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Cost Tradeoffs in Consequence Management at Nuclear Power Plants: A Risk Based Approach to Setting Optimal Long-Term Interdiction Limits for Regulatory Analyses

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COST TRADEOFFS IN CONSEQUENCE MANAGEMENT AT NUCLEAR POWER PLANTS: A RISK BASED APPROACH TO SETTING OPTIMAL LONG-TERM INTERDICTION LIMITS FOR REGULATORY ANALYSES[1]

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ABSTRACT

The consequences of severe accidents at nuclear power plants can be limited by various protective actions, including emergency responses and long-term measures, to reduce exposures of affected populations. Each of these protective actions involve costs to society. The costs of the long-term protective actions depend on the criterion adopted for the allowable level of long-term exposure. This criterion, called the "long term interdiction limit," is expressed in terms of the projected dose to an individual over a certain time period from the long-term exposure pathways. The two measures of offsite consequences, latent cancers and costs, are inversely related and the choice of an interdiction limit is, in effect, a trade-off between these two measures. By monetizing the health effects (through ascribing a monetary value to life lost), the costs of the two consequence measures vary with the interdiction limit, the health effect costs increasing as the limit is relaxed and the protective action costs decreasing. The minimum of the **total** cost curve can be used to calculate an optimal long term interdiction limit. The calculation of such an optimal limit is presented for each of five U.S. nuclear power plants which were analysed for severe accident risk in the NUREG-1150 program by the Nuclear Regulatory Commission.

1 INTRODUCTION

The consequences of accidents at nuclear power plants are estimated in terms of the radiological doses to the affected populations due to the release of fission products from the core inventory following core damage and (possibly) containment failure. The resultant health effects arise from several exposure pathways whose relative importance is a function of the time period following the release.

In the short-term, i.e., within a few days following the accident, the important pathways are: inhalation exposure due to breathing of contaminated air; cloudshine exposure from the passage of the radioactive cloud plume; and groundshine exposure from standing on ground contaminated by the deposition of radioactive material. Short-term exposure and the resultant acute health effects, such as prodromal vomiting, fatal impairment of vital organs, etc., can be reduced by emergency protective actions. These include evacuation or sheltering and relocation of potentially affected populations downwind of the release.

The long-term population dose is due primarily to three exposure pathways: groundshine from living on contaminated land, inhalation exposure from resuspended particles deposited on the ground, and ingestion of contaminated food or water. The long-term population dose (and thus the number of latent cancers) can be reduced by decontamination of contaminated land and buildings, by relocating people away from contaminated areas, by prohibiting the consumption of contaminated food or the production of crops including dairy and meat products on contaminated farmland, or by permanently prohibiting the reoccupation of land or property which cannot be decontaminated in a certain period of time in a cost-effective manner.

Each of these actions involve costs to society. The sum of these costs are usually termed as the "offsite costs." The short-term emergency action costs depend on the population immediately affected by the release and the fraction of that population which is assumed to be evacuated and temporarily

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relocated away from the passage of the radioactive plume. The costs of long-term protective actions depend on the criteria selected for the allowable levels of long-term exposure of potentially affected populations. This criterion, called the "long term interdiction limit," is expressed in terms of the projected dose to an individual over a certain time period from the long-term exposure pathways. In the probabilistic risk assessments carried out for the WASH-1400 program (U. S. NRC, 1975), the consequence calculations performed using the CRAC code (U. S. NRC, 1975) assumed a long-term interdiction limit of 25 rem over a 30 year period. The consequence analyses carried out in the NUREG-1150 program (U. S. NRC, 1989) using the MACCS code (Jow, 1990) assumed a long-term interdiction limit of 4 rem in 5 years (2 rem in the first year following an accident and 0.5 rem per year thereafter over the next 4 years).

Relaxation of the long term interdiction limit, i.e., allowing a higher dose over a certain period of time, will lead to higher doses to the population and more latent cancers but will decrease the offsite costs since smaller amounts of property and food will have to be condemned. Conversely, a more stringent long term interdiction limit, i.e., a lower level of dose over the same time period, will lead to smaller health effects but increase the offsite costs. Thus, the two measures of offsite consequences—health effects and offsite costs—are inversely related and a particular choice of an interdiction limit is, in effect, a trade-off between these two consequence measures.

For a given source term involving a release of long-lived radionuclides, e.g., isotopes of cesium, strontium, lanthanum, etc., the offsite costs and the latent health effects can, in principle, be calculated using a consequence code for a particular choice of the long term interdiction limit. By monetizing the latent health effects through ascribing a monetary value to life lost, the tradeoffs between the offsite costs and the latent health costs can be studied. As the interdiction limit is varied, these two costs will vary inversely, the health costs increasing as the interdiction limit is relaxed and the offsite costs decreasing. The general shape of the curves of the two costs as a function of interdiction limit is shown in Figure 1. The sum of these two costs are the **total** costs and the minimum of the total cost curve can be used to obtain an optimal interdiction limit.

This paper presents the results of a calculation of the optimum long term interdiction limit for each of five U. S. nuclear power plants which were analyzed for severe accident risk in the NUREG-1150 program by the U. S. Nuclear Regulatory Commission. Based on accident source terms representing the entire spectrum of releases considered at each of the five plants (Grand Gulf, Peach Bottom, Sequoyah, Surry, and Zion), site specific calculations using the latest version of the MACCS probabilistic consequence assessment (Chanin, 1993) code were carried out to obtain values of the consequence measures, latent fatalities and offsite costs, as a function of the long-term interdiction limit.

The latent fatalities were monetized and the total cost curve of Figure 1 was evaluated based on the approach developed in Section 2 below. The monetization of latent fatalities depends on the selection of a statistical value of life (SVOL). Section 3 contains a review of various methods for estimating the SVOL, including the Human Capital (or Loss of Output) and the Willingness-to-Pay (WTP) concepts which are widely used in the economic valuation of risk and safety. Data from a number of surveys of the nuclear, chemical, and hazardous employment industries are synthesized to arrive at an estimate of the SVOL.

