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ON THE DEVELOPMENT OF QUANTITATIVE RISK ACCEPTANCE CRITERIA

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NOTICE

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1. INTRODUCTION

Society is becoming increasingly aware of the fact that risks accompany the benefits and other costs of its technological ventures, large or small. These risks cannot be totally eliminated; they can only be reduced and managed and they are only one of many sets of issues considered in the decision process. Uncertainties arise in the technical estimation of both risks and benefits, and in addition, differences among individuals in the assignment of values result in controversies over the evaluation of risks and benefits. The field of risk acceptance has been reviewed by the works of Lowrance (1976), Rowe (1977), and Van Horn and Wilson (1976), among others.

Considerable costs to society arise from the conflict over accepting technological risks: anxiety and dismay due to conflicting information; litigation costs; retrofits; and misplaced investments and costly delays that result from industry's inability to predict public risk acceptance or to plan for regulatory requirements (Starr and Whipple, 1980).

Management of risks is as much a socio-political problem as it is a technical one. It is difficult in that it is intrinsically multidisciplinary. Some of the multidisciplinary aspects are investigated in a report of work done for the National Science Foundation at UCLA (Okrent, 1977). The main question that arises is, "How safe is safe enough?" given the other costs and benefits of the technological facility. Attempts to answer this question usually employ some combination of historical precedents implied by past regulatory decisions or by statistics on a wide range of human risks (Starr, 1969; Rowe, 1977) and psychometric surveys concerning societal perceptions and evaluations of risk (Fischhoff, et al 1978; Otway, 1977). Because of the trade-offs involved in the economic, socio-political, and technical decisions to build or not to build a large technological facility, the question "How safe is safe enough?" will not be subject to a unique answer.

The societal decision to build a particular facility ideally would be based upon the balance between all the benefits and costs of the proposed facility. Considerations would include the costs of the facility itself and the cost of choosing one of the alternatives, as well as the costs of building no facility at all. Risk costs would be included in the decision process, and general risk management criteria would be applied to all technologies. However, in the United States decisions are not usually based upon such broad considerations. Regulation of risk is most often done separately from the political and/or financial decision to go ahead with a particular project, and becomes a matter of reducing and managing the adverse impacts associated with the endeavor. There are many separate regulatory agencies, and no uniform approach to the regulation of risks exists, even within a single agency like EPA.

The realization that society as a whole has limited resources that can be expended for risk reduction has led to concern over the cost-effectiveness of safety measures. There exists a large variation in the levels of risk imposed upon society by various technologies (Okrent, 1977) and in the amount of money allocated to reduce these risks (Schwing, 1979; Cohen, 1980). Although large sums of money have been spent to make nuclear reactors safe, many people are still greatly concerned over reactor safety. Others believe that reactors are safe enough already and that a large amount of our resources is being wasted on unnecessary safety measures (Siddall, 1979). Most would agree, however, that the resources allocated for safety of reactors should be used effectively.

The large variation in the regulatory approaches of the various agencies causes some decisions to seem quite arbitrary. Also, the practice of specifying the methods for meeting the risk goals at a particular facility removes some of the incentive to develop more efficient methods of risk control. Innovative means to control risk could be encouraged by specifying the risk goals alone. However, this course may result in unduly long delays if appropriate means are not forthcoming or are themselves subject to debate. While it may not be possible to employ a completely general approach to risk management, regulatory decisions based upon a more broadly founded management philosophy and at least some quantitative decision rules may offer considerable improvement over current regulatory practice.

Specification of a justifiable and workable quantitative risk management framework is a major task if only because there is no general consensus as to the aspects of risk that must be considered or to their relative importance. Added to these problems is the difficulty of risk estimation for facilities having potential hazards which involve high consequence, low probability events, or facilities which pose relatively unfamiliar or potentially large delayed and chronic hazards. Furthermore, a particular facility or activity may appear to be the best alternative to meet an essential societal need, even though it poses a large identified hazard which must be managed.

In this paper, some of the major considerations for effective management of risk are discussed, with particular emphasis on risks due to nuclear power plant operations. Although there are impacts associated with the rest of the fuel cycle, they are not addressed here. Next, several previously published proposals for quantitative risk criteria are reviewed. They range from a simple acceptance criterion on individual risk of death to a quantitative risk management framework. The final section discusses some of the problems in the establishment of a framework for the quantitative management of risk.

We do not consider occupational risks within the context of this paper.

2. RISK MANAGEMENT CONSIDERATIONS

2.1 Decision Levels and Impacts

Several levels are involved in the decision to build a particular power plant. These focus on the need for power, the technological options, alternative sites and risk acceptance. The interactions between economic, socio-policical, environmental and public health and safety impacts should be considered and factored into the decision at each level. For example, health is to some extent positively correlated with standard of living, which may be lowered if energy is not available or if energy costs become much higher as a result of expenditures for safety improvements. Also, the costs of required safety measures for one technology may force the choice of an alternative technology having larger impacts, if the overall economics of the first technology become unfavorable.

Acceptable risk is most properly addressed in the context of alternatives, including the option of not building a facility to supply a particular societal need or want. Large uncertainties in the level of risk must also be considered. The uncertainties arise from shortcomings both of data and of models to predict risk. Sometimes conservative estimates are used to put upper bounds upon risk. However, without estimates of the uncertainties or methods to determine the relative amount of conservatism among alternatives, conservative estimates may distort the relative impacts of the various options and may lead to a less than optimal choice between them. The problem is further complicated becasue the different types of impact are not readily comparable.

In order to gain perspective it might be useful to construct a hierarchy of impacts according to magnitude and to extent, i.e., local, regional or global effects. Moderate negative effects which are local in nature may be preferable to moderate negative effects which are regional in extent, etc. The regional need for power, based upon economic and socio-political considerations, may be such that a power plant should be built; the accepted environmental and public health and safety impacts (local and regional) will be determined by the choice of site and technological alternative and by the resources allocated to reduce those impacts. The impacts of procuring and processing the fuel will also depend upon such choices.

2.2 Approaches to Risk Management

Technological hazards arise as a consequence of endeavors to satisfy societal needs and wants. In part, such hazards can be modified by changing societal wants, by choosing a different technology to satisfy the wants, or by improving the technology to prevent the occurrence of the hazard or to mitigate the consequences (Fischhoff et al., 1978). The Nuclear Regulatory Commission (NRC) has the authority to require and approve improvements in the nuclear power plant, once the choice to build a reactor has been made. It must decide if the plant is safe enough, or in other words if enough resources have been spent to ensure safety. While the NRC in environmental impact statements assesses and compares the use of alternative technologies with nuclear, the NRC may not have the authority to choose between power generating technologies. However, it may force an alternative choice by its stringent safety requirements.

Various approaches have been used to determine whether a technological facility is safe enough; these include professional judgement, cost benefit and cost effectiveness considerations, comparison with background hazards, public preferences, or comprehensive analysis of various options. Each approach has its advantages and disadvantages. A catalogue of caveats for these approaches has been compiled by Fischhoff et al. (1980).

