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# Technical Guidance for Siting Criteria Development

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Prepared for  
**U.S. Nuclear Regulatory  
Commission**

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TECHNICAL GUIDANCE FOR SITING CRITERIA DEVELOPMENT

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## FOREWORD

On July 29, 1980 an advance notice of rulemaking was published for the siting of nuclear power reactors. One of the principle elements contained in the advance notice was the development of a comprehensive analysis of all technical issues relevant to siting. Sandia National Laboratories was contracted by the Nuclear Regulatory Commission to perform the analysis and document the technical guidance to support the formulation of new regulations. This report completes the effort to provide the technical guidance.

The work has been primarily focused toward the development of generic siting criteria, uncoupled from specific plant design. To achieve this end, the NRC staff developed a representative set of severe accident release source terms which covers the full spectrum of postulated severe accident releases for typical light water reactors. NUREG-0773, "The Development of Severe Reactor Accident Source Terms: 1975-1981," provides the detailed description of the considerations that went into the development of the spectrum of source terms (SSTs) in general terms; a more specific discussion of the concept of a representative or generic spectrum of source terms is given in pages 6 through 21 of NUREG-0771, "Regulatory Impact of Nuclear Reactor Accident Source Term Assumptions." From the results of Probabilistic Risk Assessments available at the time of the preparation of this report, the NRC staff would assign typical probability values to the source terms for a range of light water reactor designs as follows:

Probability of SST1 release	$1 \times 10^{-5}$ /reactor year
Probability of SST2 release	$2 \times 10^{-5}$ /reactor year
Probability of SST3 release	$1 \times 10^{-4}$ /reactor year

Table 2.3.1-3 presents the comparative impact of these releases in terms of public health effects. These ratios indicate the relative importance of the source terms given equal probability of occurrence. Their absolute and relative probabilities of occurrence affect their significance for the selection of siting criteria.

There are very large uncertainties associated with these numbers. The absolute values and the ratios of these probabilities for a given facility are design specific. To accurately portray the risk, very specific accident sequence probabilities and source terms are needed. Thus, the results presented in this report do not represent nuclear power risk.

The siting source terms were used to calculate accident consequences at 91 U. S. reactor sites using site specific meteorology and population data and assuming an 1120 MWe reactor. These calculations treat siting factors such as weather conditions and emergency response probabilistically but postulate the siting source term release. The results are thus conditional consequence values.

Currently there is significant controversy about the realism of accident source terms, that is, the accuracy with which they describe potential releases of radioactivity for a given sequence of events in a core melt accident. The work done to date on siting uses the source terms developed for the Reactor Safety Study, held unchanged by newer projections as explained in NUREG-0772, "Technical Bases for Estimating Fission Product Behavior During LWR Accidents." The staff expects newer information to be available by mid 1983 to modify these source terms. In the meanwhile, sensitivity analyses are given to explore how the calculated consequence values would change with various source term reductions.

Contained in this report are sensitivity studies for the major parameters important to siting decision making. Only through consideration of material such as this can reasoned decisions be made concerning recommendations for improved siting regulations.

This report represents some of the work being done to support the expanding use of probabilistic risk assessment in the regulatory process. The NRC must be careful with the results of such analyses, considering the very large uncertainties in the results. The studies shown in this report must be used in a manner that is consistent with the stated objectives. The results are to provide technical perspective on siting-related issues. Results presented in this report are not significantly different than results of consequence studies that have been available in the open literature for decades. Given the source term assumptions, large consequences are calculated. However, the risks (probabilities times consequences) posed by such accidents are very small. Therefore, the absolute numbers should only be quoted with the associated probabilities and with the stated assumptions recognizing the uncertainties in the analyses.



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## Abstract

Technical guidance to support the formulation and comparison of possible siting criteria for nuclear power plants has been developed for the Nuclear Regulatory Commission by Sandia National Laboratories. Information has been developed in four areas: (1) consequences of hypothetical severe nuclear power plant accidents, (2) characteristics of population distributions about current reactor sites, (3) site availability within the continental United States, and (4) socioeconomic impacts of reactor siting.

