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A DECISION MODEL FOR THE REGULATION OF HAZARDOUS WASTES

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ABSTRACT

This paper presents a systematic procedure that can be used by regulatory agencies to establish guidelines and standards for the disposal of hazardous industrial wastes. A general economic-decision model has been developed to provide an operational framework for weighing the risks, benefits, and costs associated with the underlying process. To begin, the concepts of utility (benefit) and probability (risk) are made explicit, and then, whenever possible, converted into common units. In performing this conversion, it was necessary to draw upon the criteria that society has evolved for accepting risks. The problematic and uncertain nature of the data has been dealt with through a secondary reliability analysis.

INTRODUCTION

Rapid and unabated growth of hazardous wastes has precipitated a growing national concern. The Environmental Protection Agency (EPA) has been charged with the responsibility for formulating sound, effective, operational guidelines for control of these pollutants. Since inadequate control offers the potential for causing adverse public health and environmental impacts, a balance must be struck between social well-being and economic value.

In general, the government has the basic responsibility for assuring the health and safety of society. There are many possible actions the regulatory agencies might take in this regard, ranging from ignoring the public good completely to throwing out the market system and running things by fiat. In trying to find a middle ground, decisionmakers are increasingly faced with the prospect of evaluating uncertain risks and benefits to human health and to the environment. Estimating the magnitude, probability, and distribution of risks, and assessing the

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costs and benefits of regulatory policy are not easy tasks. They are fraught with the uncertainties of technological and economic forecasting, as well as the anxieties of a concerned and often vocal public.

In this paper, the techniques of risk-benefit analysis are used to make explicit the often hidden tradeoffs between human loss, dollars spent, and environmental quality [1-3]. Specifically, a general economic-decision model has been developed to provide the conceptual framework for regulating the disposal of hazardous industrial by-products. A normative approach is assumed. Data inputs on risks and fatalities are merged with economic loss relationships and control cost functions to yield the expected societal cost associated with the utilization of a particular material. These costs are then compared with a measure of societal well-being, first to determine levels of risk acceptability, and ultimately, to formulate decision rules for regulating hazardous waste disposal.

In the next section we discuss a variety of factors which must be considered when determining acceptable levels of risk. This is followed by the derivation of the cost and benefit relationships. Historic risk data are relied upon to estimate society's willingness-to-pay for economic benefits. In the fourth section, these functional forms are combined to form the general decision model. We conclude with the development of a procedure for assessing the reliability of the overall analysis.

FACTORS AFFECTING RISK ACCEPTANCE

Risk can be loosely defined as the probability of suffering injury, damage, or loss from direct or indirect participation in some activity. Therefore, in taking a risk, an individual or a group, presumably have some notion of benefit or gain. It is not always clear though how the acceptability of a risk should be judged in comparison to this gain, or what criteria should be used when deciding among alternative courses of action. If a choice were solely between freezing to death or burning unclean coal, the decision would be easy. If the choice were between higher prices for energy or reduced air quality, the decision is not so straightforward.

Van Horn and Wilson point out that there are no hard rules for equating risk and benefit measures, and when the numerous risk situations in society are considered, things become increasingly complex [3]. Retrospective studies of the previously accepted levels of risk in society may be a guide to understanding past behavior [2, 4, 5], but comparing predicted future risks to statistically determined past risks can be misleading. This is especially true if the predicted risks are presented without corresponding information on their uncertainties.

In general, the interplay of many factors makes policy making (by the individual for himself or by the government official for society) highly complex. The measurement of benefits and risks in the face of a divergent set of social values adds to the difficulty. The environmental impact statements required by the National Environmental Policy Act are a good case in point. While measurement of the economic benefits of building a new power plant may be relatively easy, the environmental implications, particularly the aesthetic considerations and effects upon public health, are commonly associated with a nonmonetary value system.

Nonetheless, in establishing a methodology for decisionmaking, it is essential to know:

- How people make judgments about the utility or disutility of various things that might happen to them, and how these valuations can be measured.
- How people judge the probabilities of events that control what happens to them, and how these subjective probabilities are derived.
- How the judged probabilities change on the arrival of new information.
- How utilities and probabilities combine to control decisions.