Professional judgement relies on good professional practice to ensure that failures are not likely. However, failures in equipment do occur, and some means must be developed to decide what failure rates are acceptable. The costs of the failure rates can be estimated, and the expected consequence per year can be added to the overall costs of the facility in a cost-benefit analysis. However, serious problems arise in assessment of both costs and benefits (Baram, 1980). The measures of effect are not easily converted to a single unit such as money, and some cannot be estimated without tenuous assumptions which often are not adequately stated in the report of the results. This lends itself to intended and unintended bias in the presentation of the analysis and distortions in its interpretation.

In any case, the risk benefit type of analysis for a particular technology for the generation of electricity should be done for the whole fuel cycle. Similarly, comparative risk studies may be used to help choose between two alternative technologies; however, such comparative analyses become less applicable for determining the level of acceptable risk for separate parts of the fuel cycle such as mining and milling operations, or just the power plant itself.

In order to efficiently allocate societal resources for risk reduction, limits may have to be set not only on the expected risk of a facility but also (or rather) on the amount of money spent per unit risk reduction. Beyond a certain expenditure the money may be better spent to reduce the risk associated with other societal activities. It has been suggested that there is a lower bound below which total risk cannot be reduced for each facility. The cost per unit of total risk reduction will become infinite when the risk involved in producing the safety equipment becomes equal to the anticipated reduction in risk (Black et al., 1979) or when risk increases more in other segments of society because resources have been diverted (Siddall, 1979).

Care must be used in the application of cost effectiveness criteria. For example, it was found that to reduce local health effects from facilities which burn fossil fuel, it was less cost-effective to remove more sulfur and particulates from the flue gas than it was to increase the stack height and disperse the pollutants. However, it has been found that the longer residence time in the air allows more of the sulfur dioxide to be converted into sulfate and results in acid rain great distances from the stack. The pollution problem has not been solved; a local health problem has only been converted into a regional environmental problem and may still result in significant health effects because, while the risk to each individual has been reduced, more people may be exposed.

As an alternative to or in conjunction with economic considerations, acceptable risk could be determined by some assessment of societal preferences. Some indirect assessments employ retrospective examination of choices implied by statistics on a wide range of human risks or by past regulatory decisions (Starr, 1969; Rowe, 1977). At least two major assumptions are made if one applies this approach without modification: that what existed in the past was accepted then and is indicative of what will be accepted in the future; and that society was well informed concerning the nature of risks associated with its actions. Neither of these assumptions is generally valid (Slovic _et al._, 1980; Fischhoff _et al._, 1978). Using precedents implied by past regulatory decisions is also difficult because the different types of risk are not easily compared and the statutory mandates of the regulating agencies vary significantly. And, societal preferences cannot easily be deduced from hazard statistics since the level of risk will depend not only upon the hazard potential of a particular activity but also upon the public awareness of the hazard, the ease and cost of its control, and the relative political power of those who benefit from the activity and those who are burdened by the risk.

Direct methods to assess public preferences include opinion polls and psychometric surveys concerning societal perception and evaluation of risk (Otway, 1977; 1978; Slovic _et al._, 1980; Fischhoff _et al._, 1978). Studies have shown that perceptions of risk by groups of lay people sometimes have systematic variations compared with each other and with the statistically measured risks (Slovic _et al._, 1980; Fischhoff _et al._, 1978); that perceived benefits are negatively correlated with perceived risks (Otway, 1977: Fischhoff _et al._, 1978); that expert risk assessments are also susceptible to bias, particularly underestimation; and that new evidence is often interpreted to reinforce existing beliefs (Slovic _et al._, 1980). These findings indicate that it would be no simple matter to incorporate aggregated public attitudes and perceptions in a meaningful and useful way into risk acceptance criteria. Even the solicitation of these attitudes requires care because the form and sequence of the survey questions may strongly influence the responses (Plott, 1978; Hershey and Schoemaker, 1980).

Basing risk acceptance solely on perceived risk and without consideration of the alternatives has a number of disadvantages. It virtually assures that limited resources for risk abatement will be misallocated, and leaves open the possibilities that societal needs will not be met or that some risks will be much higher than necessary. Furthermore, societal perceptions have been subject to reversals in thinking in the past (e.g., the U.S. attitude to civil rights in the 1930's; the German attitude to Hitler in the 1930's; and the U.S. attitude toward oil shortages and an energy crisis in the mid 1970's).

2.3 Special considerations for LWRs

Risks have been frequently categorized according to several dichotomous factors such as whether the exposure to the risk is voluntary, new, common, catastrophic, dreaded, lethal or man-originated, etc. (Starr, 1969; Lowrance, 1976; Rowe, 1977; Otway, 1977; Fischhoff et al., 1979; Litai, 1980). Nuclear power is unique in that it is in a category by itself on these perceptual scales. It is perceived as new, uncommon, dreaded, most likely lethal, involuntary and potentially catastrophic. These factors have been used to explain the public's special concern over nuclear power. They also hinder the determination of acceptable risk by simple comparison with other technologies.

Current opposition to nuclear energy might be reduced by requiring lower risk acceptance limits for reactors than for other technologies. However, according to Otway (1978), the reasons for opposition to nuclear power are related to social and psychological factors which probably would not be affected by changes in reactor technology that reduce risk. Bodansky and Schmidt (1979) develop this point by discussing the opposition to nuclear power in three parts: (1) concerns about nuclear radiation; (2) concerns about nuclear weapons proliferation; and (3) concerns about the general nature of society and its future development. They suggest that the last set of concerns relating to big government, centralized and impersonal technology, and a technological elite, gives rise to the largest opposition to nuclear power, which is a symbol for these concerns.

Stricter safety criteria may not calm these concerns. In fact, overly strict criteria may give the impression that the strictness is needed to compensate for some unknown factor that may have been overlooked (Otway, 1978). If it cannot be demonstrated that the strict criteria have been met, the acceptance problem may be aggravated if at some later date the criteria are relaxed. Nevertheless, it can be argued that society wishes nuclear plants to be safer than alternative energy sources. It can also be argued that much of the concern about LWR safety arises from a considerable uncertainty as to whether the stringent criteria intended to limit the frequency of a serious accident have actually been met.

Proliferation of nuclear weapons is a concern not so much for the nuclear power plant itself as for the entire fuel cycle. As such, the concerns over proliferation as well as those over the nature of society may strongly influence the choice of technology to generate the desired electricity but are not such important factors in determining the acceptable risk due to the power plant itself.

The possibly catastrophic nature of the effects of a large radiation release coupled with a low frequency of occurrence make the acceptable risk question much more complicated than just setting limits on the expected average consequences per year. While large, fairly constant yearly losses may usually be planned for and accommodated by societal adjustments, a large catastrophe requires consideration of the resilience of society, that is, its ability to recover.

