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ABSTRACT

Rational regulation of environmental hazards may be based on the implicit underlying principles that government actions should enhance the average quality of life for those governed and maintain some degree of equity in the distribution of benefits, costs, and risks. Issues arising from these principles have practical implications for risk management policy in general and for the development and application of radiological protection criteria in particular. One of the issues is the appropriate distribution of expenditures for regulating different risks. The total resources available for risk regulation are finite; hence, minimizing the total risk subject to this constraint is an appropriate strategy for optimum risk management. Using a simple model, it is shown that this strategy leads to a distribution of expenditures between different risks such that a greater fraction is allocated to a risk with a higher cost of mitigation or control but the allocation is limited in such a manner that the fractional contribution of that risk to the total risk is also higher. The effect of deviating from this strategy is examined. It is shown that reducing a single risk of concern below the optimum value by a factor 1/F can increase the total risk by about F times the risk of concern. Taking into account the large uncertainties in risk assessment for establishing radiological protection criteria, it is argued that an optimum strategy for remedial action should (1) set basic risk limits as high as reasonable; (2) use realistic, case-specific data and analyses in deriving allowable residual contamination levels from basic risk limits; and (3) implement a policy of reducing residual contamination to levels that are as low as reasonably achievable (ALARA) within the constraints imposed by optimum resource allocation.

INTRODUCTION

The development of radiological protection criteria is an evolving, largely empirical, process that raises fundamental issues concerning the balancing of benefits, costs, and risks. Lack of scientific means for estimating the benefits, costs, and risks as well as lack of agreement on the ethical issues preclude a rational (as contrasted with empirical) approach in which criteria are derived from fundamental scientific and moral principles. An occasional effort to examine the underlying issues and principles can, nevertheless, be of some value if undertaken from the viewpoint of assessing the consistency between radiological protection criteria and the societal goals that these criteria are expected to advance.

A key point emerges from the re-examination of underlying issues presented herein--viz., there is an optimal balance of expenditures to regulate different risks and attempts to reduce a specific risk by increased expenditure for that risk can increase the overall risk. This point is not new and is intuitively obvious. However, it is often ignored in establishing risk-related criteria such as radiation protection criteria--in large part because institutional procedures for developing criteria focus on one kind of risk at a time and institutional means for establishing a balance between different risks, other than the overall political process, are lacking. The political process is influenced by public perception of different risks, which may differ from an objective assessment of the risks and lead to political pressure for an unbalanced distribution of resources for risk mitigation. A simple model that demonstrates the need for balance and enables one to derive relative risk limits may therefore be useful as a reminder of the need to maintain a proper balance. Data, more detailed discussions, and references related to this problem are given by Rowe (1977), Crouch and Wilson (1982), Cohen (1983), and Covello (1983). In order to place the model in an appropriate context, other topics discussed in this presentation are the rationale for societal regulation of risk, some of the problems in applying this rationale, and the implications for development of radiological protection criteria.

UNDERLYING PRINCIPLES AND PROBLEMS

One may start from the democratic ideal that government laws and regulations should be based on a policy of (a) maximizing the average quality of life for those governed:

$$\langle QOL \rangle = \frac{1}{N} \sum_{i=1}^{N} QOL(i) \qquad (1)$$

where QOL(i) is the quality of life for the ith individual; and (b) maintaining an equitable distribution of the quality of life for different individuals. The first of these principles is widely accepted; the second is controversial. The controversy centers on interpretation of the word "equitable", the extent to which a government can and should attempt to control the distribution, and the extent to which constraints on the distribution affect the average. A problem in applying both principles is that means for determining the quality of life for an individual are lacking.

