working paper
department
of economics

Siting Nuclear Power Plants

by

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Number 245 August 1979

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SUMMARY

We discuss the selection of sites for nuclear power generation. The procedures used for making reactor siting choices in the United States exclude the social costs of catastrophic accidents from consideration. We first suggest an alternative procedure which emphasizes potential accident consequences and uses empirical data, on the atmospheric dispersion of particulates and on the biologic effects of radiation, to structure siting policy. Our proposals incorporate implicit limits on the scope of agency decisionmaking in the presence of scientific uncertainty.

We then examine the effects of remote siting on the potential consequences of reactor accidents and on the costs of power transmission and reactor cooling. Our analysis suggests that siting 50 to 150 miles from city centers would reduce the consequences of major accidents and would not damage the competitive position of nuclear power vis-a-vis conventional energy sources. Siting at hundreds of miles from cities would, however, make nuclear reactors uneconomic in comparison to coal-fired power plants. Over half the approved reactor sites in the United States lie within 50 miles of cities with population greater than 100,000. We conclude more remote siting may help to resolve our energy supply problems by providing a visibly effective, economically feasible method for guarding against catastrophe.

Finally, we discuss quantitative methods currently used for nuclear risk estimation in the siting context. Those methods are based on tacit assumptions which lead to subtle changes in the division of authority between primary decisionmakers and agency staff. They make future policy changes, and the correction of past errors, more difficult, and create serious problems for assuring effective external checks on agency actions.

INTRODUCTION

More than twenty years have passed since commercial nuclear power plants began operating in the United States. Nearly seventy reactors generate electricity today, and well over a hundred are under construction or on order. Over the years our society has not learned to live comfortably with nuclear power. On the contrary, as the nuclear industry has grown the controversy it engenders has sharpened. The debate is animated in large measure by the complex set of issues surrounding nuclear reactor safety. We focus on one of those issues here: How far from heavily populated areas should commercial reactors be placed? Obtaining answers to that question is crucial, for a restrictive siting policy may help to resolve our energy supply problems and cool the nuclear safety controversy by providing passive, visibly effective means for guarding against catastrophe. Responding to the siting issue, the Senate has included in the 1980 Nuclear Regulatory Commission (NRC) authorization legislation a provision requiring the Commission to specify, for licensing purposes, "the minimum distance from [a commercial reactor] site to the nearest boundary of any densely populated area" *(1)*.

This paper addresses the reactor siting question on three levels:

First, we propose an alternative procedure for choosing reactor sites. Our procedure leaves open *ab initio* the question whether present siting practices are appropriate, but requires explicit consideration of the probabilities and consequences of major accidents in site selection. As we shall explain, that requirement differs sharply from current NRC practices which effectively exclude formal consideration of the potential for catastrophic accidents in regulatory decisionmaking. Our procedural suggestions have important regulatory implications: they incorporate implicit limits on the scope of agency decisionmaking in the presence of scientific uncertainty.

Second, any method for making decision about risk-creating technologies embodies rules or reasoned arguments for evaluating and combining a set of underlying "risk factors" in order to "assess" the overall risk of a proposed program. Under special circumstances in which major damage may be caused to the fabric of society itself, we suggest that the potential consequences of a proposed technology deserve greater emphasis in risk assessment than do the associated probabilities. That suggestion derives support from federal appellate court reasoning in recent major environmental cases.

Third, we discuss the practical implications of our proposals in light of the relations among distances from cities at which reactors are placed, the potential consequences of accidents, the costs of long-distance power transmission and the accessibility of sources of cooling water.

Section I presents our general procedural approach. Section II discusses the relations between accident consequences and distances of reactors from urban centers. Sections III and IV discuss, respectively, the economics of long-distance power transmission and potential restrictions on siting due to the necessity for access to cooling water. Section V discusses current U.S. nuclear siting practices. Section VI summarizes our conclusions and draws their general implications.

I. THE DECISION PROCESS

Individual and Societal Risks - To an important degree, the debate over nuclear safety turns on the relative merits of policies which emphasize low accident probabilities as opposed to those which emphasize high accident consequences. This comparison in turn embodies a more subtle distinction between risks faced by the individual citizen qua individual and risks faced by society as a whole. An examination of the arguments of nuclear power proponents within the government and of nuclear opponents makes these distinctions clear.

The Government's Position: Low Probabilities Dominate Risk - The NRC excludes the potential for major accidents from consideration in environmental impact statements, and generally from licensing proceedings *(1A)*. In the leading federal court case dealing with the justification for this exclusion, the Government took the position that the engineered safety features of commercial reactors make major accidents "so extremely improbable as not to be a realistic possibility" *(2)*. At the more subtle level of risk assessment, proponents of nuclear power argue that because the probability of fatal accidents is small, reductions in individual life expectancy due to the operation of nuclear reactors are less than analogous reductions due to a wide range of activities integral to modern life *(3)*. This emphasis on *individual risks* underlies regulatory efforts to make nuclear power "safer." In particular, it has lead to a philosophy of "defense in depth," in which increasingly numerous and costly "engineered safety features" have been required on the assumption that such features will reduce the probabilities of small, but "credible" precursors of major accidents *(4)*. In relying on the "defense in depth" approach, regulators have eschewed policies designed to mitigate directly the consequences of a major release of radioactivity *(5)*.

To give their risk analysis a societal dimension, proponents assert that when the consequences of a major accident are discounted by its probability, the resulting *expected values* are smaller than analogous estimates for other activities society appears willing to accept *(6)*. Setting aside any question as to the justification for such comparisons, their use reinforces our observation that individual risk concepts dominate nuclear proponents' arguments. Their expected value calculations consist of a summation, over the affected population, of estimated consequences to individuals discounted by accident probabilities. The essence of social life, relations among individuals, plays no role in these "risk assessments." Nor do the calculations reflect the strong social response to concentrated accident consequences *(7)*. These *non-linear* attributes of societal risk are not encompassed in proponents' *linear,* expected value scheme.

The Opponents' Position: Focus on Consequences - The case that nuclear power is "unsafe" is based mainly on estimates of the consequences of major accidents, rather than their probabilities. Opponents of nuclear power take the view that estimates of individual risk are not appropriate safety criteria for nuclear reactors. They argue reactor accidents can cause thousands of immediate deaths and tens of thousands of future cases of cancer and genetic disease, all in a single metropolitan area *(8)*. Such accidents, it is asserted, may well force the long-term evacuation of millions of homes and permanently damage the social fabric of the affected communities. Furthermore, opponents claim the nuclear industry's safety record does not suggest the probability of accident is so low it can be ignored *(9)*. Implicit in their arguments is the notion that the *societal risks* of nuclear power are primarily determined by potential accident consequences, and that the prevailing focus in industry and government on *individual risks* excludes considerations essential to responsible decisionmaking.

Process, Mathematical Methods and Uncertainty - Both sides in the nuclear debate present arguments which deserve attention in policymaking. On the side of nuclear power opponents, there is evidence that industrial catastrophes can lead to the destruction of community, and in consequence to a heightened sense of individual isolation and helplessness which over the long term may permanently alter social life *(10)*. In and of itself, this possibility does not suggest hazardous modern technologies should be abandoned, but it strongly implies the full range of their consequences cannot be ignored. On the other hand, the individual risk approach also has merit. A process which takes account of societal risks should not exclude consideration of individual risks as well. The risks of industrial programs cannot be evaluated independently of the dangers they pose to individual citizens.

In the face of irreconcilable views of the relative significance of probabilities and consequences in risk evaluations, the challenge is to create a process within which rationally and ethically defensible decisions can be made. We attempt to do so here by suggesting a procedure which heavily emphasizes the use of qualitative burden of proof concepts and empirical data. Our approach differs sharply from that of the bulk of the nuclear safety literature. Previous analysts have described the reactor accident spectrum in terms of combined estimates of probabilities and consequences *(3,11)*. The resulting probabilities decrease rapidly and monotonically with increasing consequences *(12)*. Using relationships of that kind, the conventional approach reduces the policy problem underlying the nuclear safety debate to the question: What are the smallest probabilities which should be given attention in decision-making? The conventional analysis presumes, at least in principle, that there is a discernible level of "acceptable risk" *(13)* which can be specified by a threshold probability, and that accidents which pose "risks" less than that level do not deserve attention in policymaking *(14)*.

Judgments as to the policy significance of potential accidents must be made, and they depend in part on probability estimates. Provided those judgments are reached openly and independently, based on evidence and arguments explicitly presented for public scrutiny, and provided flexibility is maintained to respond to future advances in understanding, society justifiably should bear the residual risks. But, as we discuss below in Section V, the mathematical analyses on which the exclusion of serious accidents from NRC consideration has been based do not conduce to open decisionmaking and raise serious questions concerning the effectiveness of external control of the Commission's actions. Furthermore, there are large uncertainties in nuclear risk estimates which have not been treated with proper care in reaching policy judgments. Reactor accident analyses depend on a wide variety of meteorological, biologic and demographic variables *(15)*. To incorporate that complexity in decisionmaking, detailed probability estimates have been made, using computer simulation models and assuming the occurrence of accidents with specified isotopic compositions and time patterns of release *(16)*. It is in the nature of the problem that attention must be directed to the "tail" of the computed probability distributions, if for no other purpose than to decide at what point a probability cutoff should be applied. In the present state of knowledge, however, probability estimates associated with the less likely consequences are highly uncertain *(17), and that uncertainty invites decisionmaking which, however well considered, appears arbitrary and inconsistent.* In particular, it opens the door to decisions based on the will of administrators rather than on reasoning from evidence *(18)*. In the face of uncertainty, the temptation to value expediency over logic has not been resisted. The uncertainties in nuclear accident probability estimates are so large, and their interpretation so unclear, that the Government finds it possible to argue on the one hand that major nuclear accidents are so *unlikely* that they should not be considered in environmental impact statements for individual reactors *(2)*, in reactor design *(4)* or in emergency planning *(19)*, and on the other hand that major accidents are *sufficiently likely* that special legislation is necessary to indemnify

reactor owners and operators against unlimited financial loss and assure the public of adequate compensation *(20)*.

Here, we explore the implications of an alternative approach to nuclear siting. This alternative places greater emphasis on the potential consequences of accidents than do existing policies. Our proposal calls for: (1) setting "threshold" consequences that trigger special regulation of particularly hazardous industrial activities; (2) making a decision as to the general reactor siting policy which should be undertaken, given the possibility of accidents with consequences exceeding the threshold; (3) placing a heavy burden of proof on those who propose a particular site to show, primarily through the use of empirical data, that the chosen policy objectives will be met; (4) given such a showing, shifting the burden of proof to those who oppose a particular siting choice; and (5) assessing the appropriate engineered safety features of a reactor, given the residual distribution of probabilities and consequences after application of (1) - (4).

Our proposal heavily emphasizes the use of empirical data to structure siting policy. For purposes of the present analysis, we formulate two questions which in principle can be answered empirically. *First,* for what distance from a reactor, given reasonable assumptions about the time and intensity of exposure - *and using the least favorable empirical observations of atmospheric transport of particulate materials* - can lethal doses of radioactivity occur? *Second,* at what distance from a reactor can long-term relocation of residents of urban areas (i.e., for months or years) become necessary? In light of these questions we consider four siting alternatives: (A) near-city siting, where engineered safety features are principally relied upon to avoid lethal radiation doses to large numbers of people; (B) mid-range siting designed to avert specified lethal and sub-lethal injuries; (C) siting at distances such that ground contamination will plausibly not force the long-term relocation of residents of urban areas; and (D) extreme remote siting, where at worst trace contamination of metropolitan areas is expected. In Section II, we give rough estimates of the distances associated with alternatives (A) - (D). It is important to emphasize that our distance estimates, the specific form of our empirical questions, and the structure of our siting categories are logically separable from our general approach to the siting problem. At the initial level of argument we assume only that the possibility of major accidents merits attention in decisionmaking and that burden of proof concepts based on empirical data, rather than procedures which center on the results of probabilistic simulation models, should be given primary emphasis in making siting choices.

The use of a threshold, consequence "trigger" for special regulatory action carries general implications for the siting of hazardous industrial facilities. We do not explore the general issues here, but set a threshold consequence level which appears a reasonable first step: where feasible consequences of the activity in question substantially exceed the consequences of previous industrial accidents, we suggest our procedure be applied. Judged by potential short-term fatalities alone, feasible nuclear accident consequences clearly exceed that guideline. In this century, peacetime industrial catastrophes in the United States have caused the sudden death of at most five to six hundred people *(21)*. Reactor accident consequences, taking account of high-dose "prompt fatalities" alone, could feasibly exceed that previous experience by a factor of ten or more *(22)*.

Our four siting categories incorporate criteria that underlie the general siting policy called for in the second stage of our procedure. For example, if the basic policy decision is to tolerate the possibility of large numbers of high-dose, short-term fatalities, near-city sites within region A are acceptable. The only issues that remain are the appropriate level of engineered safety features, and the depth of emergency planning required. As we shall discuss, this is the essential implication of current U.S. nuclear siting practices. On the other hand, if it is decided that the possible occurrence of large numbers of prompt fatalities is not socially acceptable, then sites within region A should not be permitted. Similarly, if the basic policy precludes long-term evacuation of metropolitan areas, then sities located within regions A and B are impermissible, etc.

In introducing burden of proof concepts in the third and fourth stages of our proposal, we recognize that neither precision nor certainty in the achievement of safety goals is possible. Our proposals require instead that particularly hazardous industrial activities meet a high qualitative standard of proof that explicitly stated safety objectives will be met. Qualitative standards of proof are in order when irreconcilable differences over values must be integrated into a decision process, when large uncertainties make mathematical precision meaningless or when the freedom to change decisions in future must be maintained. In much the same sense, because of the high individual stakes, the powerful social interest in a demonstrably fair process, and the irreconcilable differences among individuals as to the strength of evidence necessary to support a verdict of guilt or innocence, a high, but in no way precise, standard of proof is required for conviction in a criminal trial *(23)*.

Our proposals would restructure the nuclear safety inquiry, and we recognize that reasonable people will differ with us as to the appropriateness of the procedural course we suggest. Some will argue that large numbers of potential fatalities can be tolerated if their probability is sufficiently low, and that it is more "cost-effective" to use engineered safety features and emergency planning to reduce probabilities to "acceptable" levels than to site reactors further from population centers. Others will assert that while we do not live in a risk-less society, industrial activities which involve the possibility of catastrophic reactor accidents are simply unacceptable. Finally, there are those who will insist that given the mere possibility of large numbers of fatalities, a restrictive siting policy is in order only if it can be implemented at a "reasonable" cost, without unduly delaying socially valuable technological development.

The relative merits of these views cannot fairly and effectively be evaluated through a mechanical "cost-benefit analysis." In its extreme form, such an analysis assumes the net social costs of technological programs can be measured by multiplying probabilities by "consequences," both beneficial and deleterious *(23a)*. But the results of any such "measurement" lie at the heart of the dispute over siting policy and over nuclear safety generally. Transforming the problem into an arithmetic formula cannot meaningfully resolve it. Nor does it give any hope of a wiser outcome. Our alternative procedure recognizes the inherent differences in values underlying the nuclear debate, confronts them directly in establishing siting standards, and forces policy makers to support their decisions with reasoned arguments based as fully as possible on empirical data.

Siting Policy — If the consequences of major accidents cannot be reduced without eliminating reactors entirely, the debate between the individual risk and societal risk viewpoints requires a final decision for or against nuclear power. *That choice is not forced.* For it may be possible to mitigate potential accident consequences significantly through remote siting. We explore that possibility in Sections II and III below, presenting rough estimates of the economic costs and potential accident consequences associated with alternative siting policies *(24)*. We provide a simplified treatment in which policies differ only in the distance from population centers at which reactors are placed. No such formulation can capture the complexities of detailed, site-by-site analysis, but a suitably simplified, general discussion is essential if agreed upon principles of reactor siting are to be reached.

II. ACCIDENT CONSEQUENCES AND REACTOR SITING

A. Prefatory Remarks

Reactor Operating Experience

By definition, in a major nuclear accident an amount of radioactivity sufficient to cause grave damage to public health escapes confinement and is emitted into the atmosphere. With the exception of the 1957 fire in a plutonium-production reactor at Windscale, England - and possibly an incident of unknown origin in the Soviet Union *(25)* - no such accident has yet occurred. There have, however, been several serious accidents involving multiple failures of reactor safety systems. The three most recent of these are a 1975 fire in electrical control cables at Browns Ferry, Alabama *(26)*, a complex of electrical control failures in 1977 at Rancho Seco, California *(27)* and, most serious, the recent combination of human errors and cooling system failures at Three Mile Island, Pennsylvania *(28)*. In view of the relatively short history of commercial reactor operations during which they have taken place *(29)*, the occurrence of these accidents suggests that a major release of radioactivity must be considered a practical possibility, and in particular that the "defense in depth" philosophy *(4)* may not adequately protect the public. An exploration of non-engineering methods for reducing accident consequences therefore seems in order.

Methods For Consequence Mitigation

A number of methods for accident consequence reduction have been proposed: prophylaxis against radioiodine exposure *(30)*; emergency evacuation; decontamination of land and structures; long-term relocation from contaminated areas; more stringent siting policies; underground siting; and sheltering within existing structures *(31)*. These are not mutually exclusive means for improving safety, but to some degree complement one another. Here, we take the view that for purposes of protecting high population areas, restricted siting should play an important, though by no means an exclusive role. As we shall explain, while it is generally accepted that siting restrictions must play a role in regulatory policy, there is controversy over the degree of emphasis siting restrictions merit, and in particular over whether restricted siting should be used as a principal means for mitigating the consequences of major accidents.

Accident Consequences

Following catastrophic failure and breach of the containment building, a reactor acts as the source of a large amount of radioactivity. The emitted material will be dispersed by natural forces and eventually deposited on the ground. The physics of the underlying diffusion and deposition processes is described in standard texts *(32)*. An idealized accident configuration is shown in Figure 1. People in the contaminated area will receive a radiation dose from external exposure to the emitted "plume," inhalation of radioactive particles and exposure to contaminated ground *(33)*. Furthermore, if food production in the affected area is not restricted, exposure by ingestion will occur *(34)*.