Siting policy can be especially effective in helping to reduce the probability and the magnitude of early fatalities from an accident. The number of latent health effects from a serious accident, however, depends upon the integrated man-rem dose, which would be hard to reduce markedly by siting practice alone in the eastern United States, although it can be clearly affected (e.g. consider the Zion versus the Browns Ferry sites). The incremental risk of cancer above background from an exposure of 1 rem to an individual is not large statistically, but there may be substantial trauma that is real and far exceeds the statistical risk in its impact and importance. In fact, it may be that safety criteria should deal with accidents of the nature and magnitude of that at Three Mile Island, which did not have large, offsite, radiological consequences.

More study appears to be needed concerning the potential costs and effects of contaminating important resources such as a large aquifer, a large area of fertile farm land, or large residential areas.

As mentioned above, the question of acceptable risk must be raised in the context of several interacting decision level and impact considerations. The nuclear power option is not alone in its potential for very large adverse consequences. Large scale use of fossil fuels appears to lead to an increasing CO_2 content in the atmosphere, which may cause devastating climatic changes if it continues. Of course, the more immediate effects of the fossil fuel combustion are potentially major air pollution effects on health and the increase in the acidity of rain downwind. The latter effect has become a major environmental problem by degrading whole ecosystems. Unfortunately, the economic and health impacts of this damage are not easily assessed, though the impacts may be significant. On the otherhand,should excessive dependence of the United States (and other industrial powers) upon foreign oil supplies significantly increase the chances of war, this may dwarf all other risks.

Societal willingness to accept the risks of potentially large impacts of the nuclear option must depend upon the potentially large impacts of the alternatives. The only certainty in the consideration of criteria for acceptable risk is that there will be conflicts whenever societal decisions impose risks on a particular group. Analysis will help clarify the issues, but it will not remove all of the uncertainties or bring about consensus. Quantitative decision rules in a clear framework may provide a practical compromise between analytical and judgemental approaches to acceptable risk (Starr and Whipple, 1980). In order to fulfill this function, the logic behind the rules and framework must be easily understood both by technical people and by the general public and there must be some logical straightforward way to demonstrate that the criteria have been met (Rasmussen, 1978/79). Development of the framework and the numerical values used in the rules will require much work and input from many parts of society.

3. SOME PREVIOUSLY PRESENTED PROPOSALS

The overall philosophy and intent of the particular policies toward risk determine the form and scope of the various risk acceptance criteria reviewed below as well as the proposed numerical parameters. The criteria may deal with effects such as deaths or property damage, with exposures to harmful agents such as radiation or pollutants, or with the frequency of certain types of accidents. Criteria that address effects might be more easily related to a generalized policy toward technological risks, yet be more difficult to apply than criteria that deal with technology-specific issues.

The risk criteria described below can be roughly categorized into three groups: those that set limits on individual risk of death only; those that consider frequency of accidents and magnitude of the consequences; and those that imbed the criteria in risk management frameworks that, at least in part, consider risks from alternatives or other societal endeavors. Some, but not all, of the criteria apply specifically to nuclear reactors.

3.1 Individual Risk Criteria

- One of the early proposals for quantitative risk criteria for nuclear reactors was made by Adams and Stone (1967) of the Central Electricity Generating Board of Great Britain at an IAEA Symposium on Siting and Containment. They proposed that the parameter determining acceptable siting be taken as individual risk. Although the numerical limit would be a matter for governmental decision, they suggested that an incremental increase in an individual's chance of death per year that is smaller than the demographic variation in the United Kingdom of that chance of death per year would be inappreciable and acceptable on those grounds. Differences significantly greater than 10^{-5} per year occur between England, Wales, Scotland and Ireland, and they proposed that an incremented individual risk of 10^{-5} chance of death per year would be acceptable. For immediate deaths and a plant lifetime of 30 years this would correspond to a statistical loss of life expectancy of about 6 days, while for death delayed until 10 years after exposure the statistical loss is about 3 days. Of course, the loss is much larger for the actual victims and zero for all the others.

Adams and Stone arrived at a siting policy based on the above criterion which requires the following: an exclusion area; a controlled area, where development that would prevent emergency action would not be allowed; and then an area of unrestricted population. They did not, however, discuss how one should demonstrate that the criterion had been satisfied. In fact, they argued that community or aggregate risk criteria based on the total potential number of casualties would not be useful because the uncertainty in that number, due to the magnitude and conditions of release in an accident, is far greater than the differences that choice of site could make. The policy did not consider property or other resource damage.

- The apparently positive correlation between standard of living and health has been used by Bowen (1975) to develop a general risk acceptance criterion for technological activities in the United Kingdom. He suggests that the risks imposed upon society should be negligible or balanced by benefits. However, risk levels that can be scientifically supported, say a 10^{-5} chance of death per year, cannot be considered negligible in all situations and balancing by direct individual benefits is not possible in cases where the victim cannot be readily identified in advance, for example, the one excess cancer fatality that might be expected from the TMI accident. Bowen argues that the balance should be done macroscopically.

He assumes that the observed annual increase in life expectancy in the U.K. is due to overall societal efforts, i.e., its investment in "the industrial machine" of which any technological facility forms a part. An additional yearly risk of death of 10^{-5} from a new facility roughly balances the expected increase of an individual's life expectancy during one year. Bowen asserts that if no investment is made in the industrial machine, the annual increase in life expectancy may stop altogether. Hence, he chooses 10^{-5} per year as a reasonable limit on the individual risk of death from a single facility and assumes that no individual is exposed to more than a very few technological facilities.* If the increase in life expectancy per year is larger than that in the U.K. (i.e., 0.05 years/year), a country might accept technological activities involving a correspondingly larger risk, at least for accidents which are not truly catastrophic.

With regard to accidents having a potential for a major disaster, Bowen argued against requiring a lower frequency limit for which compliance would be difficult to demonstrate or even achieve. He suggested instead that the 10^{-5} limit should be demonstrated to a high confidence level when there is potential for a large catastrophy. He felt that if a large accident were to occur, it would not be easy to distinguish between just being

*In a personal communication, he has since indicated that a larger level of risk, more like 10^{-4} per plant per year, may be more practical for the individual living near a large chemical facility (Okrent, 1977).

"unlucky" or having accepted a risk analysis that greatly underestimated the risk. Being "unlucky" could be prevented by achieving a lower probability for large accidents but at the expense of investments into the industrial machine. Bowen argued that, if the aim is to have a small chance (i.e. 1%) of having a large catastrophe in one's lifetime, a limit of 10^{-5} events/year demonstrated to high confidence, say 99% or so, would be adequate; it would not help to restate the aim as 10^{-7} events/year, and besides, it may divert resources, attention and effort.

Bowen did not distinguish between deaths occurring immediately after an accident and those that are delayed for a few years, nor did he consider risks other than individual fatalities.

