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THE RANKING OF HAZARDOUS MATERIALS BY MEANS OF HAZARD INDICES

C.J. JONES

Waste Research Unit, Chemical Technology Division, Harwell Laboratory, near Didcot, Oxon. OX11 0RA (Gt. Britain)

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Summary

A variety of Indexing Models for use in landfill management, transport of dangerous goods, environmental quality assessment and other areas are reviewed. The shortcomings of existing models are discussed and the difficulties of developing a consistent, generally applicable model considered. Experimental and theoretical work are both necessary if a satisfactory model is to be developed for evaluating waste management options.

Introduction

In recent years a variety of methods have been described for ranking materials according to the environmental hazard they present. The methods used are not generally compatible and in some cases seek to achieve rather different objectives. Some indexing systems relate to specific hazards such as toxicity in water or flammability, others attempt to compare the total environmental effects of a material. In view of the diversity of indexing systems appearing it is perhaps appropriate to consider what is meant by the term 'Hazard Index' and why there is any need to devise a ranking system based on 'Hazard Indices'.

Assignment of Hazard Indices to materials usually results from an attempt to quantify value judgements about their relative environmental impact or potential for causing harm. These value judgements may be based on qualitative, and possibly subjective, concepts such as 'less toxic than' or 'slightly toxic', on prescribed limits such as Threshold Limit Value or on measured parameters such as LD_{50} or flash point. Materials are assigned numbers on a numerical scale (for example 0 to 5 where 5 indicates an extremely hazardous substance and 0 a negligibly hazardous substance) to rank the hazard they present in order of severity. The ranking may be on an ordinal scale in which substances are compared pair-wise and ranked as more or less hazardous. Alternatively a cardinal or interval scale may be used such that the numerical interval between adjacent materials on the scale indicates the relative severity of the hazard they present. To give an example take two substances A and B with an LD_{50} for rats of 0.5 mg/kg and 50 mg/kg respectively. On an ordinal scale of 0 to 5, Hazard Indices of 4 and 2 for A and B would indicate that A was more toxic than B and that at least one other material was known which was less toxic than A but more toxic than B. This could be assigned an index of 3 on the ordinal scale. On an interval scale of 0 to 5 corresponding with a range of 5 orders of magnitude (i.e. LD_{50}'s of 0.05 to 5000 mg/kg) Hazard Indices of 1 and 3 would indicate that A was toxic at levels 100 times less than the toxic level for B. In fact, where the Hazard Index scale is defined the index is directly related to the parameter used to assign it (in this case the index is defined as $\log_{10}$ $(LD_{50}/0.05)$ in mg/kg).

The reasons for developing a Hazard Index are many and varied, as demonstrated by the different methods of indexing which are in use. A by no means exhaustive list of reasons is given below to indicate this diversity:

(i) To simplify large collections of data by grouping substances with properties in a defined range under one index e.g. an indexing of materials by TLV on a 0—4 scale of Vapour Hazard:

Not hazardous	0	TLV greater than 1000 ppm
	1	TLV 500—1000 ppm
	2	TLV 100—500 ppm
	3	TLV 10—100 ppm
Extremely hazardous	4	TLV less than 10 ppm

(ii) To aid in rapid response to emergency situations, different Hazard Indices requiring different degrees of action. An example being the assignment of indices 1 to 10 for road spillage where 1 indicates the material is safe and may be hosed to sewer or removed by unprotected personnel and 10 indicates the need to evacuate the area of the spillage and use full protective clothing in removal operations.

(iii) To provide the basis for a waste management scheme where Hazard Indices are used to indicate what types of disposal route are appropriate for particular material.

(iv) To ensure a reasoned consideration of the hazards involved in transporting substances. An index within a certain range might, for example, require that the material be transported in a specially constructed vehicle driven by a person with appropriate training in the handling of the material.

(v) To provide a means of deciding which materials present the gravest overall environmental hazard in order that research and legislative considerations may give them priority.

In view of the diverse reasons for developing Hazard Indices it is hardly surprising that those proposed should be generally incompatible. However, there does not appear to be any good reason why the basic data used in formulating Hazard Indices should not be common to all methods. Although there is always some dispute over the meaning of certain experimentally measured parameters, the bulk of data relating to toxicity, solubility, vapour pressure etc. should be universally acceptable. Thus the handling and interpretation of the data is the area in greatest need of unification. To illustrate some of the comments made above it is useful to review some of the existing Hazard Index systems.

Existing indexing systems

BARRINC model (Booz Allen Applied Research Inc.) [1]

The general approach adopted by this model was summarised as follows:

(a) Identify a representative list of Hazardous Substances.
(b) Establish criteria for evaluating quantitatively all adverse effects that may result from exposures to the hazardous substances.
(c) Establish criteria for evaluating the extent of the hazards involved, i.e. the extent in terms of geography and frequency of occurrence.
(d) Develop an algorithm for combining the individual ratings determined on the basis of the criteria to arrive at a total rating for each substance.
(e) Rank substances on the basis of the ratings.

A matrix of factors was developed for rating the effects of the substances listed in terms of air, water and land pollution hazards. The toxic effects on human and other populations were considered as well as the fire, explosion or reaction hazard to humans (Table 1).