The biologic consequences of exposure to radiation include "prompt" death within days to weeks after exposure to very high doses, the induction of cancer and genetic disease over years to decades, loss of fertility,

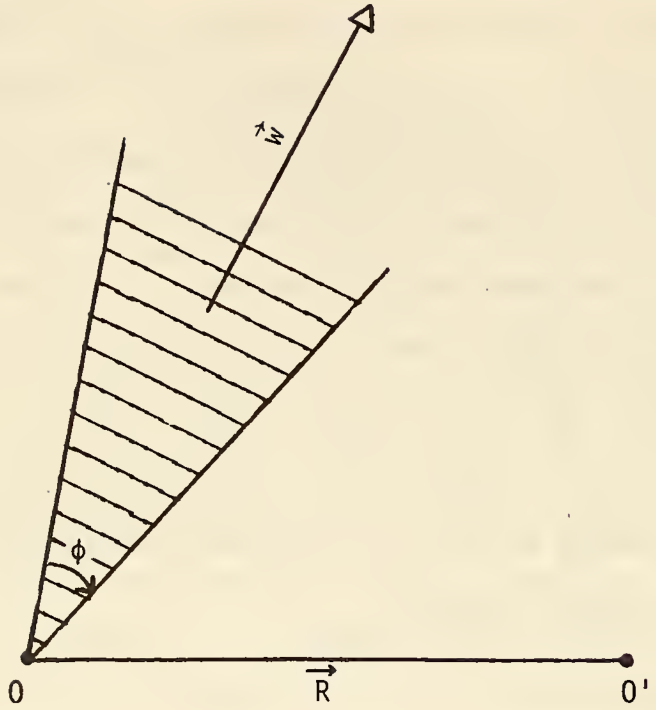

Figure 1

Idealized configuration for major accident assumed to occur at reactor site 0, at distance R from city center 0'. Area contaminated by emitted plume of radioactive material is shown as cross-hatched wedge with opening angle ϕ, bisected by wind direction $\vec{w}$.

spontaneous abortion, thyroid abnormalities *(35)*, non-fatal digestive disorders *(36)*, immunologic injuries and abnormalities in growth and development following prenatal exposure. Dose-response relationships corresponding to these categories of injury are controversial and uncertain to varying degrees *(37)*. For simplicity, unless otherwise noted, accident consequences in the discussion to follow are characterized by the number of "prompt fatalities" due to high-dose radiation exposure, by the number of cases of cancer and genetic disease, and by the period of evacuation necessary to reduce chronic, low-level doses (from contaminated ground) to levels below international exposure standards. Detailed assumptions underlying our analysis are listed below.

Diffusion and Dispersion

As a general matter, in particularly calm (or wet *(37a)*) weather conditions, radioactive material will be heavily deposited within a few miles of the site. Immediate evacuation or effective sheltering is then essential in order to prevent the acute illness, and quite possibly the death of nearby residents. On the other hand, in turbulent, dry weather conditions emitted material will disperse over a wide area, with trace activity detectable hundreds of miles away. In turbulent conditions, there is no danger of short-term, high-dose fatalities, the main health concerns are delayed cases of cancer and genetic disease. Weather conditions between the two extremes will lead to both high-dose, short-term fatalities and low-dose, latent disease.

In essence, restrictive siting policies rely on the passive, dispersive properties of the atmosphere to reduce radiation doses drastically. The key to the effectiveness of the process is the rate of decrease of radiation levels with distance from the reactor. As will become clear in the discussion to follow, this distance dependence is sensitive to a variety of underlying assumptions and to numerous parametric choices. However, in general it is fair to say *a priori* that the fall-off is sufficiently rapid that protection - at least against high-dose effects - can be afforded by siting more remotely *(38)*. At issue, however, are the degree to which protection will and should be afforded as siting distances increase, and the extent to which other strategies such as evacuation and sheltering can be substituted for remote siting. We address those questions below.

Contrast with Conventional Modeling Approach to Consequence Estimation

As we have already stressed, our approach to nuclear risk estimation differs sharply from the one currently in general use. The conventional approach is mainly based on simulation models which express, in probabilistic terms, the biological and physical properties of an idealized system comprised of a known radiation source, an atmosphere with idealized turbulence characteristics and a human population with specified responses to radiation. If this idealized system yielded well understood approximations to reality, and if extensive empirical data on long-range atmospheric transport and radiological dose-response mechanisms were available, numerical modeling would provide "accurate" statistical information on which policy relevant risk estimates arguably could be based. In particular, it would then be possible to specify with confidence the conditional probability, under assumed accident conditions, that specified radiation doses would be exceeded at different distances from a reactor. In principle, such a calculation would allow siting distances to be set following society's choice of the maximum "acceptable" level of nuclear risk.

In practice, however, no such accurate calculation is possible. Relevant biological and meteorological data are sparse or non-existent, and there is limited scientific understanding of the physical and biological processes involved. The results of existing models are therefore highly uncertain. As discussed in Section I, such uncertainties invite manipulation. In practice, simulation calculations embody no inherent limitations on analysts' opportunities to reach a pre-assumed result by making the appropriate parameter choices and initial assumptions. We have therefore chosen to proceed here by depending as much as possible on empirical observation - however fragmentary - and burden of proof concepts, avoiding the use of simulation models. Ultimately, the choice between the simulation and empirical approaches will depend on comparing the results of each. However, the history of nuclear risk estimation *(39)* suggests that formal incorporation of such comparisons in agency decision-making may be in order. It may be wise to require proponents of policies based in part on the results of a complex, simulation model to show that the results of the model contain more information than would a purely empirical analysis.

Technical Assumptions

Any analysis of the relations between reactor sites and accident consequences requires assumptions about the nature and size of the radiation source, the geographic distribution and size of the regional population, and the regional topography. In addition, information is required about the atmospheric transport of particulates and the biologic effects of radiation. Finally, the analysis must consider the speed and effectiveness of emergency evacuation procedures and the period of long-term evacuation. Unless otherwise noted, our discussion is based on the following assumptions:

(a) We consider a hypothetical accident in a 1000 MWe pressurized water reactor (PWR). For comparability with previous discussions in the literature, we assume the composition of the reactor core at the time of the accident is given by the ORIGEN program, as applied in NRC report WASH-1400 *(40)*. We take release fractions of 60% for the radioiodines, 10% for the alkaline earths, 1% for the heavy metals and 50% for the other fission products *(41)*. Where it is convenient, we scale accident consequences to those caused by the release of 50 million curies of Iodine-131, assuming I-131 contributes 5-10% of the total short-term dose *(42)*.

(b) We consider a variable regional population distribution $\rho(\vec{r})$.

(c) We assume flat topography *(42a)*.

(d) To specify the biologic response to radiation we assume:

1. The statistical dose-mortality relation for any *individual* has a "sharp" threshold

$$p_1[D] = \begin{cases} 1 \text{ for } D \geq D_{\text{Thresh.}} \\ 0 \text{ for } D < D_{\text{Thresh.}} \end{cases} \qquad (1)$$

However, the *population averaged* dose-mortality relation, $P_1[D]$, is represented by a smooth, signoidal curve which results from averaging over *individual* threshold doses, $D_{\text{Thesh.}}$. In other words, we take the view that the probable biologic response of large groups of people to high-dose radiation is dominated by differences among individuals, rather than by the mechanics of radiation injury. Lethal radiation doses are in fact observed to vary greatly. For example, a dose less than 100 rads *(43)* to bone marrow can cause early fetal death *(44)* while adult leukemia patients under intensive care survive therapeutic doses of 1000 rads *(45)*. As is conventional, we characterize our population response curves $P_1[D]$ by the dose, LD_{50}, sufficient to cause the death of half the affected population. In our calculations we use LD_{50} = 350 rads *(45a)*.

2. The population-averaged dose-response relationship for the induction of cancer and genetic disease by radiation is linear, with

$$P_2[D] \propto D, \qquad (2)$$

as suggested by two recent National Academy of Sciences study groups *(46,47)*. The "linear hypothesis" embodied in Eq. (2) is controversial, and we indicate in our discussion points at which low-dose thresholds for carcinogenesis or mutagenesis would make a difference.

(e) Consistent with the discussion above, our atmospheric transport calculations are mainly based on empirical observations. In particular, they depend on the results of transport experiments at Hanford in the early 1960's, and on the observed pattern of deposition following the 1957 accident at Windscale, England.

Existing consequence calculations use variants of the standard Pasquill-Gifford turbulent typing scheme *(48,49)*, and a simplified "uniform diffusion" model has been used in nuclear safety analysis by an American Physical Society study group *(50)*. The physical situations to which these models are applied are far from the ideal for which they were conceived. As a result, there are large meteorological uncertainties in conventional consequence estimates *(51)*. For completeness, we indicate at appropriate points comparative results based on the standard and uniform diffusion models.

B. Results and Discussion

Our qualitative results are shown in Table 1. We find a gross difference in the distance dependence of latent and prompt effects, as would be expected from comparison of Eqs. (1) and (2). Furthermore, it can be shown that latent effects will in general heavily dominate prompt effects, an expected result since many more individual low doses than high will naturally occur. If $D(\vec{r})$ is the spatial dose distribution, then the number of people suffering health-effect i is

$$N_i(\vec{R}) = \int_A d^2\vec{r} \cdot \rho(\vec{r}-\vec{R}) \cdot P_i[D(\vec{r})], \qquad (3)$$

where the integral runs over the contaminated area A -- schematically shown as a wedge in Figure 1 -- and $\vec{R}$ is a vector directed from the reactor to an assumed city center. Equation (3) is a general phenomenological relationship underlying any consequence calculation. It states that *the total number of people* N_i *suffering health effect* i *is equal to the probability* $P_i[D(\vec{r})]$ *of suffering effect* i *at point* $\vec{r}$, *times the number of local residents (per unit area)* ρ, *summed over the entire contaminated area* A.

Dominance of Latent Facilities

Heuristic estimates of the ratio of latent cancer to prompt fatalities N_2/N_1 can be obtained as follows. The radial population densities, ρ, of major American cities can roughly be fit by an exponential distribution of the form $e^{-\lambda r}/r$ *(52)*. The simplest diffusion model also gives a spatial dose distribution $D(\vec{r})$ of the same form *(50)*. Using Eqs. (1) and (2) in Eq. (3), and inserting reasonable values for ρ and D,

	Injuries			
Distance to Major City	Prompt Fatalities	Latent Disease	Urban Evacuation Period[c]	Siting Policy
Less than 25 miles	High[a]	High[b]	Months to Years[d]	Near-city siting. Assure safety by reactor design features alone.
Greater than 25 miles	None	High[b]	Weeks to Months[d]	Mid-range siting. Guard against large numbers of acute fatalities in metropolitan areas.
Minimum of 150-200 miles	None	Low[b,e]	Days to Weeks[e]	Avoid long-term evacuation of metropolitan areas.
Hundreds of miles	None	Undetectable	None	Assure negligible exposure of urban population, with trace ground contamination at worst.

Table 1

Siting distances for commercial nuclear reactors by safety objective.

[a] Sensitive to effectiveness of emergency evacuation procedures.

[b] Incidence of cancer and genetic disease sensitive to long-term evacuation period and effectiveness of decontamination.

[c] Length of time necessary to meet annual exposure limit of 0.5 rem per person and lifetime exposure limit of 5 rem (see text).

[d] Sensitive to effectiveness of decontamination procedures.

[e] Sensitive to presence of low-dose threshold for induction of cancer and genetic disease.

we estimate that under the assumptions above 10 to 1000 cancer cases will accompany each prompt fatality for reactors sited anywhere from 10 to 50 miles from a city *(53)*. This ratio will be somewhat smaller if there is a low-dose threshold for carcinogenesis, but the qualitative dominance of latent over prompt effects will be preserved.

"Near-city" Siting

We estimate first the maximum distance from a reactor, under the assumptions above, that high-dose, lethal effects can occur. This defines region A in Table 1, for which we show a distance of 25 miles. A recent NRC study of "nuclear parks" also asserts that lethal doses can occur within 25 miles *(54)*, and a similar judgment led the WASH-1400 study group to assume emergency evacuation out to 25 miles *(55)*.

We briefly sketch the reasoning underlying our 25-mile estimate. Atmospheric transport experiments at Hanford, performed in 1959-62, provide deposition patterns of fluorescent zinc sulfide powder out to 15 miles from the source *(56)*. Following Fuquay *(57)*, we use the Hanford data to infer spatial dose patterns for a hypothetical core-melt accident. We assume an instantaneous, "puff" release of 50 million curies of Iodine-131, scaling other radioisotopes in the ratios given by the release fractions above. We take a mean windspeed of 5 meters per second, an effective release height of 70 meters, an angular plume spread *(58)* of 0.05 and an I-131 deposition velocity 0.017 meters per second. These are unfavorable, but not "worst-case" conditions. We also assume 24-hour exposure and a shielding factor of 0.35 *(59)*. The 24-hour exposure period is discussed below. The calculation leads to a high-dose region extending 18 to 29 miles from the reactor in which bone marrow doses are 430 rads, sufficient to cause death in roughly half the exposed population *(45a, 60)*. Because the calculations require extrapolation somewhat beyond the observed 15-mile range and ostensibly apply to less than ideal situations, one should expect uncertainties of a factor of two or more in the dose pattern *(51)*. The Hanford data apply to extremely stable conditions such as obtain in near-desert environments. The computed dose distributions are therefore pessimistic *(61)*.

These calculations lead to an instructive interpretation of the transport and exposure process. They suggest that in unfavorable, stable weather conditions a relatively small area, of order 10 square miles, will be contaminated to life-threatening levels. In such an area, people not evacuated within 24 hours are likely to suffer radiation doses of 300-500 rads, sufficient to cause the death of as much as half the exposed population *(45a)*. Given the typical suburban population density of the northeast United States -- of order 500 people per square mile -- 24-hour exposure would result in several thousand short-term fatalities. That estimate is consistent with the maximum consequence estimates of the two currently available U.S. Government reactor safety studies *(3,62)*. On the other hand, if central city population densities of 50,000 per square mile *(63)* are affected, an accident could cause on the order of 100,000 prompt fatalities. In that connection, a recent calculation by the NRC Regulatory Staff, for the worst accident they projected to occur at one of several alternative reactor sites near Baltimore, leads to an estimate of prompt fatalities greater than 100,000 *(64)*. For sites with special topographic features, the lethality range may change. For example, the Indian Point, New York site lies in the Hudson River Valley, a topographic feature which channels air flow and in consequence lengthens the potential lethality range along the valley axis *(65)*.

Evacuation, Sheltering and "Mid-Range" Siting

The mid-range alternatives which define region B in Table 1 are designed to give protection against a preset range of high-dose injuries. The associated range of doses extends a priori from lethal levels of several hundred rem down to levels of 5-10 rem whose effects would presumably be the induction of long-term, latent disease *(66)*. The extreme low end of the range is suggested by an EPA "protective action guide" which calls for evacuation of the affected area when projected individual whole-body doses exceed 5 rem *(67)*. We do not attempt to estimate precise distances for mid-range siting as a function of a maximum allowable dose. We are reluctant to do so principally because data for very long-range atmospheric transport are lacking *(68)*. Furthermore, there are complex, competitive relations among the preset limiting dose, the required siting distance and the effectiveness of evacuation and sheltering. As the maximum allowable dose decreases, the required siting distance increases. But the required siting distance decreases with the increasing effectiveness of emergency evacuation and sheltering. The uncertainties are sufficiently large that in Table 1 we show only that appropriate region B distances lie between regions A and C, and must largely be determined on a case-by-case basis. The question remains, however, whether restricted siting adds an important dimension of safety, beyond that obtainable with evacuation or sheltering alone, and a brief, qualitative discussion is in order.

Studies of Sheltering vs. Evacuation — A number of recent reports suggest that combined sheltering-evacuation strategies are preferable to evacuation alone *(16, 69)*. Those strategies presume that a portion of the public who live near a reactor remain in basements or other protected areas during the passage of the emitted "cloud" and then leave the area. Studies of such strategies are not directly applicable here, for they do not consider high population density situations *(70)*. The results nevertheless are instructive: they suggest that in areas neighboring, but not immediately adjacent to a reactor, ordering immediate evacuation can result in otherwise avoidable exposure to the passing cloud *(71)*.

High Population Density Effects — These results raise the natural question whether in congested areas evacuation may be greatly delayed, enhancing the relative benefits of a mixed sheltering-evacuation strategy over evacuation alone, but vitiating its practical importance. Three recent governmental reports suggest that for major metropolitan areas, large-scale emergency evacuation is likely to pose special difficulties. A 1975 U.S. Environmental Protection Agency manual for emergency actions in response to nuclear accidents takes the view that areas of relatively low population density can be evacuated in a few hours, but that "[h]igh population, high density areas such as those around Indian Point [Westchester County, N.Y.] present a different situation, and evacuation times are more complex, probably longer, and must be analyzed on a case by case basis" *(72)*. A 1978 NRC-EPA report on emergency planning *(4)* finds that "[e]mergency offsite response to large accidents may be less effective for sites located in an area of general high population density" *(73)*. The NRC report WASH-1400 is most explicit. It states that the analysis presented there makes "no presumption" that the populations of cities such as "New York, Boston, Philadelphia, Chicago and Los Angeles ... could be moved in less than 1 week" *(74)*. In light of these statements, our choice of a nominal 24-hour exposure period, in determining region A, may be optimistic *(74a)*.

Institutional Constraints — As emphasized in a recent General Accounting Office (GAO) survey, there has been a general reluctance to plan for nuclear emergencies *(75)*. The Three Mile Island accident may lead to improvement, but the prognosis is not hopeful. At this writing, the NRC Staff plans to recommend to the Commission, in accordance with an NRC-EPA report *(4)*, that the consequences of major accidents not receive attention in emergency planning *(76)*. Whether state and local governments can and will proceed independently is an open question. Such planning may well face less formidable political barriers for sites in less populated areas.

Avoiding Long-Term Evacuation: The Windscale Accident

We estimate the distance range for which long-term evacuation may be necessary by using the observed low-level ground contamination following the 1957 fire in a plutonium production reactor in Windscale, England *(76a)*. As above, we assume a hypothetical core-melt accident in a modern 1000 MWe reactor at the same site. In performing the calculations we make the following assumptions:

(i) We take the deposition in the hypothetical accident to be linear in the total released activity of Iodine-131, again assumed to be 50 million curies. Following Chamberlain *(77)*, we combine the estimates of Chamberlain *(77)* and Crabtree *(78)* and assume 27,000 curies of I-131 were actually released at Windscale. We then compute the

predicted deposition in the hypothetical accident by scaling the observed Windscale deposition by the factor $50 \times 10^6/27 \times 10^3 = 1{,}850$.

(ii) We take the deposition velocities of all released radionuclides equal to the deposition velocity of radioiodines at Windscale (measured as 0.3 to 0.4 cm/sec.). For the most important long-term gamma emitter, Cesium-137, this assumption is consistent with a comparison of the observed ratios Cs-137/I-131 of activities emitted and subsequently deposited *(79)*.

(iii) We follow previous studies and assume ground contamination decreases exponentially over time as suggested by measurements of the time dependent, mean gamma-ray dose in air, 1 meter above soil contaminated with Cesium-137 *(80)*.

(iv) We assume shielding factors $0.35 \pm .15$ from ground *(59)*.

Five cities are within 125 miles of the Windscale site: Sheffield (110 miles); Bradford (90 miles); Leeds (90 miles); Manchester (90 miles); and Liverpool (75 miles). The total population in these cities is approximately 2,800,000. The measured ground deposition of I-131 near both Sheffield and Leeds was 0.16 $\mu Ci/m^2$ (microcuries per square meter) *(77)*. By interpolation, the other cities appear to have been similarly contaminated. From the release fractions given above in assumption (*a*), and from assumptions *(i)-(ii)*, the predicted ratio of deposited activities is Cesium-137/Iodine-131 = .048. Using the overall scale factor of 1,850 given above, and the measured 0.16 $\mu Ci/m^2$ I-131 deposition at Leeds and Sheffield, the predicted urban Cs-137 deposition in the hypothetical accident is $0.048 \times 0.16 \times 1{,}850 \cong 14\ \mu Ci/m^2$.