Section 4 presents the calculation of the offsite costs and latent fatalities for various selected values of the long-term interdiction limit derived from the consequence analysis using the MACCS code based on the source terms from the plants studied in the NUREG-1150 program. The consequences have been weighted by the frequencies of the releases to provide a risk-based profile of the consequences at each site. The total cost curve is then constructed in section 5 and the minimum of the curve is used to estimate the optimal value of the long-term interdiction limit at each plant site.

2 BASES OF CONSEQUENCE CALCULATIONS

The MACCS consequence code used in this study calculates, for any specified release of radionuclides,

- Downwind transport, dispersion, and deposition of the radioactive material,
- Radiation doses received by exposed populations,
- Mitigation of doses by emergency response actions,
- The acute effects of large radiation doses received during the initial phases of an accident that result in injuries or early fatalities within one year following exposure,
- The chronic effects of lower radiation doses, including latent cancer fatalities and injuries, received over long periods that influence decisions on land interdiction and population relocation, and
- Offsite costs of emergency response and long-term protective actions for user-specified long term interdiction limits.

For calculating the incidence of latent cancer fatalities and injuries due to exposure to low-LET radiation, the original version of MACCS used dose/response models published in 1985 by Evans, et al. (1985), which in turn drew heavily from the 1980 BEIR III report (National Research Council, 1980). Subsequently, the MACCS model was modified to incorporate refinements from the 1990 report (National Research Council, 1990) of the Committee on the Biological Effects of Ionizing Radiation (BEIR V) of the National Research Council which included revised dosimetry for the A-bomb survivors, several years of additional experience of the cohort in the Life-Span study, and new analytical approaches to the risk calculations. The health effect models implemented in the latest version of MACCS are presented in the report by S. Abrahamson, et al. (1991). The central estimates for latent cancer incidence and fatalities are summarized in Table 1. The risks for non-fatal cancer were derived by subtracting the fatality risks from the incidence risks. The latency periods for each cancer type were taken from the report by Evans, et al. (1990). Note that the risks assume that leukemia and bone cancer are 100 percent fatal. This is no longer strictly true because of improved methods of treatment; however, reliable statistics on the rate of non-fatal cases are not yet available, and in any event this would cause only small adjustments in the risk estimates. It is assumed that fatalities from skin cancer and benign thyroid nodules are negligible.

2.1 Offsite Costs of Protective Actions

The offsite costs include costs of emergency actions, disposal of contaminated foods, cleanup and interdiction of contaminated land and structures, and long-term relocation of people and condemnation of land and property. The costs depend on the severity of the release, site-specific features (land and property values, etc.), and the mitigative actions taken during and after the accident. The actions taken are input to MACCS by the user. For a particular plant, a site data file is constructed using land use and economic data in the Final Safety Analysis Reports (FSARs) and the latest U.S. statistical abstracts.

In the early stages of an accident, costs are associated with emergency evacuation and relocation. These costs depend on the number of people affected and the duration of the emergency evacuation/relocation period. The evacuated individuals are allowed to return only if the projected groundshine dose does not exceed a preset criterion for the duration of the emergency phase. Otherwise, people are relocated for at least the duration of the phase which can range from one day to one week.

Following the emergency phase, there can be an intermediate period of up to one year during which people will remain relocated, depending upon projected doses from the groundshine and resuspension inhalation pathways. In the long-term phase, decontamination or interdiction decisions are made for farm and non-farm areas. Three successively higher levels of decontamination each associated with respectively higher costs can be modeled by MACCS. If the decontamination efforts plus natural decay over a period cannot reduce the projected long-term doses below a (user-specified) value or the cost of decontamination exceeds the value of the farmland or non-farm property, then the property or land is condemned. The discounted value of the condemned land (or property) is added to the other offsite costs.

MACCS takes into account costs associated with depreciation of property values in contaminated areas as well as losses resulting from interdiction of property during any period of interdiction. If people must be permanently resettled because their property is condemned, then a further cost is added, based on personal income losses and moving costs for a transitional period.

Other offsite costs are associated with the disposal of contaminated farm products and restrictions on crop production from contaminated farmland. In areas where decontamination has to be carried out or the land has to be interdicted, milk is discarded for three months and other crops for one year. In other areas, dose criteria are used to determine whether milk or other food products should be discarded. Further, farmland which has been contaminated is interdicted and cannot be used for crop production until a protective action criterion based on projected doses from ingestion of crops grown on that farmland is met. The cost of this interdiction is the estimated annual value of farm production multiplied by the number of years that production is prohibited. If the interdiction period exceeds eight years, the cost is taken to be the total estimated value of the interdicted farmland.

While MACCS calculates the offsite health impacts of radiological exposures, i.e., the number of early and late fatalities and injuries, it does not compute any costs related to the occurrence of these health effects. These costs include, for example, medical treatment costs, and costs related to loss of human life (whether calculated based on "loss of income" approach or the "willingness to pay" approach) which are analyzed in section 3.

2.2 Total Costs as a Function of Long-Term Interdiction Limit

The total cost of an accidental release can be expressed as the sum of the offsite protective action costs, OC, and the health-related costs, HRC. The offsite costs are calculated by the consequence code (as discussed in detail above) for a selected value of the long term interdiction limit, r (denoted in mrem/year). To monetize the health effects, early and latent fatalities, calculated by the consequence code, the health-related costs are expressed as:

$$HRC = EFC + LFC$$

where EFC = early fatality costs and LFC = latent fatality costs. The early fatality cost can be simply written as:

$$EFC = SVOL * EF$$

where EF is the number of early fatalities and $SVOL$ ($) is the selected statistical value of life. The latent fatalities are a function of the long term interdiction limit r and have to be discounted to present value due to the latency period between the time of exposure and the induction of the cancer. Table 1 displays the risks and latency periods for various types of cancer due to radiation exposure. We can then write the (discounted) latent fatality costs as the product of SVOL and the number of latent cancers:

$$LFC(r) = SVOL * \sum_{j=1}^{N} \frac{LF_j(r)}{(1+d)^{l_j}}$$

where

$LF_j(r)$ = number of latent fatalities due to cancer type j at the assumed interdiction limit r,

l_j = latency period of the jth type of cancer, (yrs)

d = discount rate, (%/yr)

