J. ENVIRONMENTAL SYSTEMS, Vol. 13(1), 1983-84

REGULATING NONNUCLEAR INDUSTRIAL WASTES BY HAZARD CLASSIFICATION*

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ABSTRACT

With the passage of the Resource Conservation and Recovery Act efforts to provide tighter controls on the disposal of nonnuclear industrial wastes have been steadily gaining ground. This paper first discusses the current approach to the regulatory problem and then suggests an integrated strategy based on hazard classification. Traditional methods of risk-benefit analysis are examined but found wanting in their selection criteria. As an alternative a decision model based on cost referents and socioeconomic constraints is offered as a means of comparing different policies. An example is given to illustrate the methodology and computations.

1. INTRODUCTION

Over the last two decades an increased awareness has developed for the human health and environmental risks accompanying technological growth. While individuals and societies have always been willing to bear some amount of risk to achieve an identifiable gain, changing social values have called for a closer examination of the costs and benefits associated with the allocation of resources for industrial production. If external diseconomies exist in the marketplace, or if public goods are being exploited, it is the responsibility of the government to step in and correct the underlying defects. This injunction has generally come to mean that any activity having the potential for producing adverse human or ecological effects, be they immediate, long-range, or intergenerational, should not be undertaken without a complete investigation of impacts and possible alternatives.

*The author wishes to acknowledge the Cowan Research Foundation and the College of Business Administration, Northwestern University for partial funding of this paper.

doi: 10.2190/4RLW-PFVK-HAU3-3QLU
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As a result, the Congress has enacted a series of environmental laws intended to better protect the public health and environment from a rising sea of industrial wastes (see [1] for a perspective). The responsibility for interpreting and implementing the underlying mandates rests with the Environmental Protection Agency (EPA). While this legislation represents a major step in the direction of controlling dangerous levels of exposure and reallocating costs to responsible parties, it stops short, in the area of nonnuclear industrial hazardous wastes, of setting explicit operational standards. Although a number of proposals have been forthcoming, the Agency's performance to date has been characterized by long delays and guarded discussion, thus suggesting a reluctance or inability to act decisively [2, 3]. Perhaps one of the reasons for this hesitation is the absence of a workable framework for setting public safety standards.

In the next section we discuss the current approach to the hazardous waste problem. This is followed in Section 3 with a summary of the potential advantages a scientifically based classification scheme may offer. Next, the application of risk-benefit analysis is examined, and it is decided that the traditional willingness-to-pay criterion may not be appropriate for setting either specific disposal standards or general policy. In Section 5, we develop the basic notation for risk assessment and define its major components. The issues surrounding the quantification of risk are also addressed. In Section 6, compliance costs are discussed in light of perspective control options and the EPA proposed manifest system. Finally, we present a decision-theoretic framework for comparing various regulatory strategies and highlight its use by way of example.

2. THE CURRENT APPROACH TO THE HAZARDOUS WASTE PROBLEM

The issues surrounding the classification and eventual disposal of hazardous wastes are aggravatingly complex and cannot be reduced to one-dimensional arguments. The types of waste that must be controlled cover a broad spectrum, as typified by the organic and inorganic residues created during commercial manufacturing, and by the sludges and solutions produced in heavy industry. In an ongoing effort to protect the public health and environment, the Congress has charged the Environmental Protection Agency (EPA) through the Resource Conservation and Recovery Act (RCRA) of 1976 [4] with the job of effectively regulating these wastes. As such, the EPA is required to develop from the broad guidelines of the Act a basic set of criteria which will then be adapted nationwide through individual state legislation.

The strategy developed by the EPA to implement the RCRA mandate centers on the simplified designation of wastes as either hazardous or non-hazardous. In order for a waste stream to be considered hazardous and therefore within the jurisdiction of RCRA, an evaluation must first be made by the EPA from generator-supplied data to determine whether listing is required. If not, it must then be tested to see if it meets one of the three criteria relating to hazard characteristics (i.e., toxicity, ignitability, corrosivity, and reactivity), average lethal doses in humans or animals, and hazard constituents [4]. This procedure, of course, provides for large administrative loopholes, and in practice the Agency has chosen to use considerable discretion in applying the second and third criteria [3]. In addition, all processes that generate less than 1,000 kg/month of waste, regardless of their potential hazard, have been excluded from the current provisions of the Act [5]. Although the EPA is considering a reduction in this limit to 100 kg/month, the implication that sufficiently small quantities of waste do not pose a serious health or environmental threat still remains. Such a policy ignores the acute toxicity of certain substances as well as their migratory and accumulative properties. Other exemptions include those materials covered under other environmental regulations such as the Clean Water Act, those obtained through the delisting petition process, and those designated under the recycling provision.

As a result, there has been some concern that the regulations now being proposed could eventually undermine the intent of RCRA by allowing many harmful waste materials to escape regulation. In addition, no strategies for economically managing the wastes have been put forth. This leaves open the possibility of providing more cost-effective control if an expanded classification scheme, linked with appropriate disposal options, could be developed. For example, if either the type of waste or the environmental conditions surrounding a disposal site are such that little or no migration of constituents were possible, performance standards could be adjusted to allow for less stringent controls since human or other biota contact would be greatly reduced.

