Table 4. Prediction of future environmental stresses in descending order of priority (45)

	P	R	ΣC	U
Heavy metals	5	3	9	135
Solid waste	5	3	8	120
Tritium, krypton-85 (nuclear power)	4	5	6	120
Suspended particulate matter	2	5	9	90
Waterborne industrial waste	4	3	7	84
Carbon dioxide	3	5	5	75
Oil spills	3	3	8	72
Sulfur dioxide (including oxidation products)	2	4	9	72
Waste heat	3	4	6	72
Chemical fertilizer	3	3	7	63
Organic sewage	2	3	8	48
Oxides of nitrogen	2	3	7	42
Litter	4	2	5	40
Radioactive waste (for storage)	5	2	4	40
Pesticides	2	3	5	30
Hydrocarbons in air	1	3	6	18
Photochemical oxidants	1	3	6	18
Community noise (including sonic boom)	1	3	5	15
Carbon monoxide	1	3	4	12

apply to perhaps 1000 potentially toxic chemicals in order to provide a basis for decisions on relative hazard and on research priorities.

The NAS Panel for evaluating chemicals (28) proposed the establishment of three levels of priority to be used in deciding the appropriate level of risk estimation.

> "1. High priority - Those compounds not having a safety margin of 1000 or more in a 90-day subchronic test and which are either (1) produced in high volume, (2) are chemically related to some known carcinogens, (3) are chemically nonreactive so as to lead to persistence in the environment, or (4) have an intended use involving extensive public exposure require professional evaluation.
>
> "2. Intermediate priority - Those compounds that produce acute toxic effects at doses less than 3000-5000 mg/kg and/or whose use can be expected to result in repetitive exposure levels of greater than 0.01 mg/kg/day require subchronic toxicity studies in order to determine need for in-depth evaluation, i.e. chronic, reproductive, behavioral testing.
>
> 3. Low priority - Those compounds that have low acute toxicity (i.e. produce acute toxic effects only at levels greater than 3000-5000 mg/kg) and/or whose use cannot be expected to produce human exposure rates in excess of 0.01 mg/kg/day may be considered low priority for testing."

The Toxic Substances Control Act in the United States uses a numerical scoring system to establish priorities for testing existing chemicals. The approach is described by Gusman et al. (42) as follows:

> "An Interagency Testing Committee (ITC), established by TSCA, recommends substances to EPA for priority consideration. The recommendations are in the form of a list of substances, not to exceed fifty substances at any time. The list may be revised by the Committee from time to time. (The Committee is comprised of representatives from many U.S. Federal agencies.) Its method of selecting chemicals has been a scoring system for degree of human and environmental exposure and on what can reasonably be expected about toxic effects.

> The Committee is required to consider, where relevant, the amount of a chemical produced annually, the amount entering the environment, the number of individuals exposed at work and the duration of their exposure, the extent of human exposure, whether the substance is closely related to others known to present unreasonable risk, data presently available on health and environmental effects, whether testing will yield information useful for prediction of effects, and whether facilities and personnel for testing are available. Seven types of effects have been considered by ITC: cancer, genetic effects, birth defects, acute toxicity, other toxicity, bioaccumulation, and ecological effects. The ITC scoring system is not fixed, and can be expected to be changed on the basis of ongoing experience."

Given the large number of chemicals in use, the establishment of priorities is a vital component of risk estimation. It enables more rational allocation of resources and decision on the type and level of assessment to be carried out for each chemical. Prioritization is essentially the setting out of risks on a comparative scale. Such a comparison is particularly important in deciding on how to deal with chemicals already in use and in the environment. A number of approaches have been developed, ranging from the use of experience and expert judgement to strictly quantitative ranking schemes. The former (informal) approach has proven workable and allows sufficient room for political considerations. However, it has been mainly applied to the limited number of traditional "hot spot" pollutants. This type of approach is expected to be much more difficult to apply to a very large number of substances or to use to continually reassess priorities.

The quantitative approach is advantageous because it focuses efforts on the determination of important parameters, can deal with large numbers of substances and allows, in principle, continuing reassessment of priorities. It is also an open procedure allowing criticism and comment. However, many workers in the field believe that rigid protocols of this kind do not offer the optimum allocation of resources. Attention will likely focus on the development of flexible semiquantitative hazard ranking schemes which allow considerable latitude for expert judgement.