TABLE 1

The BARRINC model of indexing hazards

Medium for disposal	Hazard in terms of potential effects		
	Human populations		Eco-populations
	Toxic effects (T_H)	Flame, explosion reaction (F_H)	Toxic effects (T_E)
Air (A)	AT_H	AF_H	AT_E
Water (W)	WT_H	WF_H	WT_E
Soil (S)	ST_H	SF_H	ST_E

The factors in the matrix (viz. AT_H, WT_H, ST_H, etc.) were evaluated on a scale of 1 to 3 with a fourth rating, U, for unknown effects.

3 severely hazardous
2 slight to moderate hazard
1 minimal hazard
U effects unknown

An appropriate descriptive statement of the rating criterion was developed for each of the rating values.For example a Human Hazard Rating Criterion for a rating of 2 under Flame Explosion and Reaction Hazards was 2, Moderate Hazard. May react violently with water but only under certain very limited circumstances. May form potentially explosive mixtures with water but requires a catalyst to ignite. Reactions may release harmful, but not lethal or residual injuries. In general effects are temporary with no residual damage. Tables of effects rating criteria are given [1].

A 'Hazard Extent Rating' (HER) was also developed based on the annual production and distribution of a substance (Table 2).

TABLE 2

The Hazard Extent Rating (HER)

Production criteria (lbs/year)	Rating value	Distribution criteria	Rating value
$> 10^8$	1.5	Wide distribution to many consumers	0.5
$\leqslant 10^8$ but $\geqslant 10^7$	1.25	Used in bulk by limited number of consumers	0.25
$< 10^7$	1.0	Largely consumed in same plant	0.00

The extent rating values were set so that toxicity would dominate the final total effects rating and the risk of exposure would distinguish between substances of equal toxicity. The extent rating should not have a negative effect on total effects rating, should allow some equivalence between small production with wide distribution and large production with limited distribution and should not exceed a value of 2.

The various effects ratings were combined to give a 'Total Effects Rating' (TER) according to the following formula:

$$\mathrm{TER} = (\mathrm{AT_H})\mathrm{W_1} + (\mathrm{AF_H})\mathrm{W_2} + (\mathrm{AT_E})\mathrm{W_3} + (\mathrm{WT_H})\mathrm{W_H} + (\mathrm{W_FH})\mathrm{W_5} + (\mathrm{WT_E})\mathrm{W_6} + (\mathrm{ST_H})\mathrm{W_7} + (\mathrm{SF_H})\mathrm{W_8} + (\mathrm{ST_E})\mathrm{W_9} \qquad (1)$$

where W_1 to W_9 are weighting factors. No justification was found for adjusting the weighting factors and all were set at 1.0. The TER value was then combined with the HER to give a Hazard Rating (HR) where:

$$(\mathrm{HR}) = (\mathrm{TER}) \times (\mathrm{HER}) \qquad (2)$$

To take account of the many unknown values in the effects ratings, two additional scores were developed. The 'Maximum Potential Effects Rating' (MPER) based on all U effects ratings being reassigned a value of 3:

$$\mathrm{MPER} = 3\mathrm{U} + \mathrm{TER} \qquad (3)$$

and the maximum potential hazard rating (MPHR) where:

$$\mathrm{MPHR} = \mathrm{MPER} \times \mathrm{HER} \qquad (4)$$

Tables of individual and combined hazard effects ratings are given for a list of over 500 substances [1].

PHL model (Pavoni, Hagerty and Lee [2,3]

The rationale used in the development of this indexing system was to weight different aspects of environmental impact according to their importance. Thus first, second and third degree parameters were defined as follows:

1st: Those parameters which directly indicate impairment of humans, animals or plants, i.e. toxicity and pathogeneity (life state and primary disease transmission).
2nd: Those parameters which directly indicate persistence in the eco system, i.e. pathogenic survival and biodegradability.
3rd: Those parameters which directly indicate mobility in landfill eco systems, i.e. absorptive capacity and solubility.

A maximum value of 40 priority ranking units (PRU) was arbitrarily assigned to first degree parameters, 24 PRU to second degree and 16 PRU to third degree parameters.

The first degree parameters considered were human toxicity, groundwater toxicity and disease transmission potential. The evaluation of human toxicity was based on the rating system of Sax [4] which used a scale of 0 to 3 where 0 = non toxic; 1 = slightly toxic; 2 = moderately toxic and 3 = severely toxic. The human toxicity (Ht) was defined as thirteen times the Sax rating (Sr):

$$Ht = 13\,Sr \qquad (5)$$

to give a scale from 0 to 39. The groundwater toxicity rank (Gt) was defined from the smallest concentration known to have caused injury to man, animals or plants. This smallest 'critical concentration' (Cc) may be defined as the maximum permissible concentration in drinking water, the threshold value for effects on fish or other aquatic toxicity criteria. The range of groundwater toxicity was found to be from 10^{-3} to 10^{4} mg/l. To quantify groundwater toxicity in terms of critical concentration as a first degree parameter the formula:

$$Gt = 6\,(4 - \log Cc) \qquad (6)$$

was used where $Gt = 0$ for $Cc > 10^{4}$ mg/l and $Gt = 42$ for $Cc < 10^{-3}$ mg/l.

