_1$	$5.12E+09 \times f_1$	$1.14E+10 \times f_1$	$1.66E+11 \times f_1$
SST2	$1.08E+06 \times f_2$	$2.53E+07 \times f_2$	$8.26E+08 \times f_2$	$2.05E+09 \times f_2$
SST3	$0.00E+00 \times f_3$	$0.00E+00 \times f_3$	$2.53E+06 \times f_3$	$2.74E+08 \times f_3$

Table 5

6. Onsite Consequences

The CRAC2 code was designed to provide estimates of the offsite consequences of reactor accidents and therefore does not provide estimates of the onsite consequences of an accident, either in terms of health effects or financial effects. In order to carry out the task of estimating the consequences of an accident, we have divided the consequences into four areas; plant personnel health effects, replacement power costs, cleanup costs, and capital costs.

An examination of NRC regulations concerning reactor operating procedures during emergencies, as well as procedures of the utilities, indicated that during a major emergency in which a significant release is imminent there would be approximately 40 persons on the site in either the control room or the technical support center, both of which are required to provide a degree of protection from a radiological release [14]. Using an assumption of essentially a worst possible case, we assume that an SST1 release results in 10 early fatalities and 30 early injuries onsite. The significantly lower levels of hazard for the other releases are assumed to cause no early effects to reactor personnel. In the discussion and sensitivity analysis section we will examine the impact of this assumption on the overall conclusions, and how to estimate the consequences under different assumptions.

Estimates of replacement power costs are based on preliminary results from an ongoing research project at Argonne National Laboratory [15]. In this method replacement power costs are estimated on the basis of the cost of replacement fuels and power availability for each National Electric Reliability Council (NERC) region. The dominant factor in determining these costs is the relative proportion of oil fired backup plants versus economical alternative sources (for example coal or hydro). In [15] the cost of replacement power is estimated to be

$$C_0 = (0.286 \times R + 0.086)10^6 \qquad \$ \text{ per MW year}$$

where R is the fraction of replacement energy by oil-fired or noneconomy power purchases. The values of R by NERC region (defined in Figure 1) are:

MARCA		20%
NPCC		95%
MAAC		50%
MAIN		15%
ERCOT		50%
SPP		40%
WSCC	California	95%
	not California	25%
SERC		15%
ECAR		5%

Table 6

This cost formula is based on the assumption that the reactor had a 65% availability prior to the accident. The value derived by this method is then multiplied by the power level of the plant, and summed over a number of years corresponding to the remaining life of the plant, with discounting and inflation in fuel price taken into account.

Using the replacement cost of electricity for the full remaining life of the plant imputes a value for the lost capital cost of the plant, since, by purchasing power, the income stream of the plant is maintained, although the net income may become negative if rates do not increase corresponding to the replacement power costs. Thus, this replacement power cost estimation procedure using actual cost for the remaining life of the plant eliminates the need to include a seperate term for the lost capital expense. It should be noted that for cases with remaining plant life greater than ten years, it may be possible to build a new facility, either coal or nuclear, that could replace the lost capacity at a lower cost than that obtained using the calculation above. However, estimating the effect of a replacement plant is very complex since it involves changes to the capacity expansion plan of the utility, interaction with other