Whereas hazard ranking schemes are comparative, the task of risk estimation for individual substances is to provide a measure of the risk to individuals and populations exposed to the chemical. This risk is governed by the characteristics of two factors. One factor is harmful exposure, the level(s) of exposure to a chemical which may result in some adverse effect on health. It is a function of the inherent toxicological properties of the substance and the nature of the target response. The second factor is actual exposure, the level(s) of target exposure. It is dependent upon the properties, sources, uses and environmental fate of the chemical. In very broad terms, if harmful exposure is greater than actual exposure, the substance as used is safe; if actual exposure exceeds harmful exposure, the substance as used is unsafe. However, both harmful and actual exposure can only be estimated, in general, with little accuracy and certainty. The estimation of exposure (actual exposure) and dose-effect relationships (harmful exposure) have evolved fairly separately. This development is not surprising because the expertise and techniques involved are quite different.

In many respects the study of dose-effect and dose-response relationships is at a more sophisticated level of development than is assessment of exposure. Even when exposure is by relatively straightforward pathways, its estimation and measurement present considerable problems.

Gusman et al. (42) have suggested a scale describing the potential for exposure based on the following hierarchy:

- chemicals used only as intermediates (intended to be consumed by chemical reaction) in a closed reaction vessel;
- chemicals used only in closed systems (such as electric capacitors);
- chemicals used in open systems (such as solvents in paints);
- chemicals used in close or continuing contact with, or proximity to, people (such as in household products and clothing);
- chemicals dispersed in the environment in large quantities (such as fertilizers).

In 1975 the National Academy of Science (46) summed up the state-of-art of exposure assessment as follows:

"1. Until a few years ago there was very little interest in following the path of chemicals through the environment and, as a consequence, very little work has been done.

2. The processes of movement of materials through the environment are very complex and include time delays that may sometimes be long but are largely unknown.

3. The physical and chemical properties of these substances, together with biological activity, greatly affect their movement, destinations, and effects.

4. Our knowledge of transformations that change substances from harmless to hazardous, and vice versa, is sparse.

5. There have been very few efforts to determine what pollutants are where and in what amounts, or to monitor changes in these baseline levels.

6. The number of different substances that are dispersed in the environment through use and disposal is probably in the hundreds of thousands. Presumably most of these are not injuring man or other organisms; however, recent discoveries that certain substances are harmful and are widespread makes it necessary to identify any that should be restricted or banned and to avoid the introduction of new substances that promise unacceptable exposure risks for man, other organisms, and the environment."

Although advances have been made since that time, above items 1, 4, 5 and 6 are still generally true today; a more recent review of research on the fates of pollutants came to similar conclusions (47).

The methods used to predict or measure exposure to a chemical depend upon a large number of variables including: whether or not chemical is new; production quantities; use category (industrial chemical, food/feed additive, pesticide or consumer product); properties (physical structure and chemical properties); "environmental" properties (kinetics, transformation, accumulation and degradation); stage of contact (production, marketing, use, disposal and transfer through

the environment); and exposure characteristics (route, level, duration, continuity and targets).

Thus, the methods of exposure estimation can be classified in a number of ways. Perhaps the main method is according to the stage at which the estimation is carried out: premarketing or postmarketing. In this review, a second classification is made on the basis of chemical dispersion in the environment. Such a classification was recommended by the OECD (48): methods of estimating exposure resulting from use or "adventitious" sources are quite different from those required to estimate exposure to chemicals dispersed in the environment. Thus, the methods reviewed here are grouped as follows: premarketing assessment of chemicals which will/will not desperse in the environment and postmarketing assessment of chemicals which do/do not disperse in the environment.

A large number of chemicals may reach man through the general environment as well as through direct use. In such cases, exposures through these two modes must be summed.

In the premarketing assessment of nondispersed chemicals the initial estimation of exposure involves a general tabulation of its use, disposal patterns and the form in which the chemical is distributed. The various stages of the chemical's life cycle must be considered: production (data on quantities produced, losses in production, transportation and storage); use (domestic, industrial, occupational, agricultural, etc.); and modes of use (contained (closed) systems, open system, etc.).

Gusman et al. (42) have proposed the development of a lexicon of uses which would suggest the degree of exposure expected in each case. Some progress has been made in developing such a nomenclature (49).

The main category of tests which can help exposure estimation of nondispersed chemicals is the acquisition of data on physical and chemical properties (e.g. chemical identity, physical state, solubility and partition and stability). Such information is a guide, for example, to the likely routes of intake.

Premarketing assessment of dispersed chemicals is extremely difficult because exposure to chemicals which will disperse in the environment requires extensive

long-term environmental data. Prediction of chemical behaviour in the environment from laboratory tests and models is difficult and the subject of some controversy. Yet, in most cases, we cannot wait until the substance is in the environment. Furthermore, the implementation of environmental monitoring systems can generally only be justified for chemicals of the highest concern.