To deduce required evacuation times from the calculated doses we apply low-level chronic radiation dose standards for the general population. Such standards have been set for the human reproductive period (mean length approximately 30 years) and for annual exposure. For radiation doses having genetic implications, the International Commission on Radiological Protection (ICRP) recommends a limit of 5 rem for the first 30 years of life, from artificial, non-medical sources *(81)*. The ICRP also recommends a maximum dose of 0.5 rem to bone-marrow or gonads, within any one year. These limits may be compared with the average individual dose from natural radiation of approximately 0.1 rem per year. The inhabitants of Bikini Atoll have recently been relocated due to excess low-level radiation exposure. For comparison with the ICRP standards, we note that the measured mean whole-body dose to the Bikini adults in 1978 was .537 rem, of which .183 rem resulted from external sources and .354 rem from internal exposure, mainly to Cs-137 *(82)*.

Radiation Standard	Shielding Factor	Evacuation Time
5 rem in 30 years	0.20	< 1 month
	0.35	12 months
	0.50	39 months
0.5 rem in 1 year	0.20	12 months
	0.35	25 months
	0.50	42 months

Table 2

Urban evacuation periods for hypothetical reactor accident at Windscale, England site, scaling estimated actual release of 27,000 curies I-131 to hypothetical 50 million curie release. Based on International Council on Radiological Protection (ICRP) standards. Shielding factors =[radiation actually absorbed]/[radiation emitted from idealized plane sources].

The calculated evacuation periods for the five cities within 125 miles of Windscale are shown in Table 2. The estimates are sensitive to the assumed shielding factor, to the radiation standard, to the considerable uncertainties in the scaling calculation and to the effectiveness and economic feasibility of methods for decontamination *(83)*. For example, if we use the 10 rem in 30 years standard of the Medical Research Council of Great Britain *(84)*, the maximum estimated evacuation period in the hypothetical accident is 6 weeks. On the other hand, if ground contamination were a factor of 2 or more greater than the estimates used here, the required evacuation periods would be considerably longer than those given in Table 2. These estimates lead us to suggest that to avoid long-term urban relocation, a minimum distance range of 150-200 miles is necessary. We emphasize that these are not precise estimates, and that the Windscale incident can in no sense be considered "typical" *(85)*. But it provides the only real data for transport of radiation at such distances and from such a source. For policy purposes it therefore must be taken into account.

Extreme Remote Siting

We do not discuss in detail the safety implications of very remote siting hundreds of miles from population centers. We assume that at such distances only trace ground contamination is possible, at levels that initially increase background doses by at most a factor of two *(86)*. In the absence of low-dose thresholds for carcinogenesis or mutagenesis, such dose increments may well result in small increases in the total incidence of cancer and genetic disease *(87)*. These increases for practical purposes will be undetectable. We do not address the difficult question whether it is ethically justifiable to neglect very low doses, either because their effects — and occurrence — are speculative, or because their consequences would be undetectable *(88)*. We note that in practice meteorological predictions of deposition hundreds of miles from a source may not be meaningful, and that very remote sities are available only in the Western states, at distances of 1000 miles or more from the prime electricity consuming areas of the Northeast. Furthermore, as we show in Section III, the cost of power transmission over hundreds of miles is sufficiently high to make nuclear reactors sited at such distances uncompetitive with less remote, coal-fired power plants.

Our discussion of siting alternatives has dealt so far only with the societal risks of exposing metropolitan areas to radiation. Consideration of extreme remote siting raises the question of individual risks, in particular those faced by rural residents *(89)*. It has been widely argued that as an ethical matter, reactors should be sited near metropolitan areas where the electricity they produce will be used. We take a different view. Nuclear reactors are part of a complex, interstate system designed to provide reliable power in quantities sufficient to satisfy demand. Because of existing transmission interties, a large and growing majority of electricity consumers are supplied, to some degree, from nuclear sources *(90)*. Given the deeply interstate nature of the electricity supply system, no state or locality justifiably can claim the right to isolate itself from one power source, and thereby make more difficult, or disrupt, service to others *(91)*.

For us, the fundamental issue underlying the decision whether to use more remote sites is not inequalities among states or regions. Assuming that the societal risks associated with sites near population centers have been properly treated, protection against individual risks must be provided. In order to do so: *(i)* there should be satisfactory arrangements for emergency evacuation, communication of information and prophylaxis against radioiodine exposure; *(ii)* full compensation for damages should be assumed by the Government and by reactor operators and manufacturers *(92)*; and *(iii)* licensees and regulators should bear the burden of showing the probability of individual injury from a reactor accident compares favorably with the likelihood of serious injury from other cases. Under a fair decision-making process, these requirements can afford adequate individual protection. But it should be emphasized that in many respects the past history of nuclear regulation is not encouraging. Strict evidentiary rules, placing heavy burdens of proof on regulators and prospective reactor licensees are therefore in order.

Communication — For example, following the Browns Ferry reactor fire of March 22, 1975 there was sharp criticism of the Tennessee Valley Authority's failure to communicate effectively during the fire, both internally and also to responsible local authorities *(93)*. In testimony before the Congressional Joint Committee on Atomic Energy, AEC officials recognized the "need for improvement" in emergency communications *(94)*. Nevertheless, four years later there were more serious communication failures during the Three Mile Island accident *(95)*.

Compensation — Federal legislation currently limits aggregate compensation in the event of a nuclear accident to $560 million *(96)*. The Senate sponsor of the Price-Anderson Act justified the aggregate limitation *inter alia* on the grounds

> [t]he Government can pick up $500 million and not be too disturbed. But if the Government has an unknown claim that could run $5 billion or $10 billion, as some people have estimated ..., then you do greatly disturb the budget *(97)*.

In an age when the philosophy of social insurance has long been accepted, such an argument is neither morally just nor conduces to public acceptance of nuclear risks. Removal of the liability limit is called for. A restrictive siting policy, existing sites aside, would drastically reduce the potential burden on federal taxpayers if a catastrophe should occur *(98)*.

Individual Risks — It has been repeatedly asserted by nuclear power proponents that the risks of serious injury to individuals from nuclear power plants are substantially less than other risks faced in everyday life. The principal NRC study on which such statements have been based is, however, no longer accepted as reliable by the Commission *(17)*. The Three Mile Island accident in principle provides additional information which should be publicly evaluated before further nuclear reactors are licensed. For example, if design features of the Three Mile Island reactors are found to have played a significant role in the accident, that will provide strong evidence that reactor operating experience should be disaggregated for individual reactor manufacturers in order to make rough actuarial estimates of upper limits for accident probabilities. The resulting bound for individual risk may well fail the likelihood requirement above, implying that fundamental design changes or passive consequence mitigating techniques *(98a)* are in order, or that abandonment of nuclear electricity generation should be considered.

To consider seriously a restrictive siting policy, particularly extreme remote siting, would transform the reactor safety debate. In its new form, the debate would parallel the growing controversy over the scope of federal versus state authority over nuclear waste disposal *(99)*. Nevertheless, as a practical matter, given the country's mid-range energy supply situation, further nuclear power development appears desirable and is probably inevitable.

The present opportunity to reform nuclear regulation is likely not to be repeated. It should be used, not to restate doctrinaire positions, but to define further government's responsibility to protect individual citizens against the risk of serious bodily harm *(100)*.

III. COSTS OF ELECTRIC POWER TRANSMISSION

Placing reactors at greater distances from major population centers can have profound effects on the potential consequences of accidents. More remote siting is not costless, however. Land must be paid for, transmission lines must be built, and long-distance lines result in energy losses that significantly affect overall cost estimates. In this section we examine the impact of remote siting on the cost of nuclear electricity generation and also on the total cost of electricity. The latter requires a projection of the future share of the nuclear sector in total electricity production. We do not consider the details of planning the requisite long-distance transmission networks. Instead, we make the simplifying assumption that the incremental cost incurred in establishing each new site is independent of costs at other other sites and of the costs of unrelated network additions. We therefore do not address questions of land use and network planning which are critical to deciding whether central-station power technology should be utilized well into the 21st century.

Multi-Unit Siting and Transmission Line Costs

A variety of geographic configurations of commercial reactors have been considered. At the extremes, nuclear generating capacity can be fully dispersed, with one reactor per site, or a dozen or more reactors can be clustered in a "nuclear park" *(101)*. We analyze two alternative configurations that reflect current utility siting practices. The first assumes four 1050 MWe reactors are sited together. To reliably transport power from a four-unit site over the distances contemplated here, a 765 Kv transmission line with three circuits is required *(102)*. The second configuration is a site with two 1050 MWe units. To achieve approximately the same level of reliability as the four-unit configuration, a 500 Kv line of three circuits is adequate *(103)*.

It is important to note that there are potential scale economies in multi-unit siting *(104, 105)* which are not fully captured here. The construction of a series of identical units by a single workforce in a single area results in considerable cost saving. On the other hand, national security and system reliability considerations militate against highly concentrated power generation *(106)*. We do not consider these matters in detail; they deserve further study.

We have obtained estimates of 500 Kv and 765 Kv transmission line costs from a variety of sources. In Table 3 we report line construction costs plus the costs of purchasing and clearing rights of way. We have escalated the average costs reported for 500 Kv lines and 735-765 Kv lines, using the Handy-Whitman transmission line construction cost index *(107)*, to reflect the price level on January 1, 1977. The three cost estimates for 500 Kv are fairly close to one another. The range for 735-765 Kv lines is considerably larger because the Bonneville Power Authority's estimates are over 20% higher than the next highest and over 35% higher than the lowest estimate. This difference may be due to more accurate Bonneville estimates, or it may reflect special construction requirements. The Bonneville estimates assume 50% rolling and 50% mountainous terrain. Construction costs over flat country will be considerably less. In our actual cost calculations, we use a range of estimates rather than point values. For 500 Kv transmission lines we take $200,000 per circuit mile (low), $250,000 per circuit mile (mean) and $300,000 per circuit mile (high). For 765 Kv lines the corresponding figures are $300,000, $400,000 and

Source	500 Kv	735-765 Kv
FPC[a]	$240,000	$345,000
Calif. Energy Commission[b]	---	300,000
NRC[c]	240,000	345,000
Bonneville Power Authority[d]	264,000	426,000

Table 3

Transmission line costs per circuit mile in 1977 dollars. Estimates are adjusted for inflation using Handy-Whitman transmission construction cost index *(107)*.

[a] U.S. Federal Power Commission *(111)*, p. I-13-7.

[b] U.S. Federal Energy Administration, *Direct and Indirect Economic Impacts of the Passage of the California Nuclear Power Plants Initiative* (Washington, D.C. 1976) Vol. III, App., p. 2B, footnote 6.

[c] U.S. Nuclear Regulatory Commission *(54)*, Pt. III, p. 4-15.

[d] Bonneville Power Authority, "Per Mile Cost Data For Preliminary Transmission Cost Estimates," May, 1977, unpublished.

$500,000 respectively.

The Cost of Nuclear-Generated Power

We now estimate the sum of "busbar" generating costs plus transmission costs for various distances. The distances we consider are conveniently thought of as increments to present siting distances. For example, if nuclear power stations typically are located 25 miles from load centers, the calculations presented here for distances of 50 miles, 150 miles and 450 miles correspond to 75, 175, and 475 miles from load centers respectively.

Our calculations assume that nuclear generating plants can be constructed at a cost of $650 per Kw ($1977)*(108)*, that operating costs are 8 mills per Kwh, that the *real* capital charge rate is 12% per year and that commercial reactors operate at an average capacity factor of 70% over their 40-year lives*(109)*. In addition we assume line losses are 1% per 100 miles of transmission distance *(110)* and that annual transmission,operation and maintenance costs are 1% of investment costs*(111)*.

We have estimated the cost of generating and transporting power 50, 150 and 450 miles from nuclear plants. Table 4 gives our results in incremental mills/Kwh and as percentage increases over the busbar generation cost, which we take to be 20.7 mills ($1977). Table 4 shows that increasing the transmission distance by 50 miles increases the cost of base-load nuclear power by 3-5%. Increasing the transmission distance 150 miles increases nuclear power costs by 6-10%. An increase by 450 miles increases power costs by 14-25%. For the longer transmission distances,high voltage DC transmission lines are probably more economic. While present experience with high voltage DC

A. Four-Unit Site (Four 1050 MWe PWR; 765 Kv transmission line with three circuits)

Increase in Distance	Mills/Kwh (% Increase)[a]		
	Low	Mean	High
50 miles	0.6(3%)	0.7(3%)	0.9(4%)
150 miles	1.2(6%)	1.4(7%)	1.7(8%)
450 miles	2.9(14%)	3.6(17%)	4.4(21%)

B. Two-Unit Site (Two 1050 MWe PWR; 765 Kv transmission line with three circuits)

Increase in Distance	Mills/Kwh (% Increase)[a]		
	Low	Mean	High
50 miles	0.7(3%)	0.9(4%)	1.0(5%)
150 miles	1.4(7%)	1.7(8%)	2.0(10%)
450 miles	3.6(17%)	4.4(21%)	5.1(25%)

Table 4

Increase in nuclear-electricity generating costs due to siting reactors further from city centers.

[a] *Base case:* Busbar cost of nuclear generation = 20.7 mills/Kwh. Estimates are based on $650/Kw generating capacity, 8 mills/Kwh operating cost, 12% real capital charge rate, 70% capacity factor. Low, mean and high values reflect differences in transmission line costs (see text and Table 3).

transmission is too limited to make precise cost estimates, such lines appear less expensive at long distances and possibilities remain for cost reducing innovations *(112)*. The use of DC transmission should enter into any consideration of cluster siting, whether nuclear or non-nuclear or a combination of the two.

In a decentralized economy with (private) cost minimizing firms, there are two major economic effects of siting restrictions: an increase in electricity prices, and a shift from nuclear power to the next best generating alternative, probably coal. The extent to which such substitution will occur depends on cost increases due to transmission distances, and on the relative costs of alternative techniques for base-load electricity generation.

Almost all the nuclear capacity predicted to be operational at the end of this century will be located in five of the nine census regions *(113)*. The East North Central Region, which includes Chicago, is typical of the areas where nuclear penetration should be relatively high. A recent study *(114)* estimates that for base-load generation in the Midwest, nuclear power had an average cost advantage of 3.3-4.6 mills per Kwh over coal in mid-1976. As shown in Table 4, siting plants 50 miles further from load centers would increase nuclear-electricity generating costs by less than one mill ($1977). Such a requirement appears to have only a marginal impact on the competitiveness of nuclear power. Siting plants 150 miles further would increase the cost of nuclear generation from 1 to 2 mills per Kwh. Such cost increases would probably engender some substitution of coal for nuclear in regions where the comparative economics are "close." But it appears to us, based on current cost estimates, that nuclear generation in those regions where it is now competitive will remain so. On the other hand, 450-mile increases in distances from load centers will lead to cost increases of 3-5 mills per Kwh, and this probably makes nuclear generation uncompetitive. Furthermore, in areas where nuclear power could remain competitive despite remote siting, such as New England, sites 450 miles from major cities are unavailable.

We conclude there are important qualitative differences between siting policies which require reactors to be located 50 to 150 miles further from load centers, and policies which impose much more severe remote siting constraints. The former have relatively small effects on the comparative economics of coal versus nuclear generation. The latter make nuclear power uneconomic almost everywhere and have essentially the same effects as a formal nuclear moratorium.

The Effect of Remote Siting on Total Electricity Costs

In this section we attempt to answer a question in "counterfactual history": If a remote siting policy had been in effect during the entire history of the U.S. nuclear program, how would that have affected the production costs of electricity and the prices of electricity faced by final consumers? We do not try to define a specific remote siting policy, but examine the cost implications of placing reactors at a range of distances from population centers. Because only 25% of the officially planned, commercial reactor capacity is currently operative *(115)*, we focus on the year 1990, comparing the likely situation under current institutional arrangements with what might have been if remote siting policies had been pursued.

We note first that the average price of electricity delivered to residential, commercial and industrial consumers was about 32 mills per Kwh in 1977 *(116)*. Residential consumers pay a price higher than this. The residential price reflects reliance on the low-voltage distribution system, and on the time-pattern of individual household electricity use. Industrial consumers generally pay lower rates because of the high voltage at which they take power and their particular load characteristics. For our purposes, it is sufficient to focus on the average delivered price of electricity to all consumers as a group. The 32 mill figure is higher than the 20-22 mill figure used for busbar costs in Table 4; the former includes all transmission, distribution and overhead costs, as well as the generation costs associated with non-nuclear generating facilities operated as base-load, cycling and peaking capacity.

We use as a starting point the Base Case reported by Baughman, Joskow and Kamat *(108)*. This Case predicts total electricity generation of roughly 3.8 x 10^{12} Kwh in 1990, of which 1 x 10^{12} Kwh are nuclear generated. The latter estimate probably represents an optimistic projection of nuclear penetration, even setting aside current public safety concerns, so that our estimates of the overall cost of a remote siting policy are likely to be high. Table 5 shows total annual costs of more remote siting of nuclear reactors expected to operate in 1990. Our estimates are for 50, 150 and 450 miles, as above. Siting nuclear reactors 50 miles further away from load centers increases projected 1990 electricity costs by less than $1 billion, or less than 1% of projected total costs. For 150-mile increments, 1990 electricity costs increase from 1 to 2 billion dollars, or between 1% and 1.6% of total costs.

We observe, for purposes of comparison, that the EPA's recently issued New Source Performance Standards are estimted to increase 1995 electricity costs by about 2%, or $3.5 billion *(117)*. Remote siting 450 miles further, however, increases 1990 generation costs by between 3 and 5 billion dollars, or between 2.4% and 4.2% of total electricity costs. If 450-mile distances had actually been historically required, and if similar restrictions were not in effect for conventional plants, coal-fired capacity would probably have been substituted for much of the nuclear capacity that is now projected. In addition, it should be emphasized that our estimated transmission cost increases would not be distributed uniformly across the country. In the absence of explicit or implicit federal subsidies, the five regions where nuclear penetration is expected to be greatest *(113)* would bear most of the costs.

A. Four-Unit Sites

Increase in Distance	$Billion/year (% Increase)		
	Low	Mean	High
50 miles	$0.6(0.5%)	$0.7(0.6%)	$0.9(0.7%)
150 miles	1.2(1.0%)	1.4(1.1%)	1.7(1.4%)
450 miles	2.9(2.4%)	3.6(3.0%)	4.4(3.6%)

B. Two-Unit Sites

Increase in Distance	$Billion/year (% Increase)		
	Low	Mean	High
50 miles	$0.7(0.6%)	$0.9(0.7%)	$1.0(0.8%)
150 miles	1.4(1.1%)	1.7(1.4%)	2.0(1.6%)
450 miles	3.6(3.0%)	4.4(3.6%)	5.1(4.2%)

Table 5

Increase in total annual electricity costs due to siting reactors further from city centers. Estimates are for 1990 ($1977).

Base Case: 3.8 x 10^{12} Kwh total electricity production in 1990 *(113)* with average total cost of 32 mills/Kwh ($1977) and 1.0 x 10^{12} Kwh nuclear generation in 1990.

IV. SITING RESTRICTIONS AND ACCESS TO COOLING WATER

In this section we briefly consider the implications of more stringent siting policies for the availability and costs of cooling water for nuclear-electric generating plants. For more remote siting to have significant adverse effects on the cost of electricity, two conditions must be met. First, cooling water sources must be located primarily near metropolitan areas. Second, the costs of the alternative cooling techniques required to implement remote siting must be relatively large.

The net efficiency (electrical output/thermal energy input) of the current generation of light-water reactors is 31%-34% *(118)*. Unlike fossil-fired electric generators, nuclear plants reject substantially all their waste heat to circulating cooling water. They require a high internal flow of coolant: 900-3,000 cubic feet/second (cfs) for a 1200 MWe plant *(119)*. Such flow rates represent significant fractions of total flow in major rivers. In principle, therefore, the necessity for access to a large water source places constraints on siting.