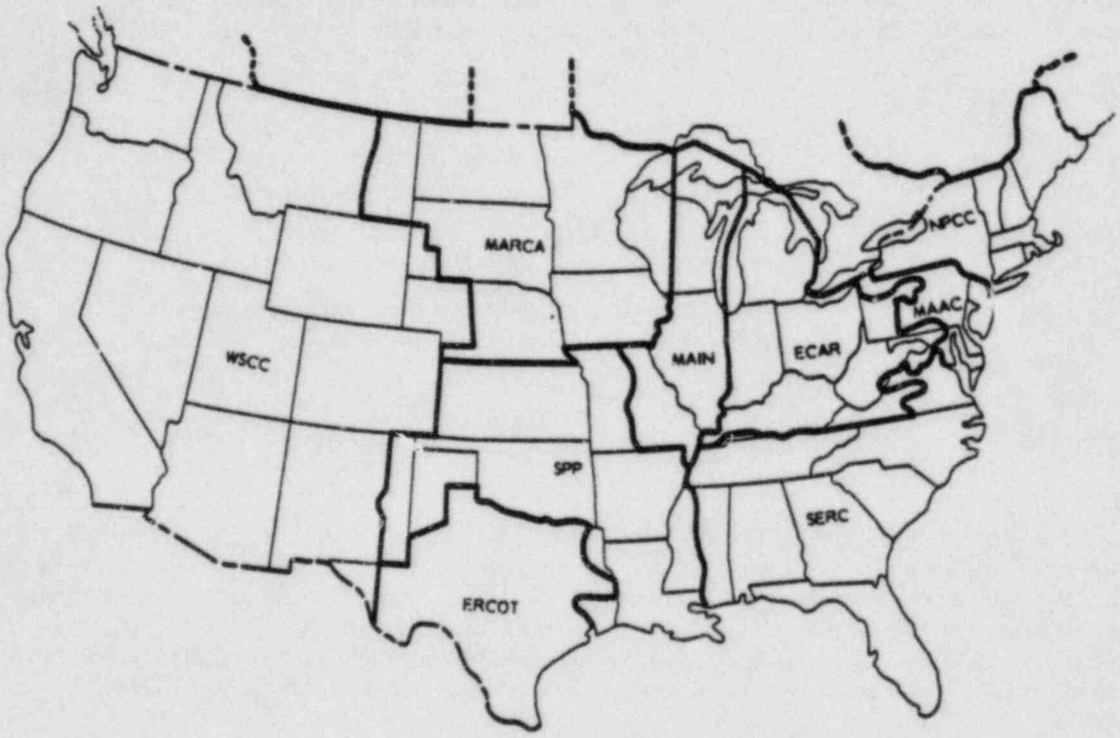


Figure 1. NERC Regions

utilities in the region, as well as other factors relating to the overall economy. Means of incorporating these factors are currently being researched at Argonne. Estimates of the impact of including these effects will be included in the discussion section at the end of this report.

Cleanup costs for reactor accidents are difficult to estimate due to a lack of experience and data. For the initial stages of this project we will use a value of $100 million dollars per year for ten years which represents the cost of early decommisioning or cleanup and repair, depending upon the severity of the accident. This figure is comparable to current estimates of the cleanup costs for the Three Mile Island accident [16].

Table 7 below shows the estimates of these contributors for the Indian Point Unit 2. Note that the health effects costs only apply to SST1, and the other costs to SST1, 2, and 3. SST4 and 5 are not expected to produce any onsite health effects, and may leave the plant in a repairable state. Thus, the replacement power may not have to be purchased for the remaining life of the plant, but rather for a shorter period. The discounted value of that cost could be estimated using discounting formula (2). At the moment, we have no estimate for the cleanup (or repair) costs of SST4 or 5.

	Indian Point 2	
Onsite Health Effects:	$ 1.30E+07	(conditional on SST1)
	$ 2.35E+08 × f_1	(discounted over remaining plant life)
Replacement Power:	$ 3.12E+08	(per year, conditional on SST1,2, or 3)
	$ 7.14E+10 × f_i	(discounted over remaining plant life)
Cleanup:	$ 1.00E+08	(per year, conditional on SST1,2, or 3)
	$ 1.49E+10 × f_i	(discounted over remaining plant life)

Table 7

Table 8 below shows the mean (average) costs of an accident at Indian Point in 1982. The health effects costs are magnitude times the dollar values discussed earlier, the offsite property damage costs are the scaled estimates of means from CRAC2, conditional on the release, and the onsite costs are the per year conditional costs from Table 7 above, summed over the period for which they are paid (10 years for cleanup costs and 32 years (remaining plant life) for replacement power), and discounted assuming a 4% real discount rate. Thus all the entries are the present net value in 1982 of an accident occurring in 1982.