3.2 Frequency-Consequence Approaches

The previous criteria dealt specifically with individual fatality risks without directly including limits on other types of risk or addressing the effects of a large scale accident. In the four following proposals, special attention is given to the magnitude of an accident. A basic common assumption is that the limiting frequency on a particular accident should depend in some way upon its magnitude. Three of the sets of risk criteria deal with nuclear power plant risks. The first proposal suggests a limit on the frequency of accidental release of radioactive material, the second, on frequency of individual exposure, and the third is concerned with limits on the fatalities due to accidental exposure. The final proposal in this section relates the required structural integrity of a building to the intended use of the building and the number of expected injuries, should it fail.

● At an IAEA Symposium on Siting and Containment, F.R. Farmer (1967) of Great Britain, presented a much-to-be quoted paper, "Siting Criteria - A New Approach." In it he proposed that probabilistic analysis be employed in reactor safety assessment and suggested that the safety criterion of less than 0.01 premature deaths per reactor year be adopted. In addition, he proposed that a risk acceptance limit line be used to judge the acceptability of the estimated occurrence frequency for any particular accident. The severity of the accident was measured by the release in curies of iodine-131, one of the volatile fission products of greatest importance in thermal reactor accidents.

The Farmer limit line is reproduced in Fig. 1. The acceptable frequency of occurrence of an accident fell off as the consequences increased with a rate such that the expected contribution to risk (frequency times consequences) was less for very large accidents than for smaller ones (a negative slope of -1.5 on a log-log plot). Farmer suggested that only a relatively few events would be near the line for any reactor, and that these would lead to the principal contribution to premature deaths. Later British papers (Beattie et al., 1969; Farmer and Beattie, 1976) developed a mathematical interpretation of the line and gave it a slope of unity. Risk assessments were made by assuming that accidents could be grouped to occupy each decade, both in frequency and magnitude of release, out to some limiting release.

The Farmer limit line does not deal specifically with effects dependent upon population density and other conditions around the site. Therefore, the actual limits on effects, such as risk to the individual, property damage, or number of expected fatalities, must be estimated from site specific analyses.

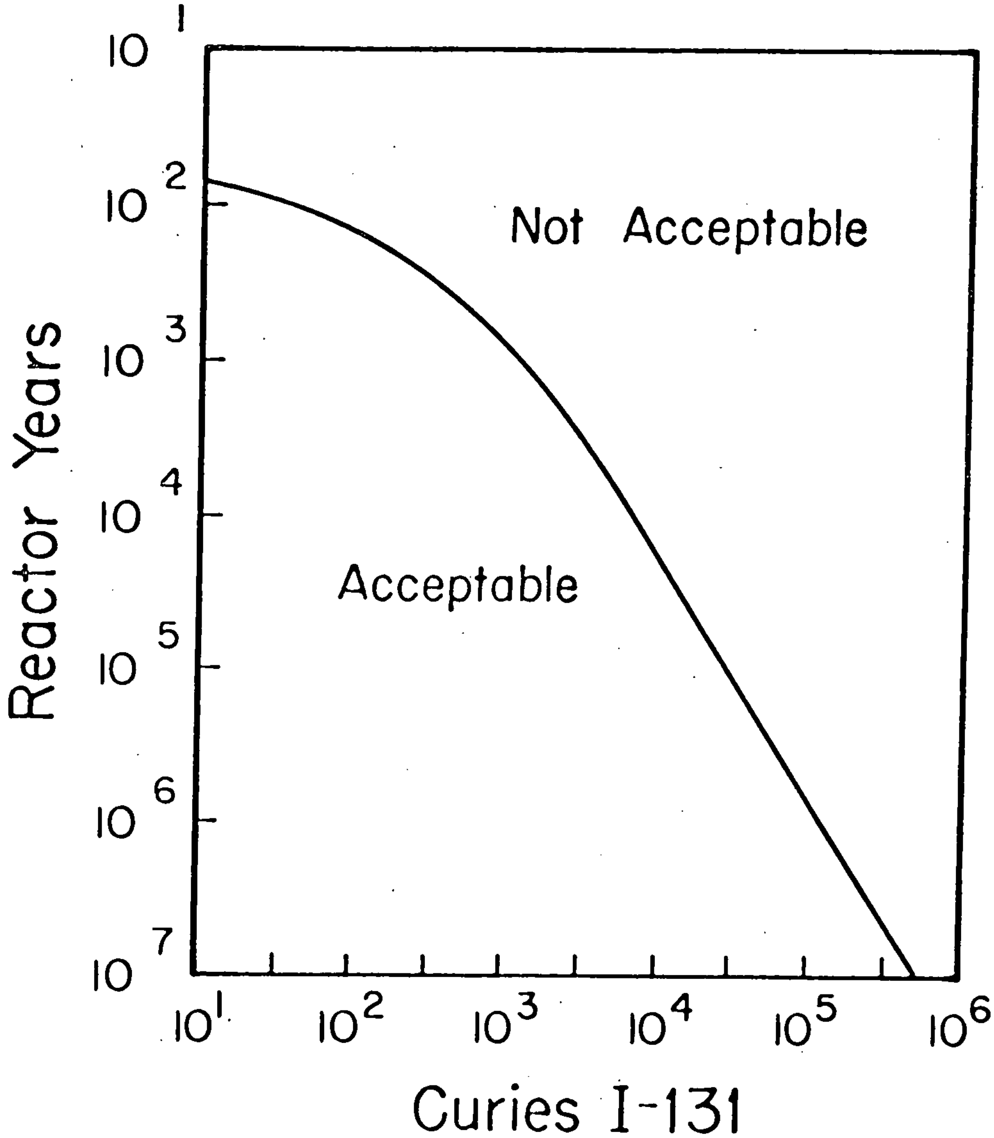

Fig. 1. Farmer release frequency limit line (Farmer, 1967)

● In late 1978, a proposal for probabilistic safety requirements for use in licencing CANDU nuclear power plants was submitted by the Inter-Organizational Working Group to the Atomic Energy Control Board of Canada for general public comment (AECB, 1978). The requirements are in the form of quantitative frequency dose limits and were intended to be conservative in ensuring that the likelihood of a lethal dose (200-400 whole body rem) to any nearby resident would be less than 10^{-6} per reactor year. Table 1 gives the proposed reference values for radiation exposure.

The process failures include any problems with the reactor core, heat removal systems, control rods, or instrumentation needed for regulation and control in normal operations. Special Safety Systems include "protective devices," such as the automatic shutdown system and emergency core cooling system, and "containment provisions."

Serious process failures would be required to occur less than 10^{-3} per year, and the unavailability of the Special Safety Systems should be less than 10^{-3}. Estimates of the process failure rate might turn out to be less than the limit, but the credit to be used in calculating release frequency was to be no less than 10^{-3} per year. Similarly, the lowest unavailability of the Special Safety Systems that could be used in the exposure frequency calculation was 10^{-3}. These restrictions were intended to compensate for the uncertainties involved in the risk assessments and to force consideration of both prevention and mitigation of accidents.