3. ADVANTAGES OF THE HAZARD CLASSIFICATION APPROACH

The biological and environmental effects of hazardous wastes are manifest in a variety of forms including toxicity, genetic impairment, ecosystem changes, and birth defects. Exposure to a waste stream, however, does not necessarily produce any of these manifestations. For the most part adverse effects are engendered by a complicated interplay of waste constituents over time which depends on their physical and chemical properties, as well as the exposed organism's sensitivity and thresholds. With minor exceptions any chemical will produce adverse effects in any organism if the dose is high enough, while sufficiently low doses will prove harmless.

Strictly speaking, the classification system proposed by the EPA is not firmly grounded in the concept of degree-of-hazard. The arbitrariness in its listing criteria which permits certain conspicuous exemptions, and its failure to address disposal technologies, at least generically, calls into question its efficacy.

Arguments can be made that an all-inclusive system (i.e., one that classifies all industrial wastes without excluding any from some level of regulation) would be most effective in the long run. In a general sense, the hazard classification approach [6], to waste management attempts to deal with the shortcomings of the current EPA approach by first identifying those wastes that pose the most severe threats to human health and the environment, and second by facilitating the development of management strategies that reflect the differences in potential risk. In a specific sense, the following benefits are likely to be realized [7].

1. Reduction in, and prevention of, excessive regulation.
2. Establishment of priorities and goals to assist in regulation at the source.
3. Reduction in the volume of waste handled.
4. Effective concentration of the limited resources of generators, disposers, and government overseers.
5. Increase in the public's understanding of the need for and rationale behind environmental control.

In addition, it is likely that an all-inclusive system will eliminate the uncertainty that is created when potential exists to relist currently exempted wastes and to exempt those that are currently listed. Finally, a hazard classification approach based on classifying and regulating all industrial byproducts should go a long way in reducing transaction costs by shifting the present emphasis from litigation to private investment treatment facilities and other abatement programs.

A number of classification schemes have been proposed and, in fact, are now being used by some states to meet the objectives of RCRA [6-8]. These include categorizing wastes using technical criteria, rank-ordering hazardous wastes based on results of specified tests, grouping wastes by particularly important characteristics that concentrate on exposure and effects data, and classifying wastes and facilities according to the potential for environmental containment. Since the purpose of this article is to develop evaluative procedures, the accompanying model will not be tied to any of these schemes per se; but to the implicit assumption that a workable, scientifically based classification scheme can be devised and coupled with the regulatory apparatus.

4. APPLICATION OF RISK-BENEFIT ANALYSIS

Decision makers in both the public and private sector generally have goals, other than purely profit maximization, that involve choices with uncertain outcomes. For example, the degree to which a private sector organization is willing to endure risk may be viewed as a tradeoff between perceived benefits and potential costs. In the public sector, the emphasis is often on output rather than cost-effectiveness or profit maximization, and this generally tends to reduce the propensity of a decision maker to take technological risks [9]. When anticipated return on investment for, say, treatment control equipment in terms of improved efficiency is low, decision makers in the private sector might tend to incur penalties or practice evasion and defer as many capital expenses as possible. As anticipated return on investment grows the reverse situation is generally true.

Risk-benefit analysis has become an integral part of decision making under uncertainty [10]. The term itself denotes a variety of techniques encompassing risk assessment and the inclusive evaluation of risks, costs, and benefits of alternative projects or policies. The principal task is to express numerically, insofar as possible, the risks and benefits which are likely to result from the particular options. When applying this methodology to the hazardous waste problem a number of difficulties arise because of the inequitable distribution and unquantifiable nature of many of the potential outcomes.

In addition, the complications in measuring benefits for most production externalities such as air and water pollution are magnified many fold for hazardous wastes. While the willingness-to-pay approach might work well for determining occupational safety standards or exposure to other voluntary risks, it fails for involuntary case where benefits are inadequately or sparingly perceived [11, 12]. For many goods and services the determination of worth is reasonably easy because a market exists in which consumers can express the value they place on particular items. But there is no market for clean air, for instance, and although it is fair to assume that this good has value, there is no way to measure it directly.

In most situations those who are substantially profiting from the generation and disposal of hazardous wastes do not share proportionally in the risks. While it can be argued that a chemical plant producing toxic residues as a byproduct of its manufacturing operations provides benefits to the community in terms of tax revenues and employment, there may be no relationship between the population at risk and the persons who benefit. In fact, these residues might be dumped at a remote site without even notifying the local community of the potential hazards [2].

5. RISK ASSESSMENT

Too often the process by which risks are assessed is inexplicit and wanting in consideration for the underlying distributional relationships. As used here, the term "risk assessment" denotes the total process of risk analysis, embracing both the determination of levels of risk and their societal valuation [1, 13, 14]. Risk determination consists of identifying risks and estimating the likelihood of their occurrence. Risk evaluation measures both risk acceptance, or appropriate levels of safety, and risk aversion, or methods of avoiding risk that can be used as alternatives to involuntary exposure.