Indian Point Unit 2
MEAN TOTAL COSTS: Conditional on Release

RELEASE CATEGORY	OFFSITE HEATLH COSTS	OFFSITE PROPERTY COSTS	ONSITE COSTS	TOTAL COSTS
SST1	1.56E+09	9.20E+09	6.43E+09	1.72E+10
SST2	4.73E+07	1.14E+08	6.43E+09	6.59E+09
SST3	1.40E+05	1.52E+07	6.43E+09	6.45E+09

Table 8

The following table shows the discounted present value of the life cycle risk from Indian Point Unit 2. This risk represents the sum over all future years of operation, and therefore is not conditional on an accident. Rather, the expressions contain a term for the accident frequency f, which must be multiplied out to arrive at a discounted present value for the life cycle risk.

Indian Point Unit 2
DISCOUNTED PRESENT VALUE OF TOTAL COSTS

RELEASE CATEGORY	OFFSITE HEATLH COSTS	OFFSITE PROPERTY COSTS	ONSITE COSTS	TOTAL COSTS
SST1	$2.82E+10 \times f_1$	$1.66E+11 \times f_1$	$8.66E+10 \times f_1$	$2.81E+11 \times f_1$
SST2	$8.52E+08 \times f_2$	$2.05E+09 \times f_2$	$8.63E+10 \times f_2$	$8.92E+10 \times f_2$
SST3	$2.53E+06 \times f_3$	$2.74E+08 \times f_3$	$8.63E+10 \times f_3$	$8.66E+10 \times f_3$

Table 9

7. Summary of Results

This section summarizes the detailed results presented in Appendix A. It is important to again caution the reader and potential user of these data that the results are derived from CRAC2 analyses assuming an 1120 MWe PWR at each site. These results were then scaled linearly by power level. Thus, the data do not represent the conclusions of PRAs performed for each site and reactor, but rather are approximations. As in all applications of this nature, the data are subject to uncertainty. However, we believe that the nature of the uncertainties is such that comparisons among plants are fairly accurate in relative rankings.

Early fatalities show the most variability of the various health effects. Figure 2 is a CCDF (complementary cumulative distribution function) of the mean number of early fatalities at each of the 156 reactor-site combinations, conditional on an SST1 release. The mean of this CCDF is 69, which is exceeded almost 25% of the time. As can be seen in the CCDF, the mean number of fatalities for the various reactor-site combinations span more than four orders of magnitude.

Figure 3 is the CCDF of mean early injuries. Mean early injuries for the reactor-site combinations span about two and one-half orders of magnitude, compared to the four orders for mean early fatalities. The mean of this CCDF is 345, and like early fatalities, the mean is exceeded approximately 30% of the time. The CCDF of latent cancer fatalities is shown in Figure 4. With the exception of one outlier, the data fall within two orders of magnitude. The mean of the distribution is 1450, and is exceeded about 30% of the time. Thus, the shape of the three health effects CCDFs are very similar to each other in that each has a mean exceeded 25–30% of the time, and each has an 's'-shape (indicative of a lognormal distribution).

Figures 5,6,and 7 are the CCDFs of mean person-rem for SST1,2, and 3 respectively. The three curves are almost identical in shape, each is just the next larger release shifted to the left. As in the CCDFs presented earlier, the mean of each of these distributions is exceeded 30–40% of the time.

Figures 8,9, and 10 illustrate the CCDFs for various economic consequences. Figure 8 is a plot of the mean offsite property damage costs, conditional on an SST1 release. There are about two orders of magnitude spread, although 90% of the values fall within a one order of magnitude range. Figure 9 is a CCDF of mean total health effects costs conditional on an SST1 release. These costs show about two orders of magnitude of variation, which is much less than the four orders observed in early fatalities. The narrowing of the spread indicates the importance of the costs of latent cancer fatalities in determining the overall health effects costs. Figure 10 is the CCDF of mean total financial costs for an SST1 release. The CCDF shows very little variability. This is due to the dominance of cleanup costs and replacement power costs in determining the overall cost. (The Indian Point site used in the example tables in this report is the exception to this general conclusion.)