Each individual has some concept of the quality of life and seeks to maximize his or her quality of life subject to constraints imposed by economic conditions, governments, and cultural and religious mores. Individuals do not require formal specification of the quality of life; each individual utilizes intuitive concepts based on his or her perception of the benefits, costs, and risks involved. A more formal approach is needed to provide a basis for resolving conflicts that could otherwise reduce the average quality of life and lead to inequities. Common, consensual measures of benefits, costs, and risks are needed. The following formal relation between the quality of life and benefits, costs, and risks is useful for structuring this problem:

$$QOL(i) = \sum_j b(ij)\, B(ij) - \sum_k c(ik)\, C(ik) + \sum_l rb(il)\, RB(il) - \sum_m rc(im)\, RC(im) \qquad (2)$$

where: B(ij), C(ik), RB(il), and RC(im) designate different benefits, costs, and risks for gain and loss, respectively; and b(ij), c(ik), rb(il), and rc(im) are "trade-off factors" that correspond to the value each individual attaches to a particular benefit, cost, or risk. Substitution of Equation 2 into Equation 1 leads to corresponding decomposition of the average quality of life into benefit, cost, and risk components: $\langle QOL \rangle = B - C + RB - RC$.

A completely general formulation should include both nonmonetary and monetary benefits and costs. Nonmonetary benefits include personal relations, harmonious surroundings, autonomy, esteem, power, etc.; nonmonetary costs include anxiety, frustration, ill health, etc. The difference between benefits and costs on the one hand and risks on the other hand is that the former consist only of those benefits and costs that can be predicted with reasonable certainty whereas the latter are uncertain and include an assessment of the probability of realization. For the purpose of benefit-cost-risk assessment, one may define RB as the product of a benefit and the probability that it will be realized and RC as the product of a cost and the probability that it will be realized. Thus, B and C correspond to the special cases of gain or loss where the associated probabilities are unity--or, in practice, close to unity. (These definitions differ from the definitions customarily used in benefit-cost-risk analysis. In the traditional approach, the uncertain benefits RB are included with the benefits or ignored, and the risks are defined as the uncertain costs RC.) Discount factors for future benefits, costs, and risks must also be taken into account, but are not shown explicitly.

Equation 2 serves to identify some of the problems of formulating government policies for enhancing the average quality of life in an equitable manner. Objective quantification is not feasible for many of the benefits and costs. Quantification of risks requires data on representative samples from which the probability factor may be extracted; such data are available for only a very few risks. Trade-off factors involve perception variables that exhibit large variations between individuals and are sensitive to changing circumstances and events. It is extremely difficult, perhaps impossible, to devise methods of measurement that can give stable, representative values. Furthermore, a single average value for a particular trade-off factor would not suffice; in a democratic society, criteria should accommodate diversity in values. These problems of quantifying and measuring the benefits, costs, risks, and associated trade-off factors preclude the use of Equation 2 as a basis for a "first principles" approach to the problem of developing risk-protection criteria. However, Equation 2 is still useful as a starting point for inferring certain relations that merit consideration in the development of risk-protection criteria.

For the purpose of examining the problem of risk balancing, it is convenient to follow the customary procedure of lumping benefits and risk of gain (uncertain benefits) together as benefits ($B + RB \rightarrow B$) and to limit the use of the word "risk" to "risk of loss" ($RC \rightarrow R$). We may also express the total cost C as $C = C' + CB + CR$, where C' represents the nonmonetary costs, CB the monetary costs incurred to realize the benefits, and CR the monetary costs incurred for risk mitigation. Equation 1 may then be rewritten as:

$$\langle QOL \rangle = (B - CB) - C' - (R + CR) \qquad (3)$$

A critical decision for benefit/risk balancing is the allocation of available public resources between CB and CR. There is no formal procedure by which the appropriate balance may be derived; the balance is determined by political processes and reflects an average of the individual trade-off factors--with weighting factors proportional to the influence of individuals. However, regardless of the value of CB or CR, or their ratio, we can reasonably assert that there is some limiting value of CR that represents the maximum public expenditure that society is willing or able to allocate to risk mitigation. We may, therefore, proceed on the assumption that CB and CR have assignable values, even though we may not know what these values are. This decouples the problem of maximizing the net benefits, $B - CB$, from the problem of minimizing the risk and associated costs, $C' + (R + CR)$. Each becomes a problem of optimum strategies for allocation of limited resources.

The nonmonetary costs, C', include psychological costs such as anxiety; these costs present a difficult problem because they cannot be quantified and there is no known procedure for taking them into account in a systematic manner. One may deal with this problem by first developing an optimum objective strategy for allocating monetary resources available for risk mitigation (CR) in order to minimize the total risk (R), and then considering adjustments for subsequent reduction of nonmonetary costs as a separate problem. The latter problem is beyond the scope of this discussion because it involves public concerns based on individual perceptions. Some of these concerns may be valid and require adjustments in strategy; others may be based on misperceptions that indicate the need for greater dissemination of information but can, nevertheless, create political pressures that necessitate adjustments in risk management strategies.