In applying the proposed criteria, the applicant for a nuclear power plant construction permit would be instructed to: 1) list all events for

TABLE 1.A - PROPOSED REFERENCE VALUES (AECB, 1978) Serious Process Failures		
Reference Dose Interval (In absense of Special Safety Systems) Rem		Reference Value for the Sum of the Prediceted Rates of Occurrence of Failures within the corresponding Reference Dose interval
Whole Body	Thyroid	(Per Reactor Unit Per Annum)
0-0.05	0-0.5	10^{-1}
0.05-0.5	0.5-5	10^{-2}
0.5-5	5-50	10^{-3}

TABLE 1.B - PROPOSED REFERENCE VALUES Process and Special Safety System Failures		
Reference Dose Interval Rem		Reference Value for the Sum of the Predicted Rates of Occurrence of Failures within the corresponding Reference Dose Interval
Whole Body	Thyroid	(Per Reactor Unit Per Annum)
5-10	50-100	10^{-4}
10-30	100-300	10^{-5}
30-100	300-1000	10^{-6}

Note: The actual dose to the individual in table 1A will be less than reference value which does not give credit for the Special Safety Systems.

which rates of occurrence and consequences are to be predicted. 2) analyse each event and predict its rate of occurrence and its consequences; and 3) sum the rates of occurrence of all events whose consequences fall within each of the reference dose intervals. No sum would be allowed to exceed its corresponding reference value.

There was difficulty in fitting events such as earthquakes and sabotage into the framework and rationale used for dealing with equipment failures caused by component weakness or system maloperation. The report did not make clear how completeness of the risk analysis was to be ensured nor did it elaborate on how to treat human error or other internal situations that might compromise the independence of the process equipment and Special Safety Systems, causing them to fail simultaneously.

The magnitude of a particular accident is measured in this proposal by expected dose to an individual. The concern is to ensure that lethal doses to the individual arise at a rate less than 10^{-6} per reactor year. As such, the criteria do not address the total number of immediate fatalities that might be caused by the accident. The report does not discuss latent effects such as cancer, but individual latent risk limits are implied by the frequency dose criteria.

- G.H. Kinchin of the Safety and Reliability Directorate of the UKAEA has proposed a quantitative set of public health and safety criteria for nuclear reactors (1978;1979). Because of the difficulty in balancing economic advantages against health risks, he suggested that the criteria should be conservative. Unlike the previous two sets of criteria, Kinchin proposes limits on the expected effects rather than on the magnitude of release or expected dose. The criteria put limits on individual and aggregate societal risks of both immediate and delayed death due to reactor accidents.

The conservative objective was to make the risk of immediate death to an individual member of the public small compared with other involuntary risks, and a value of 10^{-6} per reactor year was suggested. Kinchin stated that possibly a higher value would be acceptable.

Kinchin suggested that in the attempt

> "to arrive at a criterion for the risk of delayed death, the following thoughts might be kept in mind:
>
> (a) death at some relatively distant date in the future is preferable to immediate death;
> (b) the effect of radiation-induced cancers on the life expectancy of a young person is greater than on that of an older person;
> (c) an annual death rate of 10^{-6}/year, as proposed above, would be caused by an accident giving a total probability of delayed deaths of 3×10^{-5};
> (d) it seems that radiation exposure just insufficient to cause immediate death may not give rise to fatal malignancy;
> (e) for the specific malignancies induced by irradiation, comparison should be made with some of the figures for cancer... rather than with the lower probabilities of early death due to, say, electrocution or drowning." (Kinchin, 1978)

Taking these points into account, he proposed that the limit on the annual accidental probability of inducing delayed death to the individual should be 3×10^{-5}/year. Although noting that this was a factor of 3 higher than the upper end of the range suggested by ICRP, he felt it difficult to justify a relative acceptable limit factor of less than 30 between death in 10 years time and death today (Kinchin, 1979).

Limits on aggregate societal risk of immediate and delayed deaths are specified by a pair of frequency versus consequence curves.

The rationale for the early death limit curve was: "It would not seem unreasonable to propose a criterion that the total risk from nuclear reactors should be roughly comparable with that from meteorites." Each of an assumed population of 100 reactors in the U.K. was assigned 1/100 of the total risk. The societal delayed death curve was formed using the same factor of 30 used to set the limit on individual delayed death risk. The limit curves are shown in Figure 2 redrawn from Kinchin's 1979 proposal.

Specification of limits on effects allows comparisons with other risks and flexibility in design and siting to achieve the safety goals. Kinchin emphasized that the design goals have to be supplemented by good engineering practice and quality assurance programs to ensure that the safety goals are met. For any particular case, individual risk of early and delayed death at the site boundary and the corresponding societal risks of early and delayed deaths would be examined. The most limiting criteria would then be applied.

- The Construction Industry Research and Information Association (CIRIA) of the U.K. has attempted to rationalize the safety and serviceability factors for structures such as buildings and bridges by relating them to social and economic criteria (CIRIA, 1977).