Table 1
Impacts of Hazardous Waste Exposure

Human Health	*Environment*	*Economic*	*Social*
Chronic dysfunction	Biota destruction	Property value deflation	Change of lifestyle
Acute illness	Natural resource damages	Industrial dislocation	Change of value system
Genetic impairment	Bioaccumulation	Loss of income, taxes	Personal dislocation
Reproductive defects	Irreversible losses	Technological innovation	Increased awareness
	Habitat destruction	Improved efficiency	

Risk identification is of particular concern because of the increasing load of new hazardous wastes being generated. Both our ability to accurately perceive their effects, and the environment's capacity to recover from their damage, are being taxed to the limit. New risks associated with the introduction of synthetic materials such as PVCs pose immediate threats, while latent risks not appearing for up to twenty years after exposure (as in the case of some cancers such as asbesteosis), or until the next generation in the case of mutations, pose severe regulatory challenges. Table 1 identifies the major impacts or hazardous waste exposure. These include risks to health and life, such as those resulting in morbidity and premature death; risks to the local industrial base and the economic well-being of the population; and risks to the social welfare of the community. Risk identification efforts in the United States currently focus on screening chemicals for toxicity and carcinogenesis, and identifying technological threats to ecological systems. In this regard, one of the most telling provisions of RCRA requires that generators identify the multiplicity of risks posed by their wastes, thus placing the burden of proof at the source. This is the first step that must be taken in order to determine dose-response relationships and acceptable levels of exposure.

The process of risk estimation for hazardous waste disposal greatly depends on the technology employed and the exposure pathways, both measured against a backdrop of uncertainty. In particular, five steps can be distinguished as illustrated in Figure 1: identifying the hazard level after treatment or disposal evaluating risk exposure; determining dose-response relationships; defining the impacts of exposure; and valuing their consequences.

The first step involves an analysis of the waste stream after a specific control technology has been selected and applied. The output level will be denoted by the fraction z, the ratio of output to input quantities. In the case of incineration

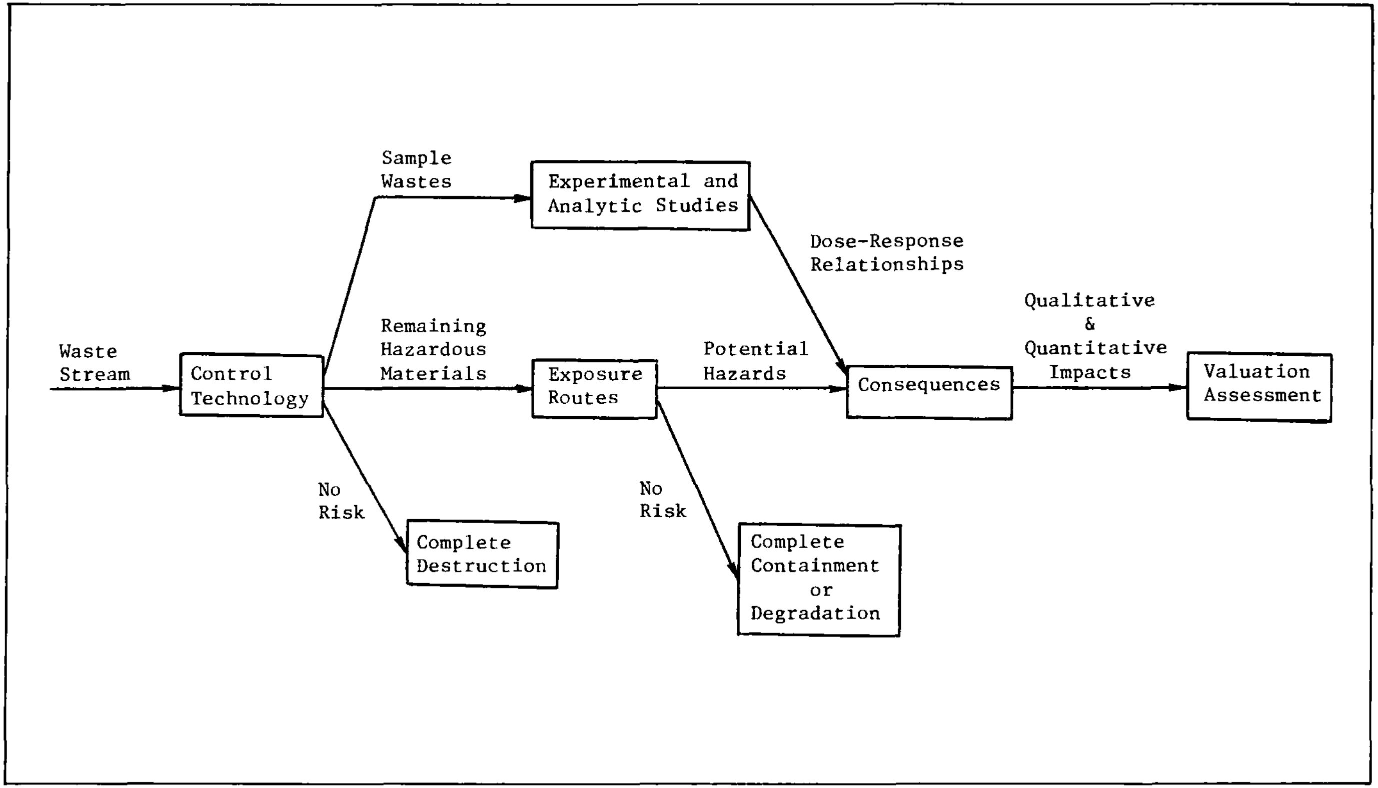

Figure 1. Risk estimation for hazardous waste disposal.

or recycling, z will be close to zero. In general, its value will be determined by the control technology, T, which in turn will depend on the hazard classification, H, of the waste stream. Therefore, z may be expressed as follows:

$$z = f_z(T(H))$$

where f_z is the decreasing technological correspondence.