There is a sharp distinction between once-through cooling and systems using recirculated coolant *(120)*. For practical purposes, once-through systems require a nearby source of water, capable of supplying a flow of several thousand cubic feet per second without disruption of other uses. Though the coolant flow internal to the reactor is the same, the net water consumption of recirculating systems is at most 50 cfs per 1200 MWe unit, on the order of one percent of once-through requirements *(121)*. Furthermore, the discharge heat of once-through systems raises concerns over thermal pollution, and current EPA regulations governing all power stations formally prohibit once-through cooling *(122)*. In some cases, notably for the Seabrook, New Hampshire site, variances have been granted *(123)*, and it is not clear whether EPA will in fact enforce its regulation. If once-through cooling is abandoned, water availability cannot be a strong constraint on siting. Net water consumption per plant is then so low that flexibility is retained in the types and sizes of satisfactory water sources.

Large cost differences among alternative cooling systems of course remain. Government cost estimates for 1973, escalated to current dollars, show that dry cooling towers are five to six times more expensive than wet cooling towers *(124)*. These estimates imply that a very restrictive policy, requiring siting in arid regions of the Southwest, will increase the cost of nuclear generated electricity by as much as 10%. Even in such a case, the possibility remains that cooling supply and effluent could be carried by pipeline at costs comparable to those of dry cooling towers. We have not independently analyzed that possibility. However, a recent NRC study *(54)* suggests that the costs of such a pipeline as an addition to a wet-tower system are less than the costs of a dry tower, natural draft system alone. For a 12-unit site, the NRC figures indicate the breakeven distance for a wet-tower plus pipeline system is 300 miles for a fresh-water source and 150 miles for salt water *(125)*.

In summary, placing additional constraints on the location of power plants does eliminate some cooling water sources. However, because proximity to load centers has played such an important part in power plant siting it is not generally true that the "best" water sources have been utilized. Evaporative cooling systems are in growing use, and in most areas of the country water supplies appear to be adequate *(126)*. The Southwest may be an exception, but there nuclear energy does not appear to be a cost-effective alternative to coal-fired power plants. In most parts of the country the introduction of more stringent siting criteria therefore does not entail a significant cooling cost penalty. In arid locations where such a penalty is entailed, the economic consequences of remote siting will be considerably more severe than would be suggested by focusing on incremental transmission costs alone.

V. UNITED STATES NUCLEAR SITING POLICIES

Burdens of Proof in Site-Selection

In the U.S. nuclear regulatory scheme, the initiative for choosing nuclear sites comes from prospective reactor owners and operators, rather than from representatives of the public, regulators or officials of other interested government agencies. As was anticipated in early congressional debate on the atomic energy program, private responsibility for siting has lead to placing commercial reactors in or near utility service districts. From the standpoint of utility decisionmakers, the limited sources of once-through cooling water in high population areas with multiple water use, the legal, regulatory and political obstacles to ownership of distant generation facilities, and the apparent high costs of long-distance transmission sharply constrain siting choices. Because of the applicant focus of site selection, unless a remote site is originally proposed, the burden of proof that such sites should be considered falls heavily on third-party intervenors. This pattern of allocation of burden extends throughout the history of the nuclear commercialization program. An early example is the AEC's positive safety finding with respect to the Fermi-1 reactor, the first liquid-metal breeder reactor to supply electricity to a metropolitan power grid. A division of the United Auto Workers challenged the AEC's issuance of the Fermi-1 construction license *(127)*. They particularly objected to the proposed site, which was roughly halfway between Toledo and Detroit *(128)*. After lengthy agency proceedings, the Commission found:

> It is possible that there may be presently unknown effects in large fast reactor systems. A prototype of the proposed reactor at a remote location has been urged as affording greater assurance against the possibility of such unknown effects than does the presently planned experimental and theoretical programs.

> *The Commission finds that the necessity, however, for constructing such a prototype has not been shown.* If the program of meltdown investigation should prove inconclusive, it will be necessary to reconsider the question of need for a prototype *(129)*.

In recent years the site selection process has been somewhat more structured, but the focus on the applicant's preferences, and its implied restriction to nearby sites, have been retained *(130)*. Furthermore, despite passage of the National Environmental Policy Act of 1969 (NEPA)*(131)*, the courts remain reluctant to interfere. Acknowledging that NEPA's full implications for reactor site selection remain undecided, the United States Court of Appeals for the First Circuit nevertheless recently re-emphasized the weight reviewing courts accord to the de facto service area restriction *(132)*. Upholding the NRC's approval of the Seabrook, New Hampshire site, the First Circuit reasoned:

> Especially as these [alternate sites proposed by the environmental petitioners] were remote from PSCO's service area, they were not of such obvious significance that the Commission was required, at its peril, to consider them on its own initiative *(133)*.

Within the statutory scheme of the Atomic Energy Act, there nevertheless is room for regulatory initiatives. In evident recognition that this is the case, President Carter requested in the National Energy Plan of April 1977

> that the NRC develop firm siting criteria with clear guidelines to prevent siting of nuclear plants in densely populated locations, in valuable national areas, or in hazardous regions *(134)*.

There have been recent discussions within the NRC of the necessity for changes in siting policy, but new regulations of the kind requested by the President have not been forthcoming *(135)*.

Siting Patterns and Practices

Siting criteria in actual use are not set out in formal regulations. Current NRC regulations contain no explicit, numerical distance restrictions but imply only that reactors may not be sited within a few miles of population centers *(136)*. The site-selection process itself is informal. Once an applicant makes a siting proposal, it becomes a matter for negotiation with the NRC Regulatory Staff. Those negotiations take place in the context of the NRC's advisory position papers on siting and its instructions for preparing licensing applications *(137)*.

Tables 6 and 7 summarize the historical results of the site-selection process. As a rough indicator of the remoteness of existing sites, we use distances from cities with populations greater than 100,000. Table 7 shows that cities of 100,000 or more within 25 miles of reactors almost without exception are located in metropolitan areas with populations greater than 200,000. This population level seems a reasonable lower bound for sites deserving the highest level of scrutiny. In particular, it seems reasonable that sites within 25 miles of population concentrations of 200,000 or more should presumptively be classified in region A of Table 1. As discussed in Section II, emergency evacuation of hundreds of thousands may well take long enough that large numbers of lethal doses could occur.

Table 6 shows no apparent change in siting policy, comparing reactors already in operation with more recently chosen sites at which construction licenses have been granted. Table 7 shows there has been no apparent change in willingness to site reactors within 25 miles of cities with populations greater than 100,000 *(138)*. From Table 6, such

Distance to Nearest City	Sites With Operating Reactors[a]	Sites Under Construction[b]
< 25 miles	12	11
25-50 miles	17	16
50-75 miles	8	9
> 75 miles	11	4
Totals	48	40

Table 6

Distances of approved U.S. commercial reactor sites to nearest city with population greater than 100,000, comparing sites with operating reactors with sites at construction permits have been granted.

[a] Includes sites at which one or more reactors are in operation or in power ascension phase.

Source: U.S. Nuclear Reg. Comm'n, "Operating Status Report," NUREG-0020 (September, 1978).

[b] Includes sites at which one or more construction permits have been granted, but with no reactor units in operation. In some instances, actual construction has not yet begun.

Source: U.S. Nuclear Reg. Comm'n, "Construction Status Report," NUREG-0030 (September, 1978).

Site	Date of Construction License	City	Distance (miles)	SMSA (Population in thousands)[a]
†Indian Point	5-04-56	Yonkers, N.Y.	23	[b]9,561
†Haddam Neck (Connecticut Yankee)	5-26-64	Hartford, Conn.	13	732
†Ginna	4-25-66	Rochester, N.Y.	17	971
†Quad Cities	2-15-67	Davenport/Rock Island/Moline, Iowa/Ill.	19	370
†Fort Calhoun	6-07-68	Omaha, Neb	19	573
†Surry	6-25-68	Newport News, Va. Hampton, Va.	20 22	347
†Rancho Seco	10-11-68	Sacramento, Calif.	25	880
†Zion	12-26-68	Racine, Wis.	20	[c] 1,409 [d] 7,015
†Fitzpatrick	5-20-70	Syracuse, N.Y.	17	648
Sequoyah	5-27-70	Chattanooga, Tenn.	18	392
†Duane Arnold	6-22-70	Cedar Rapids, Iowa	11	---
†Beaver Valley	2-26-70	Pittsburgh, Pa.	25	2,322
†Davis-Besse	3-24-71	Toledo, Ohio	24	779
Fermi	9-26-72	Dearborn, Mich.	24	[e]4,424
Zimmer	10-27-72	Cincinnati, Ohio	22	1,381
McGuire	2-28-73	Charlotte, N.C.	15	593
Shoreham	4-14-73	Bridgeport, Conn. New Haven, Conn.	20 25	395 414

(CONTINUED NEXT PAGE)

Bailly	5-01-74	Gary, Ind.	11	643
Waterford	11-14-74	Metairie, La. New Orleans, La.	19 24	--- 1,094
Catawba	8-07-75	Charlotte, N.C.	18	593
Riverbend	3-25-77	Baton Rouge, La.	23	412
Shearon Harris	1-27-78	Raleigh, N.C.	20	469

Table 7

United States commercial reactor sites within 25 miles of city of 100,000 population or more, by date of construction permit. Shown also are local Standard Metropolitan Statistical Area (SMSA) populations reported in 1970 Census.

[†] Operating license granted for one unit or more.

[a] *Source:* U.S. Bureau of the Census, *Statistical Abstract of the United States 1977* (Washington, D.C. 1977), Table 21, July, 1975 estimates.

[b] New York SMSA

[c] Milwaukee SMSA

[d] Chicago SMSA

[e] Detroit SMSA

sites comprise fully 25% of all approved sites. Table 7 should not be taken as an inclusive listing of "unacceptable" sites. Site-specific conditions may justify classification in region B of some sites less than 25 miles from cities with populations greater than 100,000. And there are sites with cities slightly beyond the 25-mile limit which clearly warrant classification in region A. An example of the latter is the Limerick, Pennsylvania site, which lies within 26 to 28 miles of the most densely populated part of the city of Philadelphia. An example of the former is the Duane Arnold site, near the relatively small city of Cedar Rapids.

The Pre-Commercial Era

The siting practices of the commercial era represent a significant change from the safety philosophy of the early post-World War II period. Under the AEC's military program, there was greater receptivity to the explicit use of siting as a safety device. The earlier approach is exemplified by a 1948 memorandum of the AEC's Reactor Safeguard Committee *(139)*. Reporting on the risks to the general public posed by the graphite-moderated, plutonium production reactors then in operation at Hanford, Washington *(140)*, the Committee recommended establishment of an AEC "control area" around each reactor, *within which residential population was to be completely excluded*. The suggested minimum radius for this area was $0.01\sqrt{P}$ miles, P being the total thermal power in kilowatts. For the power levels of 250,000 KWth then in use at Hanford, this radius is 5 miles. The Committee reached the unanimous judgment that the minimum radius could not "be sensibly reduced at present or in the foreseeable future," *(141)* and suggested that settlement of the control area be allowed only after the development of "some inherently *infallible* device to overcome the danger from instability of these piles [reactors] to loss of water and positive temperature coefficient of reactivity ..." *(142)*. The Committee's reasoning parallels in many respects the discussion in Section II. They distinguish between individual and societal risks, and between risks faced in the "control area" and smaller risks in regions beyond. They emphasize, moreover, the directional character of the hazards, and their dependence on local conditions:

> Outside [the] control area there is a region of real but much smaller hazard -- hazard so small as to be considered tolerable for any individual resident because of the combined effect of safety afforded by the isolation distance contained in the control area and by the low probability of a major reactor accident with good design and careful operation. It seems to us reasonable that this area be inhabited, but we recommend that it not contain any large center of population. We believe it is not possible to set any definite radius for this "hazard area," because in any case not only are the type and power of the reactor significant, but also local meteorological, climatological, topographical, and hydrographic conditions lead to different evaluation of the hazards in different directions. In the case of the existing Hanford Piles we estimate that this "hazard area" extends far enough to include the city of Spokane *(143)*.

Later Developments

If the Reactor Safeguard Committee's view of safety and siting had been adopted in the commercialization program, a remote siting policy would have been the natural result. The required exclusion areas are large - with radii of approximately 20 miles for 1100 MWe reactors - and to achieve such isolation, sites necessarily must be remote. It is likely, however, that remoteness of available sites would have discouraged utility participation in the program, and would have led to extensive public control, if not outright ownership, of nuclear generation facilities. In the practical, political context of the Atomic Energy Act of 1954, which represented a major victory for proponents of private ownership of electric power plants *(144)*, a remote siting policy was not a feasible possibility *(145)*. The policy actually adopted represents a compromise between the objectives of assuring safety and of encouraging private participation: license applicants are given credit, in siting terms, for "engineered safety features" such as containment buildings and specialized safety equipment, while de facto minimum restrictions on distances to population centers are maintained *(146)*. As shown in Table 7, under the de facto distance regulations, reactors have not been allowed within 10 miles of a city of 100,000 or more.

The de factor minimum distance restrictions represent the tacit admission that potential major accident consequences warrant consideration in making siting choices, and in part the realization - evident from the debate over the Fermi-1 reactor - that public reaction to proposed reactor sites within cities is likely to be severe. The de facto restrictions have not, however, gone unchallenged. During the 1960's, utilities proposed a number of high population sites. Most notable is the Consolidated Edison Company's attempt in 1962 to site a reactor underground in the Borough of Queens, New York City. That proposal, and others, were discouraged by the AEC Regulatory Staff on the grounds that the neighborhood "population distribution was several times higher than the highest ... previously approved ..." *(147)*. More recently, the NRC Staff disapproved a high population site 16 miles north of Baltimore *(148)*.

Justifying the De Facto Restrictions: Quantitative Methods For Risk Assessment

With the passage of NEPA, its direct application to the AEC by the United States Court of Appeals for the District of Columbia Circuit *(149)*, and the growing political pressure generated by the environmental movement, it became clear that more explicit justification for nuclear reactor regulations, including siting as a critical element, was essential. During the 1970's, in parallel with the efforts of other agencies, the AEC and its successor NRC began to develop quantitative methods for justifying safety-related decisions *(150)*. The introduction of quantitative risk assessment subtly changes the regulatory process. In particular, it shifts the relative emphasis on scientific and process-related matters, alters the overlapping spheres of authority and competence of risk analysts and decisionmakers, and modifies in important ways the task of assuring there are adequate external constraints on regulatory actions. We close this section by remarking briefly on the issue of external control, raising the question whether effective external scrutiny of NRC actions is possible within the framework of the Regulatory Staff's quantitative methodology. Similar questions can be raised concerning the quantitative risk assessment methods employed by other agencies, such as EPA and OSHA.

The General Risk Estimation Problem - To make the discussion clear, we outline an idealized, quantitative risk assessment. Assume there exists a set of N risk-creating situations (S_1, S_2 ..., S_N). With each S_i are associated an estimated probability P_i and health consequence C_i. Without loss of generality, we number the C_i in order of decreasing consequences *(151)*.

We call the P's and C's "primary risk factors." At a deeper level of analysis, let the consequences C_i be represented as simple products $(a_i b_i)$ of "secondary risk factors" a and b, assumed to be empirically observable. For example, a_i may represent the frequency with which the wind blows in a given direction (i) and b_i the population within the corresponding angular sector (cf. Fig. 1). For simplicity, assume the probabilities P_i, and their uncertainties, are externally set and generally agreed upon. Then the risk assessment procedure calls for:

(1) evaluation of the secondary risk factors (a_i, b_i).

(2) computation of the corresponding consequence estimates C_i, including the statistical uncertainties flowing from empirical data governing the a's and b's.

(3) description of the potential uncertainties in the assumed relation between the C's, and the a's and b's.

(4) statement of the estimated probabilities P_i, including their uncertainties.

(5) formulation of an explicit rule $R(P_1, P_2, \ldots, P_N; C_1, C_2, \ldots, C_N)$ for combining the P's and C's into an overall yardstick for "risk." Risk yardsticks in actual use include the *expected risk* $\Sigma\ P_i C_i$, the "worst-case" consequence C_1, the "worst-case" probability P_1, and the expected risk $P_1 C_1$ of the "worst-case" alone. In practical applications, the risk rule R may not be labelled as such, but may merely appear as an index used to compare situations or alternative programs.

Two examples of the NRC's use of quantitative methods make the practical implications of this procedure clear.

Population Averaging - In considering siting applications, the NRC Regulatory Staff examines certain population related indices of hazard. In particular, the Staff takes the position that

> If the population density, including weighted transient population, projected at the time of initial operation of a nuclear power station exceeds 500 persons per square mile averaged over any radial distance out to 30 miles (cumulative population at a distance divided by the area at that distance), or the projected population density over the lifetime of the facility exceeds 1,000 persons per square mile averaged over any radial distance out to 30 miles, special attention should be given to the consideration of alternative sites with the lower population densities.
>
> .... The transient population should be taken into account by weighting the transient population according to the fraction of time the transients are in the area *(152)*.

This position is based on important tacit assumptions: *(i)* Cumulative, radial population densities, averaged over angle, and over time spent by part-time residents, constitute appropriate hazard indices for comparing alternative sites; *(ii)* At a deeper level, mean consequence values are appropriate in risk assessment and can justifiably be estimated using averaged secondary risk factors. The tacit assumptions underlying the use of averaging procedures obscure the basis for siting choices, and make it impossible, for all but the most knowledgeable, technically sophisticated observers, to challenge NRC decisions. For example, given the averaging procedures above, it is extremely difficult to credibly raise such questions as whether the Pilgrim, Massachusetts site warrants special attention due to the lack of effective evacuation routes from Cape Cod *(153)*, and whether the channeling effect of the Hudson River Valley *(154)* raises the level of scrutiny which should be accorder the Indian Point, N.Y. site.

These questions concern serious accidents on the "tail" of the probability and consequence distributions. *But averaging over secondary risk factors can effectively eliminate such tails from consideration: It grossly truncates the distributions* ($P_1, P_2, \ldots, P_N; C_1, C_2, \ldots, C_N$) *on which risk estimates and final policy judgments must be based.* In truncating these distributions, the NRC's averaging procedures subtly alter the accessibility of information within the agency, and also therefore the division of authority between agency decisionmakers and risk analysts. Furthermore, the introduction of quantitative methods may make future policy changes, and in particular correction of past errors, more difficult. The complexities of ad hoc quantitative methods and the political costs of challenging them may well have contributed to the reluctance of several sitting NRC Commissioners to involve themselves in the details of safety matters delegated by tradition to the Regulatory Staff *(155)*.

Siting Distances and Emergency Planning Zones - Similar, but more complex criticisms apply to a recent NRC-EPA Task Force recommendation that an "emergency planning zone" of radius 10 miles be established around commercial reactors, in order to reduce accident consequences *(4)*. In part, the Task Force based its recommendation on a finding that "core melt accidents can be severe, but the [conditional] probability of large doses drops off substantially about 10 miles from the reactor" *(156)*. As discussed in Section II, there are intimate connections between siting policy and emergency planning, and the Task Force's findings therefore carry important implications for the choice of objectives for siting policy, and the analysis of the appropriateness of existing metropolitan area sites.