Eliminating nonmonetary costs from consideration leads to the following statement of the risk management problem: to minimize R subject to the constraint that CR is fixed. If the starting point for inferring this statement is the premise that government policy should be to maximize the average quality of life, then R is the total of all regulatable risks for all individuals and CR is the total cost of regulating these risks. CR should include all costs--for support of regulatory agencies, and for monitoring, control, mitigation, and remedial action by public agencies or private corporations or individuals. (Dividing the total risks and costs by the number of individuals in order to obtain average total risks and costs does not affect the optimum allocation because this number is fixed.) If, on the other hand, the starting point is the premise that government policy should be to prevent an inequitable distribution of risk by limiting the risk to the maximally exposed individual or to a critical group for each risk, then R becomes the sum over all different regulatable risks of the risk to the maximally exposed individual or the average risk to the critical group. CR is still the total cost. The allocation of costs between regulatable risks will be different for these different policies because the relative cost of regulating two risks to the same level (and, hence, the risk-cost relation) will be different depending on whether this level is the average of the risk to the entire population, the average over the critical group for that risk, or the risk to the maximally exposed individual.

AN OPTIMUM RISK-MANAGEMENT STRATEGY

Let R(n), n = 1,2,...,N, be the different regulatable risks to which individuals in a society are exposed. A catalogue of such risks would include exposure to different sources of radiation, exposure to different toxic substances, traffic risks, commercial travel risks, risks from consumer products, and a variety of health risks. The full list would include every risk that could be regulated. The total of all regulatable risks will be designated by:

$$R = \sum_{n=1}^{N} R(n) \qquad (4)$$

(It is assumed that all risks are expressed in common units, e.g., fatalities per year, using appropriate trade-off factors if necessary.)

A strategy for management of a particular risk has two parts, which may be referred to as "procedure-related" and "cost-related". The former refers to risk reduction measures that can be taken by altering the way in which something is done without incurring any appreciable additional cost. For example, traffic risks can be reduced by careful driving and the use of a seat belt; occupational risks can be reduced by following safety procedures and by proper use of available safety equipment; and individuals can reduce health risks by not smoking, engaging in moderate exercise, and following good nutrition. Cost-related measures are measures that require significant additional expenditures--for example, more frequent aircraft inspections, improved traffic lighting, and lower limits on concentrations of industrial pollutants in the air and water.

For the purpose of the following discussion, it is assumed that each risk has been reduced to the maximum extent possible by procedure-related risk management and that further reduction can be accomplished only by additional expenditures for regulating that particular risk, i.e., cost-related risk management.

The cost of regulating a risk will increase as the level to which the risk is reduced decreases. The functional form of the cost/risk relation can be quite complicated and will be different for different risks. As an example, consider the risk from a radioactive residue located in a readily accessible, uncontrolled area. Let CR(R), or the inverse relation R(CR), be the cost/risk relation for this one risk. If no mitigation or remedial action were carried out, the cost would be zero (CR = 0) and there would be some maximum value of the risk, RMAX. Any reduction of risk below this level would involve an initial fixed cost CRF. The variable cost would be proportional to the quantity of material removed; hence, one might have a relation of the form CR(R) = CRF + A [RMAX - R] if conditions were such that the reduction in risk was proportional to the amount of contaminated material removed. If the contamination were unevenly distributed in such a manner that either the amount of additional material that had to be removed or the difficulty of removing it increased as the risk decreased, an inverse relation, CR(R) = A/R, might be a reasonable approximation over a limited range. For naturally occurring radionuclides, the cost of risk reduction would increase rapidly as natural background levels were approached and would become infinite for risk reduction to levels below the risks due to natural background concentrations.