Methods for predicting exposure to a chemical which will disperse in the environment include the transfer of knowledge and data from the environmental behaviour of similar but better characterized chemicals, selected laboratory tests, and application of environmental behaviour models.

The NAS panel on the fates of pollutants (47) concluded that knowledge about the environmental behaviour of any particular substance is not used efficiently to identify productive areas of research for other substances. Extrapolation of information from a well-studied pollutant to a less well-studied but similar substance could be of substantial benefit, particularly if the information transfer is organized in the framework of the biogeochemical cycle.

In the scientific literature, knowledge transfer is utilized. For example, one substance's biochemical reactions have been used to predict those of others as described by Wood (50). "It is possible to predict which (other) heavy metals can be transformed in the same way as mercury. For example, by using the same approach as that used with methylmercury, one can predict that tin, palladium, platinum, gold and thallium will be methylated in the environment, but that lead, cadmium and zinc will not be methylated". The transfer of information is much more accepted in toxicological evaluations. For example, Slesin & Sandler (49) proposed that where little or no specific information on a substance is available, EPA should use a categorization scheme based on structure-activity relationships. Under such a scheme, inferences may be made about the toxicological properties of one substance based on what is known about others in the same category.

Data on environmental persistence/degradation, accumulation, transport and transformation provide a basis for estimating exposures, but these parameters are generally difficult to determine directly. However, they

can themselves be estimated to a degree by use of tests on the substance concerned and the media through which it moves. The purpose of this review is not to describe the details of these tests. However, Table 5 may be useful in relating the main environmental parameters of transport, transformation, persistence and accumulation to actual tests/properties.

The acquisition of the above type of information enables preliminary estimates to be made of the most probable routes of the chemical through the environment and of the range of exposure levels to be expected. More refined estimates of exposure, if required, are generally based on models of one kind or another. Models of chemical transport through the environment are usually based on the mass balance approach. However, numerous environmental pathways to man are possible. An attractive simplification has, therefore, been developed and is sometimes referred to as the critical pathways approach. This approach is based on the identification of the most significant pathways to human targets. Once this step has been done, the complexity of the models for more refined estimates of exposure are reduced. Furthermore, the implementation of monitoring systems along the critical pathways becomes practicable.

Premarketing assessment of new chemicals means that environmental data is not available. Thus, such models are impossible to verify using field data. In these cases, some verification and/or estimation per se may be possible through the use of simulated environments. These vary from highly complex field trials to simple laboratory systems. For example, the research and development cost for a new pesticide is estimated to be currently well over US $10 million (51). About one third of this sum is spent on environmental risk assessment, including extensive field trials.

This scale of model building is far from necessary for many chemicals which may be more limited in production, use, dispersion and toxicity. Here, model ecosystems such as laboratory microcosms may be used. They may be built at one of several levels. For example, a fairly elaborate controlled microcosm was designed by Metcalf (52) to model the ecological processes involved in a complex terrestrial-aquatic ecosystem. The model included a plant, an herbivorous insect, an alga, a crustacean, a snail, an aquatic insect and a fish, monitored under

Table 5. Relationship of certain environmental parameters to properties of substances and media

Environmental parameter required		Properties of substance	Properties of media
TRANSPORT	(distribution transfer remobilization)	vapour pressure solubility chemical species chemical structure partition coefficients stability constants latent heat of solution latent heat of vaporization	temperature pH salinity redox potential cation exchange capacity surface area flow adsorption
TRANSFORMATION	photochemical (biological) (chemical)	absorption spectra solubility chemical species chemical structure synergisms antagonisms	metabolism pH redox potential temperature
PERSISTENCE		oxidative reactions reductive reactions hydrolytic reactions chemical species	redox potential
ACCUMULATION	biological	octanol/water partition coefficient stability constants chemical structure solubility (water/lipid)	species ecology
	soil	chemical species	cation exchange capacity pH redox potential organic matter content particle size distribution

controlled conditions for a 30-day period. The system was used primarily to trace the transport, metabolism and bio-accumulation of some fairly persistent chemicals (46). The applicability of various types of microcosm was reviewed by Draggan (53).

Apart from occupational exposure of a relatively easily identifiable group of people, consumer products and food are the main sources of exposure to nondispersed chemicals. The intake is mainly through ingestion but sometimes by absorption through the skin or inhalation. In such cases the general environment is not a significant pathway to man, and the circumstances and habits of the individual concerned, rather than his geographical location, are the main determinants of exposure. Thus, monitoring in the environment is not applicable; exposures must be identified, estimated or determined through appropriate surveys of lifestyle, habits, etc. or through biological monitoring. Additionally, the methods of premarket exposure estimation for nondispersed chemicals are also relevant.