N = number of cancer types, and

r = interdiction limit, (mrem/year)

The total cost, TC, of an accidental release can then be written as:

$$TC(r) = OC(r) + SVOL * \left\{ EF + \sum_{j=1}^{N} \frac{LF_j(r)}{(1+d)^{l_j}} \right\}$$

With the exception of the statistical value of life, SVOL, and the latency period of different types of cancers, l_j, all the other quantities in the above equation are calculated by the consequence code. The latency periods for different cancer types are obtained from the central estimates of Table 1. Various approaches to obtaining estimates of SVOL are discussed below in section 3.

3 THE STATISTICAL VALUE OF LIFE (SVOL)

For regulatory purposes, the health consequences of radiation doses must be expressed in units that can be compared with other damages from a radiation release (loss of production, abandonment of property and buildings, etc.) and with the costs of potential safety enhancements for reducing the risks of an accident and/or mitigating its consequences. This implies assigning a monetary value to human injuries and fatalities. Whatever method is utilized to make this assignment will inevitably require societal judgments to be made at some point in the analyses about the Statistical Value of Life (SVOL) to be used in the regulatory decision making process.

A number of methods have been suggested for valuing the benefits of safety measures and costing of risk. Two broad sets of objectives underlie these methods: national output maximization and social welfare maximization. In the output based method, the cost of an incidence (fatality or illness) is estimated to be the discounted present value of the loss of the person's future output (or earnings) due to the incidence. Allowances are typically made for non-marketed output (such as housewives' services) and various other costs, such as medical and legal expenses. The main objection to the output based method is based on the argument that most people value safety because of their aversion to death and injury, not because they want to save productive resources and enhance the Gross National Product (GNP). There have been some ad-hoc methods suggested to deal with this criticism: the present value of future output is multiplied by a factor that takes into account "pain, grief, and suffering."

In the social welfare maximization approach, the individual willingness-to-pay for safety is estimated, and aggregated over all the affected individuals. Economists appear to favor willingness-to-pay (WTP) because, in theory, it reflects a person's real utility (or value) of safety. Also, the notion is that, if there was a market for "buying" safety, then this approach would yield the price that consumers would be willing to pay. In most cases where public policy is involved, the analyst would estimate the maximum willingness-to-pay of individual stakeholders and average these figures over all the people involved.

It is usually more straightforward to estimate the discounted present value of future output than WTP. In addition, as we will discuss below, the WTP approach has a number of inherent difficulties associated with it. The strongest argument for the WTP approach is that it is better at conceptually assessing the premium that people put on "pain, grief, and suffering" than merely evaluating lost output or income. Given the advantages and disadvantages of each approach, one cannot say that either is preferred by an overwhelming preponderance of evidence. In recent years, the WTP approach is the one that appears to have gained the most popularity among risk analysts and economists.

Estimates of individual WTP are typically obtained through either the "revealed-preference" (or "implicit value") or the "questionnaire" (or "contingent market") approaches. The revealed preference approach involves estimating marginal incomes (or wage differentials) in cases where people trade-off income against risk of fatalities (or illnesses). Examples of the use of revealed preference include, the existence of higher wages for riskier jobs like working on oil rigs, the use of a more costly, heavier, but safer, car at a loss of fuel economy etc. This approach has the advantage of being based on real world situations where markets actually exist. However, it is usually quite difficult to isolate the income trade-off associated with only the particular safety issue under consideration. In addition, there is insufficient data on WTP for safety enhancements at nuclear power plants or other nuclear facilities. Thus one cannot rely totally on revealed preference from past cases for providing WTP estimates for the issue under consideration. Another limitation of the revealed preference approach is that, in most cases, it provides only information on what the aggregate (or average of aggregate) revealed preference would be. This limitation could be overcome by using a fairly disaggregated population set, and examining the individual revealed preference; however, this is usually not done because of procedural limitations.

The questionnaire ("contingent valuation") approach essentially involves asking a sample of the population of interest how much they would be willing to pay, or would require in compensation, for a decrease in the risk of a given type. Mitchell and Carson (1989) give a detailed and comprehensive account of the contingent valuation method. The advantage of this method include its straightforwardness and the ability to ask those directly affected by the problem what they consider to be the value of safety. The main difficulty in implementing the questionnaire approach is in ensuring that the questions are understandable in both scope and content.

The problem is that most people show a great deal of ambiguity when dealing with low probability, high consequence events. Thus the response to seemingly simple questions may show a high degree of inconsistency. In addition, there is ample evidence from the public economics literature that people frequently respond to value elicitation questions by deliberately misrepresenting their true preferences. There has also been additional theoretical work in recent years that show that people's behavior when subjected to risky situations does not follow the axioms which lead economists to believe that WTP was the best method to elicit a person's maximum expected utility responses.

Assessing the SVOL for the purposes of decision-making is another controversial issue. Zeckhauser (1975), for instance, contends that many would argue that life is priceless, and thus there is difficulty in coming to an agreement on how to value life. Indeed, the valuation of life involves sociological, legal, philosophical, and political issues, not just economics.

In spite of all these problems with using the WTP approach for obtaining the value that people (and society) place on improving safety, there is a general agreement among economists that such an approach is better than either using some ad-hoc method to estimate the SVOL, or the output (present value of income foregone) approach.

3.1 WTP for Nuclear Safety

In estimating the SVOL in the nuclear power industry, there is the notion that one could use a single measure across the board. In the case of nuclear facilities, a distinction can be made between two types of risk: public exposure risk versus risks that are experienced by workers in the nuclear industry. In the risk perception and communications literature, these would fall into the nonvoluntary versus voluntary risk categories. It is clear from the recent literature on risk perception and risk communication that people assess voluntary and nonvoluntary risk differently. There is much greater concern among the public about risk situations that they do not control, such as nuclear power production, than risk situations that they voluntarily participate in such as driving an automobile.