For costs and risks within the range where action to reduce the risk is necessary, one may reasonably assume that the cost increases as the risk is reduced, that the incremental increase in cost for an incremental decrease in risk (-dCR/dR) will increase as the risk becomes small, and that the cost will become practically infinite as the risk approaches zero or some threshold value. (This last relation may not apply for some risks; e.g., the risk from a particular food additive that does not occur in nature may be reduced to zero at moderate cost merely by banning the additive. However, for risks that cannot be eliminated in this manner--e.g., transportation risks and risks from generation of electric power--the assumption that the cost becomes practically infinite for a reduction of the risk to zero is unavoidable. At some point, banning activities that cause risk can only lead to substitution of one risk for another.) A cost/risk relation of the form CR = A/R, where A is a constant characteristic of the type of risk, has the aforementioned attributes; this relation will be used as a simplified model for examining the effect of risk management strategies that allocate different amounts to the reduction of different risks.

On the basis of the foregoing considerations, the problem of optimum management of multiple risks may be stated as a problem of minimizing the sum given by Equation 4 subject to the constraint that

$$CR = \sum_{n=1}^{N} A(n)/R(n) \qquad (5)$$

be constant, where A(1),...,A(N) are constants that specify the relative costs for regulation of the different risks.

Data are available on the expenditures for risk mitigation that society is willing to support, expressed as dollars per fatality averted. This quantity corresponds to $-dCR/dR(n) = A(n)/R(n)^2$. Cost constants for risks to the entire population may, therefore, be obtained by multiplying the dollars per fatality averted by the square of the number of fatalities, and the cost for that risk may be obtained by multiplying the dollars per fatality averted by the number of fatalities. Representative order-of-magnitude values for expenditures per fatality are $100,000 for traffic safety, $1,000,000 for civilian aircraft safety, and $10,000,000 for general radwaste safety (Cohen 1983). (The data for aircraft safety are for France; for the purpose of obtaining exemplary numbers, it will be assumed that data for the United States would be comparable.) The order-of-magnitude risk totals for the entire population of the United States are 50,000 fatalities per year for traffic and 10 fatalities per year for airlines (Rowe 1977). Risk data for radwaste practice are lacking. An estimate based on the very conservative assumption that 100,000 individuals live close to radwaste facilities and might receive an exposure of 10 mrem/yr suggests a total risk of 0.1 fatality per year or less.

The data for total risk to the population of the United States can be used for estimating the cost constants for a risk management strategy based on the total risk to the entire population. Different data must be used if the strategy is to limit the risk to the critical group or maximally exposed individual for each risk. If the distributions of risk among the population were the same for all risks, then the result--the optimum allocation of expenditures between different risks--would be the same for all strategies because the data used for the different strategies would differ only by a common multiplying factor for the different types of risk. If, however, for two different types of risk--e.g., n and n'--one is uniformly distributed among the population and the other is non-uniformly distributed, then the ratio R(n)/R(n') will be different depending on whether R(n) and R(n') are the risk to the entire population, critical group, or maximally exposed individual. Consequently, the ratio A(n)/A(n') will also change. The total cost, CR(n) = A(n)/R(n) will be the same for each risk; hence, the ratio A(n)/A(n') will increase proportionately with R(n)/R(n'). If the distribution for the nth risk is less uniform than the distribution for the n'th risk, then the ratio A(n)/A(n') will be larger for a strategy based on limiting the risk to a critical group or maximally exposed individual than for a strategy based on limiting the risk to the entire population.

One may readily show that the solution to the problem of minimizing Equation 4 subject to the constraint given by Equation 5 is:

$$R(n) = b\ A(n)^{\frac{1}{2}} \qquad (6)$$

where $b = (1/CR)\sum_{1}^{N} A(n)^{\frac{1}{2}}$, and

$$CR(n) = A(n)^{\frac{1}{2}}/b \qquad (7)$$

where $CR(n)$ is the cost of regulating the nth risk.

We may infer from this result that the optimum strategy for minimizing the total risk subject to a constraint of fixed resources would allocate a share to each risk that increased as the cost of regulating that risk increased. However, the share would not be sufficient to fully offset the increased cost; hence, the contribution to the total risk would be greater for risks that were more costly to regulate.

The specific functional form of the risk and cost relations for optimum resource allocation is a consequence of the assumed cost/risk relation. However, the general conclusion that both the cost share and risk share for a given risk will increase with the regulation cost if resources are optimally allocated can be expected to be valid when the general relations stated in the first sentence of the paragraph preceding Equation 5 are applicable.