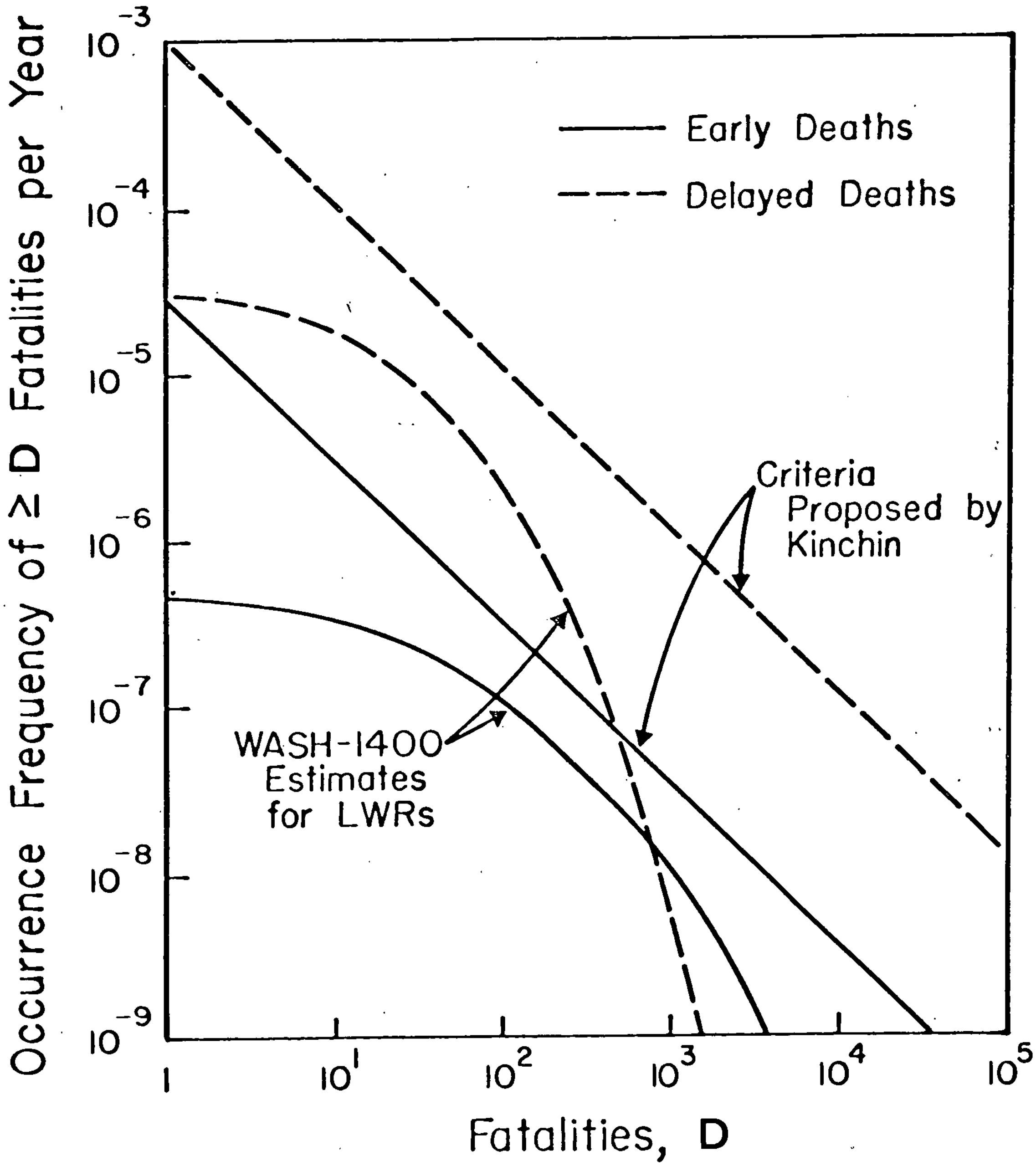

Fig. 2. Criteria proposed by Kinchin (1979)

These criteria were expected to vary with the size and intended use of the structure and with the prevailing social and economic climate in the country in which it would be built. They found it convenient to consider human life and economic consequences of failure separately, but acceptable risk levels in heavily populated buildings may be found by a combined socio-economic criterion.

Historically, the annual risk of death to any person in the U.K. due to collapse of a structure is on the order of 1.4×10^{-7} per year. This was taken to indicate that the public expects these risks to be small compared to other risks to which they are exposed. The degree of safety required also was intended to reflect the public aversion to the failure of each class of structure.

By reference to statistics on each class of structure, the yearly acceptable risk of failure, R_f, was deduced to have the form

$$R_f = \frac{10^{-4} K_s}{N_r}$$

where N_r is the average number of people expected to be withn or near the structure if it were to collapse and K_s is the social criterion factor, given in Table 2 for various types of structures. The failure risk limit in each class is inversely proportional to the number of people affected by the failure. However, the social criterion factor is also seen to be smaller for structures that generally involve more people or serve important public functions, so that there would be a very strong aversion to failures that could injure a large number of people if the criterion were to be used.

Table 2 Social Criterion factors, K_s (CIRIA, 1977)

Nature of Structure	
Places of assembly, dams	0.005
Domestic, office or trade and industry	0.05
Bridges	0.5
Towers, masts, offshore structures	5.0

The economic criterion was formed by minimizing a total cost function E_t, given by

$$E_t = E_i + E_f R_f n_d$$

where E_i is the initial cost, E_f is the consequential cost of failure, and n_d is the design life in years.

CIRIA noted that, historically, society has responded in a very risk averse manner to large consequence failures and this has lead to a disproportionate expenditures to reduce those risks. Although this aversion cannot be totally eliminated, they suggested that it could be rationalized somewhat by setting a limit on the expenditure, M, to prevent a failure:

$$M \leqslant \frac{\nu N_r}{K_s}$$

where ν is a constant and N_r and K_s are defined as above. If ν is set at £25000, this would imply an expenditure of about $\$10^6$ per life saved for low risk structures for which $K_s = 0.05$.

3.3 Risk Management Approaches

Two commom premises of the following risk management approaches are: that society has a limited amount of resources to allocate for the reduction of the risks that accompany the benefits of its endeavors and that these resources should be allocated wisely. They reflect concern that improper actions to reduce risks may not minimize risk and may even give rise to an increase in overall risks. The first two approaches are concerned with general societal risk while the last two deal specifically with nuclear power plant risks.

- As a starting point for discussion on the subject of risk acceptance criteria, Okrent and Whipple (1977) described a simple quantitative approach to risk management which incorporated the following principal features:

  Risk assessment

  Each risk-producing facility, technology, etc., would have to undergo assessment both of risk to the individual and to society. The risk assessment would be performed under the auspices of the manufacturer, owners, etc. It would be independently reviewed and evaluated. The decision on acceptability would be made by a regulatory group. For practical reasons, there would be some risk threshold below which no review was required.

  Graduated limits on individual risk

  Societal activities would be divided into major facilities or technologies, all or part of which are categorized as essential, beneficial, or peripheral to society. There would be a decreasing level of acceptable risk to the most exposed individual (for example, 2×10^{-4} additional risk of death per year for the essential category, 2×10^{-5} for the beneficial category, and 2×10^{-6} for the peripheral category).

Allowance for uncertainties

The risk would be assessed at high level of confidence (say 90 percent) which thereby reflected the uncertainties and provided an incentive to obtaining better data, since the expected value of risk must be smaller, the larger the uncertainty.

Internalization of residual risk costs

To provide incentive to reduce risk and balance some inequities between those who receive the benefits and those who are burdned by risk, the cost of the residual risk would have to be internalized, generally via a tax paid to the federal government, except for risks which are fully insurable and, like drowning, are readily attributable. The government would, in turn, redistribute the risk tax as national health insurance and/or reduced taxes to the individual.

Modest risk aversion

Risk aversion to large events would be built into the internalization of the cost of risk, but with a relatively modest penalty. If some technology or installation posed a very large hazard at some very low probability, and many do, a case by case decision would be required, with considerable emphasis on the essentiality of the venture.

Cost effective reduction of residual risk

A limit on the marginal cost of risk reduction could be imposed.

A safety improvement would be required if the marginal cost was lower than the limit, but not required if above. This would be a quantification of the ALARA (as low as reasonably achievable) criterion, although an incentive to reduce risk as well as the uncertainty in knowledge of risk would already have been provided by establishing a suitable level for the risk tax.

The authors realized that their approach may be both too complex and too simple but hoped it would stimulate discussion of the question, "How safe is safe enough?"