The second step is concerned with exposure routes or the means by which risks are transmitted. Hazardous waste materials have the potential to move into the environment through several pathways. Some organic chemicals are volatile and may evaporate easily into the air. Many hazardous wastes are sufficiently soluble in water that they may enter surface or groundwater and contaminate valuable resources. In addition, contaminated water carries hazardous chemicals away from the original site of disposal and into contact with susceptible populations. Some materials accumulate in biological systems, reaching ever higher concentrations as they move up the food chain. Thus, whenever toxic substances are freely deposited on land, a proportionate quantity of soil is also contaminated, and future use of the land jeopardized. Associated with each pathway is an exposure probability, P_x, which is a function of the substance's mobility, concentration, and degradability as well as time.

In the third step dose-response relationships are defined and their relative probabilities, P_{dr}, determined. The causative event and output level do not themselves constitute risk until human or environmental exposure occurs. The probabilistic relationships between events and outcomes can be measured through laboratory experiments, analysis of sample data, and analogue models, and are a function of z and time, t.

The fourth step is defining the possible consequences of exposure and determining for each hazard the probability, P_c, that one or more of these consequences will occur. To be more precise, if the health, environmental, economic, and social impacts listed in Table 1 are denoted by $\theta_h, \theta_e, \theta_c, \theta_s$, respectively, and for the moment assumed to be independent then it is possible to define corresponding consequent probabilities for each as a function of P_{dr} and P_x as follows:

$$P_{c\theta_i} = f_{c\theta_i}(P_{dr}, P_x); \qquad \text{for each } i \epsilon I = \{h, e, c, s\} .$$

The corresponding impacts R_i are a function of the output z, and in a full analysis would have to be disaggregated to a level that took into account all damage effects. This implies that $P_{c\theta_i}$ is really a probability distribution over all manifestations of each impact, and is likewise a function of z and t.

The final step in risk estimation considers the value placed by affected individuals on the consequences of risk exposure and will play a large part in determining the level of resources ultimately devoted to risk reduction. This is often the most controversial phase of the assessment because it requires a direct confrontation of all the issues surrounding risk; that is, voluntary versus involuntary exposure, distributional inequities, risk aversion, comparison of incommensurables, and assessment of qualitative factors. Some individuals, for example, may be unconcerned about consuming minute amounts of pesticides from their tap because they believe the effects to be negligible, while others may be sufficiently alarmed to drink only spring water. In any event some form of quantification is necessary if only in units directly related to consequences, such as expected fatalities or acre-feet of ground water contaminated. The value placed on each consequence is then a function of θ_i and $P_{c\theta_i}$ and can be expressed collectively as:

$$V = f_v(\theta, P_{c\theta})$$

where V is a 4-dimensional vector. If it is assumed that each consequence has a monetary value and that all risks are assigned a relative weight, w_i, based on a societal preference ordering, then the expected cost associated with a specific waste stream, hazard classification, and control technology may be calculated as follows:

$$R = \sum_{i \in I} w_i \theta_i P_{c\theta_i}; \quad \sum_{i \in I} w_i = 1 \tag{1}$$

If this assumption cannot be justified then each component should be treated separately. The entire assessment process from generation to valuation is depicted in Figure 1. Those impacts which do not lend themselves directly to monetary valuation may be evaluated on an individual basis by comparing their levels to an idealized or acceptable referent. In this way it will be possible to not only compare the cost-effectiveness of alternative policies, but also their less tangible effects. An option that implies the destruction of a natural habitat or the elimination of a recreational facility may be the least cost solution to a community's disposal problem but may not find acceptance because of its wider ramifications.

Quantification of Risk

For a given waste stream potential exposure is a function of the effectiveness of the control technology and the environmental fate of the escaped components. Potential impacts depend upon the outcome of the fate analysis, concentrations of hazardous compounds, sensitivity of the target organisms and the length of the exposure period. Human health effects may initially be evaluated in terms of fatalities, disability days, and medical costs. Although each presents a problem in reckoning an equivalent dollar amount, the former stands out as the most troublesome. A number of studies have attempted, with varying degrees of intellectual appeal, to come to grips with the value of a human life [15-17]. The approaches used primarily focus on foregone wages, insurance principles, wage premiums for dangerous occupations, and societal valuations.

Costs associated with disability and medical treatment have also been variously estimated and have become an accepted part of the risk-benefit calculus [11, 18]. Although it is possible to present estimates for the complete range of health effects, for purposes of exposition it is simpler to talk in terms of the aggregate $C_{\theta_h}(t)$. Likewise, environmental effects will be aggregated to include loss in property values [17], loss in rent or income, and future cleanup costs. A total environmental cost, $C_{\theta_e}(t)$, may then be postulated as a function of t (as well as the selected technology) and combined with total health costs to provide a dollar measure of risk. The more qualitative economic and social impacts delineated in Table 1 may be treated as constraints. The next step is to compute the present value of risk, CR, to obtain an integrated picture of the associated costs over the planning horizon T; i.e.,

$$CR = \sum_{t=0}^{T} \frac{(C_{\theta_h}(t)P_{c\theta_h}(t) + C_{\theta_e}(t)\,P_{c\theta_e}(t))}{(1 + r)^t}$$

where r is an appropriate discount rate. It should be noted that the relative net present values and the ranking of alternative policies with substantially different timing of the relative costs and benefits are likely to depend upon the choice of a discount rate.