The numerous and complex environmental pathways of chemicals from the sources to the targets illustrates the interconnection of the physical environment (air, water, soil, etc.) and the biological environment (crops, livestock, wildlife, etc.). We are therefore dealing with a linked series of source-exposure-(effect) relationships. If these relationships could be interconnected, a summary source-exposure curve could be constructed, linking emissions directly with exposure. This would allow the control of risks to the appropriate level by regulating emissions - and only a minimal amount of environmental monitoring would be required. However, for even the most intensively studied pollutants, we are still some way from being able to quantify such relationships, particularly if the pathways between source(s) and target(s) are long and complex.

In general terms, a combination of modelling and monitoring is required to estimate exposure to dispersed chemicals. However, the resources required can be quite significant, and, therefore, as in the case of premarketing assessment, the sophistication of the estimation process should be carefully tailored to the chemical in question. In fact, the case for undertaking any monitoring and/or modelling at all should be carefully examined.

SECTION V

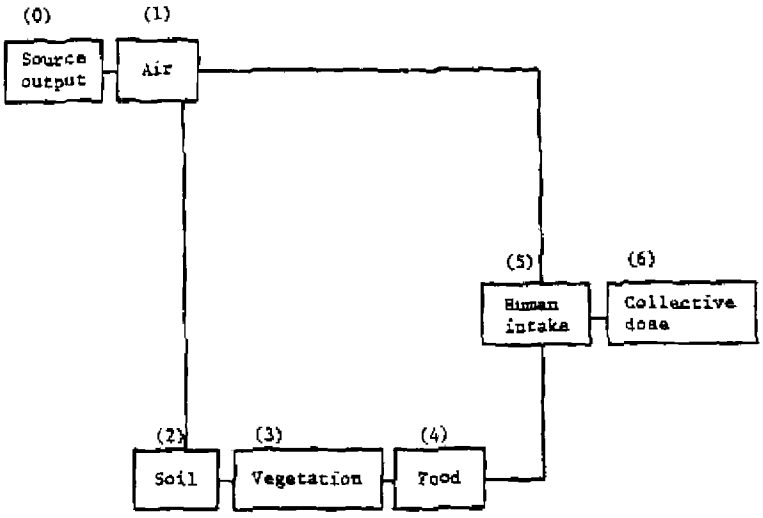
Two basic types of transport models exist: time-dependent (dynamic) and time-independent. As the name suggests, time-dependent models are intended to estimate exposure levels and their variation in time. Time dependence is a crucial factor in some environmental situations at, for example, close to discreet sources of atmospheric pollution or in evaluating adherence to an environmental quality standard. However, the data requirements are correspondingly heavy.

In some situations, particularly for low-level, long-term exposures, short-term fluctuations may be neglected and instead, estimates of the sum or integral of the required parameters, including exposure, made. Time-independent models have been successfully applied by UNSCEAR to estimate population exposure resulting from nuclear weapons testing in the atmosphere (54). This approach, known as the dose commitment, is now being applied to nonradioactive persistent pollutants, such as lead and mercury (55).

Time independence considerably reduces the need for monitoring data. In principle, all that is needed is a knowledge of the transfer coefficient P_{mn} for pollutant movement from compartment m to compartment n - over all the compartments. The coefficients are derived from monitoring data on the levels of the substances in each compartment. The method for determining the collective dose (or exposure) is illustrated in Fig. 1. The time delay in the build-up of the chemical may be several years or decades in duration. The commitment method calculates total exposure due to a given release and it takes into account any such time delays. Although the data requirements of this approach are relatively modest, they should only be considered for priority chemicals; their applicability to each problem must also be carefully examined.

In many countries, chemical pollution is controlled on a media basis (e.g. air, water or land pollution). The measurements of any single pollutant in the various media are usually uncoordinated in time, space, frequency, etc. In such cases and where the pollutant is of high priority (e.g. Pb, Cd, Hg or PCB), special one-off surveys may be made of the situation. In these surveys, an expert group is usually given the task of gathering and evaluating all available data on the sources of the pollutant, its levels in the environment, exposure levels and variability, the

Fig. 1. Method for determining collective dose (or exposure)



$S = \text{Output } [(P_{01}\ P_{12}\ P_{23}\ P_{34}\ P_{45}\ P_{56}) + (P_{01}\ P_{15}\ P_{56})]$ where S is the collective dose from a given source

results of epidemiological and toxicological studies and evaluation of effects.

Such surveys are "snapshots" of the overall situation regarding the pollutant and have been undertaken in the United Kingdom (lead, mercury, cadmium and CFCs), the United States (lead, mercury, cadmium, PCBs, etc.) and other countries. The Environmental Health Criteria series of the World Health Organization is a similar exercise, although its emphasis is more on dose-effect than on actual exposure levels.