The impact on consequences of source term magnitude, meteorology, population distribution and emergency response have been analyzed. Population distributions about current sites were analyzed to identify statistical characteristics, time trends, and regional differences. A site availability data bank was constructed for the continental United States. The data bank contains information about population densities, seismicity, topography, water availability, and land use restrictions. Finally, the socioeconomic impacts of rural industrialization projects, energy boomtowns, and nuclear power plants were examined to determine their nature, magnitude, and dependence on site demography and remoteness.

## 1. Introduction and Summary

### 1.1 Introduction

At the request of the Nuclear Regulatory Commission, Sandia National Laboratories has performed a study to develop technical guidance to support the formulation of new regulations for siting nuclear power reactors [1]. Guidance was requested regarding (1) criteria for population density and distribution surrounding future sites, and (2) standoff distances of plants from offsite hazards. Studies were performed in each of these two areas of concern.

The study of offsite hazards had two areas of concern: (1) determination of which classes of offsite hazards are amenable to regulation by fixed standoff distances, and (2) review of available methods for the determination of appropriate standoff distances. The hazards considered included aircraft, hazardous chemicals, dams, faults, adjacent nuclear power plants, tsunamis, meteorite impact, etc. The study concluded that none of the hazards are suitable to treatment by fixed standoff distances and that sufficient methods exist for evaluating the risk for most types of hazards. Because they have been published elsewhere [2], the results of the study of offsite hazards are not included in this report.

The studies of site characteristics, which are presented in this report, involved analyses in four areas, each of which could play a role in evaluating the impact of a siting policy. The four areas were: (1) consequences of possible plant accidents, (2) population distribution characteristics for existing sites, (3) availability of sites, and (4) socioeconomic impacts.

Accident consequence analyses were performed to help define the risks associated with existing sites and with alternative siting criteria. Consequence analyses also help to evaluate the dependence of risk on factors such as meteorology, population distribution, and emergency response which can be mandated or constrained by regulations. Population distributions at existing sites were examined to provide perspective on demographic characteristics as well as to determine whether there have been trends with time or regional differences in site selection. The site availability

analysis examined the impact of various population distribution criteria on the amount of land restricted from siting. Impacts of environmental and legal constraints were also examined. In addition, studies were performed to evaluate the extent of socioeconomic impacts and the degree to which they are dependent on site demographic characteristics. These four areas of analysis provide information that could be used to assess and compare alternative siting criteria.

The information developed by this study is presented in four chapters and six appendices. Chapter 2 presents the results of the consequence analyses that were performed to identify factors that have a significant impact upon risk. The factors examined include source term magnitude (Section 2.3), meteorology (Section 2.4.1), population (Section 2.4.2), emergency response (Section 2.5), consequence distances (Section 2.6), reactor size (Section 2.7.1), plume heat content (Section 2.7.2), dry deposition velocity (Section 2.7.3), characteristics of population distributions (Section 2.7.4), and criteria for the interdiction of contaminated land (Section 2.7.5). CRAC2 [3,4], the computer model used to perform these consequence analyses, is described briefly in Section 2.2.1 and more fully in Appendix E. Model input data are described in Section 2.2.2. Site specific input data are presented in Appendix A and core radionuclide inventory data in Appendix B. Data and model uncertainties are discussed in Section 2.2.4. Finally, a series of site specific calculations were made using a standard set of source terms uncorrected for the characteristics of the reactor at the site. The results of these calculations are presented in Appendix C.