6. COMPLIANCE COSTS

As a result of imperfections in the marketplace, the impacts associated with hazardous waste disposal are necessarily borne by those on whom they initially happen to fall; that is, individuals residing near dumping sites, or the general populace when damage is to public lands and natural resources. Of the 52 million tons of these wastes produced annually in the United States, more than 90 percent are disposed of improperly. This translates into a total cleanup bill somewhere between \$26.2 and \$44.1 billion in 1979 dollars [19]. Although this paper is not specifically concerned with remedial action and past mismanagement, the magnitude of these figures (coupled with the perception of long term liability) should go a long way in tempering any resistance on the part of generators to the imposition of tighter standards.

Two types of costs may be ascribed to compliance with disposal regulations: control costs and transaction costs. The former are associated with proper or legally permitted disposal, and generally involve capital, transportation, and perhaps research expenditures. The latter include governmental administrative costs for monitoring and litigation, generator record keeping costs required by law such as those occasioned by the manifest system [20], and the cost of acquiring information needed to meet a burden of proof.

The relative magnitude of these different costs vary considerably, but an analysis of the Love Canal catastrophe reveals a typical pattern: control costs of

$4 million, cleanup costs of $125 million, and compensation costs of more than $2.5 billion in claims for personal injury [19]. These figures suggest that proper disposal is the least expensive method of dealing with hazardous wastes. However, the prevalence of improperly disposed wastes indicates that from the industry's vantage point, the out-of-pocket cost of current disposal methods plus anticipated liability has historically been considered less than control assets. RCRA and its companion legislation are intended to correct this misallocation by shifting the burden to the generators. The challenge is to do so while maintaining an appropriate balance between economic and social interests.

Control Technology

EPA estimates that the RCRA hazardous waste program as it is currently envisioned will cost industry $510 million per year [3]. Although this is a significant figure, it amounts to less than 0.2 percent of the $350 billion total gross sales of the regulated generators. As such, EPA believes that these expenditures constitute a "real bargain" compared to the excessive costs of improper disposal, and points out that the $510 million estimate, in fact, grossly overstates the true costs by ignoring many indirect benefits. There is substantial empirical evidence that regulation is itself a major stimulus for new markets, new jobs, and—most importantly—for basic innovation [21].

In the past, the cost of extracting and reusing the hazardous component from the waste stream, has generally been uneconomical so this option has received short shrift. The reduction in exposure probabilities leading to increased costs of disposal mandated by RCRA, however, provides a strong incentive to reduce the waste load and recovery as much as possible through improved technology. If a hazard classification approach is adopted by EPA, it may be possible to link particular waste streams with specific technologies to achieve an overall cost reduction. Actually, a variety of processes and generic technologies exist for controlling hazardous wastes as delineated in Table 2, but no process can be universally applied to all types of waste streams.

Table 2
Generic Control Options and Technologies for Hazardous Wastes

Control Options	*Associated Technologies*
Source Reduction	Product Substitution, Production Innovations, Improved Operational Efficiency
Waste Exchange	Recovery, Reuse, Recycling
Treatment	Neutralization, Detoxification, Biodegradation, Solidification, Destruction (incineration)
Disposal	Landfill, Deep-well Injection, Storage

The costs associated with each of the above vary considerably. For example, it has been estimated that a small, privately owned incinerator now costs from $0.5 to $1 million, while a commercial-scale facility can run upwards of $30 million [22]. This translates into an average cost of about $110 per ton for mildly toxic materials, but can reach several hundred dollars per ton for highly chlorinated residues.

To a large extent, control costs, including transportation, are a function of the classification system in use and the prevailing disposal standards. These factors strongly influence the choice of technology and the research effort devoted to its advancement. As a result, control costs, denoted by CL(t), vary with time and are likely to decrease as the need for efficiency increases and innovative methods supervene.

Transaction Costs

Deterring improper disposal and management should be an integral part of any strategy for assuring that control costs are allocated responsibly. If regulations are violated, to be effective, penalties must be prompt, foreseeable, and reasonably certain to occur in response to each instance of "illegal" activity. A firm will probably not modify its behavior appropriately in anticipation of uncertain costs to be borne far in the future. Direct regulation provides an alternative approach. The deterrent may still be financial (taking the form of civil or criminal penalties) but it should be determined expediently, without a case-by-case assessment of societal costs stemming from the proscribed conduct.

The manifest system is at the heart of the EPA program, and is designed to track wastes from their point of origin to their final destination and disposition. As conceived, any firm that produces more than 100 kgs of hazardous material per month will be required to provide accompanying manifests if offsite disposal is planned. Any service that transports the waste must carry the manifest, have it signed at the disposal site, and return a copy to the generator. The company that disposes of the wastes must do the same. As such, both the generator and the EPA will be able to monitor each transaction. Long-term monitoring and maintenance will also be required, even after closure, as will insurance against liability for possible future releases of material from the site.

As the regulations become more stringent for the more hazardous wastes, compliance costs will increase and the incentive to employ illegal means of disposal will become more attractive. Close monitoring will therefore be critical in assuring that proper procedures are followed. On the other hand, as the regulations become less stringent for the low level wastes the risks associated with improper disposal will begin to out weigh the cost of compliance. In this instance, monitoring costs should decrease. The degree-of-hazard approach recognizes that less costly control methods may be more appropriate for less hazardous wastes, and makes this accommodation in its management plan. This should reduce the incentive for midnight dumping, which in turn will reduce the monitoring costs.