These surveys are very useful in assessing the current overall health risk from the substance and the success (or

otherwise) of controls; however, they are inevitably aggregated and as such can fail to pinpoint hot spots, susceptible groups or individuals. Furthermore, their one-off nature makes a prospective approach to pollution management difficult to take.

The estimation of exposure levels is extremely complex and at a less sophisticated level than dose-effect assessment. Our knowledge of environmental processes is not sufficient to enable accurate estimations of chemical pathways and exposures to be made.

A variety of methods in exposure estimation are available, ranging from the cataloging of user groups to the use of sophisticated field trials and/or mathematical models. Monitoring is of crucial importance for exposure estimation of dispersed chemicals. However, the large resources needed for the more sophisticated methods of exposure estimation require that care be taken in tailoring the methods chosen to the likely level and nature of the risk involved.

At the same time, the uncertainties involved in exposure estimations require that the possibilities of chemical build-up in the environment or of adverse exposures should be carefully watched even after the initial estimation has been carried out. According to Gusman et al. (42): "Many of the more disturbing impacts of chemicals on man and on animals in recent years have been due to substantial unrecognized buildup of chemicals in the environment".

Risk Evaluation

Risk evaluation is the process of measuring the significance of the risk in the context in which it occurs. This task not only involves social judgement of the risk as estimated but also the balancing of the risk against perceived and/or estimated social gains. According to many workers in the field (e.g. 13, 56) decision-making institutions are not by any means fully prepared for this task.

A number of evaluation methods have been developed and are discussed below. They are at a relatively early stage and have not been widely applied. Nevertheless, they do provide the basis for longer term development and more systematic evaluations of risk. According to

Fischoff et al. (56) of Decision Research in the United States, generally regarded as one of the leading groups in the field, better approaches are unlikely to be developed. However, "what we can hope for is to understand the various approaches well enough to be able to use them in combination so that they complement one another's strengths, rather than compound each other's weaknesses".

Methods

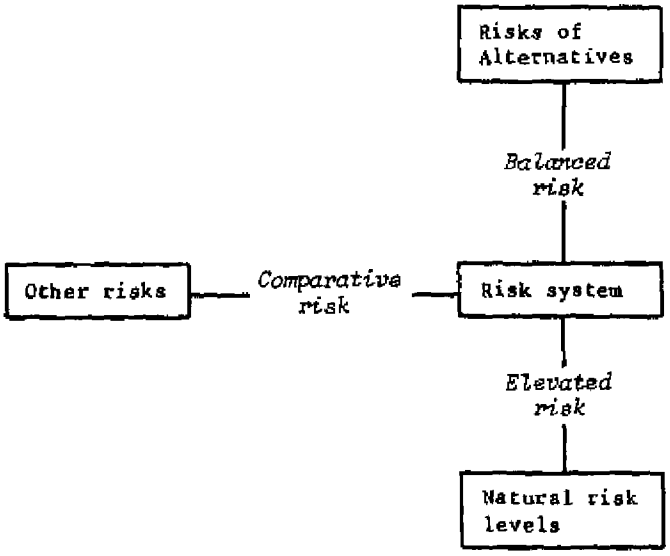
The main reviews in this field show general agreement as to the available methods of evaluation. However, less agreement appears in the way in which these methods are classified. In broad terms the methods can be divided into those that use economic criteria and those which rely on analysis of public preference and political considerations. In turn, these methods either measure the required degree of risk aversion (reduction) or the level of risk acceptance.

Three types of analytical methods are required to judge the acceptability of a given risk: contextual analysis, public preference analysis and equity analysis (2). Contextual analysis involves comparing the risk in question in one (or more) of the following ways: with other risks, e.g. natural levels, risk of alternatives, other unrelated risks (risk comparison); with benefits of the product or activity (cost-benefit analysis); and with the costs of risk reduction (cost-effectiveness of risk reduction). Public preference analysis involves comparisons of perceived risks according to the following criteria: compared to currently accepted products or activities of similar benefit (revealed preferences) and what people say about the acceptability of the risk (expressed preferences). Equity analysis seeks to analyse inequities in the distribution of risks, costs and benefits over various social groups, different regions and generations.

Risk comparison

The risk in question can be compared to other risks in three basic ways, each of which either ignores the different benefits of the alternatives or deliberately makes them equal (Fig. 2).