Disease transmission potential, the remaining first degree parameter, proved difficult to quantify but was broken down to three sub-groups. Sub-group I related to mode of disease contraction and was assigned a maximum of 40 PRU. This sub-group was divided into three areas, as follows:

(i) direct contact — assigned a value of 40 PRU because of its immediate threat;

(ii) infection through open sores — assigned a value of 28 PRU since danger may not be apparent but can be reduced by immunisation;
(iii) infection by vector — assigned a value of 16 since insect and rodent vectors should be controlled by proper landfill management.

Sub-group II related to the pathogenic life state of the organism and was considered as important as Sub-group I. Again three areas were identified and given scores as follows:
(i) pathogenic micro-organisms with more than one life state (e.g. viruses and fungi) — assigned 40 PRU;
(ii) pathogenic micro-organisms with only one life state (e.g. vegetable pathogens) — assigned a value of 20 PRU;
(iii) pathogenic organisms which cannot survive outside their host (*Treponema Pallidum*) — assigned a value of 0 PRU.

Sub-group III related to the ability of pathogens to survive in air, water or soil. Survival in air was assigned 10 PRU in water 10 PRU and in soil 5 PRU. Thus the total maximum score in sub-group III was 25 PRU. Totalling scores for each of the three sub-groups the total disease transmission potential rating (Dp) was obtained which had a minimum value of 0 and a maximum of 105 PRU.

To allow for degradation of materials a biodegradability factor (Bd) was defined as:

$$Bd = 16\,(1 - (\mathrm{BOD}/\mathrm{TOD})) \qquad (7)$$

where BOD is the biochemical oxygen demand and TOD is the theoretical oxygen demand for complete oxidation. As BOD approaches TOD in value the magnitude of Bd decreases from 16 to 0 where BOD = TOD.

The mobility of a substance was assessed from its ionic charge and solubility. An absorptive value (A) was defined as:

$$A = 3 + C \qquad (8)$$

where C is the ionic charge or net charge calculated from its reaction with water at pH 7.0. A solubility value (Sv) based on solubility (S) was defined as:

$$Sv = 6 - \log S \qquad (9)$$

and these values combined to give the mobility rank (Ms) as follows:

$$Ms = 16 - A - Sv = 7 - C + \log S \qquad (10)$$

where Ms may range from 0 to 16 PRU. For liquid wastes the mobility does not depend on solubility and absorption in the same way and the mobility rank for liquids (Ml) was defined as:

$$Ml = 16 - A = 13 - C \qquad (11)$$

where Ml may range from 10—16 PRU.

Totalling all the various ranking factors the hazardous waste rank (HR) is obtained as follows:

$$\mathrm{HR} = Ht + Gt + Dp + Bd + M \qquad (12)$$

Substances with HR of 0—30 PRU were considered non-hazardous, with HR of 31—60 PRU slightly hazardous, with HR of 61—80 PRU moderately hazardous and with HR > 80 PRU, hazardous.

A landfill site ranking system was also developed by Hagerty and Pavoni following similar general reasoning to that used for hazardous substances. Factors affecting the immediate transmission of waste were given a first degree priority ranking of 20 PRU. Factors affecting waste transmission after its contact with water were assigned a second degree priority ranking of 15 PRU. Parameters relating to the present conditions of groundwater at the landfill site were assigned a third degree priority ranking of 10 PRU and, finally, parameters representing transmission outside the site were assigned a fourth degree priority ranking of 5 PRU.

The infiltration potential (*Ip*) of a site was described as the ratio of the amount of water entering the site to the amount required to produce a full passage of moisture through the soil cover. Taking *i* as the amount of water entering the site excluding run-off and evaporation, *FC* as the field capacity of the soil for moisture expressed as a decimal and *H* the thickness of the soil cover (in inches) *Ip* is calculated from:

$$Ip = i/(FC)H \qquad (13)$$

Ip having a practical range of 0.02 to 20 PRU as a first degree parameter.

The bottom leakage potential (*Lp*) was also assigned a maximum priority ranking of 20 PRU and was defined by:

$$Lp = \frac{1000\,K^{1/3}}{T} \qquad (14)$$

where K = permeability of the bottom layer of soil (cm/sec); T = thickness of the bottom soil layer (ft.).

The expected range of K was 10^{-4} to 10^{-10} cm/sec, while for T the expected range was 5 to 50 ft. Thus giving a range of values of 0.02 to 20 PRU for *Lp*.

The filtering capacity of the bottom soil of a site was assigned a maximum of 16 PRU as a second degree parameter. Filtering capacity (*Fc*) was defined as:

$$Fc = -4 \log \frac{2.5 \times 10^{-5}}{\phi} \qquad (15)$$

where ϕ the average soil particle diameter in inches and may vary from 0.25 to 2.5×10^{-5} in.

Absorptive capacity (*Ac*) was assigned a second degree maximum priority ranking of 16 PRU and was defined by

$$Ac = \frac{10\,(Or)}{(\log \mathrm{CEC}) + 1} \qquad (16)$$

where *Or* is the organic content of the bottom soil layer expressed as a decimal and CEC the cation exchange capacity in meq/100 g. Thus soil with a high organic content or low cation exchange capacity will have a high value for *Ac*.