Denoting the transaction costs over time for high and low level hazardous wastes as $CT_h(t)$ and $CT_\ell(t)$, each component may be described as a function of the hazard classification and the prevailing standards. As the latter become more stringent for the high level wastes the administrative and liability costs are likely to increase. These will be balanced by a reduction in the corresponding costs for the low level wastes. Over time, however, as procedures become established and technological improvements reduce control costs, both components, $CT_h(t)$ and $CT_\ell(t)$, will decline.

7. ANALYTICAL FRAMEWORK

Selecting the best course of action among alternatives depends to a great extent on the capacity to identify event outcomes, assess their valuation, and ascertain the probability of their occurrence. A rational theory of choice typically involves the assignment of numerical measures to these probabilities and values, followed by the aggregation of the results into a single index to be optimized. The policy which gives the most favorable index value is then judged the optimal choice.

When attempting to apply this procedure to the hazardous waste problem, two difficulties, foreshadowed in previous sections, immediately present themselves. The first centers on an inability to quantify or even identify many of the potential outcomes, while the second concerns the inappropriateness of adding dissimilar units when only a partial quantification is carried out. Although it is certainly possible to assign a dollar value to each sequence and then seek a policy that minimizes total costs (i.e., CT+CL+CR) it may be more desirable to minimize expected risk, CR, subject to a set of constraints that preserves the community's economic interests. These constraints may, in part, be expressed as an upper bound on compliance costs, CL+CT. In fact, this is the approach recommended for reconciling the risk inequities attending the disposal of hazardous wastes, since it is in keeping with the conflicting goal of protecting the environment and public health while accommodating socioeconomic objectives.

Policy Alternatives

In order to address the specific details of a regulatory program let us define a set of n policy alternatives $A = \{a_1, a_2, \ldots, a_n\}$, where each member a_i is characterized by a hazard classification scheme and a management strategy. a_1 will denote the EPA's current plan which simply designates wastes as either regulated or unregulated rather than as hazardous or nonhazardous. Improving upon this scheme by employing hazard classification, though, may not be as

Table 3
Alternative Systems for Classifying Hazardous Wastes
By Technical Criteria

	System 1	*System 2*	*System 3*
Class I	Genetic impairment and persistence; or high-level acute toxicity; or moderate acute toxicity and persistent; exceeds 1000 X drinking water standards.	High acute toxicity and concentration exceeding 100 mg/kg-waste; or reactive at normal temperature and pressure; or forbidden explosive (by law).	Moderate to high acute toxicity; or genetic impairment, persistent or bio-accumulates; or reactive or infectious.
Class II	Genetic impairment, not persistent; or moderate acute toxicity and bioaccumulates or persistent; or 300-1000 X drinking water standards.	Flash point 100°F, considered hazardous during management; or flammable compressed gas; or pH 2 or 13; or corrodes steel; or highly reactive; or exceeds 100 X drinking water standards.	Low acute toxicity; or ignitable, corrosive or reactive; or low infectibility.
Class III	Low acute toxicity and bioaccumulates or persistent; or 100-300 X drinking water standards.	Flash point 100°-200°F; or hazard during burning; pH 3-12; or less than 100 X drinking water standards.	

straightforward as it first appears since an overly complex system might prove to be too costly and unmanageable. A system using three or four broad, tightly defined classes, however, might successfully incorporate the contemplated exemptions and provide a stronger basis for management. As an example, Table 3 enumerates possible technical criteria for classifying hazardous wastes [6]. Three different systems are proposed; the first two employ three distinct levels of classification while the third employs only two.

The remaining step in the definitional phase of alternatives deals with the specification of a management strategy for each waste stream. This involves associating one or more control technologies from Table 2 with each hazard class. Risk reduction is more likely to occur if wastes with a high escape potential (such as those readily soluble in water) and not rapidly degraded in the

Table 4
Additional Policy Alternatives for Hazardous Waste Management

	ALTERNATIVES		
	a_2	a_3	a_4
	System 1	*System 2*	*System 3*
Class I	Incineration	Recovery and Neutralization	Incineration or Solidification
Class II	Detoxification	Incineration	Destruction or Neutralization
Class III	Landfill	Deep-Well Injection	

environment are processed at sites which minimize the probability of leakage and exposure, then if all wastes are treated equally.

Thus, a primary management objective might be to match containment time with degradation time or mobility potential. Those facilities that assure permanent containment or are capable of complete destruction could be used to handle wastes that are highly persistent and nondegradable. If it is known that controlled release is likely or that there is potential for surface or ground water contamination at some time in the future then these sites could be used to handle those wastes with degradation potentials that match the expected time of escape from the facility.

Based on the three systems postulated in Table 3, it is possible, for purposes of discussion, to develop three more policy alternatives. Each is presented in Table 4. Taking a_2 as an example, class I wastes are marked for incineration, Class II for detoxification and solidification, and Class III for landfill. These assignments do not necessarily imply the elimination of all risks, but only that their scope has been narrowed and their expected impacts have been reduced. A combination of economic incentives and legislative initiatives should be sufficient to encourage industry to select the control technologies specified by each alternative.