Thus it is important in the assessment of nuclear power safety to consider public exposure risk and industry worker exposure risk separately. Public exposure risk is something that affects people who do not control the event or events leading to the exposure situation. Also the effects may occur over a long period of time. Conversely worker exposure risk is due to situations that are closer to things that can be controlled by those who are at risk. Further, these risks are much more immediate and may be more severe.

Since there has not been a comprehensive study based on the WTP concept for analyzing these two types of risks in the nuclear industry, we have to use information from closely related situations. In the case of public exposure risk, we use the numerous studies of radon exposure and radon reduction in private residences to evaluate the SVOL. In addition, we will also summarize SVOL estimations from other related risks such as carcinogenic chemicals.

In the case of worker risk, there are a number of studies in "hazardous" industries such as mining in which WTP studies have been done. These studies will be the basis of our estimates for WTP in reducing risk to workers in the nuclear industry. However, most people are faced with a number of voluntary risk situations in their day-to-day life. There are a number of studies that have estimated cost-of-life saved for everyday decisions, such as installing and using smoke alarms. Some of the pertinent data from these studies are summarized in the following sections.

3.2 WTP for Reducing Public Exposure Risk

In this section we provide some data on risk reduction measures for radon which also presents a radiological risk. The main purpose for reporting on SVOL estimates from reducing radon risk is that radon is the closest analogy to radiological risk due to nuclear power plants for which some numerical estimates are available. However, a number of caveats are in order. There is a continuing debate as to the magnitude of radon in U. S. homes and the level of risk and, for a number of reasons, householders have been reluctant to spend money to avert radon in the home. Thus, we are left with "expert judgment" estimates made by the Environmental Protection Agency (EPA) of how much it will cost to reduce the risk of radon, rather than true WTP estimates that are obtained from either questionnaires or market behavior.

Radon gas is considered to be the second leading cause (after smoking) of lung cancer in the United States. Much of the initial work on radon was on exposure of mine workers in the U.S. and Czechoslovakia. Subsequently, there was the realization that insulation of homes to conserve energy also trapped radon gas inside the buildings for much longer, resulting in added health effects of radiation. The UNSCEAR (1977) Report estimated the average ^{222}Rn concentration to be 1 pico-curie per liter (pCi/L). Another measure for reporting radon concentration is "working level" (WL) which is the radiation level of 100 pCi/L of Rn in equilibrium with its daughters. Clearly since the duration of exposure is also an important indicator of whether or not radon would be a health hazard, the measure working level months (WLM) is also used.

The estimates of risk due to inhalation of radon decay products in homes are extrapolated from epidemiological studies of underground miners. Based on published information up to 1986, Puskin and Nelson (1989) used a linear relative risk model to make their radon risk projections. In calculating risks for indoor exposures to the general public, they made corrections, on an age specific basis, for differences in breathing rate and lung morphology, which reduced the projections by about 40%. The central estimate of risk from constant lifetime exposure was 3.6×10^{-4} fatal cancer/WLM (working level months). The range of their estimates is from 3.05×10^{-4} to 4.2×10^{-4} fatalities/WLM.

EPA considers any indoor air radon concentration of more than 4 pCi/L to be unsafe, and advises mitigation. Reducing the indoor radon to 4 pCi/L will affect about 4.4 million houses, and avert 6,000 fatal cancers annually. The time period for taking action varies from a few years for concentrations of near 4 pCi/L, to months for near 20 pCi/L, and weeks if above 200 pCi/L.

The EPA estimate is that each pCi/L reduction in radon concentration in a single residence corresponds to roughly 0.01 lung cancer deaths averted over a 50-year period. Puskin and Nelson (1989) have estimated that if the households that had 7 pCi/L were targeted for remedial measures, about 2400 lung cancer deaths would be reduced annually.

The cost of mitigation would be \$400 to \$5000 in "up-front costs" plus annual costs of \$100-\$200 in operations, monitoring, and maintenance, depending on the remedial action taken (1989). Given these figures, Puskin and Nelson have calculated the SVOL in the context of radon to be between \$400,000 and \$7,000,000. The average of these figures would be approximately \$3.7 million.

Since the public's perception of its risk of exposure to accidents at nuclear power plants is partly based on the risk of getting cancer, it is also of interest to examine chemical carcinogens as well. A recent study by Travis, Pack, and Fisher (1987a) examined 23 regulated and seven unregulated chemical carcinogens to determine cost per life saved. A related paper by Travis, et al. (1987b) provides figures on lifetime risk estimates for 131 chemicals. The SVOL (in 1990 $) estimated in their study varies over a wide range from $0.12 million to $208 million. The mean value of SVOL in their study was $31.7 million.

In addition, there have been a number of studies that have examined the WTP for reducing public risk generally. The results of major studies show a range from $93,000 to $22 million (1990 $). Very few of these are related to radiological risk, although safety is the main concern. The mean value of these studies works out to $4.4 million per life saved.

3.3 WTP for Reducing Occupational Risk

Recent estimates of the dollar value of avoided dose in the ALARA (as-low-as-reasonably-achievable) context, and the actual values being used in the nuclear industry, appear to be based on a trend toward acceptance of the WTP approach to the valuation of detriment. A greater concern on the part of management and workers with radiation safety along with the additional costs of hiring and training crews to perform in high radiation environments and stricter limits on exposure have led to higher monetary values of avoided dose than the earlier estimates based on the approach of estimating medical costs and the loss of potential earnings. A recent article by Baum (1991) on the valuation of avoided dose at U. S. nuclear power plants reported that in 1989 U. S. nuclear power plants were using values that ranged from $1,000 to $20,000 per person-rem. The mean and median were calculated by Baum to be $7,000/person-rem and $10,000/person-rem in 1990 dollars, respectively.