8. Sensitivity and Discussion

In a number of areas discussed above there is considerable uncertainty regarding the values selected. In this section we will examine the sensitivity of results and conclusions to the particular values selected.

The area which may contain the greatest uncertainty is the selection of values for loss of life, since this value cannot be determined in a technical manner; it is really a social or political question. Using the values for health effects given in Section 5, health effects costs account for approximately 12% of the total offsite discounted costs for the SST1 release. (This is the average over all sites and reactors.) The minimum value was 5% of total offsite cost, while the maximum was less than 25%. Figure 11 is a CCDF of the ratio of health effects costs to total offsite effects costs (health effects costs plus property damage), conditional on SST1. It is apparent that the 12% mean is exceeded approximately 40% of the time. Thus, in general an order of magnitude or greater increase in the value assigned to loss of life is necessary to increase the cost of health effects to a level making it a significant contributor to the offsite cost of an accident. Figure 12 is a CCDF of the ratio of discounted health effects costs to total accident costs including replacement power and cleanup costs, conditional on SST1. At most, health effects costs contribute just over 10% of the total cost, and more typically contribute 5% or less, further reducing the impact of changes in values assigned to loss of life. The portion of total offsite costs represented by health effects costs for SST2 is 16% minimum, 30% average, and 48% maximum, while SST3 is 0.5% minimum, 3% average, and only 11% maximum. Thus, SST2 has a greater sensitivity to change in life values, although a factor of five change is still necessary to bring health effects costs to the level of offsite property damage. It should be noted, however, that for SST2 and 3 the total offsite costs are more than an order of magnitude smaller than the onsite costs, and therefore an order of magnitude change in the health effects costs would have negligible effect in determining the overall costs for these accidents.

Some participants in the debate on the valuing of human lives argue that it is improper to discount the dollars associated with loss of life, since this is implicitly discounting the value of a life lost in the future. While we do not agree with this argument since it can lead to inefficient utilization of social resources, we have examined the impact on the conclusions presented in this paper if health effects costs are not discounted. Figure 13 is a CCDF of the fraction of total offsite costs which represent non-discounted health effects, conditional on SST1. In comparing this figure to Figure 11, one can see that the maximum fraction has increased from about 20% of the total costs to 50%. However, this large fraction occurs with very low frequency, and 80% of the time health effects, even without discounting, account for at most 25% of the offsite costs, which in turn represent only a fraction of the total costs.

Recently, some attention has been focused on the use of $1000 per person rem averted as the basis for an ALARA criterion on reduction of public risk from reactor accidents [17]. For SST1 accidents, the discounted present value (over the life of the plant) of person rem times $1000 ranges from a minimum of 79% of the total (onsite and offsite) cost of an accident to more than 16 times the total cost, with average discounted present value cost equal to 9 times the total cost using the formulation described in this paper. SST2 has a minimum of 6%, maximum of almost 1000%, and a mean of 200%. For the SST3 release, the maximum value represented by using the $1000 per person rem value is only 3% of the total accident cost. The use of the $1000 per person rem as a proxy for only the health effects costs is also subject to considerable variability. For the the SST1 release, the person rem estimates exceed the modeled value by factors ranging from 50 to over 450, with an average of approximately 240. SST2 and 3 both have overestimates by factors averaging 450. Thus, even if the values assigned to loss of life were to be increased by an order of magnitude, the person rem proxy value would still overestimate the value of health effects by a large amount.

Several uncertainties are associated with the onsite cost estimates. The first is the magnitude of the onsite health effects. Onsite health effects account for less than 1% of the total onsite costs for SST1, and therefore a significant increase in the values assigned to loss of life would be required to have any impact. (It seems implausible that more injuries would occur, since the 40 casualties used assumes a 100% casualty rate, with 25% of the casualties being fatal.) Even assuming this level of casualties would have little or no effect on the other releases since the cleanup costs and replacement power costs remain the same, and completely dominate the onsite costs.