Comparative Analysis

Once a particular industry and its waste components have been identified the analysis can be performed. The first step involves the construction of the set A and the designation of referent costs which will be limited here to include risk (CR*), compliance (CC*), and the remaining intangibles (CS*). The natural hazard mortality rate may be used as a basis for determining CR* [11]; CC* may be developed from a combination of industrial analogues (such as the costs associated with air pollution technology), industry-wide data on revenue-to-damage ratios, and accepted return on investment figures for regulated industries; CS* may be set by appealing to current societal goals and expectations. The proposed decision problem then is to select an alternative from the set A that minimizes expected societal risk subject to economic and dislocational constraints. Using the previously developed notation, this can be stated as follows:

$$\min_{a_i \epsilon A} \; (CR : CC \leqq CC^*, CS \leqq CS^*) \tag{2}$$

where each alternative a_i is a function of a hazard classification scheme and a management strategy. If the optimal solution produces a value of CR greater than the referent CR*, this would suggest that none of the alternatives provides sufficient protection so more stringent options would have to be formulated.

Solving problem (2) first requires that the risk assessment outlined in Figure 1 be carried out for each alternative and for each waste stream. This will be difficult to do in many cases unless more data, especially on dose-response relationships and exposure routes, are generated. Nevertheless, in order to illustrate how the decision model might work let us suppose that a waste stream comprising 1000 tons of organic materials per month must be controlled under one of the following three policy alternatives:

a_1: Current EPA classification system; waste is designated as hazardous but no control technology is specified; generator selects procedure that minimizes his compliance costs.

a_2: Degree-of-hazard classification system such that the wastes fall into the highest class; disposal guidelines require incineration.

a_3: Degree-of-hazard classification system such that the wastes fall into the middle class; disposal guidelines suggest either incineration or recycling/reuse.

Assume that three control options are available: secure landfill (T_1); incineration (T_2); and recycling/reuse (T_3). The associated compliance costs per ton, consequence probabilities, and impacts are listed in Table 5. In addition, let CR* = \$4000 and CC* = \$12000. To keep the example simple, it will be assumed that all costs are stated in present value terms, dose-response probabilities and exposure probabilities are subsumed in consequence probabilities (P_c), and only health and environmental impacts are evaluated—each being given in an equivalent dollar amount per ton. As can be seen from the data if only compliance costs are considered landfill offers the least expensive option at \$5000/month. Therefore, this would be the choice under alternative a_1; alternative a_2, on the other hand, is immediately precluded because $CC(a_2) > CC^*$. In order to fully evaluate each alternative, though, it is necessary to calculate the expected risk associated with each. Figure 2 depicts the decision