The issue in the nuclear industry is the risk to workers in the power plants and other nuclear facilities. The perceived risk to nuclear industry workers is similar to the perceived risk of working in hazardous industries, such as mining, oil rigs etc. Graham and Vaupel (1983) examined a number of cases involving hazardous occupations and obtained SVOL estimates ranging from $0.03 million to $336 million (1990 $). There have been a number of WTP studies on occupational risk as well. In this context, the measure used is "revealed preference" where the willingness-to-accept wage differentials in order to compensate for a risky job is taken to indicate how people value the risk. Based on this concept, a number of authors have evaluated the SVOL. These range from a low of $250,000 to a high of $10 million (1990 $) with a mean of $3.1 million.

A number of organizations such as the Consumer Product Safety Commission, Environmental Protection Agency, the Health and Human Services Department, the National Highway Transportation Safety Agency, and the Occupational Safety and Health Agency have estimated the cost per life saved in a number of cases, other than direct employment. These figures are also indicative of how people perceive their day-to-day risk. The estimates range from a low of $80,000 to a high of $29 million.

Graham and Vaupel (1983) show that OSHA figures that are directly related to hazardous occupations had a median value of $24 million per life saved. The figures estimated by the other organizations ranged from $100 thousand for the Consumer Product Safety Commission to $5.2 million estimated by the EPA.

3.4 Summary of SVOL based on Willingness To Pay

The information presented above is summarized in Table 2. The mean estimates of the SVOL from the various public exposure risk studies ranges from 3.7 to 31.7 million (1990 dollars).

Table 2 also shows that the ***mean*** values of SVOL from the hazardous occupation risk studies range from a low of $3.1 million to a high of $14 million (1990 dollars).

The mean of these values of SVOL works out to approximately $10 million (1990 $). We adopt this value to estimate the total cost given in Equation (3) above.

4 OFFSITE CONSEQUENCES ESTIMATED IN THE NUREG-1150 STUDIES

We report below the offsite consequences including the health effects and offsite damage costs calculated from the source terms developed in the NUREG-1150 study of severe accident risks for five commercial nuclear power plants. NUREG-1150 is a comprehensive, integrated risk study which incorporates the most recent information and insights on accident progression, phenomenology, containment response and source terms to obtain quantitative estimates of the risk and its uncertainty for various consequence measures, such as early fatalities and latent cancers. The plants analyzed in NUREG-1150 are: Unit 1 of the Grand Gulf station (a BWR-6 boiling water reactor, with a Mark-III containment), Unit 2 of the Peach Bottom plant (a BWR-4 boiling water reactor with a Mark-1 containment), Unit 1 of the Surry station (a three-loop pressurized water reactor, PWR, with a subatmospheric containment), Unit 1 of the Sequoyah plant (a four loop PWR with an ice condenser containment), and Unit 1 of the Zion plant (a four loop PWR with a large dry containment).

In the NUREG-1150 methodology, the accident sequences leading to core damage are binned into plant damage states which serve as the entry points to the accident progression event tree (APET). The outcomes of the APET are binned into the accident progression bins (APBs) whose characteristics are used to generate the source terms for each bin. By repeated sampling from the distributions which characterize the uncertainty in the key variables, many thousands of source terms are generated.

Each source term is characterized by a set of variables which includes: fractional releases from the core inventory of nine radionuclide groups (noble gases, iodine, cesium, barium, strontium, ruthenium, cerium, and lanthanum), timing and duration of the release, and the release height and energy. Since it would be impractical to run the consequence code for all of the source terms they are partitioned into groups based on their health effect weights, i.e., their potential for causing early and latent fatalities. The source term parameters which mainly impact the health effect weights are the radionuclide release fractions and the timing of the release (the latter is especially important for the early fatalities category). Consequence calculations are then performed for the mean source term in each group. The distributions of the outputs of the consequence calculations, which sample the effects of the variability due to weather at each site, are then combined with the distributions resulting from the analyses of plant damage states and the accident progression bins to obtain the integrated risk of a particular consequence measure. Further details of the methodology used to obtain integrated risk in the NUREG-1150 study are contained in Reference (U. S. NRC, 1989).

The consequence calculations reported for each of the NUREG-1150 plants are based on the mean source term groups (after partitioning) for accident sequences initiated by internal events, equipment failures and human errors, while the plant is at full-power operation. The source term groups analyzed cover a wide range of accidents such as:

- small and large loss of coolant accidents (LOCAs),
- containment bypass releases (interfacing system LOCAs and steam generator tube ruptures),
- anticipated transients without scram (ATWS) events,
- loss of all ac power (station blackout) events.

These source terms cover a wide spectrum of releases and consequences ranging from small radionuclide releases with negligible or minor consequences (less than the population dose reported for the Three Mile Island accident, for example) to very large releases and consequences (approaching or surpassing the Chernobyl accident). Hence, these source terms are believed to be a reasonably representative sample of the range of releases and their frequencies which could arise from (internally initiated) severe accidents at U.S. nuclear power plants. They are thus appropriate for use in a study devoted to examining the offsite costs of accidents at nuclear power plants.

The source terms analyzed in this study have been taken from the individual plant reports of NUREG-1150. These reports are contained in the NUREG/CR-4551 series of reports and include Grand Gulf (Brown, 1990), Peach Bottom (Payne, 1990), Sequoyah (Gregory, 1990), Surry (Breeding, 1990) and Zion (Park, 1993). In performing the consequence calculations, the emergency response assumptions were the same as those assumed in the NUREG-1150 study. The long term protective assumption used in NUREG-1150 were to interdict land which could give a projected dose to an individual via the groundshine and resuspension inhalation pathways of more than 4 rem in 5 years (2 rem in the first year and 0.5 rem per year for the next 4 years). Banning of contaminated food and interdiction of agricultural land for crop growing was based on FDA protective action guides for exposure from ingestion for the food groups and crops modeled in the MACCS code (representative of an average U. S. diet).