Chapter 3 and Appendix D present an examination of the population distributions surrounding existing sites to provide perspective on demographic characteristics and to determine (1) whether there is evidence of a trend over time to less-dense siting and (2) whether site characteristics differ significantly in different regions of the country. The site availability analyses developed a capability for measuring the impact of population criteria on the availability of reactor sites. Also considered in these analyses were the seismicity, topographic character, availability of surface and ground water at potential sites, and the restriction of power plant siting because of the presence of

national parks or wilderness areas. This study, which was performed by Dames and Moore [5] under contract to Sandia, is presented in full in Chapter 4 and Appendix F. Finally, a study was performed to examine the socioeconomic impacts of reactor siting and the dependence of the magnitude of these impacts on site demography. The study examined impacts caused by large construction projects, energy boomtowns, and the construction of nuclear power plants. Also examined was the impact of site remoteness on transmission costs. The study, performed by Battelle-HARC under contract to Sandia, is summarized in Chapter 5 and presented in full in a separate report [6].

## 1.2 Summary

This report contains the results of numerous calculations and analyses performed at Sandia National Laboratories, Dames and Moore, and Batelle-HARC. The principal results or conclusions reached are:

- o Estimates of the number of early fatalities are very sensitive to source term magnitude. Mean early fatalities (average result for many weather sequences) are decreased dramatically (about two orders-of-magnitude) by a one order-of-magnitude decrease in source term SST1 (large core melt, loss of most safety systems). Because the core melt accident source terms SST1-3 used in this study neglect or underestimate several depletion mechanisms, which may operate efficiently within the primary loop or the containment, consequence magnitudes calculated using these source terms may be significantly overestimated.
- o The weather conditions at the time of a large release will have a substantial impact on the health effects caused by that release. In marked contrast to this, mean health effects (average result for many weather sequences) are relatively insensitive to meteorology. Over the range of meteorological conditions found within the continental United States (1 year meteorological records from 29 National Weather Service stations), mean early fatality values for a densely populated site show a range (highest value/lowest value) of only a factor of 2, and mean latent cancer fatalities a factor of 1.2.

- o Peak early fatalities (maximum value calculated for any weather sequence) are generally caused by rainout of the radioactive plume onto a population center. For an SST1 release, the peak result is about 10-times less probable in a dry locale than in a wet one.
- o The distances to which consequences might occur depend principally upon source term magnitude and meteorology. Frequency distributions of these distances, calculated using large numbers of weather sequences, yielded expected (mean), 99 percentile, and maximum calculated distances (expressed in miles) for early fatalities, early injuries, and land interdiction as follows:

<u>Source Term</u>	<u>Consequence</u>	<u>Mean</u>	<u>99%</u>	<u>Maximum Calculated</u>
SST1	Early Fatalities	<5	≤15	<25
	Early Injuries	~10	~30	≤50
	Land Interdiction	~20	>50	>50
SST2	Early Fatalities	~0.5	<2	<2
	Early Injuries	<2	<5	~5
	Land Interdiction	<2	~7	~10

The maximum calculated distances are associated with improbable events, (e.g., rain-out of the plume onto a population center). For the SST1 release reduced by a factor of 10, early fatalities are confined to ~5 miles, early injuries to ~20 miles, and interdiction of land to ~25 miles.

- o Calculated consequences are very sensitive to site population distribution. For each of the 91 population distributions examined, early fatality, early injury, and latent cancer fatality CCDFs were calculated assuming an SST1 release from an 1120 MWe reactor. The resulting sets of CCDFs had the following ranges:

Early Fatalities. ~3 orders-of-magnitude in the peak and mean numbers of early fatalities and in the probability of having at least one early fatality.

Early Injuries. ~ 3 orders-of-magnitude in the means, ~ 2 in the peaks, and ~ 1 in the probability of having at least one early injury.

Latent Cancer Fatalities. ~ 1 order-of-magnitude in the peaks and the means and in the probability of having at least one latent cancer fatality.

Generally, mean results are determined by the average density of the entire exposed population, while peak results (especially for early fatalities) are determined by the distance to and size of exposed population centers.