The second area of question in onsite costs is the assumption that replacement power is purchased for the remaining life of the plant. Because of discounting, approximately 60% of the present value for replacement power is due to expenditures in the first 10 years which is probably the minimum amount of time necessary to build a new plant. In addition, even the remaining years would still have a cost, which could be no less than one-fourth the estimated replacement power cost, and therefore the total replacement power costs would change by no more than 30%. Replacement power costs account for 50% of the total costs (average over all sites) for SST1, and therefore the approximation based on purchasing replacement power for the remaining life of the plant could change the total costs by no more than 15%

Different discount schedules (with identical discount rates) are used for various costs and therefore changes in the discount factor affect different costs in different ways. For the health effects and offsite property damage which are discounted at the time of occurrence, and cleanup, which has a cost recurring for ten years, the present value increases by about 40% when the discount rate is dropped from .04 to .02. Eliminating discounting altogether (0.0 discount rate) causes present values to double for plants with start dates near or before 1982. As the start date moves farther into the future, the difference increases to almost a factor of four for start dates well into the 1990s. The value drops by about 40% when the discount rate is doubled to .08. The present value of the replacement power changes only slightly faster than these first two terms.

A series of sensitivity calculations was performed as part of the siting study [2] to evaluate the impact of uncertainties in the source term, especially in line with reductions suggested in [5]. The table below shows the relative reductions in mean offsite consequences at the Indian Point site, with all consequences scaled to 100 for the original SST1 source term. In general, it appears that the relative contribution to offsite costs of its constituent factors will remain unchanged with reductions in the source term (although the importance of early fatalities does decrease somewhat). The contribution of offsite costs to total cost is reduced however, since the onsite costs are fairly independent of the size of the source term.

Sensitivity of Mean Consequences to Reductions in SST1

RELEASE SIZE	EARLY FATALITIES	EARLY INJURIES	LATENT CANCER FATALITIES	PERSON REM	PROPERTY DAMAGE
SST1	100	100	100	100	100
SST1×.5*	30	35	74	82	62
SST1×.1	1	4	32	39	11
SST1×.05	0.2	2	19	24	5
SST1×.01	0.03	1	5	6.7	0.71

*Release fractions reduced for all isotopes except noble gases

Table 10

A number of costs for an accident were not included in the calculations presented in this report. These costs include medical care, litigation, and indirect costs. It is difficult to estimate these costs, but some very crude estimates indicate that some may be of importance. Medical costs can be divided among treatment of early fatalities, early injuries, and latent cancers, both fatal and non-fatal. The costs assigned to the early effects will probably be small in comparison to the $1 million and $100,000 assigned to these effects. The costs of medical treatment of the latent cancers may be larger than the $100,000 associated with latent cancer fatalities, especially when non-fatal cancers are taken into account. The indirect costs could be very large if they are to take into account national economic repercussions such as closing of other nuclear power plants, loss of industrial capacity and jobs, effects on financial markets, socio-economic impacts, etc. Estimates of these effects [18,19] indicate that they may be larger than all the effects discussed in this report. However, many of these costs are widely dispersed and would be difficult to link to the accident, at least in terms of establishing legal liability.

While the range of variation due to uncertainty may have significant impact when comparing estimated values to absolute figures, such as the cost of a design modification, they do not significantly change the relative contributions of the various factors to the overall financial consequences of an accident. In addition, except for possible indirect costs which were not evaluated in this paper, the magnitude of these changes is generally within the range of uncertainties due to the CRAC2 code, the selection of source term, the estimation of accident probabilities, and onsite cost estimates.