Because of its potential for supporting microbial growth the organics content of the groundwater was assigned a third degree maximum priority rating of 10 PRU. The organic content rating (*Oc*) was defined by:

$$Oc = 0.2\,\mathrm{BOD} \qquad (17)$$

where BOD is the biochemical oxygen demand of the groundwater in mg/l and *Oc* has a maximum value of 10.

The buffering capacity of groundwater was also assigned a third degree maximum priority rating of 10 PRU and was defined by:

$$Bc = 10 - \mathrm{Nme} \qquad (18)$$

where Nme is the smallest number of milliequivalents (up to a maximum of 10) of either acid or base required to displace the original groundwater pH below 4.5 or above 8.5.

The potential for travel of a leached substance leaving the landfill site in groundwater was also evaluated as a fourth degree parameter. The potential travel distance was arbitrarily defined as the distance a molecule of water could travel from a point directly beneath the landfill through the ground and surface water systems to the sea. Rating factors were assigned as follows:

Potential travel distance	Rating factor
0—500 ft.	0
500—4000 ft.	1
4000 ft.—2 miles	2
2 miles—20 miles	3
20—50 miles	4
more than 50 miles	5

Groundwater velocity affects the rate of dispersion of leached substances from a landfill site and was assigned a fourth degree priority. Groundwater velocity (*V*) is defined by:

$$V = kS \qquad (19)$$

where *V* is the velocity or quantity of water flowing through a unit cross sectional area, *k* is the coefficient of permeability (cm/sec) and *S* the gradient or loss of head per unit length in the direction of flow (ft./mile). Values of *k* vary from 10^{-1} to 10^{-9} cm/sec whereas values of *S* vary from 0 to 20 ft./mile.

The groundwater velocity rank (Gv) was then defined by:

$$Gv = \frac{S}{\log\left(\frac{1+1}{k}\right)} \tag{20}$$

where K is the permeability in cm/sec and Gv falls within the range 0 to 20 as a first degree parameter.

The effect of prevailing wind direction on the dispersal of airborne matter leaving the site was assigned a fourth degree maximum priority rating of 5 PRU. The prevailing wind potential rank (Wp) was obtained by the following procedure. A circle of radius 25 miles is constructed with the landfill site at its centre. The circle is divided into four quadrants by north-south and east-west lines. The population of each quadrant is determined and a point in the quadrant assigned to represent the population centre for that quadrant. The prevailing wind direction is drawn on the diagram as a radius of the circle and each of the population centres are joined by a line to the centre of the circle. The angles between the prevailing wind direction vector and the population centre vectors are measured (α, β, γ, δ) and Wp calculated as follows:

$$Wp = \sum_{i=1}^{4} \frac{\frac{Ai}{[(S-36)\log Pi]}}{15} \tag{21}$$

where Ai is the angle from the prevailing wind direction vector to the population vector and Pi is the population of each quadrant.

The final factor considered in the rating scheme was the population factor (Pf) which defines the number of people within a specified distance from the site and is given by:

$$Pf = \log p \tag{22}$$

where p is the population within a 25 mile radius of the site. Pf is expected to fall in the range of 0 to 7 PRU.

The total site rating was simply obtained by adding all the individual ratings described above.

$$\text{Site rating} = Ip + Lp + Fc + Ac + Oc + Bc + Td + Gv + Wd + Pf \tag{22a}$$

The site rating has a practical range of 0—110 PRU and the first four factors describe the soil system, the second four the groundwater characteristics and the final two air pollution hazards. The lower the site rating value the more suitable the site for toxic or hazardous wastes disposal. Two worked examples were given for Louisville, Kentucky; one site in clean sandy soil had a rating of 57 while another in heavy clay had a rating of 23.

BNW model (Batelle Pacific Northwest Laboratories) [5]

This model attempts to assign a 'global' hazard rating based on annual production and toxicity data. The form of the rating factor (R) is given by:

$$R = \frac{Q}{CP} \tag{23}$$

where Q is the annual production quantity of the waste in question, C is the lowest concentration at which any hazards due to the waste stream have become manifest and P is an index representing the wastes mobility in the environment. For example the index P for water borne pollutants is obtained by dividing 10^6 mg/l by the solubility of waste in mg/l. This eqn. 23 is converted to:

$$R = KQHS \tag{24}$$

where K is a suitable constant (10^{-6}), S is the solubility (or volatility for airborne pollutants) and H is the reciprocal of C. Eqn. 23 may also be modified to take account of effluent treatment and a regulatory efficiency factor E can be included to allow for attenuation of hazard by treatment processes in use as follows:

$$R = \frac{QE}{CP} \tag{25}$$

This method of assessment closely parallels one employed for evaluating hazardous material spills [6].

U.S. Coast Guard system [7]

This system is one of a number which apply to the transportation of materials but differs from them in that it was developed specifically to cover water transportation. It is essentially an ordinal system and does not attempt to assess the total hazard posed by a substance. Four main classes of hazard were identified, viz. fire, health, water pollution and reactivity. These were further divided to give a total of ten sub-classes. Each sub-class was assigned a numerical rating of 0 to 4 and for each sub-class five descriptive definitions of the ratings from 0 to 4 were given. Some definitions were purely qualitative while others were related to measureable parameters, for example fire hazard was assessed by flash point as follows:

0 chemicals that are non-combustible;
1 closedcup flash point above 140° F (minimum fire hazard);
2 closedcup flash point between 100° and 140° F
3 closedcup flash point below 100° F and boiling point above 100° F (flammable liquids);
4 closedcup flash point and boilding point below 100° F (volatile flammable liquids).