Using the data given above for costs and risks from traffic, airline travel, and radwaste practice, one may estimate the relative risks and costs that would result from optimum allocation of costs based on a strategy of minimizing the total risk to the entire population of the United States. One obtains the ratios: traffic:airline:radwaste = $1:6\times10^{-4}:2\times10^{-5}$. These ratios may be compared with the actual ratios of the risks, $1:2\times10^{-4}:2\times10^{-6}$, and the cost ratio estimates based on the assumption of an inverse cost-risk relation, $1:2\times10^{-3}:2\times10^{-4}$.

These numbers suggest that expenditures for regulation of radwaste risks are excessive compared to regulation of traffic and aircraft safety _if_ the chosen strategy is the risk to the entire population. For a strategy based on the risk to a critical group or maximally exposed individual, the imbalance may not occur because the distribution of risks among the population can be expected to be more uniform for traffic risks than for air travel or radwaste risks, and probably more uniform for air travel risks than for radwaste risks. Data for allocation estimates based on critical groups or maximally exposed individuals for air travel and radwaste risks are lacking; hence, exemplary figures for these cases cannot be given. It should be noted that the estimate given for the radwaste risk to the total population is very speculative.

CONSEQUENCES OF NON-OPTIMUM RISK MANAGEMENT

Uncertainties in Risk Management

A risk must be regulated by controlling the hazard or exposure to the hazard. (In the terminology used here, a hazard is a condition that creates a risk. A pothole is a hazard; it becomes a risk when there is traffic. An ocean storm is a hazard; it becomes a risk to a person in a boat crossing the ocean. A risk may be reduced by either reducing the exposure or reducing the hazard.) In the case of radiological protection for remedial action, the hazard is residual contamination. Occupational risk from residual contamination may be controlled by controlling exposure; public risk in an uncontrolled area requires reduction of the hazard, i.e., of the residual contamination (which will be referred to generically as the "source"). In order to manage the risk, one must establish a level of acceptable risk, derive a source level that corresponds to this risk and then implement appropriate measures for controlling the source level.

The level of acceptable risk is established as a "basic risk limit". The corresponding source level must be derived from this risk limit by a risk analysis. The relation between risk and source is given by a pathway sum:

$$R = (R/D) \sum_{\substack{\text{pathways} \\ \text{radionuclides}}} (D/E) \times (E/S) \times S \tag{8}$$

where R is the individual risk (fatalities/year), D is the individual radiation dose (mrem/yr), E is the exposure (quantity of radionuclides inhaled or ingested or external radiation level), and S is the residual contamination (radionuclide concentration in pCi/g for soil contamination). This relation may be written schematically as the formal product:

$$R = (R/D) \times (D/E) \times (E/S) \times S \tag{9}$$

where R/D (the risk factor), D/E (the dose conversion factors), and E/S (transfer factors for transport by environmental pathways) are quantities that must be calculated by appropriate models. If RL is the established risk limit, the source limit, SL [also referred to as the "allowable residual contamination level" (ARCL) (Napier 1982)], may be obtained from the inverse relation:

$$SL = (S/E) \times (E/D) \times (D/R) \times RL \tag{10}$$

A large uncertainty in the estimate of the source limit results from uncertainties in the risk limit and the conversion and transfer factors. A generic value is commonly used for the risk limit. One cannot, therefore, take into account case-specific conditions, such as different benefits and costs and the many variables that can affect the acceptability of a risk in a particular situation. The uncertainty in the risk limit estimate may well be an order of magnitude or more (Rowe 1977--Sec. 17.4).

The risk factor, R/D (or its inverse, D/R), is based on an extrapolation of dose-response data for health effects observed at doses on the order of 10 rems or higher down to doses of a few millirems. If the prudent assumption that there is no threshold for low dose rates is valid, then uncertainty in the risk factor at the radiation levels of interest is probably less than a factor of 10. However, the existence of a threshold cannot be excluded on experimental grounds (Webster 1981, 1983), and the observation of radiation hormesis in simpler organisms suggests that this possibility must be taken seriously (Luckey 1980). Thus, one may reasonably claim that the risk factor is also uncertain by at least an order of magnitude.