For each source term, the MACCS code calculates distributions of the consequences based on Monte Carlo sampling from one year of site-specific hourly weather and wind direction data. Apart from the variability due to weather, there is a very large variation in the consequences arising from the different source terms at each plant due to differences in the release parameters such magnitude (that is, fractions of the core inventory released), timing and energy. To obtain a single value of mean (averaged over weather) consequences which is representative of all of the source terms analyzed at each plant we constructed frequency-averaged mean consequences defined as follows. For any mean consequence, C_i, for a source term i, the frequency-averaged value $\bar{C}$ is

$$\bar{C} = \sum_{i=1}^{N} \lambda_i C_i \bigg/ \sum_{i=1}^{N} \lambda_i$$

where λ_i is the frequency of source term i and N is the total number of source term groups. $\bar{C}$ can be understood as a frequency-averaged ***conditional*** mean consequence value, that is the mean value (averaged over weather) of the consequence conditional on the occurrence of the accident and weighted by the frequency of the accident. The results are shown in Table 3 for each of the NUREG-1150 plants.

4.1 Variation of Offsite Costs and Doses with the Long-Term Interdiction Limit

To estimate the effect of varying long-term interdiction dose limits on offsite costs, latent fatalities, and population doses, we have recalculated the consequences at each of the NUREG-1150 plants for the following limits: 3.5 rem in 5 years (0.7 rem or 700 millirem per year), 2.5 rem in 5 years (500 millirem per year) and 1.5 rem in 5 years (300 millirem per year). These calculations were performed for all of the source terms at each plant out to a distance of 50 miles.

From these results, frequency-averaged mean conditional consequences were constructed at each plant for each of the long term interdiction limits in the manner described above. The results out to 50 miles are shown in Tables 4 through 8 for Grand Gulf, Peach Bottom, Sequoyah, Surry and Zion, respectively.

The results show the features qualitatively displayed in Figure 1. As the interdiction limit is reduced the offsite costs progressively increase while the population dose and latent cancers decrease. Ultimately, a law of diminishing returns should set in as the interdiction limit is reduced; the reduction in total dose (and thus the number of latent cancers) should get smaller as progressively larger costs of condemning land and property are incurred.

5 MINIMIZATION OF TOTAL COSTS

The data on offsite costs and latent fatalities in Tables 4 through 8 has been used in equation (3) to obtain the variation in total costs out to 50 miles as a function of long-term interdiction level for each of the five plants. These calculations assumed an SVOL of $10 million and a discount rate of 7% per year. The latency period of different latent cancer types were taken from Table 1. The values of EF, early fatalities, were taken from Table 3; early fatalities do not change with variation of the long-term interdiction limit.

The results for the total costs as a function of the long term interdiction limit are shown in Figures 2 through 6 for each of the five plants. These results display quantitatively the qualitative curve shown earlier in Figure 1. For most of the plants, the minimum of the total cost curve for the chosen SVOL lies in the range of 500 to 700 mrem per year. For this particular SVOL, an interdiction limit of 500–700 mrem per year thus represents an optimum from the standpoint of minimizing the total costs. This finding has significance for regulatory cost-benefit analyses of safety enhancements at nuclear facilities.

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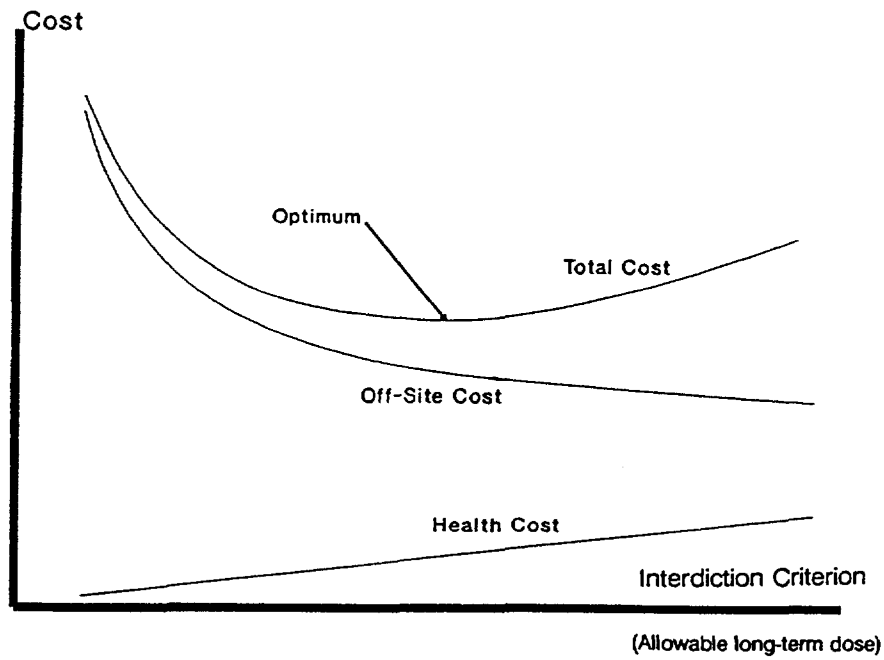