The ten sub-classes considered were:

(i) fire hazards (assessed from flash point data);

(ii) vapour irritant effects (assessed from effect on eyes and respiratory system);
(iii) liquid and solid irritant effects (assessed by effect on skin);
(iv) chemical poisoning (assessed from Threshold Limit Values);
(v) human toxicity (assessed from LD_{50} data);
(vi) aquatic toxicity (assessed from Threshold values for fish);
(vii) aesthetic effect (assessed from volatility, odour, colour and miscibility with water);
(viii) reaction with other chemicals (assessed qualitatively by class of chemical e.g. carboxylic acid, aldehyde, hydrocarbon etc.);
(ix) reaction with water (assessed from hazard produced on mixing with water);
(x) self reaction hazard (assessed from hazard of self reaction e.g. explosive polymerisation).

A total of 337 industrial chemicals were classified using the rating system.

Chemical reaction hazard index (D.R. Stull, Dow Chemical Co.) [8]

This method of indexing uses chemical composition and thermodynamic data to evaluate the hazard presented by flammable or explosive materials. A computer programme for calculating chemical equilibria was modified for use in this context. The compositions and heats of formation of 50 compounds were fed into the computer which used stored information on the thermodynamics of potential reaction products to predict the heat release, temperature rise and pressure rise of the compound on decomposition. Graphs of the form $(X—Y)$ against Y were plotted for the three cases of heat release, temperature rise and pressure rise where X = heat release, flame temperature or flame pressure and Y = heat of formation, decomposition temperature or decomposition pressure (obtained from drop weight tests) respectively. The three graphs obtained correlated extremely well with the temperature data giving the most consistent results and following a straight line plot. The graphs were each divided into five zones assigned ratings of 0 to 4 to correspond with the National Fire Protection Association (NFPA) ratings [9] already in use. Thus each compound could be assigned an index on the basis of three parameters.

Inconsistencies between the ratings assigned to a given substance by each of the three parameters totalled 7 out of 150 indices showing a high degree of correlation between the three parameters used. Thus the model was deemed to provide a quantitative means of using the composition and heat of formation of a material to rank it according to the hazard presented by its decomposition.

Other indexing systems

Although it is beyond the scope of this review to give a detailed consideration of all hazardous material ranking systems, it is appropriate to briefly describe some of the other systems which have appeared in the literature. In particular models developed for landfill site selection and codes developed for use in the transportation of hazardous substances have some relevance to the overall problem of Hazard Indexing materials. Indices of environmental quality have also been described in the literature and these too relate to the assignment of indices to hazardous materials.

Taking landfill site selection models first, three references to systems other than that described by Hagerty and Pavoni were found. A set of landfill selection criteria were developed as a result of a three year programme investigating gas evolution, compaction rate and leachate emissions from uncontrolled landfill sites [10]. The results were not considered generally applicable to sites outside the Los Angeles area in which the experiments were carried out. A leachate pollution index based on laboratory experiments was developed. Three series of leaching tests were carried out, two involving sampling of leachate from totally immersed refuse and one involving replacement of the water in which the refuse was immersed and analysis of the leachate removed. Sampling was carried out after one, eight, twenty-three and forty days. A correlation between chemical oxygen demand (COD) and total dissolved solids (TDS) was observed and, for the columns where the water was replaced, the initial decrease in COD and TDS following replacement of the water was followed by a build up to the original levels. Thus the leachate metabolic products and other materials in the refuse were being continually extracted. The ratio of COD to TDS initially increased during decomposition then declined slowly as decomposition tended to cease. The TDS value was suggested as an index of leachate quality.

LeGrand has proposed a landfill site evaluation system based on five parameters [11]. These relate to the depth of the water table, the permeability of the ground, the sorption capacity of the ground, the hydraulic gradient and the distance from the site to the nearest point where groundwater is used. Scales are given for each parameter and an index is linked to the scale. The index does not necessarily bear a linear relationship to the scale of the parameter in question as exemplified by the water table depth. Indices of 1 to 5 cover a depth of 9 to 38 ft. while indices of 8 to 10 cover a depth of 100 to 1000 ft. The indices for each of the five parameters are added to give a total site rating and thus different sites may be compared. Low total ratings are unfavourable; one example of a septic tank situated in sandy ground 50 ft. from an abstraction point gave a site rating of 6 which was considered unsafe.

A mapping technique has been developed [12] for landfill site selection based on core data from borehole drilling. A computer uses data on soil type, stratification and depth to first occurrence of water to estimate the contaminant attenuation capacity of the ground. Other information on groundwater such as its final use, quality required and quantity required can be used in the computer model and the result is a map of areas with contaminant attenuation capacity greater than a specified value. This may then be used as an aid to selecting suitable sites for landfill in areas of high contaminant attenuation capacity.