- Also to promote discussion on risk management, the late C.L. Comar wrote an editorial for Science (1979) entitled: "Risk: A Pragmatic De Minimis Approach" which is reproduced below:

> Society is becoming well informed and anxiety-prone about technology-associated risks, which leads to desire their elimination. The logical and traditional approach is first to estimate the risk, a scientific task. Then comes the issue of risk acceptance, a most difficult step--moving from the world of facts to the world of values. Ideally, judgements involving risk acceptance should be made on society's behalf by a constitutionally appropriate body. But no such public decisionmaking process exists. We make do with disparate efforts of individuals, special-interest groups, self-appointed public interest groups, and legislative, judicial, and regulatory systems. However, if at least very large and very small risks were dealt with on the factual basis of effects, the individual and social value systems could be accommodated to some degree and much confusion avoided.
>
> It is human nature to be concerned primarily with effects on our own person and family and secondarily with effects on the population at large. Unfortunately, although we can predict statistical effects on populations, there is no way to predict effects on individuals. This is why fortune-tellers never become as rich as insurance companies. We need them to define actuarially the existing state of well-being and calculate effects on it.
>
> Each person has a probability of dying in any particular year, the value depending mainly on age. The existing

probabilities are well known for the United States. For example, in 1975, 1.89 million died out of a population of 213 million, giving an overall probability of 1 in 113. For some specific age groups the values were: 1 to 4 years, 1 in 1425; 5 to 14 years, 1 in 2349; 25 to 34 years, 1 to 692; 55 to 64 years, 1 in 67. We can now answer the question, What does changing a risk do to a person's existing probability of dying? For instance, if a young child were exposed to an additional risk of 1 in 100,000 (0.014 in 1425) in 1975, his overall risk for that year would be 1 in 1425 plus 0.014 in 1425, or 1.014 in 1425. For the purpose of discussion some guidelines, which may depend somewhat on age, can now be stated in terms of numerical risk:

1) Eliminate any risk that carries no benefit or is easily avoided.
2) Eliminate any large risk (about 1 in 10,000 per year or greater) that does not carry clearly overriding benefits.
3) Ignore for the time being any small risk (about 1 in 100,000 per year or less) that does not fall into category 1.
4) Actively study risks falling between these limits, with the view that the risk of taking any proposed action should be weighed against the risk of not taking action.

Clearly, these suggested guidelines are a gross oversimplification. The unfortunate, overtaken by a one-in-a-million catastrophe, have a 100 percent chance of harm. The hard fact is that attempts to eliminate risks for the unfortunate few tend to markedly increase them for the rest of a large population. This idea is most difficult to defend practically, especially when the unfortunate few are known and the unfortunate many are nameless. In addition it is necessary to take into account such matters as validity and uncertainty in risk estimates, nonlethal and esthetic effects, voluntary versus involuntary risks, societal abhorrences, and the strange versus the familiar.

Nevertheless, other than depriving the news media of a ready source of attention-grabbing items, the pragmatic de minimis approach should serve to promote understanding about how to deal with risk in the real world; encourage identifiers of risk to provide risk estimates; focus attention on actions that can effectively improve health and welfare and at the same time avoid squandering resources in attempts to reduce small risks while leaving larger ones unattended; and prevent anxiety, apathy, or derision as a response to the increasing recognition that we apparently live in a sea of carcinogens (the "today risk").

Various groups within the nuclear industry have been advocating quantitative safety goals for some time, and the following two approaches to the formulation of such goals illustrate some of the current thinking.

- The director of the Nuclear Safety Analysis Center (NSAC), E.L. Zebroski, has presented their thoughts at the 7th Energy Technology Conference in Washington in March of 1980 (NSAC, 1980) and later in July at a subcommittee meeting of the Advisory Committee on Reactor Safeguards (NSAC, 1980a).

A safety goal is needed to regulate hazards, according to NSAC, because without a practical safety goal, there is a tendency to strive in vain for near-zero risk from any defined hazard. Extreme reductions in a particular risk may lead to increases in other, less well-studied risks. No guide is found in present legislation for regulation to avoid alternative risks due to short sighted policy. These risks include deprivation, social chaos and possible contribution to chance of war due to over-regulation of domestic energy supplies. As one measure of social cost, they estimate that nearly one trillion dollars will be added to fuel bills in this century due to delays, cancellations or non-commitments of nuclear units.

NSAC suggested that any set of safety goals for nuclear power plants should have the following attributes: 1) They must provide an objective basis for regulator and utility analysis and agreement on what is "safe enough." This must be clearly a "non-zero" risk goal that considers the relative risks of the main alternative sources of electricity and the social cost of shortages, interruptions and large increases in costs. 2) They must be describable in terms of which are understandable and acceptable to reasonably informed laymen. They need not be acceptable to everyone, especially those with extreme uncompromising views. And finally, 3) They must include definitions of practical methods for design and operating decisions that make full use of best-available data and decision processes.

As a possible first cut at the formulation of a safety goal, Zebroski suggested the following features:

a) Reactor design and operation should insure that the expected time to another core-damaging accident is not less than 30 years for the whole population of reactors in the U.S.

b) Reactor and containment system design and operation should insure that, given the occurrence of a core damaging accident, there would be only a 1/1000 chance that radiation would be released causing a total dose of greater than one rem to any member of the public.

c) The nuclear risk should be maintained at no more than one-third of the total risk of the two largest alternative sources of electricity.

d) Improvements to reduce nuclear risk to 1/10 or less of the main practical alternative sources should be sought, but implemented only if they are cost effective and have no measurable effect on the cost or availability of energy.

e) Emergency plans should provide a less than 1 in a hundred chance that the total population dose be more than 5000 man-rem even if containment failure were to occur.

To implement a) and b) relative risk assessment methods were to be used with existing operating experience as a base. A factor of five improvement was considered adequate to meet the goals. Statistically rigorous formulations with defined confidence levels and permissible error bounds were to be used and the cumulative effects of the actual total population of operating reactors were to be included.

It was also suggested that the goals should be stabilized for at least 10 years to prevent the delays associated with regulatory uncertainties.

The proposal clearly indicates that NSAC believes that the reactors are very much safer than the alternatives and that the goals suggested are conservative relative to the safety levels achievable by the alternatives. However, there is some question as to how one would compare the risks of different types which arise from the various alternatives (e.g. expected number of fatalities may not be an adequate measure when comparing low frequency, high consequence accidents with the chronic risks of the coal fuel cycle). The limit of 5000 total man-rem, given an accident which breaches the containment, drew comment at the ACRS subcommittee meeting. It was considered very low; in fact, it is comparable to some of the estimates for exposures due to the TMI accident which released a very small amount of radioactive material compared to that expected to be released in the event of containment failure after a core melt accident.

- The Atomic Industrial Forum (AIF) is also actively involved in developing the use of probabilistic risk assessment (PRA) in the regulatory process (AIF, 1980; 1980a). They have proposed that PRA should support, not supplant, the current deterministic requirements and be used to suggest and justify changes in those requirements. Its use then would be as a basis for generic requirements and not, under present conditions, as a licensing condition for construction permit or operating license applicants. A common PRA methodology would be developed so that the PRA could be done as realistically as possible, with the degree of uncertainty and conservatism explicitly stated. Finally, quantitative safety goals would have to be established for PRA-based decision making. The AIF proposal is outlined below.

Basic principles for safety goals

- The goals should be generally applicable to all technologies or risk related activities.
- Acceptable societal risk should reflect societal benefits.
- No individual should bear an inordinate share of the risks.
- The goals should promote optimum allocation of resources in reducing risk.