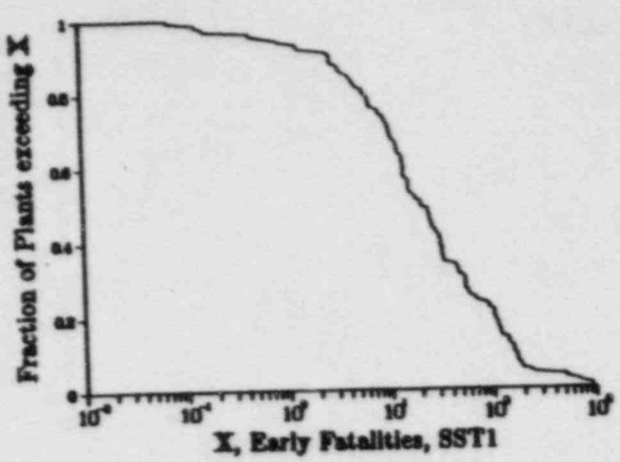


Figure 2

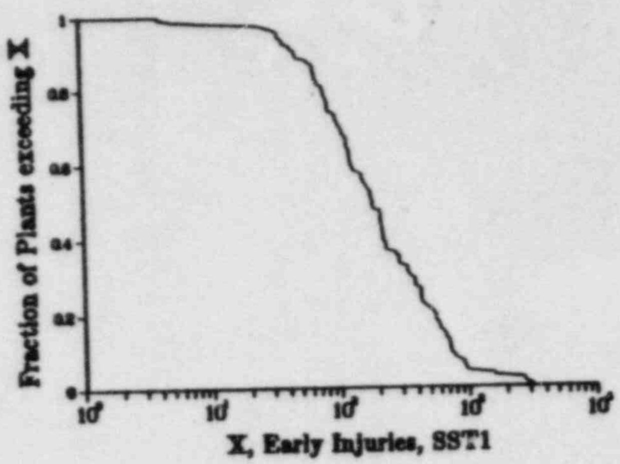


Figure 3

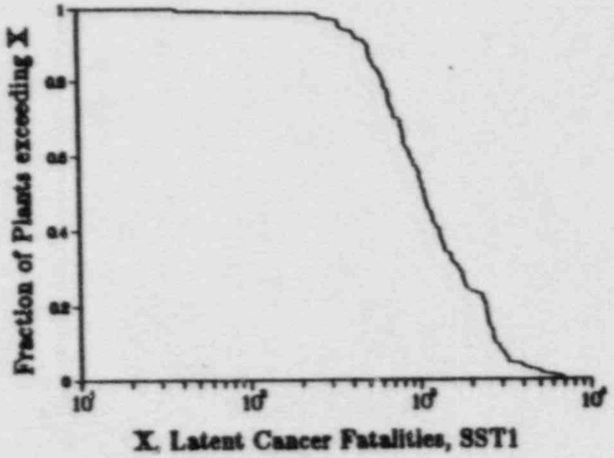
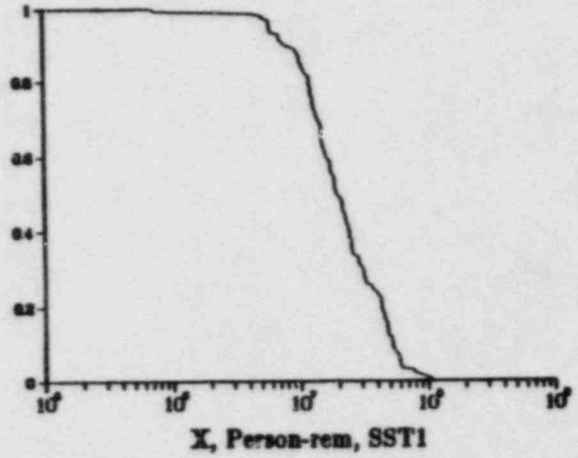