A variety of indexing systems have been developed to indicate the hazard materials present during transportation. Some of these only provide information relating to the hazards presented by the material rather than to the properties of the material. There is a need for unification of the diverse systems in use owing to the international traffic in hazardous materials and progress is being made towards this goal. In the U.K. the 'Hazchem' scheme has been devised by the London Fire Brigade [13], this uses a three character code to define the appropriate response to an accident or spillage involving the material in question. However, for loads crossing international frontiers in Europe a Kemler hazard identification number is required (ADR code) which consists of two digits [14]. The first digit indicates the primary hazard presented by the material and the second digit any secondary hazard; where both digits are the same an extreme hazard is implied. To give an example the Kemler number 68 indicates a toxic substance which is also corrosive while the number 33 indicates an extremely flammable liquid. The ADR code also requires a U.N. number which identifies the substance involved.

In the U.S.A. the situation is more complex and at least four indexing systems may be used [15]. The Department of Transport HI System combines a hazard symbol, a key word indicating the major hazard and a two digit number which corresponds with an HI card giving relevant information. The HI numbering system is broadly similar to the Kemler number of the ADR code. The other important system being used is the NFPA 704 M system in which three colour coded diamond symbols contain numbers indicating the degree of hazard. The number 0 represents no hazard and 4 an extreme hazard. The left hand diamond is blue and relates to toxicity, the top diamond is red and relates to flammability and the right hand yellow diamond relates to teactivity. There is space for a fourth symbol indicating other hazards such as radioactivity. Two remaining systems, LAPI and NIOSH, rely heavily on written descriptions of the hazard and much less on codifying the information. This will severely restrict their application to international transport in non-English speaking areas.

Other examples of indexing materials are provided by economic or environmental impact assessments which seek to compare materials on the basis of a number of parameters. The relative merits of PVC and glass as a container material have been assessed [16] using a type of indexing system. Flow sheets for the manufacture and disposal of associated waste were drawn up for the quantity of PVC and glass required to contain 1000 gallons of liquid in 1/5th gallon containers. The total energy, raw materials and transportation costs entailed in the manufacture of the containers were evaluated along with the pollution produced by manufacturing operations and disposal of waste. To relate all the parameters to a common scale the amount of energy in coal of equivalent economic value was calculated and used as a basis for comparison. An 'insult ratio' of 0.80 was obtained comparing PVC to glass indicating that use of PVC was less environmentally damaging overall. This compared well with a ratio of 0.84 obtained in an independent study of the problem. However, if the actual type of energy used in the manufacturing process was considered in terms of depletion of natural resources, an insult ratio of 0.62 was obtained. This again indicated that PVC was preferable to glass although PVC manufacture results in more air and water pollution damage. Thus the results of the comparison were dominated by energy and raw material consumption not the economic penalties of pollutant production. Post consumer disposal presents a small 'environmental insult' when compared with the raw materials production, energy production and manufacturing processes involved.

Three basic economic indices have been described to cover land and water pollution resulting from the electroplating industry [17]. These refer to effluent control (ECI), material utilisation (MU) and water productivity (WP). The first of these was defined by:

$$\mathrm{ECI} = \frac{C}{\text{Value Added}} \tag{26}$$

where C is the cost of meeting effluent quality requirements and Value Added is the value added to the product as a result of its passage through the process. The material utilisation index for a specific material was given by:

$$\mathrm{MU} = \frac{W}{T} \tag{27}$$

where W is the amount of material incorporated in the product and T the total amount of the material in the input to the process. This index is a direct measure of the proportion of the material which is put to its intended use. The third index, water productivity, is given by:

$$\mathrm{WP} = \frac{\text{Value Added}}{\text{Quantity of water consumed}} \tag{28}$$

This ratio can be used to assess the incorporation of water recycling systems. In a specific case study values of 5.2% for ECI, 88.2% for MU (nickel), 16.2% for MU (chromium) and £12.3 per 1,000 gallons for WP. These indices then provided a basis for comparing the efficiency of the plant with others performing similar tasks.

A 'two reservoir' model has been described for evaluating the rate of entry of water pollutants to the aqueous environment [18]. The model assumes that a product enters the first of two reservoirs at the annual production rate R (lbs/year). At any one time a quantity Q, (lbs) of product is in the first reservoir and three rate constants (K_1, K_{12}, α_1) define the rates at which product leaves the first reservoir as follows:

Rate at which product enters water directly, S_1 :

$$S_1 = K_1 Q_1 \tag{29}$$

Rate at which product degrades while in use, S_{11} :

$$S_{11} = \alpha_1 Q_1 \tag{30}$$

Rate at which product enters second reservoir, S_{12}:

$$S_{12} = K_{12} Q_1 \tag{31}$$

The second reservoir may be landfill site, a storage area, the atmosphere or other holding area containing Q_2 (lbs) of product at any one time. The rates at which product leaves the second reservoir are also defined by rate constants:

Rate at which product enters water, S_2:

$$S_2 = K_2 \ Q_2 \tag{32}$$

Rate at which product degrades in secondary reservoir, S_{22}:

$$S_{22} = \alpha_2 \ Q_2 \tag{33}$$

The rates of change of Q_1 and Q_2 with time are given by:

$$\frac{dQ_1}{dt} + (K_1 + K_{12} + \alpha_1)Q = R \tag{34}$$

and:

$$\frac{dQ_2}{dt} + (K_2 + \alpha_2) \ Q_2 = K_{12} Q_1 \tag{35}$$

The quantity $1/(\alpha_1 = K_1 + K_{12})$ years may be interpreted as the average lifetime, L, of a product in the primary reservoir. Under steady state conditions Q_1 and Q_2 assume limiting values given by:

$$Q_{1\,,\,\mathrm{lim}} = RL \tag{36}$$

$$Q_{2\,,\,\mathrm{lim}} = K_{12} D \times Q_{1\,,\,\mathrm{lim}} \tag{37}$$

where:

$$D = 1/(\alpha_2 + K_2) \tag{38}$$

or the average lifetime of the product in the second reservoir.