The quantification of these factors as well as physical and environmental damages, is necessarily data dependent. The Environmental Protection Agency (EPA) and the National Institute for Occupational Safety and Health (NIOSH) are actively engaged in broadening the information base on the dose-response relationships involving hazardous materials, but still, only limited data are available. This data deficiency is even more pronounced when considering low levels of exposure, since it is at these levels that the populace comes into contact with most pollutants. As we remove ourselves both temporally and spatially from the source, the links between risk and benefit become increasingly brittle. An individual's perception and appreciation of risks and benefits vary widely [6]. When he has "lived with" the risk (as does a coal miner for instance) and when the activity is an accepted practice of society, awareness of it may be less than for the risks of unfamiliar activities. The time lag between exposure to the hazard and the occurrence of injury also affects the individual's perception. Generally, the longer the time lag, the less the threat appears to him. Another factor is the level of sophistication required for understanding the basis of the benefit-risk calculation. For example, data from atmospheric toxicological studies are less explicit in cause and effect and hence, more difficult for many to understand, than are data from studies that depict simple causal or mechanistic relationships. Further, when the probability of injury or death is seen as low and the individual has had no personal experience with others who have suffered the consequences, his awareness of the risk may not be incorporated into his behavior.

DEVELOPING THE MODEL

A basis for regulatory policy for hazardous waste disposal taking into account public acceptability of risk, must provide a means of quantifying and weighing the tradeoffs between social benefit and personal risk. The model that we propose for conducting the analysis takes into consideration the following parameters:

- Risk (chance of injury, damage, or loss)
- The economic equivalent of that risk
- Society's willingness to pay to contain the risk
- The actual costs of control

Cost Relationships

Since our primary goal is to establish acceptable levels of public exposure, it is first necessary to couch dose-response and dose-disease relationships in probablistic terms. Concentrating for the moment on fatalities per person-hour of exposure (the complete spectrum of disabilities and morbidities could be considered at the expense of greater mathematical complexity) as the chief measure of risk, expected losses must be computed for a wide range of doses [7-9]. That is, fatalities per person, normalized with respect to time, at a given dosage or concentration, must be extracted from the data and quantified. This measure is essential to the success of the analysis because it portrays the casualty of risks and provides an explicit grasp of the effects of exposure.

The next and perhaps most difficult and tenuous part of the data formulation step is the translation of risks into economic impacts. A number of operational procedures (see, for example, [1, 10]) for achieving this reduction have been recommended and accepted albeit with some reservation. Aside from the complex humanistic judgments attending any of these procedures, one such approach worth pursuing rests upon the projected wages foregone in the case of mortality, and the expected health costs (both public and private) in the case of disability. As an example, the remedial and custodial care costs associated with one genetically malformed child, excluding deprivation of earnings, have been recently estimated at about $250,000 [11]. Similar costing has been developed for cancer [10] induced by environmental pollutants as well as for a broad range of health problems precipitated by air pollution [12, 13]. In light of the promise of this research, we feel that it is reasonable and worthwhile to pursue monetary quantification of personal loss.

The second element in the cost equation is that incident upon the manufacturing facility generating the waste materials. Untreated discharges occasion little or no expense. As the environmental standards become more exacting thought, costs of effluent control mount–in some cases to the point where continued production becomes economically unjustifiable.

Recognizing that the costs of pollution abatement are wont to be passed on to the consumer in terms of higher prices or governmental subsidies, it is only necessary to focus on the absolute cost and not on the means of transaction. Accordingly, it is necessary to construct cost-control relationships for the by-products at hand. These relationships will be governed by the concentrations of waste material being discharged or disposed of and hence, will be a function of the receiving media. For example, it may be more expensive to filter out toxic substances through a treatment facility and dispose of the residuals in a landfill than to simply chemically treat waste streams before discharging them into a local body of water. In each case, the controlling technology (and the required degree of application) will differ. These levels will be reflected by discontinuities in the functions associating costs with residual concentrations. In the case of land disposal, the procedures for rendering the waste material inert or preventing its diffusion into the public water supply will have a significant impact on cost.

Once the industrial cost-control and risk-cost relationships have been ascertained, they must be integrated to yield a picture (see Figure 1) of the total cost society faces for varying levels of pollutant control. In effect, the latter component of this aggregation will represent society's willingness to pay, which is in fact society's demand curve for environmental quality. The former component is recognized as industry's supply curve, or the cost of providing environmental quality.