Figure 4



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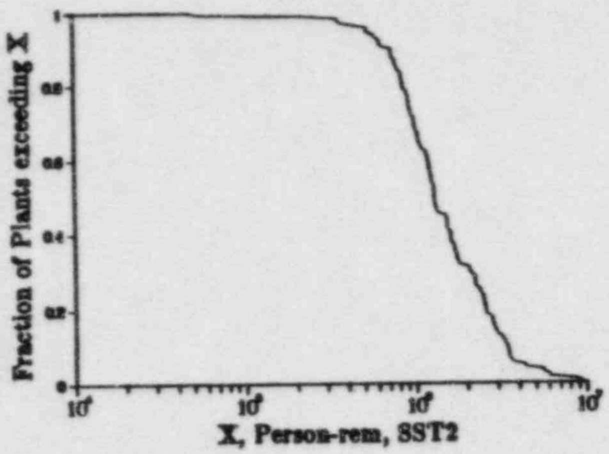

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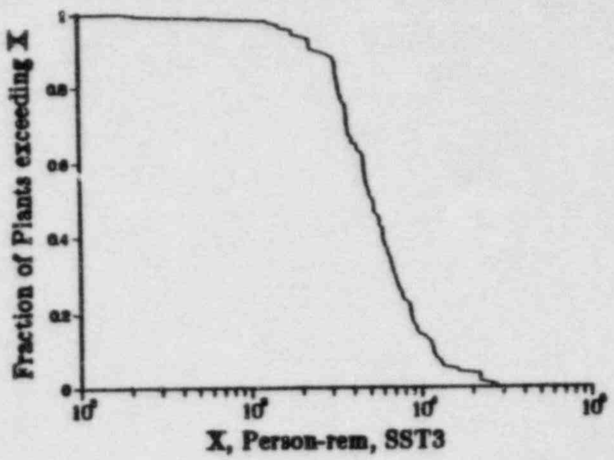