Absolute Accident Probabilities - With respect to the implications of catastrophic accidents, the Task Force's evidence for its conclusions is drawn from the probability and consequence estimates of the NRC report WASH-1400 *(3, 157)*. A fair reading of the discussion of WASH-1400 within the NRC, including the Commission's own public statement on the subject *(17)*, makes clear that the *absolute* probability estimates of WASH-1400 cannot justifiably be used for policy purposes *(158)*. Nevertheless, without conveying to the reader the seriousness of the technical criticisms of the WASH-1400 analysis, the NRC-EPA Task Force uses the WASH-1400 probabilities as a basis for its judgment that a 10-mile emergency planning zone is adequate *(159)*.

Conditional Probabilities of Accident Consequences - The Task Force's conclusion concerning the likely 10-mile extent of serious injuries is also based on its calculations of the *conditional* probability of observing high radiation doses at specified distances from a failed reactor. The starting point of those calculations is an unspecified weighted average of accident "categories" or types taken from WASH-1400 *(160)*. Any such calculation is sensitive to the probabilities of very serious accidents, in which large amounts of radioactivity are released, relative to the probabilities of minor accidents in which the bulk of material from the reactor core is retained within the containment building or harmlessly penetrates the ground *(161)*. Assuming the Task Force directly used the relative accident probabilities in WASH-1400, rather than making their own unspecified estimates, their calculations are technically unsupportable. For the WASH-1400 relative accident probabilities depend on questionable probability averaging techniques *(162)*, on internally inconsistent error propagation procedures *(163)*, and on arbitrarily chosen "human error" and "common mode" failure probabilities *(164)*. Such estimates cannot responsibly be used to make an important policy decision.

Controlling Agency Actions

This brief discussion of quantitative nuclear risk assessment raises serious questions about the effectiveness of external checks on regulatory action. More fundamentally, it calls into question the legitimacy, both perceived and actual, of the nuclear regulatory system. James O. Freedman lists four principal sources of legitimacy for the administrative role in American government: political accountability; indispensibility; effective performance; and demonstrably fair decisionmaking *(165)*. We do not discuss the political accountability of the AEC and NRC here *(166)*. And in the sense that no one would seriously propose self-regulation of the nuclear power industry, the nuclear regulatory system is indispensible. However, the past usage of quantitative risk assessment displays neither fairness nor effectiveness. We have proposed a partial solution, calling for an explicit assessment process, heavily dependent on the use of empirical data, in which the separate elements of risk are explicitly addressed.

These are substantive suggestions which may lead to improvements. But deeper, institutional problems must also be faced. Traditionally, the courts have been the principal means for external control of agency action. We do not question that in principle judicial review constitutes an effective check on government decisions which directly affect individual citizens: social security, health care and the provision of welfare benefits generally. Nor are we concerned over the effectiveness of judicial review of the qualitative aspects of economic regulation. Aside from the more arcane aspects of economic modeling, judges can appreciate the qualitative subtleties of rate-making or antitrust litigation. Our exploration of nuclear regulation suggests judicial review of scientific decisionmaking may be far more problematic. Courts can require agencies to provide checklists of the issues they have addressed in reaching decisions *(167)*. But we are skeptical whether the logical connections among the items on any such list can effectively be plumbed in court *(168)*. If they cannot, external control of scientific decisionmaking may well require institutional innovation.

VI. DISCUSSION AND SUMMARY

We have shown that nuclear siting policies can be used to implement a variety of criteria for limiting the health consequences of accidents. We have expressed those criteria in terms of "prompt fatalities" due to high doses of radiation, and in terms of the period of long-term relocation required to avoid dangerous, chronic exposure to radiation. By siting reactors further from major population concentrations, the maximum number of deaths due to high doses of radiation plausibly can be reduced to levels comparable to those that have been experienced in other modern, peace-time, industrial catastrophes. If effective emergency evacuation and sheltering procedures can be implemented, even further reductions can be made. Two "intermediate siting policies" - represented by regions B and C in Table 1 - are particularly attractive. They can be implemented at costs which do not significantly alter the relative economics of nuclear and coal-based electricity generation. In particular, pursuing either of these policies would, in the long run, be considerably less expensive than implementing the recently promulgated *New Source Performance Standards* for coal-burning power plants. However, the costs of pursuing an extreme remote siting policy - represented by region D in Table 1 - appear to be more substantial. Considering only the incremental transmission costs that would be incurred, such a policy would effectively be equivalent to a moratorium on nuclear energy development.

Our analysis raises three important questions: (1) From a *procedural* point of view, should we adopt a siting policy which emphasizes accident consequences over probabilities?; (2) If such a siting policy is implemented, which of the four policy objectives we have discussed should be pursued?; (3) How should we treat operating reactors, and reactors under construction, that do not meet the criteria established under (2)? While our discussion is specifically directed toward the nuclear power industry, similar questions arise for other industrial activities, such as storing and transporting liquified natural gas and producing and processing toxic chemicals.

1. The General Approach - The case for adopting a procedural approach of the general type we have outlined seems unexceptionable. Special measures for siting have been traditionally used to deal with particularly hazardous industrial facilities *(169)*. Though that intuition is seldom explicit, society seems sensitive to accidents with large potential consequences because it is realized that such accidents may destroy the structure of community life. Current siting practices evade the fundamental public policy issues raised here. They employ highly uncertain probability estimates, without basis in actual experience, to "discount" the consequences that are at issue, and in effect to negate their significance *(169a)*. Recent experiences and analyses suggest those practices are neither politically effective nor objectively defensible. Procedural suggestions of the type we advance will not determine the ultimate outcome of the safety debate, but they will aid in focusing the debate on the central, substantive issues and may lead to a far less arbitrary, and less divisive, decision process.

There is an additional, important implication of our general approach. It suggests the scope of agency authority can be controlled through a higher degree of emphasis on the use of empirical data. It should be understood that such control will affect agencies' opportunities to implement policies in accord with the general thrust of their legislative mandates, but unsupported by hard evidence. The federal courts have taken an opposite tack, allowing freedom of agency action when knowledge on the frontiers of science or technology is involved. The courts reason that such actions are legislative "policy judgments" over which agencies enjoy broad discretion *(170)*. Our reservations about the long-term public health consequences of the lack of external checks inherent in the courts' approach motivates in part the present discussion.

2. *Policy Objectives* - Assuming that an approach similar to the one advanced here is adopted, there remains the question of which siting policy to pursue. That decision should turn on a careful comparison of the costs and benefits of alternative policies. But mechanical cost-benefit techniques cannot be used to make the choice. For while the economic costs of pursuing each of the alternatives plausibly can be estimated, the value to society of mitigating the consequences of catastrophe cannot. Any such evaluation introduces ethical, psychological and sociological considerations which are neither well understood nor easily agreed upon. Ultimately, such a choice is a political one, and a more open process can help to insure a more equitable and wiser outcome. There are, however, practical considerations which make a more stringent siting policy the likely outcome of a process such as the one we suggest:

(i) The nuclear energy option is rapidly disappearing in the face of accelerating opposition based in part on concerns about safety. This trend predates the Three Mile Island accident, and is not likely to be reversed unless the safety issue is more satisfactorily treated than in the past. Thus far, only incremental changes have been proposed: more and better engineered safety features, criminal

penalties for knowing violation of safety regulations, improved operator training and maintenance programs and legal provisions for a shift in ultimate responsibility for decisions in situations immediately endangering public health *(171)*. Setting aside questions about the degree to which these traditional courses of action will actually improve safety, it is important to emphasize that such changes do not meet widely voiced public objections to the present system for evaluating accident risks. They continue the prevailing focus on probabilities and ignore legitimate concerns about the consequences of major accidents. These proposals entail additional costs and are unlikely to affect public perceptions of safety. On the other hand, since more restrictive siting (based on regions B or C in Table 1) entails additional nuclear power costs of less than 10% and allows substantial mitigation of accident consequences, the siting approach must be considered a potentially viable alternative on "cost-effectiveness" grounds alone.

That is not to say that the political acceptability of more remote siting is clear. The public may well continue to resist rights of way for long-distance power transmission. And even with a more remote siting policy the destruction of nearby livelihoods and communities is still possible. Congress may decide that the potential for such tragic losses outweighs the benefits of nuclear electricity production. But if it does so under a more stringent siting policy, such a decision will at least have been taken with the most defensible, not the least defensible, safety policies in mind. Nuclear power may in fact become a major, reliable component of our energy supply system. It should be given an opportunity to contribute effectively.

(ii) In the long run, more remote siting is likely to lead to greater stability and predictability in the nuclear industry. If catastrophic consequences to urban areas are no longer possible, more uniform reactor construction criteria can be seriously considered, the Department of Energy's site bank proposal *(172)* can be reexamined, and a rational institutional framework for nuclear waste disposal can be created. In sum, it is certainly possible that more remote siting is cost-effective along the stability dimension as well.

(iii) Remote siting provides a way to remove the obvious conflict between the probability estimates underlying current regulatory practices and the probability estimates on which the Price-Anderson Act is based. Public support cannot be expected for an industry which argues on the one hand that accident risks are uninsurable, and on the other that they should be ignored. In any case, the public cannot rely on traditional common law remedies to provide incentives for the private sector to consider accident costs in choosing sites, and administrative regulation logically should pick up the slack. The initiative for siting now lies with the utilities, and the fragmented structure of the electric utility industry provides strong disincentives to more remote siting. New legislation and regulations encouraging the formation of utility consortia would therefore go hand in hand with a more restrictive siting policy. Such initiatives would create a presumption that careful consideration of changes in siting procedures is essential.

3. Existing Sites - Whether these and other possible developments would lead to siting restrictions analogous to those represented by our regions B or C, we cannot say. However, assuming more restrictive siting regulations are in fact applied, the problem of dealing with existing near-city sites becomes crucial. The costs of closing plants, purchasing replacement power in the short run, and building replacement capacity are far higher than the incremental costs of building plants further from population concentrations in the first place. Under a more restrictive siting regime, existing reactors therefore require special treatment. For particularly unfavorable sites, such as Indian Point, Zion and Limerick, Pennsylvania, thorough consideration of the value of mitigating potential accident consequences may well lead to a decision gradually to derate and phase out such plants - or to cease construction. For other, more favorable near-urban sites, it would be more sensible to institute formal, particularly stringent emergency plans and to impose additional operating restrictions and special construction requirements.

We live with the risks of catastrophic reactor accidents because of conscious choices by those we have given the responsibility to protect public health and safety. The same people can choose to reduce those risks without eliminating nuclear energy entirely. Had it not been for the fear of public reaction to frank discussions of nuclear safety, decisions to reduce risk could have been made long ago. Justice Holmes reminds us we often must "wager our salvation upon some prophecy based upon uncertain knowledge" *(173)*. But Holmes would have been the last to suggest that decisions should be made in deliberate ignorance of their potential consequences. Information about those consequences cannot be swept aside, to be examined only after a serious accident. Rationality demands that we understand, as a society, the terms of our technological wagers.

REFERENCES AND NOTES

1. Proposed NRC Authorization Act, S.562, 96th Cong., 1st Sess. §108(a)(3) (1979)(Senate passage 125 Cong. Rec. S9606, July 17, 1979).

1A. It is current NRC practice to state explicitly in environmental impact statements for commercial reactors that "Class 9," or catastrophic accidents are not considered. See, e.g., U.S. Nucl. Reg. Comm'n, *Draft Environmental Impact Statement, Palo Verde Units 4 & 5,* NRC report NUREG-0522 (Washington, D.C., April 1979), Sect. 7. A regulatory amendment pending for some years would formally incorporate a rule of exclusion into NRC regulations. Proposed Annex to 10 C.F.R. § 50 app. D, *Fed. Register* 36, 22,851 (1971).

2. Brief of the Government, Carolina Environmental Study Group v. United States, 510 F.2d 796 (D.C.Cir. 1975), p. 4.

3. E.g., U.S. Nucl. Reg Comm'n, *Reactor Safety Study,* NRC report WASH-1400 (Gov't Printing Office, Washington, D.C. 1975), chap. 6.

4. The "defense in depth" philosophy is not widely understood. It is generally assumed that the design requirements of "defense in depth" are frontally directed against the occurrence of major accidents, and that engineered safety features are in some sense intended substitutes for remote siting, emergency planning and other outside-reactor safety measures. See, e.g., Union of Concerned Scientists v. AEC, 499 F.2d 1069, 1085, 1089 (D.C. Cir. 1974)(confusing the general reactor cooling *function* with the operation of the *specific cooling system* (ECCS) under controversy, and erroneously suggesting that ECCS malfunction is a necessary condition for catastrophic reactor failure). This is not so, as the current NRC definition of "Class 9" (i.e. catastrophic) accidents makes clear:

> [Class 9 accidents are] considered to be so low in probability as not to require specific additional provisions in the design of a reactor facility. Such accidents would involve sequences of successive failures more severe than those postulated for the purpose of establishing the design basis for protective systems and engineered safety features.

U.S. Nucl. Reg. Comm'n and U.S. Envt'l Prot. Agency, Joint Task Force on Emergency Planning, *Planning Basis For the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants,* NRC report NUREG-0396 (Washington, D.C., Dec. 1978), p. 26 [hereinafter cited as NRC-EPA Emergency Planning Report].

5. For example, though such steps have been widely proposed, the government has not yet provided for emergency supplies of iodine compounds for thyroid blocking in the event of major population exposure, and has not required emergency controlled venting as a way of guarding against catastrophic containment failure.

6. See, e.g., U.S. Dep't of Energy, *Draft Environmental Impact Statement: Management of Commercially Generated Radioactive Waste,* DOE report EIS-0046-D (Washington, D.C., April 1979), Vol. 1, pp. 1.20 - .21 [hereinafter cited as DOE Waste Disposal Report].

7. Linear expected value calculations effectively assume risk-neutrality. It is a commonplace that many important economic phenomena, such as insurance, hedging, diversification of security portfolios, cost-plus contracts and zero-interest money holding exhibit risk-averseness inconsistent with a linear, expected value analysis. See, e.g., K.J. Arrow, *Essays on the Theory of Risk-Bearing* (North-Holland, Amsterdam, 1970), pp. 14-15. One would hardly suppose that a society which exhibits such general risk-averseness in economic decisionmaking would be less sensitive to risks in decisions involving public health. Nor is it easy to imagine a plausible description of the societal reaction to the Chicago DC-10 crash of May 25, 1979, which took 247 lives, in other than risk-averse terms.

There is a school of thought which holds, contrary to the view expressed here, that society should prefer (assuming equal expected values) risk-creating acts with concentrated rather than diffuse consequences:

> If an explosion wipes out a community of 10,000 individuals, most of the people who would have placed a high value on the lives of those killed will have been killed themselves. By contrast, if an additional 10,000 people are killed in auto accidents, most of the major externality sufferers will still be alive. Other things equal, concentrating the lives lost on a geographic basis reduces the externality loss per death. The general lesson is that at least for those closely connected to individuals with lives at risk, it may be beneficial for society to exhibit risk-preferring behavior.

R. Zeckhauser, *Processes For Valuing Lives, Public Policy* 23, 419 (1975), pp. 443-444. On this view, society consists of relatively isolated communities with no ethical responsibility to act in response to each other's tragedies. For Zeckhauser, the fragmented, uncaring society which nuclear opponents fear will result from a reactor catastrophe is already here, and its presence has clear normative implications.

8. Statement of Ralph Nader, in *Oversight Hearings on Nuclear Energy - Overview of the Major Issues, Hearings Before the Subcomm. on Energy and the Environment of the Comm. on Interior,* 94th Cong., 1st Sess. (1975), pp. 74-75, 81.

9. "There have been too many failures, too many incredible accidents that were not deemed credible already, and the program is only in its infancy." *Ibid.* p. 81.

10. See K.T. Erikson, *Everything in its Path, Destruction of Community in the Buffalo Creek Flood* (Simon & Schuster, N.Y., 1976) and ref's cited pp. 266-67.

11. G.D. Bell, "The Calculated Risk - A Safety Criterion," in *Nuclear Reactor Safety* (Farmer, ed., N.Y., 1977), Chapt. 4.

12. See, e.g., WASH-1400 *(3)*, pp. 88-101.

13. See generally, W. Lowrance, *Of Acceptable Risk, Science and the Determination of Safety* (William Kaufmann, Inc., Los Altos, Calif., 1976).

14. The cutoff in probability could logically just as well be applied to consequences. For an interesting, though not fully consistent, attempt to specify the largest accident consequences deserving attention in nuclear policymaking, see Nuclear Energy Policy Study Group, *Nuclear Power Issues and Choices* (Ballinger, Cambridge, Mass. 1977), p. 224 [hereinafter cited as NEPS]. The NEPS group takes the position that "accidents substantially more serious than those included in the analysis of WASH-1400 need not be included in policy considerations." NEPS, p. 224. In particular, they find that maximum consequences larger than those presented in WASH-1400, see note 22 *infra,* do not have policy relevance. NEPS, *ibid.* At the same time, however, they find that nuclear reactor sites differ greatly in their safety implications, and suggest "to the extent that reactors could be located in less potentially risky sites, the average rate-of-loss risk for a particular new reactor could be lowered by a factor of 10 to 100." *Ibid.,* p. 180.

These arguments are not fully consistent with one another. The NEPS group's observations concerning the site dependence of accident consequences are well taken and generally agreed upon. See, e.g., Sprung, *infra,* note 22; Yellin, *infra,* note 65. However, if the full range of siting possibilities vis-a-vis population is considered, the WASH-1400 maximum consequence estimates do not provide an upper limit. Sites directly within major cities - which do not now exist, see Section V *infra* - could result in casualties far exceeding the WASH-1400 estimates, see p. 21 *infra,* while extreme remote sites can cause much fewer casualties. The NEPS discussion suggests their remarks on the maximum consequences deserving attention in policymaking may refer only to existing near-city sites, such as Zion and Indian Point. NEPS, *ibid.,* pp. 231-32. This position too appears incorrect. The WASH-1400 maximum consequence estimates with which the NEPS group expresses qualified agreement in fact represent an average over the maximum consequences possible at existing sites. Site-specific WASH-1400 maximum consequence estimates, particularly for Zion, are considerably higher. See note 22 *infra.*

15. Among these variables are ground roughness and more general topographic features, the rate at which suspended particulates are deposited to ground, isotope-specific coefficients of biologic response to ingestion, inhalation or external exposure, differential susceptibility to radiation by age, population density neighboring a reactor and the effects of exposure to radiation on the rate of appearance of "multi-factorial" genetic disease.

16. For a recent example of such calculations see Aldrich, McGrath & Rasmussen, "Examination of Offsite Radiological Emergency Measures For Nuclear Reactor Accidents Involving Core Melt," Sandia Laboratory report SAND78-0454 (Albuquerque, N.M., June 1978).

17. WASH-1400 *(3)* comprises the most ambitious attempt to date to quantify reactor failure probabilities. After considerable criticism from outside reviewers concerning the understated range of uncertainty in the WASH-1400 probability estimates, the NRC established an internal review group which concluded:

> We are unable to determine whether the absolute probabilities of accident sequences in WASH-1400 are high or low, but we believe that the error bounds on those estimates are, in general, greatly understated. This is true in part because there is in many cases an inadequate data base, in part because of an inability to quantify common cause failures, and in part because of some questionable methodological and statistical procedures.