Fig. 2. Different approaches to risk comparison (adapted from ref. 12)



Comparison with natural risk levels has a number of attractions. In particular, unlike the other methods of evaluation, it is independent of the particular values of any society at any one time. Thus, it would appear to be particularly relevant for latent risks, especially those which span several generations. The basic philosophy here is that one might look to geological time, assuming that the optimal level of exposure to pollutants is characteristic of the conditions in which the species evolved (56).

The best-known criteria for risk acceptability based on natural standards are those for ionizing radiation set by the International Commission on Radiological Protection (ICRP) (56). These consider natural background radiation as the basis for the development of protection levels. However, the definition of natural risk levels is difficult to determine and depends on extensive baseline studies. Even for well-studied pollutants (lead), the natural biogeochemical cycle has not been adequately

quantified. Comparison with natural risks is not really applicable for synthesized chemicals with no counterparts in nature; thus the majority of chemicals would be excluded.

The risk in question may be compared with the risks of alternatives, whether they are products, processes or activities. This approach is clearly best suited to situations where the alternatives being weighed against one another are indeed alternatives and do provide the same goods or benefits (12). Examples include alternative industrial processes, alternative use of pesticides or alternative use of numerous consumer products.

Comparison of the risk in question with others commonly encountered is perhaps the most common form of risk comparison. In this kind of analysis, the consequences are reduced to a common denominator - usually death. The benefits are usually ignored and could generally not be compared in any case. The most general type of comparison is with the other hazards of life. However, comparisons of similar parameters are generally more appropriate, e.g. risks of various occupations, modes of transport and energy strategies. This approach is particularly useful in identifying priorities for improvement of safety measures as well as for indicating major anomalies. Table 6 is an example of this comparison.

Table 6. Life valuations for different occupations in the United Kingdom derived from risk levels set by current control techniques (55)

Occupation	Annual risk of death	Implicity valuation of life (£ sterling in 1972)
Trawling	1.4 in 1 000	Negative value
Agriculture	2.0 in 10 000	£ 10 000
Steel Handling	2.2 in 10 000	£ 230 000
Nuclear Energy		£ 1 000 000
Pharmaceuticals	2.0 in 100 000	£10 500 000

SECTION V

Perhaps the most frequently used method of contextual analysis is comparison of costs (which include risks) or risks alone with benefits. The aim is to establish whether or not the expected benefits from an activity or product outweighs the expected costs. The basic steps for calculation of costs are, in principle, as follows:

1. Enumerate the expected extreme consequences.

2. Assess the probability of each adverse consequence occurring.

3. Estimate the cost to society of each consequence.

4. Calculate the net cost to society of each consequence by multiplying the cost (in 3 above) with the probability of occurrence (2 above).

5. The total cost of the product or activity is calculated by summing the net cost of each consequence (as in 4 above). The same procedure can be applied, in principle, to the benefits.

The NAS' Committee on Principles of Decision-Making for Regulating Chemicals in the Environment (28) considered information needs on benefits and costs of chemicals as well as the issues in comparing hazards, costs and benefits. Concerning the benefits from chemicals, the Panel concluded that they were to advance human health by extending life and reducing suffering and pain, reduce human work effort, help national security, conserve resources, conserve irreplacable objects for future generations, increase human convenience, and enhance aesthetics. The Panel concluded that an objective, scientific way of measuring total benefits was not possible. "Given this situation, substantial weight should be given to the summarizing of net benefits reported in the dollar sale total for those who buy particular chemicals." In deciding which benefits should be considered, the Panel concluded that in principle, "every class of benefits that is treated as significant by buyer of chemicals". In practice, however, the benefits are considered using the manufacturers' list of the classes of benefits that the chemical will provide and by use of sales figures by type of user or application.

The quantification of risks or hazards is the task of risk estimation. As pointed out, little information on the

nature and likelihood of the adverse consequences from individual chemicals is generally available.

Even if these effects were known, attaching a price tag to them poses substantial difficulties. For example, how (if at all) to assign a monetary value to life or health is subject to considerable discussion and controversy. A number of methods have been developed, none of which are totally satisfactory.

Social costs of chemicals associated with risks of adverse health effects are sometimes called direct noneconomic costs. However, additional social costs of a chemical may arise in the form of direct economic costs, indirect economic costs and structural costs. The first cost includes the regulative and administrative cost of toxic substances control. Indirect economic costs and structural costs include the indirect effects of regulation on competition by alternative products, effects on innovation, etc.

In summary, cost-benefit and risk-benefit analyses are, in principle, extremely useful methods of evaluating products or activities concerning the acceptability of the risk they pose. However, in practice, the information requirements are considerable and involve value judgements which are outside the realm of economics.