Figure 7

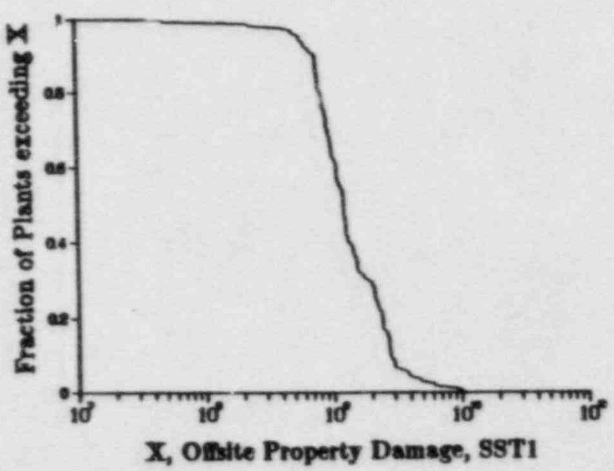

Figure 8

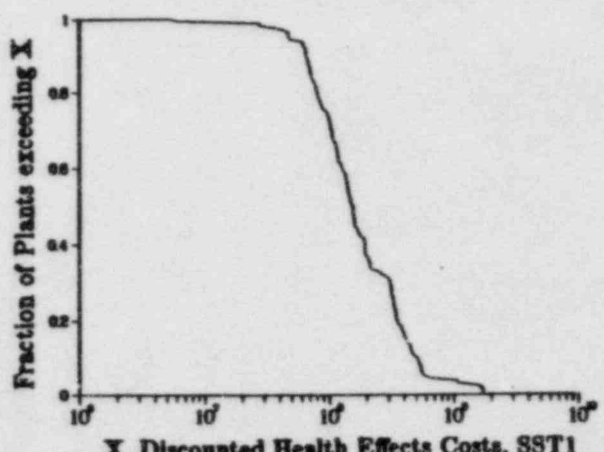

Figure 9

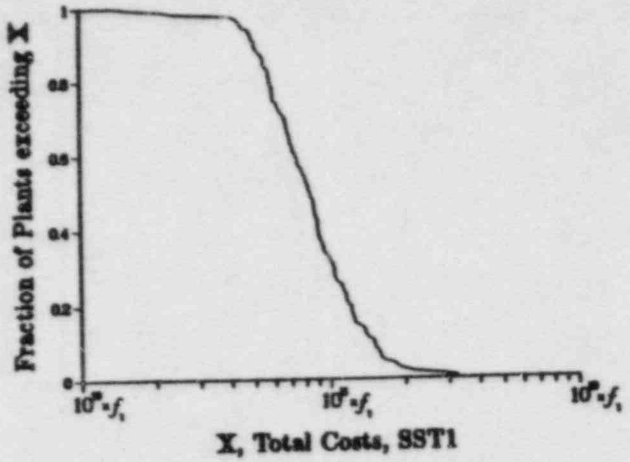

Figure 10

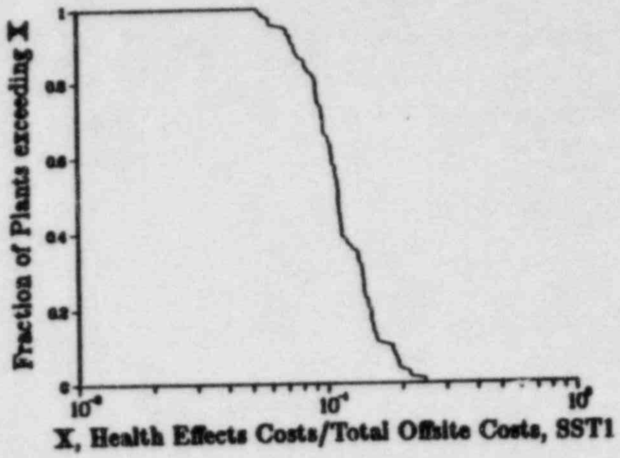

Figure 11

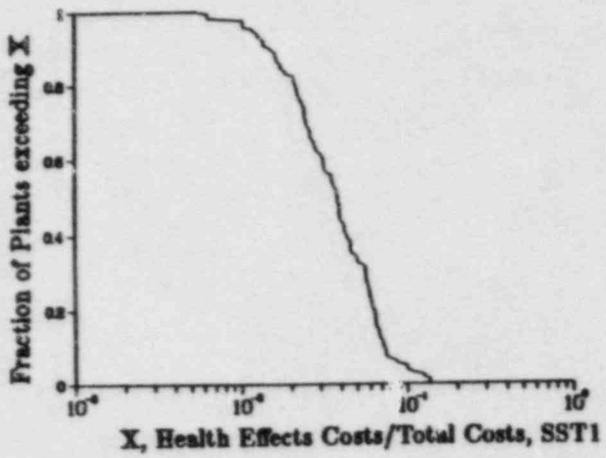

Figure 12

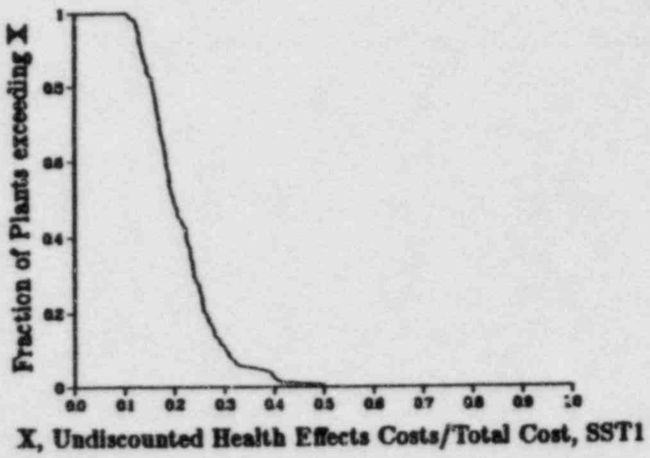

Figure 13

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NUCLEAR REGULATORY COMMISSION

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In the matter of Philadelphia Electric

Staff ______ IDENTIFIED ✓

Applicant ✓ RECEIVED ______

Intervenor ______ REJECTED ______

Cont's Off'r ______

Contractor ______ DATE 5/22/84

Other ______ Witness ______

Reporter Ann Riley