Benefit Relationships

The next step in structuring information requirements centers on the formulation of benefits accruing to society from the derivative pollution process. This

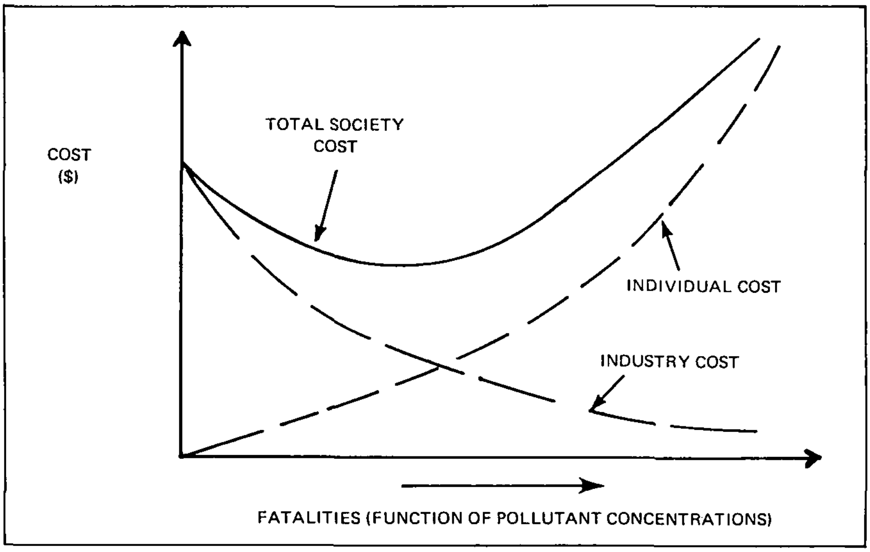

Figure 1. Aggregate cost to society as increasing function of risk.

must necessarily be done at two economic levels, the first being the occupational level and the second being the societal level. Clearly, the risks and resultant benefits are different in each case. Although this paper is primarily concerned with social welfare, much insight can be gained from exploring individual, voluntary exposure to risk.

Societal activities fall into two general categories—those in which the individual participates on a voluntary basis and those in which the participation is involuntary, imposed by the society in which the individual lives. The process of empirical optimization of benefits and costs is fundamentally similar in the two cases. In the case of voluntary activities, the individual uses his own value system to evaluate his experiences. Although his eventual tradeoff may not be consciously or analytically determined, or based upon objective knowledge, it nevertheless is likely to represent for that individual, a crude optimization appropriate to his value system.

Involuntary activities differ in that the criteria and options are determined not by the individuals affected, but by a controlling body. Because of the complexity of large societies, only the controlling group is likely to be fully aware of all the criteria and options involved in the decision process. Further, the time required for feedback of the experience that results from the controlling decisions is usually very long. The historical trends accompanying involuntary activities may therefore be more significant indicators of social acceptability than are the current tradeoffs.

As an example of the prevailing risk-benefit forces, Starr points out that the acceptance of risk is an exponential function of received wages (benefits) and can be roughly approximated by a third power relationship [2]. This turns out to be true for both voluntary and involuntary risk (including man-made and natural) although society's willingness to accept either level of risk differs by several orders of magnitude. These relationships are depicted in Figure 2. The curve labeled involuntary risk is a representation of the benefits society receives either from participating in an activity, or from the availability of a product or technology.

A CONCEPTUAL ANALYSIS OF RISKS AND BENEFITS

We are now in a position to trade off expected benefits and total costs to society as a function of risk exposure. Figure 3 has been constructed to aid in visualizing how these cost (risk)/benefit relationships might evidence themselves. Presented with these data, the policy maker must decide at what level of concentration to regulate. An optimum decision rule, in the sense of maximum expected return to society, would correspond to the point on the curve (z^*) where the difference between benefit and cost is maximum. In decision theory