Risk Assessment Review Group, *Report to the U.S. Nuclear Regulatory Commission,* NRC report CR-0400 (Washington, D.C. 1978), p. viii. The Commission subsequently announced it "does not regard as reliable the Reactor Safety Study's [WASH-1400] numerical estimate of the overall risk of reactor accident." U.S. Nucl. Reg. Comm'n, Statement on Risk Assessment and the Reactor Safety Study Report [WASH-1400] in light of the Risk Assessment Review Group Report (Jan. 18, 1979), p. 3.

18. This definition of arbitrariness is familiar in administrative law. See, e.g., L. Jaffe, *Judicial Control of Administrative Action* (Little-Brown, Boston, 1965), p. 595 (quoting ICC v. Louisville & N.R.R., 227 U.S. 88, 91-92 (1913)(Lamar, J)). The tendency to introduce arbitrariness into technological decisionmaking through the use of formulistic, cost-benefit reasoning has been stressed by L.H. Tribe, *Technology Assessment and the Fourth Discontinuity: The Limits of Instrumental Rationality, S. Cal. Law Rev.* 46, 617 (1973).

To avoid arbitrariness in scientific decisionmaking, society must face a difficult, and by now familiar, dilemma: Technical "expertise" is often essential, but in a democracy the role of narrow, disciplinary groups in making political decisions must be limited. Achieving the requisite balance is not easy. Richard Zeckhauser, *supra* note 7, provides an example in point. Having assumed that concentrated accident consequences kill all those who have mutual ties, and that dispersed consequences do not, he concludes that risk-preferring behavior may be socially beneficial. He then suggests that

> [m]any individuals not trained in utility theory and cost/benefit analysis find it difficult to understand this argument [as to the desirability of risk-preferring behavior] or accept its conclusion. This raises a difficult question of elitism. Should paternalistic decisions be made for them, i.e., doing for them what they would likely choose to do if they spent the possibly many hours that would be required to understand the situation fully, or should society respect their expressed preferences?

Zeckhauser, *supra*, p. 445 n. 30. This view does not adequately consider the possibility that leaving the responsibility for making difficult decisions to a small group of people with common disciplinary backgrounds is likely to lead to decisionmaking which is arbitrary- and therefore illegitimate, see p. 52 *infra*- and also corrosive of the scholarly traditions from which it springs. With respect for Professor Zeckhauser, and for the practitioners of decision theory generally, claims to broad intellectual authority based on technical skills for good reasons have historically been difficult to sustain.

> But, men of Athens, the good artisans also seemed to me to have the same failing as the poets; because of practising his art well, each one thought he was very wise in the other most important matters, and this folly of theirs obscured that wisdom, so that I asked myself in behalf of the oracle whether I should prefer to be as I am, neither wise in their wisdom nor foolish in their folly[.]

Plato, *The Apology* (Fowler, transl., Harvard & Heinemann, Cambridge & London 1914), p. 87. We do not say that certain formal techniques have no proper policy function, but that the integrity of both scholarly and political life demands that the role of technique in policymaking should be closely circumscribed.

19. See NRC-EPA Emergency Planning Report *(4)*, pp. 14-15.

20. See, e.g., Joint Comm. on Atomic Energy, S. Rep. No. 94-454, 1st Sess. (1975), pp. 15-16 (1975 Price-Anderson Act renewal).

21. The largest peacetime industrial disaster in the 20th century United States was the 1947 Texas City ship explosion, which killed 510 people. In addition, the Iroquois and Coconut Grove theater fires in Chicago and Boston resulted in 602 and 491 deaths respectively. For a summary of major 20th century disasters, see WASH-1400 *(3)*, Chap. 6.

22. The maximum nuclear accident consequences computed in WASH-1400 are 3,300 prompt fatalities, 45,000 eventual deaths from cancer, 240,000 cases of thyroid nodules and 29,000 cases of induced genetic disease. *Ibid.*, App. XI, p. 4-1. These consequences assertedly would occur at a frequency of one per billion years of reactor operation. *Ibid.* The probability estimates of WASH-1400 are subject to serious criticism, however, and are not accepted as definitive by the NRC. See note 17 *supra.* Furthermore, the maximum consequence estimates represents an average over widely differing existing reactor sites. Considering prompt fatalities alone, a consequence calculation using the WASH-1400 computerized consequence analysis results in maximum consequences which vary among sites by at least a factor of 100, the largest occurring for Zion, Illinois with an estimated total of 36,000 prompt fatalities. See J.L. Sprung, "An Investigation of the Adequacy of the Composite Population Distributions Used in the Reactor Safety Study," Sandia Laboratory report SAND 78-0556 (Albuquerque, N.M., Oct. 1978), p. 44. For Indian Point, the corresponding figure is 6,500. The Zion and Indian Point estimates are consistent with the statement in the text, but may underestimate the maximum number of prompt fatalities at those sites. See p. 21 *infra.*

23. An analogous view of attempts to introduce precision into the criminal process is taken by Charles Nesson, *Reasonable Doubt and Permissive Inferences: The Value of Complexity, Harv. Law Rev.* 92, 1187 (1979), pp. 1197, 1199.

23a. For attempts to apply the simple expected value formula *risk = probability X consequences* see WASH-1400, *supra* p. 9; DOE Waste Disposal Report, *supra* Vol 1, pp. 1.20-.21. A somewhat more interesting though still problematic, expected value approach to risk evaluation is suggested by Page, *A Generic View of Toxic Chemicals and Similar Risks, Ecol. Law Quart.* 7, 207, 210-12 & n. 4, 236-37 & n. 73 (1978).

24. We note in passing that the technical issues to be discussed below do not originate with us. Internal AEC discussions of the relations between siting location and safety were evidently held at least as early as 1947. See AEC report WASH-88, discussed *infra* pp. 44 - 45 . Furthermore, recent surveys of long-distance transmission costs have been made in connection with studies of remote, clustered reactor siting. See sources cited *infra,* notes 54 & 102.

25. Z. Medvedev, *Soviet Science* (Norton & Co., NY, 1978), App. II. There is independent evidence from other accounts, and from released CIA documents, that a large release of radioactivity occurred in the Sverdlovsk area in 1957. Medvedev suggests an explosion of a nuclear waste disposal facility caused the contamination. *Ibid.*, p. 235. That explanation is not convincing, for it is unclear how an explosion involving such large amounts of radioactive, but ostensibly non-explosive material could have taken place. The indirect evidence in the Soviet radiobiological literature cited by Medvedev may shed light on this question and deserves further study. See *ibid.*, pp. 237ff.

Aside from the accidents mentioned in the text, there have been a number of relatively minor incidents in which radioactivity was detected outside the reactor building. See T.J. Thompson, Accidents and Destructive Tests, in *The Technology of Reactor Safety* (Thompson and Beckerley, eds., MIT Press, Cambridge, 1964), Vol. 1. The most serious of these was the SL-1 reactor accident in 1961 at the National Reactor Testing Station, Idaho Falls, in which three workers received lethal radiation doses and several hundred curies of Iodine-131 were released. *Ibid*, pp. 653ff.

26. U.S. Nucl. Reg. Comm'n., *Regulatory Investigation Report, Browns Ferry Units 1 & 2, Fire in Cable Spreading room* (July 25, 1975, Washington, D.C.).

27. F. Finlayson, letter to H.W. Lewis, Sept. 29, 1978. (On file, NRC Pub. Doc. Room, Washington, D.C.).

28. N.Y. Times, Mar. 29, 1979, p. 1.

29. Through 1978, there were approximately 375 years of operation of commercial, light-water reactors with rated power capacity greater than 100 MWe.

30. Potassium iodide, taken prior to exposure to radioiodines from a nuclear reactor accident, would block thyroid absorption. Stockpiling of potassium iodide for emergency purposes is relatively cheap and has been endorsed by the National Council on Radiation Protection and Measurement (NCRP). See *Protection of the Thyroid Gland in the Event of Releases of Radioiodine*, NCRP report 55 (Washington, D.C. 1977).

31. Other, engineering-related consequence mitigation methods have been proposed, including fundamental reactor design changes and (less radical) modifications in light water reactor (LWR) containment buildings and safety systems. For a review of proposed LWR modifications, see Civil Operations Division, Aerospace Corporation, "Alternatives to Underground Nuclear Power Plant Siting," Aerospace Corp. report ATR-77 (7652)-1 (El Segundo, Cal., April 1977).

32. E.g., F. Pasquill, *Atmospheric Diffusion* (2d ed., John Wiley, N.Y., 1974), Chapters 4-6.

33. See U.S. Atomic Energy Comm'n , *Meteorology and Atomic Energy 1968* (NTIS report TID-21490, D.H. Slade, ed., reprinted Springfield, Va., 1977), Chapter 7 [hereinafter cited as Slade].

34. We do not discuss the ingestion pathway to exposure here. We assume that food production in any heavily contaminated area would be restricted and that the problem of ingestion would mainly result from low-level contamination over a wide area.

35. Including inflammation (thyroiditis), general dysfunction (hypothyroidism) and thyroid growths (nodules). According to one recent set of estimates, roughly 3/4 of induced thyroid nodules would be benign in children and 2/3 would be benign in adults. See WASH-1400 *(3)*, App. H to App. VI, § H 4.4. For a sense of the large uncertainties in those estimates see Lewis et al. *(50)*, pp. S101-S102.

36. Including vomiting, lack of appetite (anorexia) and diarrhea, accompanied by nausea.

37. See, e.g., the genetics effects comparison in NEPS, *op. cit. supra* p. 171. See also the discussion of high-dose lethal effects, *infra* note 45a.

37a. "Rain-out" rapidly removes atmospheric particulates, and under accident conditions could cause very heavy radiation doses in a populated area passed over by a cloud emitted from a failed reactor. For a general discussion, see Slade, op. cit. *supra,* § 5-4.

38. Roughly speaking, the distance fall-off can be represented as $D(R) \simeq R^{-a}\exp[-f(R)]$, where R is the distance from the reactor, a is a positive exponent determined in part by the assumed physics of the transport process and in part by meteorological conditions, and the exponential term in f(R) represents the combined effects of deposition to ground and spreading of the emitted material. A range of idealized formulae appears in the literature. An American Physical Society group has proposed a model in which the reactor effectively acts as a vertical line source, spreading uniformly through an angular sector whose orientation is determined by wind direction (cf. Fig. 1). In that case D(R) takes the simple form $e^{-\lambda R}/R$. See H.W. Lewis et al., *Report to the American Physical Society by the study group on light-water reactor safety, Rev. Mod. Phys.* 47 (supp. 1)(1975), pp. S96-97, [hereinafter cited as APS Report]. A somewhat faster fall off is used by the NRC in computing an index for comparing population distributions around alternative sites. The NRC index assumes $D(R) \simeq R^{-1.5}$. Deposition is neglected. See, e.g., U.S. Atomic Energy Comm'n, *Technical Report on a Technique for Consideration of Population in Site Comparison,* AEC report WASH-1235 (Washington, D.C., Oct. 1974). This behavior corresponds to the fall-off with distance of the maximum concentration of material diffusing from a point source, in a medium moving with uniform velocity. See, e.g., Carslaw & Jaeger, *Conduction of Heat in Solids,* (2d ed. Oxford, N.Y., 1959), § 10.7. A third model has been used in an early discussion of reactor safety by the

AEC Committee on Reactor Safeguards. See AEC report WASH-88 [untitled] (Washington, D.C. [undated] ca. 1948)(declassified in pertinent part, 1974), pp. 24-43, discussed *infra* pp. 44 - 45. They assume uniform spherical diffusion, so that $D(R) \simeq R^{-2}$. Because of the relatively sharp thresholds for high-dose effects, see note 45a *infra* and accompanying text, all three models suggest some protection can be afforded by using siting restrictions.

39. See Sect. V *infra*.

40. WASH-1400, *op. cit.*, App. VI, Table 3-1.

41. WASH-1400 (3), App. VI, Table 2-1, shows release fractions for serious accidents in PWR's and BWR's ranging from 40-90% for the inorganic radioiodines, 5-10% for the alkaline earths, and 30-70% for fission products such as cesium and tellurium. Our estimate of the release fraction for transuranic elements is a factor of two larger than in WASH-1400. These elements in any case contribute little to the consequence estimates.

42. These proportions appear comparable to those implicit in WASH-1400 (3). See, e.g., App. VI, Fig. 13-1. Our 24-hour I-131 ground dose conversion factors are: 130r/ci-m^2 (whole body); 163r/ci-m^2 (bone marrow). WASH-1400, App. VI, Table 3-1, shows a core inventory of 85 million curies of I-131, which we combine with our assumed release fraction of 60% to reach the estimate of 50 million curies used in the text.

42a. Standard meteorological dispersion models apply to flat, featureless terrain. See Pasquill, *op. cit.*, p. 354.

43. A "rad" is a standard unit representing 100 ergs of absorbed radiational energy per gram of tissue. A "rem" is a biological unit of dose, defined as the product of the absorbed dose in rads times an assigned "quality factor" characterizing the radiation of interest. For the gamma and beta radiation discussed here, the quality factor is essentially one, and we therefore use the terms rad and rem interchangeably.

44. Brent & Gorson, *Radiation in Pregnancy* in Moseby et al., eds., *Current Problems in Radiology* (Yearbook Med. Publ., Chicago, 1972) Vol. 2.

45. E.D. Thomas et al., *N. Eng. J. Med.* 292, 832 (1975). A recent report describes the treatment of four patients, suffering from chronic granulocytic leukemia, with 920 rads of whole-body gamma radiation. All four survived. Fefer et al., *N. Eng. J. Med.* 300, 333 (1979).

45a. Observed lethal, whole-body doses for external exposure cover a range from less than 100 rads for early fetal exposure to $LD_{50} \sim 300r$ for late fetuses -- Brent & Gorson *(44)* -- to 1000 rads for hospital patients exposed theraputically and subsequently given intensive care. E.D. Thomas et al. *(45)*. A recent discussion is given in WASH-1400, *supra*, App. F. to App. VI. For healthy adults, it appears that mortality rises from negligible to nearly 100% over the range 200 to 600 rads. See, e.g., V.P. Bond et al., *Mammalian Radiation Lethality* (Academic Press, N.Y. 1965), pp. 121-22.

To emphasize the subtlety of the biomedical questions dealt with here, we note that cooperative interaction of combined acute, external and internal radiation doses, such as may be experienced by some individuals during a reactor accident, may substantially reduce the threshold for lethality. See WASH-1400, App. F to App. VI, p. F-22.

Because of the fragmentary data and the impossibility of experiments on humans, estimates of acute dosage for 50% mortality (LD_{50}) vary widely. One useful summary, A.C. Upton, *Radiation Injury* (Univ. of Chicago Press, 1969), Fig. 12, shows an LD_{50} range 300-600r. Another discussion, Lushbaugh, "Human Radiation Tolerance," in Tobias & Todd, eds., *Space Radiation Biology and Related Topics* (Acad. Press, N.Y. 1974), Fig. 10.1, presents a fitted probit range 190-300r. Assuming that "supportive" medical care will be available, the WASH-1400 medical advisory panel recommended use of $LD_{50} = 510r$, for death within 60 days. *Ibid.*, App. VI, §9.2.2.1. Our examination of the data and consideration of the possible cooperative dose-effects, and of the likely availability of prompt, extensive medical treatment following a catastrophic accident suggests the somewhat lower value $LD_{50} = 350$ rads given in the text.

It should be emphasized that the use of population-averaged dose-mortality curves tacitly introduces assumptions concerning the relative importance of high-dose exposure of groups with different susceptibilities within the population. We choose a single numerical LD_{50} here purely for illustrative convenience. In a proper regulatory treatment, high-dose consequences should be reasonably disaggregated by age and other susceptibility indices in order to provide ultimate decisionmakers with the fullest possible information concerning risks. The importance of tacit assumptions in averaging procedures is further discussed in Section V *infra*.

46. National Academy of Sciences - National Research Council, *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation,* (NAS-NRC, Washington, D.C. 1972), p. 89.

47. National Academy of Sciences - National Research Council, *Long-Term Worldwide Effects of Multiple Nuclear Weapons Detonations* (NAS-NRC, Washington, D.C. 1975), pp. 165-167. See also U.S. Dep't of Health, Education and Welfare, *Report of the Science Work Group of the Interagency Task Force on Ionizing Radiation: Biologic Effects of Ionizing Radiation* (Washington, D.C. 1979).

48. F. Pasquill, *op. cit. supra*, Chap. 6.

49. D.B. Turner, *Workbook of Atmospheric Dispersion Estimates* (Gov't Printing Office, Washington, D.C. rev. 1970).

50. APS Report, *op. cit. supra* note 38, pp. S45-S46, S97.

51. See, e.g., American Meteorological Society, Comm. on Atmospheric Turbulence and Diffusion, *Bull. Am. Meteorol. Soc.* 59, 1025(1978).

52. See generally E.S. Mills, *Urban Economics* (Scott, Foresman, Glenview, Ill. 1972), pp. 95ff. See also J. Yellin, *J. Urban Econ.* 5, 305(1978).

53. For comparison we note that WASH-1400, *op. cit.*, App. XI, Table 4-1 estimates that, on the average, 670 cancer deaths and 130 genetic "effects" will accompany each prompt fatality caused by a reactor accident. For the largest accidents, the corresponding figures are 14 and 8 respectively. Empirical values for, λ^{-1}, the population shape parameter *(52)* range from 16 miles for Los Angeles to 1.5 miles for a small city such as Utica, New York. D. Harrison and J.F. Kain, *J. Urban Econ.* 1, 61 (1974). We use a nominal value λ^{-1} =10 miles here. Our $D(\vec{r})$ is such that 50% lethality occurs anywhere in the range 1-20 miles.

54. U.S. Nucl. Reg. Comm'n, *Nuclear Energy Center Site Survey*, NRC report NUREG-0001 (Gov't Printing Office, Washington, D.C., 1976), Pt. I, p. 4-63, [cited below as NECSS].

55. WASH-1400 *(3)*, App. VI, Fig. 11-2. The motivation behind the WASH-1400 choice of evacuation area is not made clear there, but we are informed by our colleague N.C. Rasmussen (private communication, June, 1979) that lethal doses were the main concern.

56. J.J. Fuquay et al., *J. App. Meteorol.* 3, 761 (1964). It should be emphasized that tracer measurements are not inherently absolutely reliable. See generally Pasquill, *op. cit.*, pp. 170-172.

57. J.J. Fuquay, "Environmental Safety Analysis," in Slade, *op. cit.*, pp. 382-385.

58. Defined as $\sigma_\theta \bar{u}$, the standard deviation of the horizontal wind direction times the average windspeed.

59. Here the shielding factor measures the degree to which gamma radiation from contaminated ground is attenuated by structures, ground roughness, etc., before people are exposed. For comparison, WASH-1400, *supra,* App. VI, Table 11-12 shows average shielding factors ranging from 0.26 to 0.38 for different areas of the country, for persons sheltered in existing structures, and a range 0.5-0.8 for shielding in the open above ordinary ground. *Ibid.,* pp. 11-27.

60. For the spatial deposition pattern, see Fuquay, *op. cit. supra* note 57, Fig. 8.5. The acute short-term dose is dominated by Tellurium-132 and the radioiodines.