- o Early fatalities and early injuries can be significantly reduced by emergency response actions. Both sheltering (followed by relocation) and evacuation can be effective provided the response is expeditious. Access to basements or masonry buildings significantly enhances the effectiveness of sheltering. Expeditious response requires timely notification of the public. If the evacuation is expeditious (timely initiation), evacuation speeds of 10 mph are effective. Evacuation before containment breach within 2 miles, after release within 10 miles, and sheltering from 10 to 25 miles appears to be a particularly effective response strategy.
- o Population densities (people/sq mi) about the 91 sites have the following maximum, 90th percentile and median values within the indicated distance intervals:

<u>Distance (mi)</u>	<u>0-5</u>	<u>0-10</u>	<u>0-20</u>
<u>Full Circle</u>			
Maximum	790	660	710
90th percentile	190	230	380
Median	40	70	90
<u>Most Populated 22.5° Sector</u>			
Maximum	4200	3800	4500
90th percentile	950	1000	1800
Median	330	270	480

- o At the 91 sites examined, the distance to the nearest exclusion zone boundary ranges from 0.1 to 1.3 miles and averages about 0.5 miles.
- o There appears to be a slight trend with time towards selection of reactor sites in less densely populated locations.
- o A site availability data base has been constructed on a 5 x 5 km grid cell for the continental United States. For each grid cell the data base contains information on population density, seismicity, topographic character, surface and ground water availability, and land use restrictions (wetlands, national parks, etc.)
- o Analysis of boomtown literature, studies of large non-nuclear energy projects, and economic data from existing nuclear power plant sites suggests that only siting in very remote regions has the potential for significant socioeconomic impacts, that these impacts may be both beneficial or detrimental and that the detrimental impacts can be mitigated by advance planning.
- o Outside of the Rocky Mountains, few potential reactor sites are located at a large distance from the national power grid. Consequently, site remoteness and transmission line costs are not strongly correlated.

This study examined a number of factors which could impact the development of siting criteria. The analyses, which are reported in the following chapters, can be used to determine many of the impacts of alternative criteria, and provide guidance in evaluating tradeoffs among criteria. In addition, the data and analyses contained in the study should be useful to the wider community of users interested in evaluating the consequences of reactor accidents.

## References for Chapter 1

1. Advance notice of this rulemaking appeared in the Federal Register, July 29, 1980, FR DOC 80-22643.
2. N. C. Finley, Nuclear Power Plant Siting: Consideration of Offsite Hazards, NUREG/CR-2380, Sandia National Laboratories (to be published).
3. I. T. Ritchie, J. D. Johnson, and R. M. Blond, Calculations of Reactor Accident Consequences, Version 2: User's Guide, NUREG/CR-2326, SAND81-1994, Sandia National Laboratories, Albuquerque, NM, (to be published).
4. I. T. Ritchie, et al., CRAC2, Calculation of Reactor Accident Consequences, Version 2, Model Description, SAND82-0342, NUREG/CR-2552, Sandia National Laboratories, Albuquerque, NM (to be published).
5. J. H. Robinson and K. I. Hansen, Impact of Demographic Siting Criteria and Environmental Suitability on Land Availability, Dames and Moore, Los Angeles, California, 1981.
6. C. Cluett, S. Malhotra, and D. Manninen, Socio-economic Impacts of Remote Nuclear Power Plant Siting, NUREG/CR-2537, SAND81-7230, Battelle Human Affairs Research Centers, Seattle, Washington, (to be published).



## 2. Consequences of Potential Reactor Accidents

### 2.1 Introduction

During this study, a large number of calculations were performed to provide a basis for understanding the dependence of reactor accident consequences on site characteristics. Some characteristics were examined because of the possibility of their inclusion in reactor siting criteria (e.g., population distribution, reactor power level). A number of additional parameters were investigated to determine the sensitivity of predicted consequences to variation or uncertainty in data used as input.