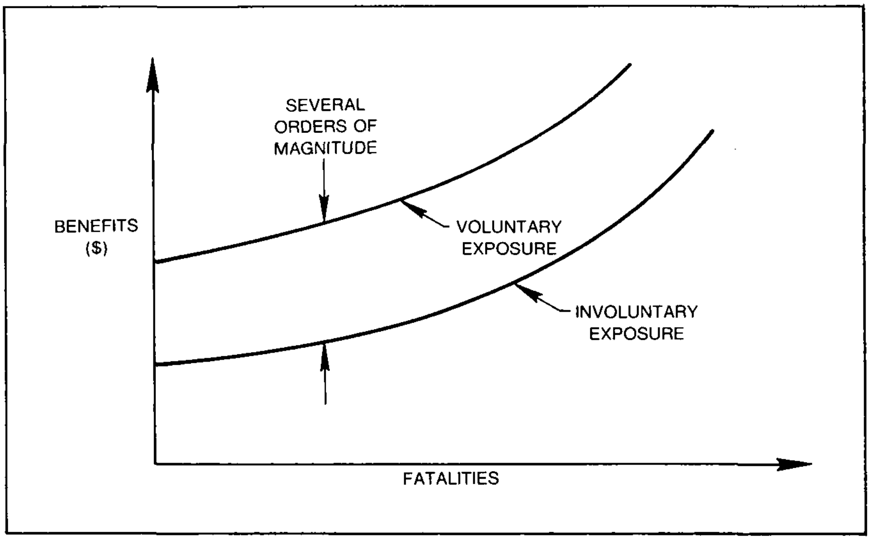

Figure 2. Benefits to the individual and society as derived from risk exposure.

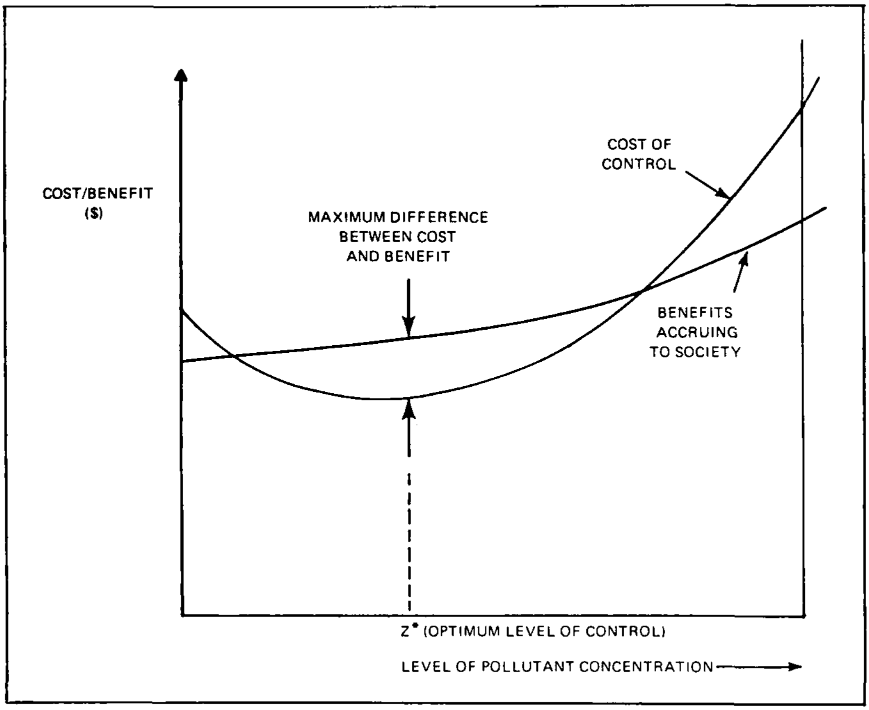

Figure 3. Comparison of control costs and benefits at varying levels of pollution.

this is equivalent to selecting a "Bayesian" strategy that minimizes the expected loss [14, 15]. This is not, however, the only decision rule available. The ultimate action will depend in part on the reliability of the analysis as well as on the unquantifiable singularities of each case. Figure 4 traces the information required to set environmental standards, while also summarizing the methodology proposed to arrive at a management strategy.

The entire procedure outlined above can be neatly expressed in the language of decision theory which provides a systematic approach to decisionmaking under conditions of imperfect information. It merges personal valuation of consequences, personal strengths of belief about the occurrence of uncertain events, and forecast information within a framework that rests upon deductions from a small number of postulates (for example, see [14]).