The third method of contextual analysis lies between risk comparison, which uses risk criteria alone, and cost-benefit analysis, which is largely a technique of economics. Here, the question is how much society wishes to spend to avoid a particular consequence. The method is, therefore, applied to choose the best possible course of action (usually the least cost) to attain a given objective. The benefit of the chemical at various levels of control would be assumed to remain constant.

The expenditures to reduce risk are known to vary. For example, Table 6 shows the different amounts actually spent on saving life in various occupations in the United Kingdom. Similarly, Wilson (57) estimated that the American public expended $1000 to avoid one occupational death arising from the use of liquefied natural gas as compared with $750 000 for nuclear power. The second major approach to risk evaluation is based upon the public's perception of risks. This approach should be

regarded as complementary rather than alternate to the method of "expert" evaluation of risks, as outlined above.

A number of approaches has been developed for evaluating public preferences. The two most frequently cited are "revealed preferences" and "expressed preferences". The former approach is based upon the assumption that by trial and error, society has arrived at a nearly optimal balance between the risk and benefits associated with any activity. Thus, statistical cost, risk and benefit data are used to reveal patterns of acceptable risk. Acceptable risk for a new technology (or chemical) is assumed to be the level of safety associated with ongoing activities (or existing products) having similar benefits to society. This approach may be applicable to groups of chemicals (e.g. pesticides, food additives, groups of consumer products). However, it does not appear to be practicable on an individual chemical basis.

The revealed preference method is based on compelling logic, especially from a political point of view. However, Fischoff et al. (56) have identified some drawbacks:

- it assumes that past behaviour is a valid predictor of present preferences;
- it ignores distributional questions (in common with most methods of contextual analysis); and
- it makes strong assumptions about the rationality of people's decision-making in the market place.

The second main technique of public preference analysis is known as expressed preferences. It tries to determine what people find acceptable by asking them to express their judgement through such instruments as referenda, opinion surveys and questionnaires (56).

By eliciting current preferences, this method allows for changing values, openness and widespread citizen involvement. However, its use is restricted to the more visible risks which people can understand and evaluate. It is unlikely to be significant in the evaluation of toxic chemicals.

Judging risk acceptability or intolerability involves guessing on behalf of the public at large. Rowe (58) defines risk acceptability as "a risk is acceptable when the public accepts it".

However, the uncertainty projected by this statement is not as serious as first indicated. For a start, upper and lower limits may be placed on risk acceptability. Risk increases in magnitude from zero through a range in which it is considered so small as not worth controlling (i.e. the benefit clearly outweighs the risk). As the risk rises above this "no-action" level, it becomes progressively more elevated until the limit of risk tolerability is reached. Above this level the risk is excessive and unacceptable: action must be taken to reduce it. This situation applies generally, regardless of the benefits involved - with perhaps a few significant exceptions such as pharmaceuticals for certain severe illnesses. The levels of action and no-action cannot be exactly specified because they depend upon a number of complex technical, economic, societal and political factors. Nevertheless, no-action levels may be comparable with risks (of death) from natural hazard (of about 10^{-6}) and the action level by the annual per capita illness and disease risk (of about 10^{-2}).

From this analysis of revealed preferences, Starr (59) drew certain conclusions, sometimes referred to as the "laws of acceptable risk".

1. The acceptability of risk is roughly proportional to the third power of the benefit (i.e. $R = KB^3$ where R is the level of risk, B is the benefit and K is a constant).

2. The acceptable level of risk is inversely related to the number of persons exposed to that risk.

3. The public seems willing to accept risk from voluntary activities (e.g. mountain climbing, skiing or smoking) roughly a thousand times greater than it would tolerate from involuntary activities (e.g. nuclear power, pesticides) that provide roughly the same level of benefit.

The "rule" relating acceptable levels of voluntary and involuntary risks is particularly important to risk management. For the case of chemicals, this rule appears to pose many problems. While exposures to certain chemicals are clearly involuntary (e.g. toxic wastes, food/feed additives and chemicals in drinking-water and in the air) and exposures to others clearly voluntary (e.g. certain consumer articles and cosmetics), a number

of chemicals, and exposures to them fall between these two groups. For example, it is difficult to decide whether exposure to certain industrial chemicals at work is voluntary of otherwise. This decision would depend on a number of factors; for example, the availability of alternative employment in the area.

Voluntary risk can also legitimately be considered involuntary when the risk taker is not aware of the existence or level of the risk concerned. From the discussion in the previous sections, this situation would clearly apply to the majority of chemicals in use. For new chemicals, however, both the appropriate United States and EEC legislation contain provisions by which the labelling of substances may be required to warn of the danger (42).