FIGURE 1 COST AS A FUNCTION OF THE LONG-TERM INTERDICTION LIMIT

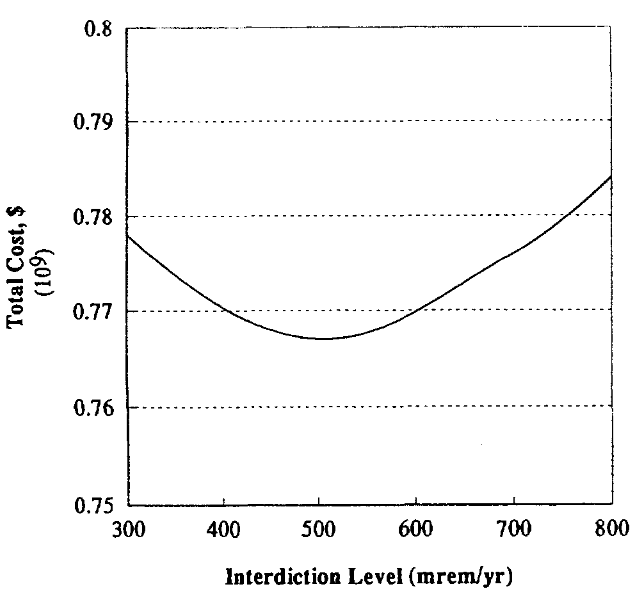

FIGURE 2 TOTAL COST AT 50 MILES VS. INTERDICTION LEVEL, GRAND GULF

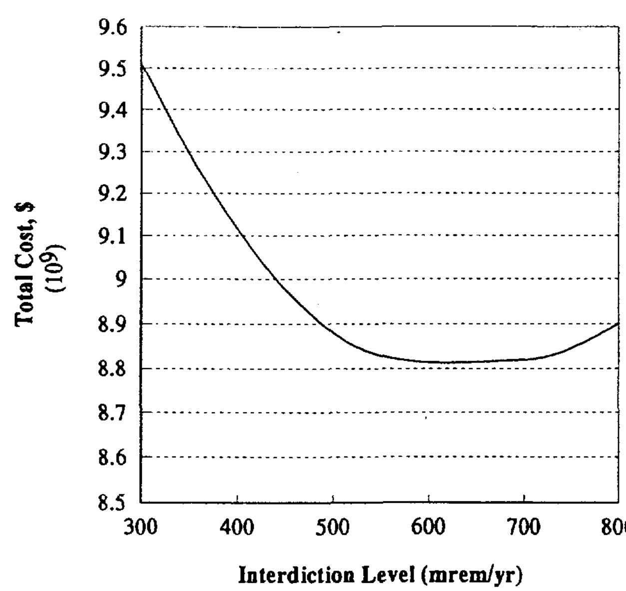

FIGURE 3 TOTAL COST AT 50 MILES VS. INTERDICTION LEVEL, PEACH BOTTOM

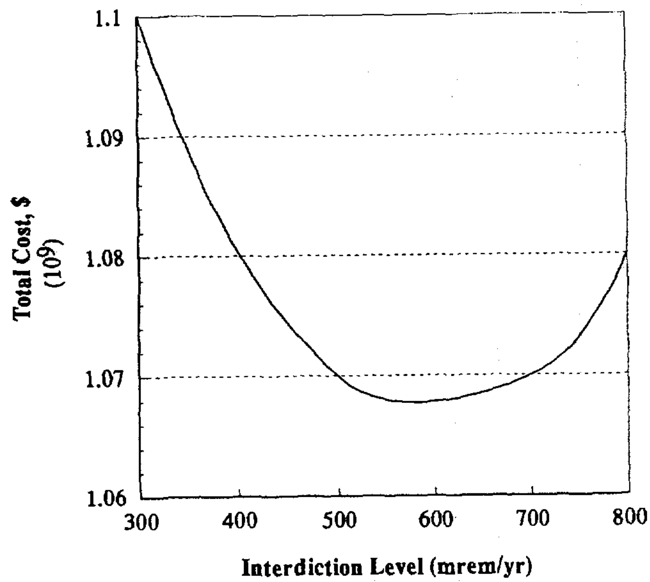

FIGURE 4 TOTAL COST AT 50 MILES VS. INTERDICTION LEVEL, SEQUOYAH

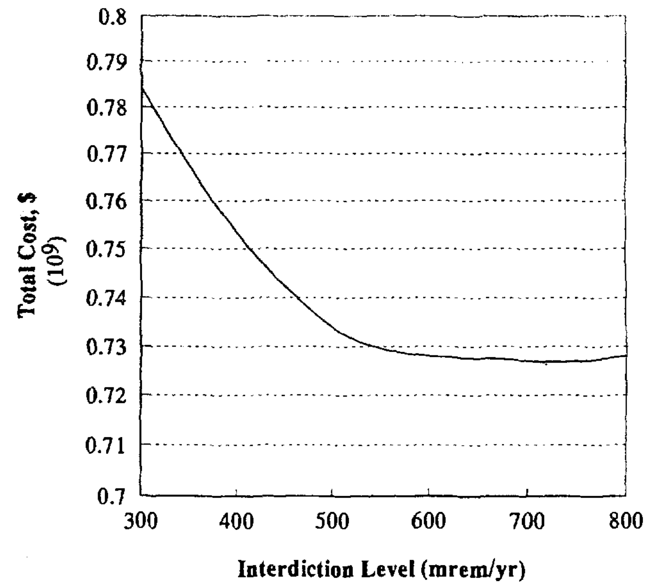

FIGURE 5 TOTAL COST AT 50 MILES VS. INTERDICTION LEVEL, SURRY

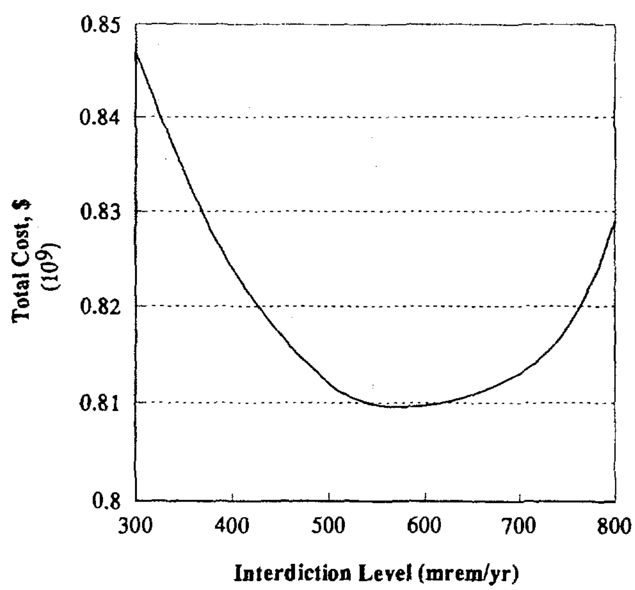

FIGURE 6 TOTAL COST AT 50 MILES VS. INTERDICTION LEVEL, ZION

TABLE 1 RISKS OF LATENT HEALTH EFFECTS FROM LOW-LET, LOW DOSE RATE RADIATION DOSES (CASES PER MILLION PERSON-REMS, CENTRAL ESTIMATES)