From the vantage point of the user of information, we consider a decisionmaker whose problem is to make a choice of an action z from some set Z of possible actions (e.g., z might represent the level of environmental standards). From this choice, the decisionmaker will incur a loss, ℓ, which depends in some known way upon the "true state of nature," θ, where θ is an element of a set Θ encompassing all possible consequences or outcomes. Accordingly, the loss function is given as:

$$\ell = \ell(z, \theta); \quad z \in Z, \theta \in \Theta$$

In our case, where Z and Θ are finite sets, the function ℓ can be displayed as a "payoff matrix" of the type used in game theory.

An operational methodology for deriving an optimal control policy is given below. Definitions of symbols and functions follow:

Θ	A set of all possible afflictions an individual might suffer from hazardous waste exposure
θ	An element of Θ; $\theta \in \Theta$
Z	A set of management actions available to the decisionmaker; the range of control levels
z	An element of Z; $z \in Z$
$p(\theta)$	A probability measure over the set Θ; risk probability function
$d(\theta)$	Personal loss associated with each outcome θ
$b(\theta)$	Resultant personal and/or societal benefits associated with each element θ
$c(z)$	Industrial cost of controlling pollution at level z.

At each level of control or environmental standard, both the individual and industry incur a cost as well as a benefit. The total loss function is represented as a probablistic function:

$$\ell(\theta, z) = c(z) + d(\theta) - b(\theta)$$

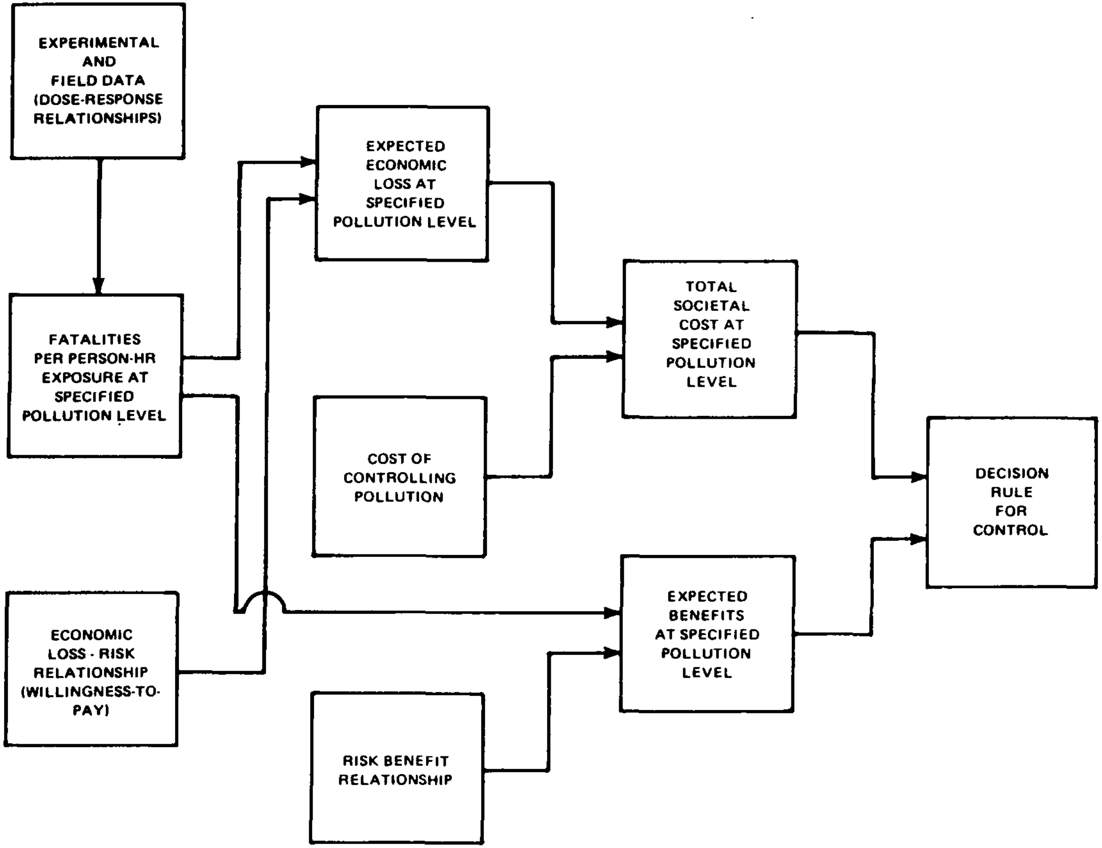

Figure 4. Information flow diagram.