The above discussion leads naturally to other aspects of public perception of risks, which do not always agree with expert evaluation, leaving the risk manager in a dilemma. The fear of cancer and the role of the media in raising public alarm have already been mentioned. Many other perception factors of this kind also influence evaluation. Given the same level of estimated risk, the public will be far more alarmed about catastrophic risks (e.g. chemical accident) than about "ordinary risks" (general exposure to chemicals), about immediate (poisoning) than about latent risks (chronic effects - with possible exception of cancer), and about uncontrollable risks (e.g. earthquakes) than about controllable ones (e.g. bridge construction).

Equity analysis was mentioned above as one of the three components of risk evaluation along with contextual and public preference analysis. Three major types of risk inequity require analysis. The first is inequity among social groups. The people most at risk from products or activities often do not receive its benefits. Examples are workers occupationally exposed to harmful chemicals and people living in polluted areas or near to toxic waste dumps.

The second type of inequity is among regions. Of these, the most publicized are the transboundary pollution problems of SO_2 emissions in western Europe which result in "acid rain" in Norway and Sweden, the discharge of effluents into the Rhine in France and Germany which cause serious pollution problems downstream in the Netherlands,

and the pollution of the Mediterranean, for which the northern coastal states are largely responsible, with deleterious effects to all the coastal states. Although the polluter-pays principle is agreed in all cases, the polluters and the victims invariably disagree as to the nature of the risk or impact and the severity and significance of the damage.

The third and perhaps most complex type of inequity is over generations. Until recently, environmental concern has concentrated on hot spot pollution problems where cause and effect are not greatly separated in time. However, concern is growing over risks which may be passed to succeeding generations (e.g. mutagenic and teratogenic effects) and over persistent substances emitted now, or in the past, to which future generations will be exposed.

This problem has not been properly addressed. The question of how to evaluate decisions taken now which will affect future generations has largely been neglected, both scientifically and politically.

At the scientific level, the dose-commitment approach, carries the advantage that it calculates the integrated exposure which results from a given release. Thus, the risk of a given quantity of chemical released into the environment is summed over all generations.

At the political level, several approaches may be taken. At one extreme the future effects of chemicals may be discounted at various rates (e.g. akin to depreciation of capital assets). At the other extreme, the suggestion has been made (42) that costs and risks should be internalized within one generation. This approach would forbid the carry-over of costs and risks to future generations. Thus, the manufacture of chemicals which would remain in the environment for more than a generation and/or produce effects on future generations would be prohibited.

Between these extremes are a number of possible principles which can be adopted. An obvious one would be that the risks now accepted on behalf of future generations should not exceed acceptable risks of today.

An individual risk may be small enough to be negligible or acceptable to the person at risk. However, if sufficiently large numbers of people are exposed to individual risks which are barely acceptable, some persons

will certainly be harmed (60). Thus, the sum of acceptable individual risk over the total population affected is not necessarily equal to the acceptable population risk.

Conventional practice is to assess acceptability of individual risks; when individuals are at excessive risk, control action is taken. This approach limits individual exposure but not necessarily the total release of the polluting substance. The latter can be assessed by means of source-related assessments based on the dose-commitment model. This dual approach is well accepted in the radiation protection field and is the basis of ICRP recommendations.

Source-related assessment assumes particular importance for the control of chemicals which do not exhibit a threshold dose for response and for which a linear dose-response relationship can be assumed. This working assumption is widely accepted for the case of radioactive pollutants, and opinion is growing that it should also be accepted for a number of chemical carcinogens. (However, the whole question of thresholds of response is the subject of intensive research and controversy.)

This assumption carries major implications for all stages of risk assessment. For example, it calls into the question the whole philosophy of ambient quality standards. These standards have often been achieved, at least partially, by dilution and dispersion rather than reduction in the total emission. As a result, while people near the source are exposed to lower levels of the pollutants, the total number of exposed people will increase. The total risk (R_T) over all the population is given by:

$$R_T = \sum_{i=1}^{n} r_i$$

where r_i is the risk of an effect to individual i and n is the number of people exposed to nonzero concentrations of the pollutant. While the application of the environmental quality standard has decreased the individual risk (r_i) near the source, the total number of people exposed (n) has increased. This may result in a

higher total risk R_T (although the burden is more equitable).

One important reason why public perception and "objective" evaluation of chemical risks differ is that while the public is generally responsive in terms of its perceived overall risk burden from toxic chemicals as a group, regulation is, of necessity, concerned with individual substances. Treating each substance individually, to the exclusion of higher level assessments, is bound to obscure problems and their solutions, lead to a misallocation of resources and produce regulatory inconsistencies (e.g. in the level of protection of particular worker groups). While continuing the necessary control substance by substance, the need for government to take a broad view of risks from chemicals grows increasingly important.

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