All consequence calculations for this study were performed using CRAC2, an improved version of CRAC,<sup>a</sup> the Reactor Safety Study [1] consequence model. Section 2.2.1 provides a brief overview of the CRAC2 model, while Section 2.2.2 describes the data used as input to the consequence calculations. Section 2.2.3 is a qualitative discussion of the sources and impacts of uncertainties associated with the consequence model. Section 2.2.4 defines the "base case" calculation which was used as a reference case for examination of the impact of variations in parameters and assumptions.

Section 2.3 briefly describes the five accident source terms used in the calculations. These source terms, denoted SST1-5, were developed by NRC and range from a full core-melt with uncontrolled release to a gap release with minimal leakage. Section 2.3.1 presents results of consequence calculations for each of the five source terms, and Section 2.3.2 examines the potential impact on consequences of reductions in the magnitude of the most severe accident (SST1).

Section 2.4 examines the impact of meteorology and population on consequence estimates. Meteorological data from 29 National Weather Service stations and wind rose and population data from each of the 91 currently approved reactor sites in the United States are examined. Section 2.5 presents the impact on consequences of various emergency response assumptions; both evacuation and sheltering scenarios are evaluated. Section 2.6 discusses the distances to which various consequences occur and the sensitivity of these distances to input

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a. CRAC stands for Calculation of Ractor Accident Consequences.

data and assumptions. Section 2.7 examines the sensitivity of consequences to variations in reactor size, energy-release rate, dry deposition velocity, population distribution, and land-interdiction criteria. Finally, Section 2.8 presents a summary of the insights gained from these calculations.

## 2.2 Background

### 2.2.1 Overview of Consequence Model

The accident consequence calculations described in this chapter were performed using CRAC2 [2,3], an improved version of the Reactor Safety Study (WASH-1400) consequence model, CRAC [1,4]. Modifications made in the upgrade from CRAC to CRAC2 are briefly described in Appendix E.<sup>a</sup> The model describes the progression of the cloud of radioactive material released from the containment structure during and following a reactor accident, and predicts its interaction with and influence on the environment and man. A schematic outline of the computational steps taken in the model is presented in Figure 2.2.1-1.

Analyses of potential plant system failures and accident phenomenology provide an estimate of accident probabilities and release characteristics (magnitudes, timing, etc.) that are used as input to the consequence model.<sup>b</sup> Given these estimates, a standard Gaussian dispersion model is used to calculate ground-level concentrations of airborne radioactive material downwind of the reactor site. Weather data for a 1-year period are input to the dispersion model in the form of hourly recordings of wind speed, thermal stability, and accumulated precipitation. The wind direction is assumed to be invariant during and following the release. Radionuclide concentrations within the cloud are depleted by deposition (both wet and dry) and radioactive decay, and integrated air and ground contamination are calculated for downwind distances.

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a. Results calculated using the two models are similar, as shown in the recent International Comparison Study of Reactor Accident Consequence Models [5,6].

b. Specific release characteristics assumed in this study are described in Section 2.3.

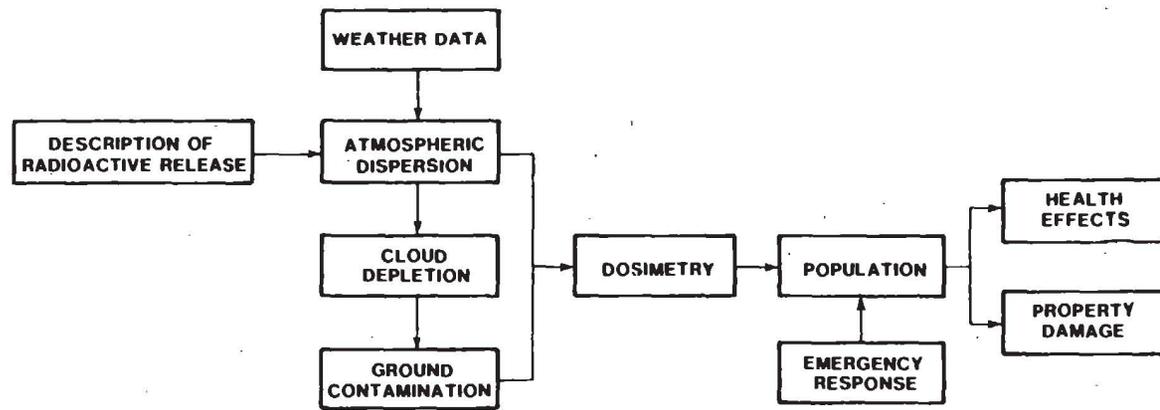


Figure 2.2.1-1. Schematic Outline of Consequence Model, CRAC2.