61. In nuclear regulatory jargon, our computation is "conservative." For comparative purposes, we note that more optimistic results follow from the simple uniform diffusion model *(50)*. A calculation using similar weather conditions to the above leads to 50% lethality within 18 miles, with a 90%-10% range of 14-22 miles. A still smaller 50% lethality range of 10 miles follows from a standard Gaussian transport model, using the F-type diffusion coefficients given by Turner *(49)*. In the text, we follow the prescriptions of Section I and depend only on the data-based, Hanford extrapolation. The difference in emphasis between the standard consequence calculations and our empirical approach can be put as follows.In estimating the consequences of a major accident at a specific site, the standard procedure uses empirical data for the frequency distributions, wind direction and velocity, and of the occurrence of standardized meteorological conditions, and inserts them into a standard meteorological model *(48,49)*.

We, on the other hand, insist that any such estimate be based on a projection of accident consequences under specific, unfavorable weather conditions, actually observed around the site in question. Ideally, these conditions would be specified by performing a series of atmospheric transport experiments at the site, under a priori unfavorable weather conditions. Neither procedure "solves" the meteorological sector of the consequence assessment problem. The standard model is not designed for use at the long distances necessary here, and it is well-known that its less favorable weather categories bear little relation to reality in a number of plausible circumstances. See e.g., *Physical Behavior of Radioactive Contaminants in the Atmosphere,* IAEA (Vienna, 1974), pp. 510-515.

Furthermore, our procedure requires a subtle and expensive experimental program, and its results would be subject to criticism on the grounds that its observations were so atypical as to grossly overestimate risks, or so fragmentary that the least favorable cases had not been observed. The choice is between sub-optimal methods for incorporating meteorological information into risk assessments. For the reasons given in the text, we prefer an emphasis on observation over simulation. For a study with many of the features we suggest, see W.A. Lyons, "Turbulent Diffusion and Pollutant Transport in Shoreline Environments" in American Meteor. Soc., *Lectures on Air Pollution and Environmental Impact Analysis* (mimeo, Boston, 1975), Chap. 5.

62. U.S. Atomic Energy Comm'n, *Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants,* AEC report WASH-740 (Gov't. Printing Office, Washington, D.C. 1957).

63. U.S. Census data for 1970 shows that average population densities in major cities range from 7,500 per square in Milwaukee and 11,000 per square mile in Detroit, to 68,000 per square mile in Manhattan, New York. Central-city densities are considerably higher.

64. E.G. Case, internal NRC memorandum to the Commissioners, SECY-78-137, Mar. 7, 1978, Table C-2. The site in question was not approved. It should be noted that the NRC calculation applies to a reactor with electric power capacity of approximately 1360 MWe, rather than the 1200 MWe capacity assumed in our calculations. *Ibid.,* p. C-3.

65. See J. Yellin, *Bell J. Econ.* 7, 319 (1976). At issue here is the combined analysis of population distribution, wind direction, air temperature, and general weather stability. The data are in Consolidated Edison Co., *Indian Point Nuclear Generating Unit No. 3, Preliminary Safety Analysis Report,* AEC Docket No. 50286, Apr. 26, 1967, pp. Z-19ff.

66. At these dose levels, there is controversy over whether biologic repair mechanisms can act to reduce the rate of induced carcinogenesis and mutagenesis below that expected in the "linear hypothesis" of ref's 46 & 47. For an attempt to quantify the effects of repair, see WASH-1400, App. VI, § G1.4.2.

67. U.S. Environmental Protection Agency, Office of Radiation Programs, *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents* (unpublished, Washington, D.C. Sept. 1975), Table 5.2.

68. Long-range atmospheric transport and diffusion have recently been reviewed by F. Gifford, *Nuclear Safety* 17, 68 (1976). He suggests that it may eventually be possible to extend the conventional Pasquill-Gifford scheme, see sources cited notes 48, 49 *supra,* to distances up to 100 kilometers (60 miles). Gifford, *supra,* p. 77. It should be emphasized, however, that at distances of 50-100 miles from a source of pollutant, the idealized pattern of straight-line travel incorporated in the conventional typing scheme is likely to break down completely. At these distances, the idiosyncracies of regional weather circulation become crucial in determining pollutant flow. For a striking example of such patterns, see Lyons, note 61 *supra.* Calculations which purport to evaluate dispersion patterns at long distances based on simple extensions of the conventional meteorological scheme should therefore be treated with great skepticism.

69. See Aldrich et al., *op. cit. supra* note 16.

70. Aldrich, Ericson & Johnson, "Public Protection Strategies for Potential Nuclear Reactor Accidents: Sheltering Concepts with Existing Public and Private Structures," Sandia Laboratory report SAND77-1725 (Albuquerque, N.M. Feb. 1978).

71. We thank N.C. Rasmussen for calling our attention to his work on evacuation and sheltering and for a helpful discussion.

72. USEPA, *op. cit. supra* note 67, p. 1.35.

73. NRC-EPA Emergency Planning Report, *supra* p. III-15.

74. WASH-1400, *supra,* App. VI, p. 11-6.

74a. At the height of concern over the potential for a major release of radioactivity at Three Mile Island, Pennsylvania officials made contingency plans for an evacuation of 650,000 people living within 20 miles of the plant. They estimated 10 hours would be required to complete the evacuation. "Lt. Gov. Scranton & Col. Henderson's Interview with the French Delegation Concerning Three Mile Island," unpublished mimeo (May 2, 1979), p. 4. This estimate presupposes timely federal aid, including additional ambulances and other equipment. *Ibid.* Evacuation plans were laid in a 24-hour period during 30 March and 31 March. State officials proceeded with the knowledge that prior warning had already been given to the population, that schools had been closed and pregnant women and preschool age children evacuated within a 5-mile radius, that many people had left voluntarily, and that ample radial highway routes were available. Taking the 10-hour estimate as a datum, and in view of the special circumstances, our 24-hour exposure period to evacuate out to approximately 25 miles in the presence of a concentrated metropolitan population seems quite reasonable. See Richard T. Kennedy, "Emergency Planning. The State-Federal Partnership," Remarks Before the Southern States Energy Board, New Orleans (June 4, 1979), *reprinted in* NRC News Releases Vol. 5, No. 23 (week ending June 26, 1979) (Commissioner, NRC) ("At Three Mile Island the planners worked under reasonably good conditions"). An obvious question which should be asked is how long it would take to accomplish an evacuation similar to the one planned at Three Mile Island, in the Philadelphia suburbs surrounding the Limerick, Pennsylvania site.

75. General Accounting Office, *Areas Around Nuclear Facilities Should Be Better Prepared for Radiological Emergencies,* GAO report EMD-78-110 (Gov't Printing Office, Washington, D.C. 1979).

76. B.K. Grimes, USNRC, private communication, June 30, 1979.

77. A. Chamberlain, *J. Roy. Met. Soc.* 85, 350 (1959).

78. J. Crabtree, *J. Roy. Met. Soc.* 85, 362 (1959).

79. The measured ratio Cs-137/I-131 was 0.02 at the point of emission *(76),* and an air filter measurement of the same ratio in air, within 1 kilometer of the site, gave 0.026. A.C. Chamberlain and H.J. Dunster, *Nature* 182, 629 (1958). Long-range deposition shows differences with these results of factors of 2-3. N.G. Stewart and R.N. Crooks, *Nature* 182, 627 (1958). Chamberlain *(77)* suggests these differences result from changing meteorological conditions. For later comments, see Pasquill, *op. cit.,* pp. 318-320.

80. H.J. Gale et al., *Nature* 201, 257 (1964). We therefore make no special provisions for the time behavior of radiation doses from contaminated structures or pavement.

81. *Recommendations of the International Council on Radiation Protection,* ICRP Pub. No. 9 (Pergamon, Oxford 1965).

82. R. Conard, "The Radiological Status of the Bikini People," Brookhaven Nat'l Lab. report (unpublished, Oct. 1978), Table 1 (measurements of R.P. Miltenberger and F.T. Cua). The comparison, however, is not straightforward, because this population received lesser, but still significant exposures over a period of years.

83. The effectiveness of decontamination methods for hard surfaces such as roads or houses, is extremely sensitive to the size of the particles to be removed. The APS Report, *supra,* pp. S95-96, suggests an aerosol of particles 2 microns in diameter could be produced in the containment following meltdown. On the arguments presented in WASH-1400, App. VI, § K 6.1.1, removal of particles of this size by firehosing, sweeping or other non-destructive techniques is likely to be ineffective. Destructive decontamination techniques, i.e. removal of contaminated surfaces, are extremely expensive, as are analogous techniques for decontaminating open land, such as physical removal of soil. Furthermore, the use of destructive decontamination techniques may be politically difficult, as would be the promulgation and public acceptance of rules governing the reoccupation and use of contaminated land. See, e.g., Whiteside, *The Pendulum and The Toxic Cloud, The Course of Dioxin Contamination* (Yale U.P., New Haven 1979), pp. 65ff.

We have nominally assumed that decontamination of residential areas is likely to be ineffective, or relatively so expensive that long-term relocation is the preferred method for reducing chronic exposure. However, if decontamination factors of 5 to 10 or more can effectively and cheaply be achieved, relocation times will be shortened to the time mechanically required for decontamination. Realistically, for a metropolitan area, this time should be on the order of weeks or months.

84. U.K. Medical Research Council, *Criteria for Controlling Radiation Doses to the Public After Accidental Escapes of Radioactive Material* (HMSO, London, 1975).

85. Compare Pasquill, *op. cit. supra,* pp. 365-366.

86. Average radiation doses in the United States are approximately .2 rem, roughly half of which is due to artificial sources. See, e.g., NEPS *(14)*, p. 163. The upper limit in the text corresponds to a Cs-137 level of roughly 5 $\mu Ci/m^2$, a third of the level inferred in the hypothetical Windscale accident discussed above. This seems a reasonable decrease over distances of 100 miles or more.

87. NEPS, *supra,* summarizes previous estimates of the excess cancer deaths expected to result from continuous exposure of the entire U.S. population at the rate of 0.1 rem per year, roughly the maximum dose discussed here. *Ibid.,* p. 168. The results range from 1,000 to 9,000 excess deaths per year, where the normal annual incidence is 311,000. Unless exposure to gamma radiation were to produce a very distinctive pattern of cancer types, such an increase would be undetectable.

Similar comparisons of genetic effects are more problematic, for recent data shows that the number of cases of "multi-factorial" disease may heavily outnumber simple dominant disorders. *Ibid.,* p. 172. The heritability of multi-factorial diseases is not well understood and estimates of radiation-induced genetic defects must be made on an essentially arbitrary basis. See *(46),* p.56. Perhaps the largest percentage effects, 20-40% increases, would occur for chromosomal diseases. NEPS, ***supra,*** p. 171. These diseases, however, occur somewhat infrequently. If linearity holds, then an accident of the type considered here would cause roughly 10-20 excess cases out of 50 in an exposed population of 20 million, a difficult effect to detect. Furthermore, it has been suggested that linearity may not apply to chromosomal aberrations, *(46),* p. 209, in which case the figures above are overestimates.

88. The importance of this question has been emphasized in a recent National Academy of Sciences study of the long-term effects of nuclear war. See *(47)*, pp. 175-176.

89. A majority of the American population presently lives within 50 miles of a nuclear reactor. A recent study points out that 78 of the 100 largest U.S. cities are located within 50 miles of a commercial reactor site. See Burwell, Ohanian & Weinberg, *A Siting Policy For an Acceptable Nuclear Future, Science* 204, 1043 (1979).

90. See, e.g., Burwell et al., *op. cit.,* Fig.3.

91. For an opposing view, see L.H. Tribe, *California Declines the Nuclear Gamble: Is Such a State Choice Preempted?, Ecol. Law Quart.* 7, 679 (1979). Professor Tribe argues the Atomic Energy Act does not preempt three recent California statutes which, in essence, delay siting new commercial reactors until methods for nuclear fuel reprocessing and waste disposal have been approved by the NRC, and a study of underground and "berm" containment of commercial reactors has been completed. See CAL. PUB. RES. CODE §§ 25524.1, .2 (West 1977); *ibid.* § 25524.3 (West Supp. 1978).

> A congressional decision to override the state's rejection of nuclear power might be justifiable if it were reasonably found that the state's resources or territory had to be harnessed to meet the energy or security needs of some other part of the nation.[216] Plainly a court should not assume such a need where the record shows no such determination by Congress.
>
> [216] .... Congress may have intended to foster the development of atomic energy, but there is no clear indication that it found nuclear power plants necessary to meet the energy needs of the nation as a whole.

Tribe, *supra,* p. 721.
With respect, these arguments are entirely mistaken.
The history of the U.S. atomic energy program is replete with evidence that Congress thought nuclear power essential to meet future national needs for energy, not merely to satisfy the energy requirements of scattered localities. For example,
JCAE chairman Holifield began the 1971 AEC authorization hearings on the commercial power program by quoting from a speech in which he said:

> The most important challenge which faces us at this time is to develop a breeder reactor. It is of prime importance to the industry and to the future development of our nation.

AEC Authorizing Legislation Fiscal Year 1971, Hearings Before the Joint Committee on Atomic Energy, 91st Cong., 2d Sess. (Mar. 11, 1970), p. 1131. Nor is direct evidence lacking that interstate electricity generation is now, and in the future increasingly will be, interstate commerce in the clearest sense. The commercial transmission of electrical energy across state lines has long ago been held to constitute
interstate commerce. See, e.g., *Fisher's Blend Station v. Tax Comm'n,* 297 U.S. 650, 654-55 (1936) (radio advertising). And, whatever its own attitudes, California will derive benefits from nuclear-generated power transmitted across its borders. For example, a share of the electricity to be generated by the Palo Verde nuclear station, near Phoenix, Arizona, has been purchased by San Diego Gas & Electric Company, to be transmitted over several hundred miles via its Devers substation. See U.S. Dep't of Interior, Bureau of Land Management, *Final Environmental Statement, Palo Verde-Devers 500KV Transmission Line* (Phoenix, Ariz. Feb. 1979). On Professor Tribe's arguments, Arizona may constitutionally exercise its sovereign powers and thereby deny or delay electricity service to Southern California consumers.

92. We leave open the question of the appropriate distribution of liability between government and industry. As matters stand now, there is a maximum aggregate public liability of $560 million for any one occurrence, see 42 U.S.C. § 2210 (e)(1976), of which $455 million represents industry liability,with the remainder the responsibility of the Government.

93. See U.S. Atom. Energy Comm'n, "Regulatory Investigation Report, Fire at Browns Ferry Units 1 & 2, Fire in Cable Spreading Room" (July 25, 1975), p. 5 (on file, NRC Pub. Doc. Room, Washington, D.C.).

94. *Browns Ferry Nuclear Plant Fire, Hearings Before the Joint Comm. on Atomic Energy, Part 1,* 94th Cong., 1st Sess. (Sept. 16, 1975), p. 19 (testimony of William A. Anders, Chairman AEC and Donald F. Knuth, Director AEC Office of Inspection and Enforcement).

95. See N.Y. Times, March 31, 1979, p. 1, cols. 5-6; Transcript, Closed NRC Meetings, March 30, 1979, Tape No. 1, Side 1, pp. 5, 9, 11-15 (remarks of Harold Denton)(on file, NRC Pub. Doc. Room, Washington, D.C.).

96. See 42 U.S.C. § 2210 (e)(1976). The Price-Anderson aggregate liability limitation has recently been held constitutional, Duke Power Co. v. Carolina Env. Study Group, 98 S.Ct 2620 (1978).

97. *Governmental Indemnity, Hearings Before the Joint Comm. on Atomic Energy,* 84th Cong., 2d Sess. (May-June, 1956), p. 121 (statement of Senator Anderson).

98. Two estimates of maximum economic damages from a nuclear accident are: (1) $14 billion, WASH-1400 *(3)*, app. XI, p. 4-1; (2) $17 billion, Yellin, *Bell J. Econ.* 7, 326 (1976), p. 327. The WASH-1400 estimate is an average over several heavily populated nuclear sites. Yellin's estimate applies to a moderately serious accident at Indian Point, N.Y. Accidents at rural sites would cause far less economic damage.

98a. See generally Aerospace Corp., *op. cit. supra* note 31.

99. See generally P. Lucas, *Nuclear Waste Management: A Challenge to Federalism, Ecol. Law Quart.* 7, 917-953 (1979).

100. Frank Michelman has argued, in a seminal article, that the state may have a duty to protect against the economic hazards "endemic in an unequal society ...." Michelman, *The Supreme Court 1968 Term, Foreward: On Protecting the Poor Through the Fourteenth Amendment, Harv. Law Rev.* 83, 7 (1969). But the Burger Court has not been amenable to providing minimal equal protection against poverty. See Tribe, *American Constitutional Law* (Foundation Press, Mineola, N.Y. 1978), § 61-50. In the text, we implicitly approach Michelman's problem from a different perspective, having in mind an alternative principle that government should provide, as a matter of right, minimum protection against major public health hazards caused by industrial activities.

101. NECSS, *op. cit. supra* note 54.

102. Center for Energy Systems, General Electric Co., *Assessment of Energy Parks vs. Dispersed Electric Power Generating Facilities,* NSF report 75-500 (Gov't Printing Office, Washington, D.C. 1975), Table 3-4 [cited below as GE].

103. *Ibid.*

104. *Ibid.,* Table ES-3. The GE study concluded that scale economies in reactor construction costs would be offset by additional transmission costs for remote siting. The study compares the cost of a nuclear park with 26 GWe to the cost of 10 dispersed sites with the same total power capacity.

105. See NECSS, *supra,* Pt. I, § 4.2.5.1. The NECSS conclusions are similar to those of GE. If equivalent siting restrictions are applied to dispersed sites and to nuclear parks, the nuclear park concept has a decided economic advantage, apart from system reliability and national security.

106. See NECSS, Pt. I, pp. 4-64, 4-67.

107. Whitman, Requardt & Associates, *The Handy-Whitman Index of Public Utility Construction Costs,* Bull. No. 108 (Baltimore, Md., July 1, 1978).

108. A recent Ford Foundation-Mitre Corporation study used a value of $667 per kilowatt in 1976 dollars. See NEPS, *op.cit.*, p. 126. M. Baughman et al. use an average figure of $590/Kw in 1975 dollars, or $670/Kw in 1977 dollars. See Baughman et al. in *Electric Power in the United States: Models and Policy Analysis* (MIT, Cambridge, MA, 1979) in press. The U.S. Government has provided estimates which are lower (in constant dollars) but government estimates have traditionally been below ultimate experience. See U.S. Energy Research and Development Administration, *Comparing New Technologies for Electric Utilities, Draft Final Report,* ERDA report 76-141, December 1976. The South Texas Project estimates the costs of two 1250 MWe plants to go on line in 1982 and 1983 at $2 billion or $800/Kw. In 1977 dollars this would be about $600/Kw. *Nucleonics Week* (Nov. 23, 1978), p. 7. Ebasco Services, Inc. estimates current nuclear plant costs at $1,684/Kw including $735 for escalation, or over $900 per Kw today. *Nucleonics Week* (Nov. 23, 1978), p. 11. Based on conversations with utility planners, our judgment is that our $650/Kw estimate is conservative on the low side.

109. In the United States, commercial reactors are now generally licensed for 40 years, but renewals or extensions are possible. See 10 C.F.R. § 50.51. Our assumed reliability performance may be optimistic. A recent Department of Energy report assumes, in analogy to the past performance of coal-fired power plants, that nuclear reactors begin operation at 40% capacity, increase to 70% in the fourth year, operate for 22 years at 70% and decline linearly to 40% in the fourtieth year. DOE, Waste Disposal Report, *supra* § 2.1.1. The effects of changes in nuclear plant capacity factors on our calculations are subtle. As reactor performance degrades, all capital costs, including the costs of long-distance transmission, increase. In our detailed cost-calculations, we use the 70% capacity factor cited in the text. However, in order to account for the change in the competitive position of nuclear power vis-a-vis coal caused by lower reactor capacity factors, our discussion of the coal-nuclear competition depends on a lower 60% capacity factor used in NEPS, *supra* Table 3-3, note b.