The fractions of product lost from the primary reservoir by the routes considered are K, L, α, L and $K_{12}L$ respectively. Attempts were made to estimate these quantities. The two reservoir model is a gross oversimplification of the real world and large undercertainties exist in the estimation of some parameters in the model. However, it does provide a framework for evaluating rates of entry of products into water at a less superficial level than using annual production figures alone.

The EEC have described an indexing system for evaluating the toxicity mixtures or commercial preparations [19]. Substances are classified as toxic (class I) or harmful (class II) and subcategories of the classes (Ia, Ib, Ic, IIa, IIb, IIc, IId) are given a numerical classification index I_1 and an exemption index I_2. Preparations containing P_i% of a substance i are considered toxic if:

$$\sum(P_i \times I_{1i}) > 500 \tag{39}$$

and harmful if:

$$\sum(P_i \times I_{1i}) \leqslant 500 \tag{40}$$

and:

$$\sum(P_i \times I_{2i}) > 100 \tag{41}$$

Substances are not considered harmful if:

$$\sum(P_i \times I_{2i}) < 100 \tag{42}$$

Substances present at levels below a percentage specified for each sub-category do not need to be considered. Lists of classification indices I_1 and I_2 are provided [19].

Three environmental impact or quality indices have been reviewed [20]. The first of these used the product of three coefficients for persistence (1 to 5), geographic range (1 to 5) and complexity of effects un humanity, resources and the environment (1 to 9). The final ranking placed pesticides as the greatest current problem with heavy metals and air pollutants second and third. Future projections indicated that the importance of pesticides would decline and heavy metals, particulates, solid waste and radionucleides would become the major problems. The National Wildlife Federation index alloted scores to seven factors of the environment which were weighted by their relative importance from soil at 30% to timber at 5%. The conclusion of this index was that the U.S. environment was generally deteriorating from 1970 to 1971 although water quality remained steady at an 'intolerable' level. An index of air pollution produced surprising results in that carbon monoxide was considered far less harmful than particulates.

A combined environmental quality index for Canada has been devised [21] based on four main areas, air quality, water quality, land quality and miscellaneous factors including pesticides and radioactivity. Each area was divided into categories for which sub-indices could be evaluated, in some cases based on sub-sub-indices arising from further sub-division of the categories. A root mean square approach was used in totalling the sub-indices so that especially large index values would not be cancelled out by a number of smaller values as with a linear average approach. To give an example of the indexes use, the area of air quality was sub-divided into three categories as follows:

(1) Index of specific pollutants (in urban areas) (I_{SP})

(i) sulphur dioxide (I_{SO_2});
(ii) carbon monoxide (I_{CO});
(iii) particulates (I_{SPM});
(iv) coefficient of haze (I_{COH});

(v) nitrogen oxides (I_{NOX});
(vi) total oxidants (I_{OX}).

(2) Index of inter-urban air quality (I_{reg})

(i) visibility at air ports I_{reg}.

(3) Index of industrial emissions (I_{ie})

(i) industrial oxides of sulphur;
(ii) industrial suspended particulate matter.

For category 1 the Index of Specific Pollutants I_{SP} was given by:

$$I_{SP} = \sqrt{\frac{{I_{SO_2}}^2 + \tfrac{1}{2}{I_{SPM}}^2 + \%{I_{COH}}^2 + {I_{CO}}^2 + {I_{NOX}}^2 + {I_{OX}}^2}{5}} \tag{43}$$

where I_{SPM} and I_{COH} were combined with equal weight of ½. A value of 1.23 was obtained for I_{SP}. The Index of Inter-urban Air Quality (I_{reg}) was based on visibility measurements at airports. The Third Index of Industrial Emissions (I_{ie}) was defined by:

$$I_{ie} = (E_c/P_c)/(E_t/P_t) \tag{44}$$

where E_c is the weight of industrial emissions in a county of population P_c and E_t the national total weight of emissions for a population P_t. These category indices were then weighted and combined to give a total air quality index I_{air} as follows

$$I_{air} = \sqrt{\frac{5(I_{SP})^2 + 3(I_{reg})^2 + 2(I_{ie})^2}{10}} \tag{45}$$

A similar approach was adopted in the evaluation of an Index of Water Quality (I_{water}), an Index of Land Quality (I_{land}) and an Index of Miscellaneous Aspects (I_{misc}). These were then weighted, normalised and combined to give the Combined Environmental Quality Index (I_{EQI}) as follows:

$$I_{EQI} = \sqrt{0.3(I_{air})^2 + 0.3(I_{water})^2 + 0.3(I_{land})^2 + 0.1(I_{misc})^2} \tag{46}$$

The meaning of this overall index is difficult to grasp in real terms and its main function is to allow the monitoring of environmental quality as a whole. A more detailed impression of the condition of the environment or changes in it can be obtained by considering the various sub-indices which were used to calculate I_{EQI}.