Now defining the risk as the expected value of the loss function,

$$r(z) = E[\ell(\theta, z)]$$

we get

$$r(z) = c(z) + E\,[d(\theta)] - E[b(\theta)]$$

where

$$E[\ell(\theta, z)] = \sum_i \ell(\theta_i, z)\, p(\theta_i)$$

Denoting z* as the action or level of control that minimize the risk, the optimal value is found from:

$$z^* = \min_j\, [r(z_j)]$$

$$z^* = \min_j\, [\sum_i \ell(\theta_i, z_j)\, p(\theta_i)]$$

Figure 3 graphical depicts this procedure.

ASSESSING THE RELIABILITY OF DECISIONS

The inherent uncertainties and shortcomings in the data indicate a need to assess the reliability of the risk-benefit analysis. In particular, the statistical nature of the dose-response relationships creates an instability that propagates throughout the model. Figure 5 depicts what might be a typical association

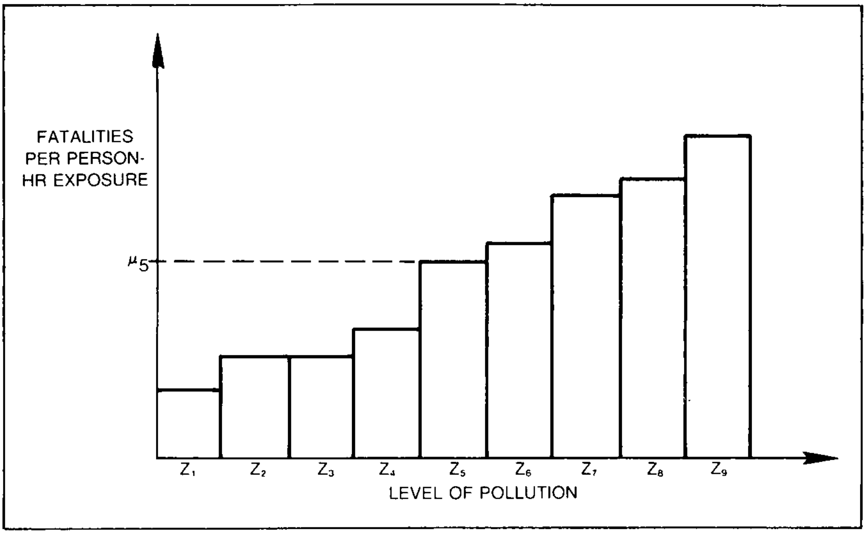

Figure 5. Fatalities as an increasing function of pollution.

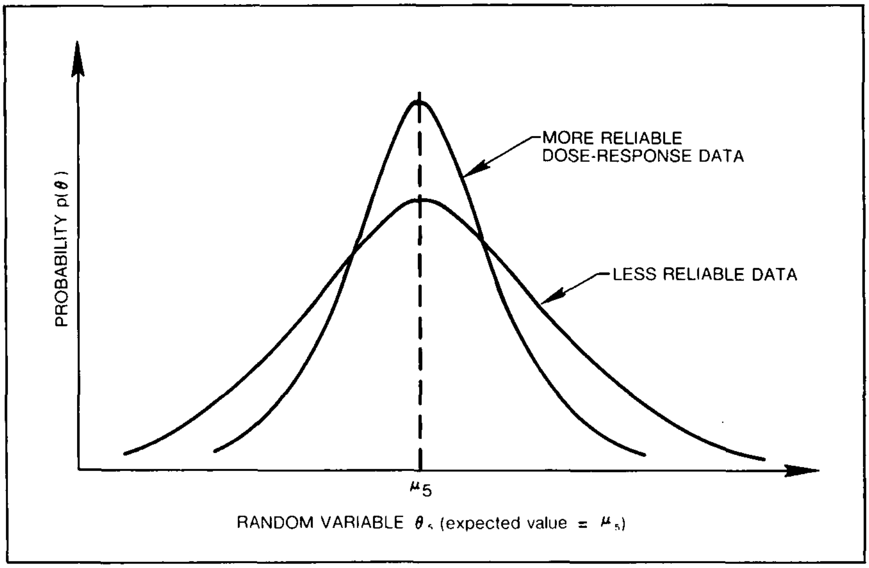

Figure 6. Probability distribution for pollution level z_5.