Dose conversion factors, D/E, are based on dosimetry models. The models cannot be validated directly by experiment because the dose to the tissue of an organ cannot be measured. Dose calculations are based on a "reference man" with characteristics that may differ significantly from any of the exposed individuals. Thus, it is not unreasonable to argue that uncertainty in the dose conversion factors may be as large as an order of magnitude, with overestimates of the internal dose equivalent from a given intake more likely than underestimates.

The environmental transfer factors, E/S, must be determined by means of models that are very simplified representations of complex systems. Data for determining model parameters are often lacking, and estimated generic values are commonly used to substitute for the missing data. In general, errors in the environmental transfer factors can be expected to be an order of magnitude or more, although they may be less for exceptional situations in which there is a single, dominant, well-characterized pathway and only the risk in the near future need be considered.

The cumulative effect of these errors is shown schematically in Figure 1 where the error bars are represented on a logarithmic scale. The overall error of the source limit derived from the risk limit can be expected to be several orders of magnitude.

In order to compensate for the uncertainty in estimates of the transfer and conversion factors, it is customary to use conservative assumptions for estimating these factors so that the derived limits are more likely to be underestimates than overestimates as indicated by the assymetry of the error bars in Figure 1. Consequently, the risk from residual contamination may be limited to a value that is less than the risk limit corresponding to optimum cost allocation by an order of magnitude or more.

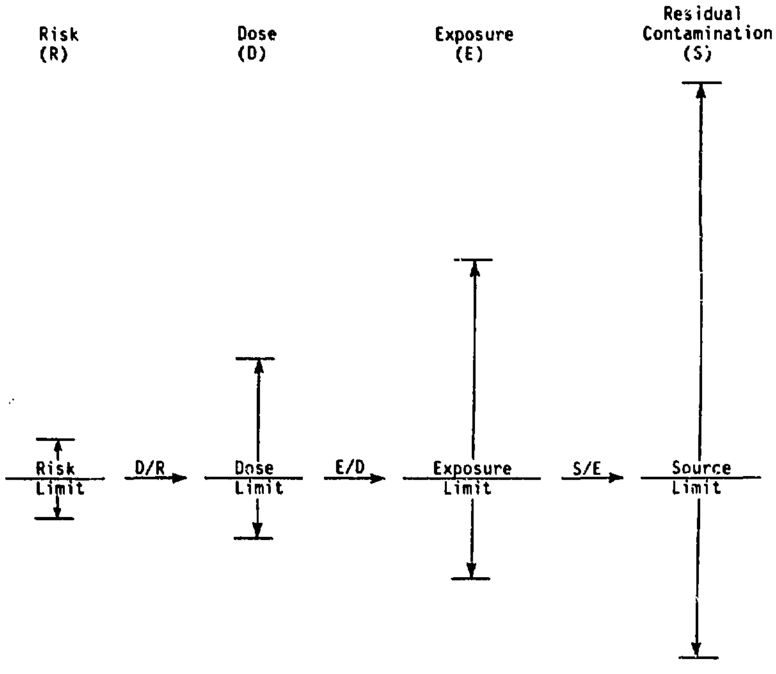

Figure 1. The Propagation of Uncertainty in Deriving Source Limits for Remedial Action from Risk Limits.

Overcompensating for Uncertainty in a Single Risk

The consequences of overcompensating for uncertainty in a single risk may be described as follows. Let R be the total risk and R(n) the individual risks for an optimum allocation of expenditures for regulation. Assume that one risk, e.g., R(1), is singled out for special consideration and that measures are implemented to reduce this risk below the optimal level by a factor 1/F. This requires an increase in the expenditure for one risk by a factor F (assuming that an inverse cost-risk relation is valid). Assume that the total expenditure for risk regulation is fixed, so that expenditures for other risks must be decreased, with a consequent increase in these risks. Assume that the allocation of expenditures between the other risks remains optimum; hence, each of the other risks will be increased by the same factor, designated by 1/f. Using these assumptions, one may readily show that:

$$f = 1 + (1 - F)CR(1)/CR' \tag{11}$$

where CR(1) is the cost of mitigating the first risk and CR' = CR - CR(1) is the cost of mitigating the remaining risks (both for optimum expenditure allocation). We note that f will decrease as F increases, and that F