110. GE, *supra*, Table 3-1.

111. U.S. Federal Power Commission, *1970 National Power Survey* (Washington, D.C. 1970), P. I-13-8.

112. See GE, *supra,* pp. 3-14 to 3-18; NECESS, *supra,* Pt. I, pp. 4-6 to 4-7.

113. Baughman et al., *op. cit. supra* note 108.

114. NEPS, *supra,* p. 127.

115. Kidder, Peabody & Co., *Status Report on Worldwide Nuclear Reactors* (N.Y., Oct. 26, 1978), p. 15.

116. Edison Electric Institute, *Statistics of the Electric Utility Industry 1977* (New York, 1977), p. 53.

117. *Electrical Week* (May 28, 1979), p. 2.

118. NECSS, *supra,* Part III, §3.2.1.2.

119. *Ibid.,* § 3.2.1.3.

120. See generally United Engineers and Constructors, *Heat Sink Design and Cost Study For Fossil and Nuclear Power Plants,* . AEC Report WASH-1360 (Dec. 1974); J. Harte and M. El-Gasseir, *Science* 199, 623 (1978).

121. For practical purposes, the net total water input required for a recirculating system ("makeup" flow) is equal to the rate of evaporative loss plus the "blowdown" or effluent rate. Evaporative loss rates are largest for cooling ponds during dry-air periods. A maximum estimate is 37 cfs per 1200 MWe reactor. See U.S. Federal Energy Admin., *Final Task Force Report, Project Independence Blueprint* (Nov. 1974). The required blowdown rate for evaporative systems is sensitive to the presence of impurities, see NECSS, *supra,* § 3.2.2.2.; 10 cfs is a reasonable value, *ibid.,* § 3.3.7.3. An evaporative cooling system for a 10-reactor site requires approximately 300 cfs. A reasonable rule of thumb suggests that maximum consumption be no greater than 10% of a suitable low flow value of a river source. NECSS, Pt. V, § 3.8.

122. See 40 C.F.R. § 423.15 *(l)* (1978).

123. See generally New England Coalition on Nuclear Pollution v. NRC, 582 F.2d 87, 93-96 (1st Cir. 1978).

124. NECSS, *supra,* Pt. III, Table 3.4.

125. *Ibid.,* § 3.3.7.3.

126. *Ibid.,* Pt. V, § 3.10.1, Table 3.6. However, Harte and El-Gasseir, *op. cit.* p. 632, conclude that assuming wide-spread use of evaporative cooling, a future, five-fold increase in total electricity production would result in unacceptable regional water shortages.

127. For a detailed, popular account of the Fermit reactor controversy, from the viewpoint of a nuclear power opponent, see Fuller, *We Almost Lost Detroit* (Reader's Digest Press, N.Y. 1975).

128. The Fermi-1 reactor was sited at Lagoona Beach, Michigan roughly 35 miles from Toledo and 30 miles from Detroit.

129. USAEC, *In re* Power Reactor Development Company, Final Decision and Order, May 26, 1959, 1 AEC 128, 163 (emphasis added). The AEC's authority to impose such a burden of proof requirement was upheld by the Supreme Court. See Power Reactor Dev. Co. v. Electrical Workers, 367 U.S. 396, 414 (1961). *Power Reactor* played an important role in the early development of nuclear power regulation. See Green, *Safety Determinations in Nuclear Plant Licensing: A Critical View, Notre Dame Law.* 43, 633,634-40 (1968).

130. For a general discussion, see USNRC, *General Considerations and Issues of Significance on the Evaluation of Alternative Sites for Nuclear Generating Stations Under NEPA,* NRC report 0499(supp.1)(Wash.D.C.Dec. 1978),pp. 4-10. The NRC's present site comparison criterion is as follows: "Only if no other candidate site appears to be obviously superior to a given site should that site be proposed or accepted as the location of a nuclear power plant." *Ibid.,* p. 6.

131. 42 U.S.C. §§ 4321-4347 (1976).

132. See Seacoast Anti-Pollution League v. NRC, No. 78-1172, slip. op. at 22-23 (1st Cir. May 30, 1979).

133. *Ibid.,* p. 17.

134. Executive Office of the President, Office of Energy Policy and Planning, *The National Energy Plan* (Gov't Printing Office, Washington, D.C. 1977), p. xxi.

135. The NRC Staff appears to be opposed to major changes in siting policy. See generally, NUREG-0499 Supplement, *op. cit. supra* note 130.

136. See 10 C.F.R. § 100.11 (1978).

137. See, e.g., U.S. Nucl. Reg. Comm'n, *General Site Suitability For Nuclear Power Stations,* NRC Reg. Guide 4.7, Rev. 1, Nov. 1975 [hereinafter cited as NRC Siting Guide].

138. Similar conclusions concerning the absence of clear trends in siting distances are reached in an NRC study. See Bunch, Murphy & Reyes, *Demographic Statistics Pertaining to Nuclear Power Reactor Sites*, NRC report NUREG-0348 (Washington, D.C., Dec. 1971), pp. 15-16. There is one exception: Bunch et al. suggest there is a "general trend toward increasing distance" from nearest cities with populations of 25,000 or more. They note, however, that the spread of actual values is large. *Ibid.*, p. 16 & Fig. 19. We see no clear trend in their data.

139. See Reactor Safeguard Committee, "Reviews of Certain Hanford Operations," in [untitled] AEC report WASH-88 (Washington, D.C. [undated] ca. 1948), pp. 24-43 (declassified in 1974 in pertinent part and reissued as General Electric/Hanford report GEH-14040) [hereinafter cited as RSC Hanford Review]. Signing the report were RSC members Teller, Benedict, Kennedy, Wheeler and Wolman.

The Reactor Safeguard Committee was originally established by the AEC, but was given an independent legislative existence by Congress, see 42 U.S.C. § 2039 (1976), following the dispute over the Fermi-1 reactor.

140. Three natural uranium fueled, graphite-moderated, water cooled, plutonium production reactors were in operation at Hanford in 1945. Five units were added in the early post-War period. At this writing, we are not aware of the precise chronology of the additions.

141. RCS Hanford Review, *supra*, p. 25.

142. *Ibid.* (emphasis in original). It should be emphasized that though there are clear parallels here with the contemporary reactor safety debate, the Committee's safety concerns rested to an important degree on characteristics specific to the graphite-moderated, uncontained reactors then in place at Hanford.

143. *Ibid.*, p. 35A. Spokane is roughly 125 miles from the Hanford reactors.

144. The extended, heavily partisan congressional debate on the Atomic Energy Act of 1954 particularly focused on the authority granted the AEC, *id.,* § 164, 42 U.S.C. § 2204 (1976), to contract with private utilities to supply electric power to the Tennessee Valley Authority (TVA). See, e.g., 100 Cong. Rec. 10438-95 (1954). Controversy over public versus private power dominated the debate; there was no evident disagreement over the health and safety provisions of the Act. See New Hampshire v. AEC, 406 F.2d 170, 194n.4 (1st Cir. 1968). The congressional debate over the respective roles of government and industry in nuclear power development continued into the early 1960's. See Green & Rosenthal, *Government of the Atom* (Atherton Press, N.Y. 1963), pp. 254-265.

145. Much the same views are expressed by A. Weinberg, *Salvaging the Atomic Age, The Wilson Quarterly* 3, 88 (1979).

146. See, e.g., C.R.McCullough, Letter to AEC Chairman John McCone (Dec. 15, 1958)(Chairman, AEC Advisory Comm. on Reactor Safeguards) *quoted in* E. Rolph, "Regulation of Nuclear Power: The Case of the Light Water Reactor," Rand Corp. report R-2104-NSF (Santa Monica, Cal. June 1977), pp. 13-14.

147. U.S. Atomic Energy Comm'n, Regulatory Staff Working Paper, "Population Distribution Around Nuclear Power Plant Sites," April 17, 1973 (released April 1974, Washington, D.C.), p. B-1. For a summary of proposed metropolitan area sites, see generally, D. Bunch, *Metropolitan Siting - An Historical Perspective*, NRC report NUREG-0478 (Gov't Printing Office, Washington, D.C. 1978).

148. See H. Denton, letter to John W. Gore, Jr., Vice-President, Baltimore Gas & Elec. Co. (Dec. 1, 1977)(on file, NRC Publ. Doc. Room, Washington, D.C.).

149. See Calvert Cliffs' Coordinating Comm. v. AEC, 449 F.2d 1109 (D.C. Cir. 1971).

150. See, e.g., USAEC Regulatory Staff, *supra* note 147.

151. If accident probabilities and consequences are inversely related, as has been claimed in the literature, see p. 5, *supra,* then the consequence ordering automatically orders the associated probabilities. Roughly speaking, the largest accidents are clearly less probable than the smallest. But it is by no means clear that there is a direct inverse relationship between probabilities and consequences. Design peculiarities or human errors which link ostensibly independent parts of a large system can lead to situations in which minor accidents with relatively high probabilities have very large consequences. A case in point, aptly emphasized by the NEPS group, NEPS *supra* p. 233n.i, is the early configuration of the United States Minuteman missile system, whose linked command and control system insured that a missile firing accident would be large. An analogous nuclear power example is the Browns Ferry fire, in which a relatively common construction fire caused by carelessness and design inadequacies escalated into serious, though fortunately temporary, loss of control of two operating reactor units.

152. NRC Siting Guide, *supra* p. 4.7-16.

153. The summer population of Cape Cod is approximately 472,500, and there are approximately 135,000 permanent residents (private communication, Hyannisport Chamber of Commerce, 1979). Access to Cape Cod is controlled by two highways crossing the Cape Cod Canal. The western half of the cape is within 25 miles of Pilgrim. The outer and eastern cape lie 25 to 40 miles from Pilgrim. We note parenthetically that the total population of Cape Cod, Martha's Vineyard (30-40 miles from Pilgrim) and Nantucket (45-60 miles from Pilgrim) assumed to be at risk in WASH-1400 is about 70,250 (computer read-out, WASH-1400 population data, on file with the authors).

154. See sources cited *supra,* note 65.

155. The depth to which individual commissioners involve themselves in safety matters was explored in testimony by the NRC Commissioners before the President's Commission on the Three Mile Island Accident (June 1, 1979) From this testimony, which is corroborated by our internal NRC sources, it is fair to conclude that prior to the Three Mile Island incident a minority of the commissioners involved themselves deeply in technical aspects of reactor safety.

156. NRC-EPA Emergency Planning Report, *supra* pp. I-37 to 38.

157. *Ibid.,* pp. I-36ff. The argument to follow also applies in large measure to the analysis presented by Aldrich et al., *op. cit. supra* note 16.

158. This point was made by one of us in an early review of the final version of WASH-1400, see Yellin, *supra* note 65 at p. 337, and has since been reinterated by other analysts. See, e.g., *Reactor Safety Study (Rasmussen Report), Oversight Hearing Before the Subcomm. on Energy and the Environment, Comm. on Interior & Insular Affairs,* 94th Cong., 1st Sess. (June 11, 1976), p. 20 (statement of W.K.H. Panofsky); *ibid.,* pp. 116, 120 (statement of Frank von Hippel)(quoting APS Report, *supra* note 38 at p. S5). The NRC subsequently appointed a review group which concluded that the uncertainties in the WASH-1400 probability estimates are "greatly understated," Risk Assessment Review Group report, *quoted* note 17 *supra,* but nevertheless recommended to the Commission that the WASH-1400 statistical methodology "should be among the principal means used to deal with generic safety issues, to formulate new regulatory requirements, to assess and revalidate existing regulatory requirements, and to evaluate new designs." *Ibid.,* p. xi. Fairly read, the review group's report is ambiguous: it gives general support to the WASH-1400 methodology, while sharply criticizing its specific applications; and it recommends that absolute probability estimates be avoided "unless an adequate data base exists," but invites their "properly qualified" use "in the absence of any better information." *Ibid.* Nevertheless, despite the ambiguities in their report, there is evidence that the review group was unable to find evidence supporting the use of the WASH-1400 results for policy purposes. The policy content of the review group's findings is well illustrated by a colloquy between the review group chairman and Commissioner Gilinsky in a public meeting at which the NRC received the review group's report:

> COMMISSIONER GILINSKY: What can you say then about overall risk as a result of ... your review of [WASH-1400]. I mean, you say you are not sure whether the numbers are high or low and you think the error bounds are probably wrong, but you don't know by how much, and in fact the results may only apply to [the] two reactors [from which the WASH-1400 results were drawn]. Where does that leave us?
>
> DR. [H.W.] LEWIS: ... I understand what you are asking and I can't answer it .... I cannot say anything ... -- speaking personally for myself now -- ... based on this implementation [of statistical risk assessment methodology in WASH-1400] about the population of reactors we have now that would be useful to you.

Transcript, U.S. NRC, Meeting with Risk Assessment Review Group 42-43 (Sept. 7, 1978)(on file, NRC Public Document Room).

159. NRC-EPA Emergency Planning Report, p. I-41.

160. See WASH-1400, App. V.

161. The "release categories" in WASH-1400 are divided into two classes: those in which substantial material is released into the atmosphere and those in which the melted core is largely contained. WASH-1400 predicts that in a boiling water reactor (BWR) two-thirds of core-melt accidents will result in a major release. For a pressurized water reactor (PWR) the corresponding fraction is one sixth. *Ibid.*, App. V, Table 2-1.

162. See *ibid.*, § 4.1.2. The NRC Risk Assessment Review Group, *supra* note 38 at p. 12, describes this procedure as "arbitrary, unnecessary and plain wrong ...," but asserts without support that its "numerical effect ... is not large." Our own independent analysis suggests that the averaging procedure, called "probability smoothing" in WASH-1400, *ibid.*, App. V, § 4.1.2, significantly and unjustifiably raises the estimated failure probabilities and increases the apparent precision of the estimates. Furthermore, evidence internal to WASH-1400 and discussions with members of the NRC Staff suggest that *the probability averaging procedure may have been introduced in the realization that the WASH-1400 probability estimates would otherwise be too low, and the uncertainties in those estimates too large, to be credible.* This supposition is supported by information obtained in extensive correspondence with the NRC during 1975-77. In the course of that correspondence, the NRC Executive Director of the study stated that

> probability smoothing incorporates physical variations in phenomena and properties. The RSS staff therefore does not feel that probability smoothing can be arbitrarily deleted since it plays a role in the physical modeling. Estimates of the unsmoothed probabilities can be simply obtained by adding the sequence probabilities in Tables V3-14 and V3-16 in Appendix V [of WASH-1400]. *However, these estimates will give unrealistically small probabilities for certain release categories. The RSS staff therefore does not feel that such evaluations are meaningful.*

Saul Levine, letter to J. Yellin, Dec. 27, 1977 (emphasis added)(on file with the authors).

163. It is asserted in WASH-1400 that in order to calculate uncertainties in the probability estimates, failure probability distributions were assigned to all components and subsystems and were then conflated according to the usual statistical rules to give 5%-95% confidence intervals for the final probability estimates. See WASH-1400, App. V, § 4.1.3. In reality, however, for some highly uncertain risk factors, no error propagation was performed. See Risk Assessment Review Group, note 38 at p. 11. One of these omissions concerns the probability of containment failure, which directly affects the relative probabilities under discussion, see note 162 *supra*.

164. Human error probabilities were specified in WASH-1400 using a mixture of subjective techniques and extrapolation from data. See *ibid.*, App. III, § 6.1. A particular salient example is the estimate of an error rate of 3 per 100,000 reactor-years, for the failure to open auxiliary cooling system valves after maintenance. *Ibid.*, App. II, p. 108. This failure evidently did occur, and was a principal contributor to the Three MIle Island accident, suggesting an "observed" failure rate roughly 1,000 times larger than the WASH-1400 estimate.

165. James O. Freedman, *Crisis and Legitimacy, The Administrative Process and American Government* (Cambridge U.P., N.Y. 1978), p. 11.

166. The effectiveness of congressional superintendancy of the AEC's safety activities during the first 20 years of the commercial power program deserves further exploration.
During most of the period, it can be strongly argued that the Joint Committee on Atomic Energy (JCAE) acted in its sphere with a degree of combined legislative and executive power unique in American history. The record of the JCAE's accomplishments is therefore a touchstone for proposals to involve Congress more deeply in health and safety regulations. For a discussion of the JCAE's role through the early 1960's, see Green & Rosenthal, *supra* note 144, Chapt. VIII.

167. See Citizens to Preserve Overton Park v. Volpe, 401 U.S. 402, 416 (1971).

168. That the boundary between enumeration and evaluation may define the practical limits of judicial authority in scientific matters has been noted by Judge Learned Hand:

> That there can be issues of fact which courts would be altogether incompetent to decide, is plain. If the question were, for example, as to the chemical reaction between a number of elements, it would be idle to give power to a court to pass upon whether there was "substantial" evidence to support the decision of a board of qualified chemists. The court might undertake to review their finding so far as they had decided what reagents had actually been present in the experiment, for that presumably would demand no specialized skill. But it would be obliged to stop there, for it would not have the background which alone would enable it to decide questions of chemistry; and indeed it could undertake to pass upon them only at the cost of abandoning the accumulated store of experience upon the subject.

NLRB v. Standard Oil Co., 138 F.2d 885, 887 (2d Cir. 1943).

169. For example, under the common law of torts, those who carry on dangerous activities in inappropriate or "unnatural" places are subject to strict liability for the consequences. See, e.g., Prosser, *Law of Torts* (4th ed. West, St. Paul, Minn. 1971), § 89. Furthermore, there was early recognition that the "police power" of states or localities extends to the siting of industrial facilities. See Commonwealth v. Alger, 61 Mass. (7 Cush.) 53 (1851)(Shaw, C.J.). And local ordinances and state laws traditionally restrict the storage of hazardous substances in or near residential areas.

169a. In two recent major cases, courts have emphasized the importance of potential consequences in evaluating environmental risks. *See* Ethyl Corp. v. EPA, 541 F.2d 1, 19-20 (D.C. Cir.)(en banc), *cert. denied,* 426 U.S. 941 (1976); Reserve Mining Co. v. EPA, 514 F.2d 492, 520, 536 (8th Cir. 1975)(en banc). For a discussion of the respective roles of probabilities and consequences in risk evaluation, see Yellin, *Judicial Review and Nuclear Power: Assessing the Risks of Environmental Catastrophe, Geo. Wash. Law Rev.* 45, 969 (1977).

170. See Industrial Union Dep't (AFL-CIO) v. Hodgson, 499 F.2d 467, 474-75 (D.C. Cir. 1974); *accord,* Amoco Oil Co. v. EPA, 501 F.2d 722, 740-41 (D.C.Cir. 1974).

171. See 1980 NRC Authorization Act, S.562, §§ 107, 109, 205(a), 207, 125 Cong. Rec. S9603-06 (July 17, 1979)(Senate passage).

172. See Department of Energy, Press Release (March 17, 1978) ("Fact Sheet" and text, proposed Nuclear Siting & Licensing Act of 1978).

173. Abrams v. United States, 250 U.S. 616, 630 (Holmes, J. dissenting).