between fatalities per person-hour of exposure at increasing levels of environmental pollutant concentration. For each dosage, however, the corresponding risk measure is not a deterministic value, but a mean value in a probablistic sense. In effect, each level of concentration possesses a probability distribution which, for expository purposes, can be assumed to be normal with mean and variance following from the accuracy of the empirical data. Figure 5 depicts mean levels of risk for a range of pollutant levels. Figure 6 graphs two probability curves about a particular mean. The more reliable the dose-response data, the narrower the normal curve and hence, the smaller the error or variability in the overall computations.

Since we are working with data from a finite population, statistical variance is an unavoidable analytic factor which can only be reduced at the expense of compiling and originating more background data. If one traces the ramifications of this uncertainty across the information flow diagram, its influence will be noticed on both the economic loss and economic benefit components. This situation gives rise to a dispersion on the respective dollar outcomes at each level of pollution control. Resultant confidence limits will depend on the variance attending the normal distribution as well as on the specified error tolerances. One way to derive the relationships between improved data reliability and environmental standards is to perform a parametric analysis treating the uncertainty in the data as the parameter. This will allow us to trade off analytic confidence with the cost of sharpening our data base. The results of this tradeoff will heavily depend upon the costs and practicalities of closing the information gaps.

As an example of the application of the above methodology, consider a policy which sets environmental standards at level z*. The loss function is now given as:

$$\ell(\theta, z^*) = d(\theta) - b(\theta) + c(z^*)$$

where the functions on the right hand side of the equation have been defined in a previous section. For the moment, let us assume that c(z*) is constant; the damange function d, and the benefit function b, however, depend on the value assumed by the random variable θ. If the distribution of θ is normal with mean μ and standard deviation, σ, its density function is given by

$$p(\theta) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{1}{2}\left(\frac{\theta - \mu}{\sigma}\right)^2\right]$$

Through the appropriate transformations of variables, we can now obtain the distributions of $d(\theta)$ and $b(\theta)$. For example, letting $f(\cdot)$ denote the distribution of $d(\theta)$, we get

$$f[d(\theta)] = \frac{p(\theta)}{\left|\frac{d[d(\theta)]}{d\theta}\right|}$$

In general, $f(\cdot)$ will not be normally distributed unless $d(\theta)$ is a linear function of θ. Assuming $d(\theta)$ and $b(\theta)$ are independent, we are now in a position to compute the distribution of the loss function denoted by $g(\ell)$. It will be the convolution integral of the distributions of $d(\theta)$ and $b(\theta)$ and will be a function of μ and σ.

The mean value of the loss function reflects the expected loss to society at pollution control level z*. If $g(\ell)$ is available in closed form, we would be able to assess the reliability of the policy z* by establishing confidence limits on the loss. That is, we would be able to assert that the loss is bounded between some upper and lower value with a certain amount of confidence.

$$\Pr[b_L \leqslant \ell - E(\ell) \leqslant b_U] \geqslant (1 - \alpha)\,\%$$

where

ℓ = loss function
$E(\ell)$ = expected loss
b_L, b_U = lower (upper) bound
α = level of significance

The bound, b, is a function of the variance of the loss function, which in turn is a function of the variance of risk data, σ^2. The cost of collecting more data in order to narrow the risk variance can now be weighed against the uncertainty, as it varies with σ, in a parametric analysis.

CONCLUSIONS

As our understanding of the correlation between pollution and human health grows, the need for setting environmental priorities, identifying technological constraints, and taking corrective action becomes more and more insistent. The primary intent of this paper has been to provide a framework in which hazardous materials used for industrial and consumer products could be regulated, and in which guidelines and standards for hazardous waste disposal could be evaluated. The methodology that we have developed to deal with these issues offers a systematic approach to decisionmaking in the face of limited and uncertain data. The proposed model relates the reliability of the hazardous waste risk-benefit assessment to the available data on dose-response relationships. In so doing, it establishes a procedure for determining how these data can be used to recommend acceptable risk levels for society. The usefulness of the model is extended by its ability to measure the value of additional information, and to effectively use this information to improve the confidence of our decisions.

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