Hourly weather recordings are used to account for weather variations during the progression of the accident. Beginning at a selected hour within the year's data, the dispersion model uses the subsequent meteorological conditions to predict the dispersion, downwind transport, and deposition of the released cloud of radioactive material. Hourly recordings are sequentially incorporated until all of the released radioactive material (excluding the noble gases) has been deposited. By using an appropriate sample of weather sequences from the year's data, a frequency distribution of estimated consequences can be produced.

The consequence model uses the calculated airborne and ground radionuclide concentrations to estimate the public's exposure to external radiation from (1) airborne radionuclides in the cloud and (2) radionuclides deposited from the cloud onto the ground, and internal radiation from (1) radionuclides inhaled directly from the passing cloud, (2) inhaled resuspended radionuclides, and (3) the ingestion of contaminated food and milk. Radiation exposure from sources external to the body is calculated for time periods over which individuals are exposed to those sources, while the exposure from sources internal to the body is calculated over the remaining life of the exposed individual.

The consequence model allows the input of either site-specific or hypothetical population data as a function of distance and direction from the reactor site. A simple evacuation model is incorporated, which is based on a statistical analysis of evacuation data assembled by the U.S. Environmental Protection Agency [7-9] (see Appendix E). The model incorporates a delay time before public movement, followed by evacuation radially away from the reactor. A range of evacuation delay times, speeds, and distances have been assumed in this study, as is described in later sections.

Based on the calculated radiation exposure to downwind individuals, the consequence model estimates the number of public health effects that would result from the accidental release. Early injuries and fatalities, latent cancer fatalities, and thyroid and genetic effects may be computed. Early fatalities are defined to be those fatalities that occur within 1 year of the exposure period. They are estimated on the basis of exposure to the bone marrow, lung and gastrointestinal tract. Bone marrow damage is the dominant contributor to early

fatalities. In both the Reactor Safety Study and this study, early fatalities are calculated assuming an LD<sub>50/60</sub><sup>a</sup> of 510 rads to the bone marrow. Supportive medical treatment of the exposed individual is also assumed. Early injuries are defined as non-fatal, non-carcinogenic illnesses, that appear within 1 year of the exposure and require medical attention or hospital treatment. The late somatic effects considered include latent cancer fatalities plus benign and malignant thyroid nodules.

The consequence model also includes an economic model to estimate the potential extent of property damage associated with the release of radioactive material. The total offsite dollar cost of the accident is estimated as the sum of (1) the evacuation cost, (2) the value of condemned crops and milk, (3) the cost of decontaminating land and structures, (4) the cost of interdicting land and structures, and (5) relocation costs (moving costs and temporary loss of income).

### 2.2.2 Input Data for Consequence Model

CRAC2 requires a large set of input data, including accident release characteristics and source terms, various site-related data (e.g., meteorology, population), reactor core radionuclide inventories, and emergency response scenarios. The accident release characteristics and source terms assumed in this study are described in Section 2.3.

The site-related data, gathered for use in this study, are presented in Appendix A. The data gathered includes:

1. General site and reactor data (e.g., reactor size, vendor, start-up date, site location) for each of the 91 U.S. sites at which a reactor is operating or a construction permit has been obtained.
2. Regional shielding factors for sheltered populations.
3. Site population data derived from the 1970 census.

a. The dose that would be lethal to 50 percent of the population within 60 days.