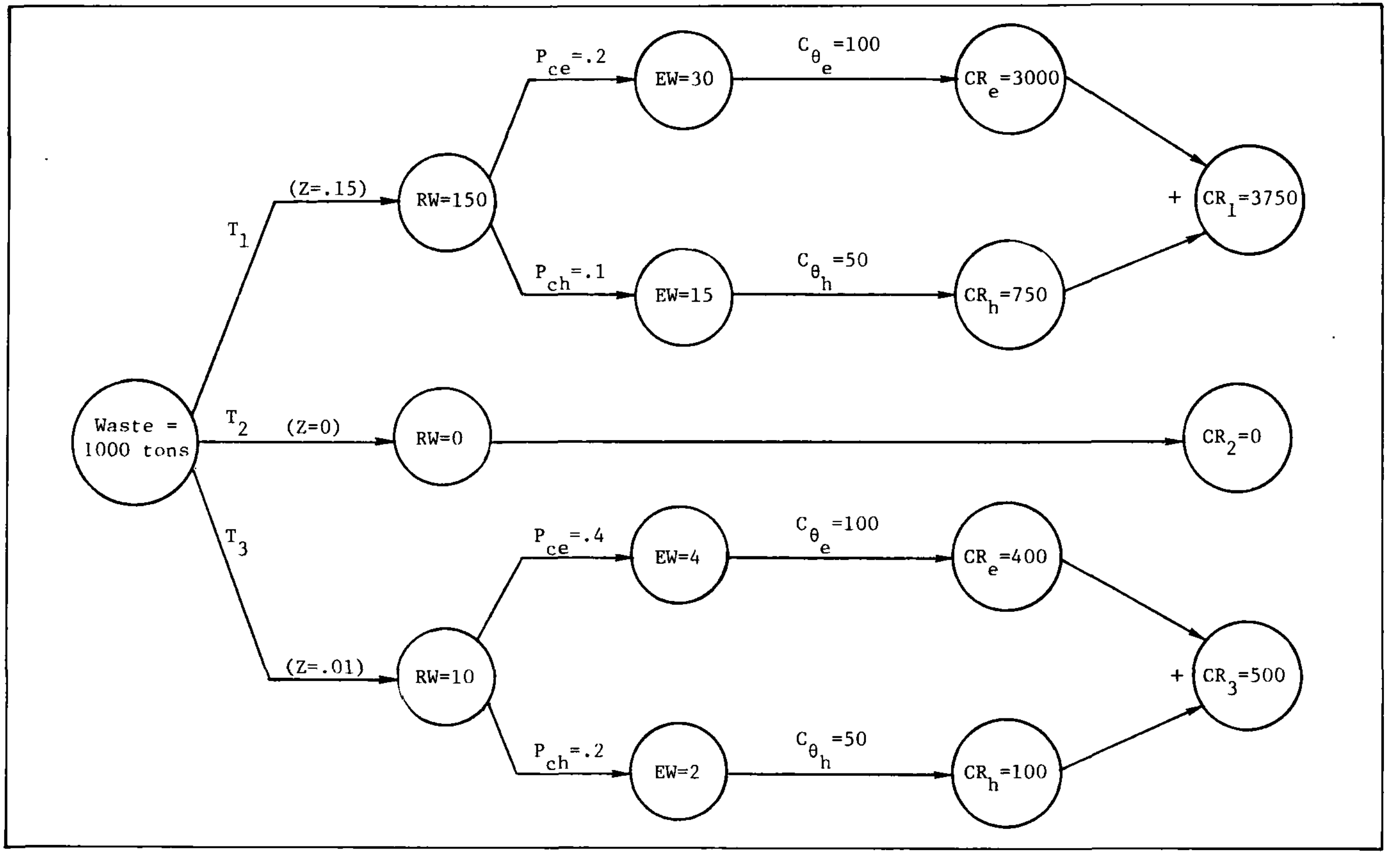

Figure 2. Decision tree for risk assessment.

Table 5
Data to Illustrate Decision Model

		Technology	
Data Items	*T_1*	*T_2*	*T_3*
Compliance Costs, CC ($1/ton/month)	5	9	11
Fraction Remaining, z	.15	0	.01
Exposure Probability, P_{ce}	.2	0	.4
P_{ch}	.1	0	.2
Impacts ($/ton), C_{θ_e}	100	100	100
C_{θ_h}	50	50	50

tree for the three technological choices and includes the risk calculations. The branches of the tree restate the data while the nodes sum outcomes. To illustrate, consider the upper path. We start by disposing of 1000 tons of waste (W) in a "secure" landfill (T_1) which has a leakage rate of 15 percent (z). This means that 150 tons per month (RW) will escape. The probability (P_{ce}) of this waste eventually producing environmental damage is 0.2, while the probability (P_{ch}) of human health damage is 0.1. The equivalent quantity of hazardous waste (EW) on either branch is then 30 tons and 15 tons per month, respectively. Multiplying these figures by environmental impact costs (C_{θ_e}) of $100/ton and human health costs (C_{θ_h}) of $50/ton and then adding the results yields a total risk cost (CR) of $3750/month. Following the same procedure for T_2 and T_3 procedures corresponding costs of $0/month and $600/month. In the case of T_2 complete destruction was assumed (z=0); in the case of T_3 small amounts of waste (z=.01) were assumed to escape through minimally constrained pathways. Assuming a greater likelihood of human and environmental contact, higher values were assigned to the exposure/damage probabilities (P_{ce} and P_{ch}) for T_3 then for T_1.

Table 6 summarizes the entire set of cost calculations. From these figures, it can be seen that a_3 provides the best alternative according to the decision rule specified by the model. This is in spite of the fact that a_1 is the least total cost alternative and a_3 offers the smallest expected risk. Of course, if CC* were set at a higher or lower level the optimal choice might be different, thus underscoring the need for reliable data and a firm understanding of societal standards.

The next step in the analysis calls for a pairwise comparison of alternatives to determine their relative effectiveness. This can be done by first measuring marginal rates of improvement and then computing the following cost-effectiveness ratio (CER_{ij}) for each pair a_i and a_j:

Table 6
Summary of Costs for Sample Problem

	Expected Cost ($/month)		
Policy Alternatives	*CC*	*CR*	*Total*
a_1	5000	3750	8750
a_2	15000	0	15000
a_3	9000	500	9500

$$\text{CER} = \frac{\text{\% Increase in Expect Risk}}{\text{\% Increase in Compliance Cost}} = \frac{(CR_i - CR_j)/CR_i}{(CC_j - CC_i)/CC_i}$$

where i and j are selected so that $CR_i > CR_j$. Note that if $CR_i \geqq CR_j$ and $CC_i \geqq CC_j$ and one inequality holds strictly then a_i is said to be dominated by a_j and can be discarded. A CER_{ij} value greater than 1 intimates that the utility of moving from a_i to a_j is more than offset by the accompanying risk reduction. Such a move will be called cost-effective although a strict dollar for dollar tradeoff is not implied unless the percentage changes are small or the values are of the same order of magnitude. In some cases, it may be more appropriate to consider absolute differences. Nevertheless, from the data in Table 6 it can be concluded that a_3 is cost-effective with respect to a_1 since $CER_{13} = 1.08$, but that a_2 is not cost-effective with respect to a_1 since $CER_{12} = 0.5$.

8. SUMMARY AND CONCLUSIONS

As we become increasingly aware of both the risks posed by the improper disposal of hazardous wastes and the limited amount of resources that society can devote to their management, the need for setting priorities, identifying constraints, and preserving future options becomes more insistent. Ultimately decisions must be made, implying a need for a systematic way to measure and evaluate attendant risks and costs. The goal of this paper has been to first place in context the issues and factors surrounding hazardous waste disposal and then to develop a model that could be used to evaluate alternative approaches to regulation deriving from hazard classification. Statistical decision theory provided the integrating structure.

While a full treatment of the hazardous waste problem must await further data collection and the resolution of technical questions concerning causative relationships, the usefulness of the recommended approach should therefore rest on its ability to identify and examine dominant issues, and to weigh alternative courses of action. As the number of independent factors increases, and as affected individuals are removed from policy formulation positions, it becomes incumbent upon the regulatory agencies to utilize procedures that make explicit the underlying cost-risk tradeoffs and intrinsic human values at stake. This is the only way to ensure that the ensuing debate will lead to informed and accepted decisions.

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