Health Effect	Latency Period[a] (years)	Incidence Rate (per 10^6 P-R)	Mortality Rate (per 10^6 P-R)	Non-Fatality Rate[b] (per 10^6 P-R)
Leukemia	2	49	49	—
Bone Cancer	2	4.5	4.5	—
Breast Cancer	10	159	54	105
Lung Cancer	10	86.5	78	8.5
G-I Cancer	10	287.5	168	119.5
Thyroid Cancer	5	72	7.2	64.8
Benign Thyroid Nodules	10	107.2	—	107.2
Skin Cancer	10	444	—	444
Other Cancer	10	276	138	138
Total Risks		1486	499	987

Source: Ref. [9], Tables 3.21 and 3.22 (central estimate).
[a] Latency periods are from Ref. [10].
[b] Non-fatality rate obtained by subtracting mortality rate from incidence rate.
[c] Risks for breast cancer are for a population composed of 50 percent females.

TABLE 2 SUMMARY STATISTICS ON THE VALUE OF STATISTICAL LIFE (MILLION 1990 DOLLARS)

Category of Analysis	Mean Value	Low	High
Public Exposure Risk			
Radon (residential) (Puskin and Nelson, 1989)	3.7	0.4	7.0
Radon (uranium mines) (Russell and Gruber, 1987)	4.4	—	—
Chemical Carcinogens (Travis, et al., 1987a)	31.7	0.12	208.0
Nonradiological Risk	4.4	0.93	22.0
Hazardous Occupation Risk			
Use in Nuclear Power Plants (Baum, 1991)	14.0	2.0	40.0
(Graham and Vaupel, 1983)	14.3	0.03	336.0
(Fisher, et al., 1989)	5.8	0.54	10.1
Wage Differential (Various Studies)	3.1	0.25	10.0

TABLE 3 SUMMARY OF FREQUENCY-AVERAGED CONDITIONAL CONSEQUENCE RESULTS AT NUREG-1150 PLANTS OUT TO 50 MILES

Plant	Average No. Early Fatalities	Average No. Latent Fatalities	Averaged Pop-Dose (Per-rem)	Averaged Offsite Costs (1990 $)
Zion	2.82E-01	9.47E+01	1.95E+05	2.23E+08
Surry	6.04E-02	6.64E+01	1.60E+05	2.30E+08
Sequoyah	4.38E-01	1.02E+02	2.46E+05	3.19E+08
Peach Bottom	6.82E-03	8.14E+02	2.00E+06	2.71E+09
Grand Gulf	1.97E-03	7.97E+01	1.93E+05	1.87E+08

TABLE 4 FREQUENCY-AVERAGED CONDITIONAL CONSEQUENCES AT GRAND GULF OUT TO 50 MILES AS A FUNCTION OF LONG-TERM INTERDICTION LIMIT

Interdiction Limit (mrem/yr)	Average Latent Cancers	Average Dose (Per-rem)	Average Cost ($)
300	6.41E+01	1.55E+05	2.98E+08
500	7.14E+01	1.72E+05	2.35E+08
700	7.71E+01	1.86E+05	2.00E+08
800	7.97E+01	1.93E+05	1.87E+08

TABLE 5 FREQUENCY-AVERAGED CONDITIONAL CONSEQUENCES AT PEACH BOTTOM OUT TO 50 MILES AS A FUNCTION OF LONG-TERM INTERDICTION LIMIT

Interdiction Limit (mrem/yr)	Average Latent Cancers	Average Dose (Per-rem)	Average Cost ($)
300	5.75E+02	1.41E+06	5.15E+09
500	6.82E+02	1.67E+06	3.71E+09
700	7.70E+02	1.89E+06	2.97E+09
800	8.14E+02	2.00E+06	2.71E+09

TABLE 6 FREQUENCY-AVERAGED CONDITIONAL CONSEQUENCES AT SEQUOYAH OUT TO 50 MILES AS A FUNCTION OF LONG-TERM INTERDICTION LIMIT

Interdiction Limit (mrem/yr)	Average Latent Cancers	Average Dose (Per-rem)	Average Cost ($)
300	7.89E+01	1.89E+05	5.13E+08
500	8.89E+01	2.13E+05	4.04E+08
700	9.72E+01	2.34E+05	3.42E+08
800	1.02E+02	2.46E+05	3.19E+08

TABLE 7 FREQUENCY-AVERAGED CONDITIONAL CONSEQUENCES AT SURRY OUT TO 50 MILES AS A FUNCTION OF LONG-TERM INTERDICTION LIMIT

Interdiction Limit (mrem/yr)	Average Latent Cancers	Average Dose (Per-rem)	Average Cost ($)
300	4.86E+01	1.17E+05	4.22E+08
500	5.70E+01	1.37E+05	3.08E+08
700	6.36E+01	1.54E+05	2.52E+08
800	6.64E+01	1.60E+05	2.30E+08

TABLE 8 FREQUENCY-AVERAGED CONDITIONAL CONSEQUENCES AT ZION OUT TO 50 MILES AS A FUNCTION OF LONG-TERM INTERDICTION LIMIT

Interdiction Limit (mrem/yr)	Average Latent Cancers	Average Dose (Per-rem)	Average Cost ($)
300	7.34E+01	1.43E+05	4.02E+08
500	8.26E+01	1.66E+05	2.96E+08
700	9.02E+01	1.84E+05	2.41E+08
800	9.47E+01	1.95E+05	2.23E+08