Elements to be addressed in quantitative safety goals

- Individual health effects.

The incremental risk of adverse health effects to the maximally exposed individual in the vicinity of a nuclear power plant site should not result in a significant increase in annual mortality risk or in significant shortening of statistical life span. The suggested goal was and incremental individual mortality risk of 10^{-5}/year. This is a small fraction of existing background risk due to all causes ($\sim$ 0.1% of the total mortality risk and $\sim$1% of the accident mortality risk).

- Population health effects

The incremental cumulative risk of adverse health effects to the exposed population per 1000 MW(e) of nuclear power capacity, considering the probability and consequences of events integrated over the spectrum of potential accidents, should be no more than a small fraction of the average background incidence of health effects. The suggested goal was 0.1 fatality per 1000 MW(e) year. This represents about 0.001% of the total mortality risk and about 0.005% of the total cancer risk, assuming a total nuclear capacity of 200,000 MW(e).

·Cost benefit ratio

The benefit, in terms of population risk reduction, afforded by a change in plant design or operating procedure should be comparable to that which is generally achievable through alternative investments of the cost of the change in other areas of public risk reduction. The suggested goal was $100/man-rem. This was stated to be equivalent to $1 million/life saved and comparable to the median cost-benefit ratios for other health and safety protective measures.

·Core degradation probability

A limit should be established for the probability of accidents involving serious core degradation such that, given the expected population of reactors, the recurrence interval for accidents as serious at the one at Three Mile Island would be on the order of one per several decades. This would establish minimum requirements for accident prevention and is intended to prevent undue emphasis on mitigation of accidents. It would also reduce the frequency of stress provoking events for populations near plants and limit the economic risks of accidents.

The AIF suggested that the initial set of values should be used on an interim basis for a trial period of three years. It was also recognized that it is important for qualitative judgement to supplement the quantitative goals, particularly in borderline cases.

3.4 Observations

The ten quantitative risk proposals reviewed above demonstrate the effect of overall safety philosophy and policy on the choice of framework and the numbers used for the various categories of risk. Concern over community losses has led to limits on the total number of fatalities (for example, Farmer, 1967; Kinchin, 1979; CIRIA, 1977, Okrent and Whipple, 1977; AIF, 1980) while other proposals are only concerned with individual risks (Adams and Stone, 1967; Bowen, 1975; AECB, 1978; Comar, 1979). Of those that address community risks, some considered a large scale accident (or catastrophe) more costly than many accidents resulting in the same number of fatalities, while others set limits only on the expected number of fatalities averaged over time. Given these variations in items considered important for safety regulation, it becomes clear that comparisons with the risks of alternate technologies will not be straightforward.

It should be noted that the criteria discussed above have dealt directly only with public health and safety issues. Any complete risk management framework must also consider property damage and threats to important resources such as forests, farmland and major aquifers.

4. SOME PROBLEMS IN THE USE OF QUANTITATIVE SAFETY GOALS

Several sets of problems have to be addressed if quantitative safety goals are to be used to improve the management of risk. They arise in the establishment of the goals, in the achievement of compliance with the goals, and in the demonstration of that compliance.

4.1 Establishing the Safety Goals

As discussed earlier, safety impacts are one of several sets of impacts that are considered in the multilevel decision whether or not to build a particular facility at a particular site. A quantitative risk management framework must be compatible with all aspects of the decision and impact considerations.

Much of the concern over the use of cost and risk-benefit assessment is due to its lack of completeness and its sensitivity to the assumptions used in the analyses, which are not always clearly stated in the presentation of results. One of the fears is that a single number, which is both uncertain and based upon tenuous assumptions, will be used to make decisions. Also, some broader philosophical problems arise. Harold Green (1975) has said that "the question is whether safety determinations of public policy import are, or should be solely within the province of any single discipline or whether they should reflect the collective wisdom of an amalgam of disciplines or viewpoints, expert as well as non-expert." He recommended that the analysts should make their results open and understandable, with the assumptions and uncertainties stated clearly, and that the analysis should be used as input to the decision process and not as a substitute for it. Reliance on a single number would not allow for a grey scale and would obscure more subtle issues (Green, 1975a). In light of these concerns, a workable risk management framework would have to be a synthesis of many viewpoints, would have to consider many aspects of risk and the various tradeoffs, and would have to deal explicitly with uncertainties.

It is noted that the Advisory Committee on Reactor Safeguards in its letter of May 16, 1979 to the NRC, in which it recommended that the NRC develop quantitative safety goals, also recommended that "Congress be asked to express its views on the suitability of such goals and criteria in relation to other relevant aspects of our technological society . . " (ACRS, 1979).

4.2 Uncertainties

Important uncertainties in the management of risk arise both in the estimation of the types and magnitude of all the impacts and in the prediction of the effects upon those impacts of various interacting policy options. Many important impacts may be left out and the assignment of a common measure of cost to the impacts that are included is not possible without controversy.

In the analysis of accidents both the frequency of each accident scenario and its consequence are uncertain. Some of the uncertainty is due to the randomness in the initiation of the possible accident sequences and therefore in the conditions internal and external to the facility at the beginning of the accident. The risk analysis is an attempt to estimate the distribution of the frequency and consequences of these accidents. However, the estimates of the distributions are also very uncertain. This uncertainty is due to inadequacies in failure rate data for the plant components, to shortcomings in the models of the plant systems and in the models of the emergency plans; and it is also due to possible omissions in the analysis.

A proper risk assessment would explicitly estimate the range and types of uncertainty. However, there will always be a lack of assurance about the estimates of low frequency, high consequence events, because comparison with historical data is not possible.

4.3 Bias and Abuse

While the analyst may attempt to make calculations in the risk assessment objective, a large amount of subjective judgement is involved in the choice of models, in the selection of data, and in the assessment of the adequacy of the large number of often subtle assumptions that are incorporated into the analysis (Van Horn and Wilson, 1976). At present, methods for some aspects of the risk analysis are just being developed, e.g., treatment of fires and earthquakes, and may lead to cursory or distorted results. The subjectivity, the subtlety and the novelty leave analysis open to bias which is unintended, as well as to outright abuse. For these reasons, measures for quality assurance in the methods and performance of the analysis should be developed and peer review should be required.

4.4 Conflict

The variation of both societal values and societal risks, as well as the uncertainties in the estimation of those risks, ensures that there will always be conflict in the management of risk. While the adversary nature of the decision process allows for each side to be heard and makes possible a better decision, there will never be complete consensus on all of the issues whenever society imposes risks on a particular group, even if it is for the overall good of society.

After the form and the numbers of a management framework have been established, there should be a clear straightforward method to decide whether the criteria have been met. The conflicts then, might logically be separated into questions of goal setting and goal achievement. The risk management framework itself will be the result of the resolution of the first set of questions and it must provide a means of resolving the second set of questions in the presence of uncertainties and even without consensus, so that the improvements in the decision are not overshadowed by the costs of the conflict and the associated delay.

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