Additive utility model

The mathematical problems encountered in defining hazard index scales and in combining indices for different aspects of behaviour have been considered by Klee [22]. The use of Utility Theory [23] to quantify the decision making process has led to the development of the Decision Alternative Ratio Evaluation or DARE method [24]. This method allows some quantification of value judgements about the importance of different parameters, and their combination to obtain an overall estimate of worth. Application of the DARE method in the context of rating waste streams by an indexing system provides the basis of the Additive Utility Model.

In essence the application of the Additive Utility Model involves the following steps:

(i) define the criteria by which the waste stream or material will be assessed;
(ii) define the least and most desirable values for each criteria and thus the range of values between these limits;
(iii) normalise the values for each criterion such that the least hazardous material scores 0 and the most hazardous 1;
(iv) evaluate the relative importance of each criterion and derive Relative Utility Ranges, the largest for the most important criterion and the smallest for the least important criterion;
(v) carry out a consistency check on the Relative Utility Ranges derived;
(vi) combine the normalised scores for each criterion with the Relative Utility Ranges according to a linear additive model (eqn. 46).

$$U_{(xy)} = W_0 + W_1 x + W_2 y \qquad (46)$$

where $U_{(xy)}$ is the rating based, in this example on two criteria for which the material has normalised scores x and y and for which the Relative Utility Ranges are W_1 and W_2 respectively.

The Additive Utility Model uses a linear additive method to combine scores for different aspects of behaviour but other methods are possible, notably the conjunctive (eqn. 47) and disjunctive (eqn. 48) methods;

$$U_{(xy)} = W_0 \, x^{W_1} \, y^{W_2} \qquad (47)$$

$$U_{(xy)} = W_0 \, (a-x)^{-W_1} \, (b-y)^{-W_2} \qquad (48)$$

where a and b are arbitrary values set greater than the maximum value observed for x and y respectively. In the conjunctive model the overall rating $U_{(xy)}$ depends on all the scores x^{W_1} y^{W_2}, etc. being greater than some minimum value. When the scores are all greater than this value the magnitude of $U_{(xy)}$ is large but, when one or more of x^{W_1}; y^{W_2}, etc. fall below the minimum value the magnitude of $U_{(xy)}$ decreases substantially. In the disjunctive model the magnitude of $U_{(xy)}$ is largely determined by the largest of the x^{-W_1}, y^{-W_2}, etc. values. Thus the final rating strongly reflects the score for the most hazardous aspect of the materials behaviour. Both of these combination methods have applications in the hazard indexing field, for example if water pollution were considered a major hazard at a site and other parameters were relatively unimportant, the use of a large Relative Utility Range for water pollution aspects and a disjunctive combination method would result in especially high scores for water polluting materials. On the other hand, if the concern were over a combination of pollution hazards occurring at once, the conjunctive model would produce high scores for materials which were hazardous in several aspects of their behaviour. However, the linear additive combination method remains conceptually the simplest and perhaps, therefore, the most useful.

Evaluation of indexing systems

General considerations

There are many reasons for developing a Hazard Index, some of which are listed in the introduction (p. 364). Thus an indexing method which is satisfactory in one context may prove quite inadequate in another. It is the purpose of this review to consider the development of an indexing system which makes maximum use of existing information, and which may be applied flexibly to meet a wide variety of needs, particularly those relating to waste management. The indexing systems reviewed here have been evaluated in this context and, since this is not necessarily the context in which they were initially devised, the evaluation does not constitute any criticism of their use for their use for their original purpose.

The factors considered in evaluating the existing indexing systems include the retention of information by the system, the flexibility of application of the system, the rationality of methods used to obtain overall rankings and whether the indices used to describe aspects of behaviour have physical meaning. The major stumbling block of most of the systems is the method used to combine indices for different aspects of behaviour. In some cases logical absurdities are possible where, for example, combination of equal parts of two waste streams, both initially considered more hazardous than a third stream, appears to result in a waste stream less hazardous than the third. This result arising from the way the information was handled rather than from any reduction in toxicity on mixing.

BARRINC model

The first steps in construction of the BARRINC model (identify substances and criteria of hazard) are fundamental to any indexing system concerned with the effects of individual materials. However, a number of objections may be raised to subsequent steps. Firstly the use of a 1, 2 and 3 scale for indexing individual ecological hazards greatly reduces the data contained in the model since any toxicity, solubility, or other data used to decide the index is only retained in an ordinal sense. This also limits the flexibility of the model. It is, for example, difficult to see how it could be usefully applied to select materials for land or sea disposal. In addition, it was stated that no justification could be found for adjusting the weighting factors from term to term (eqn. 1). This is hardly realistic since it is unlikely that one would be genuinely indifferent in choosing between hazards in any given situation. Human toxicity generally ranks higher in importance than toxicity to eco-populations to give just one example. Thus the BARRINC model does not lend itself to use in the context of this review, although the linear additive combination method (eqn. 1) is intrinsically a viable means of ranking materials.

PHL model

This model is also based on a linear additive combination approach, but, unlike the BARRINC model, effectively applies weightings to different aspects of behaviour. The human toxicity term (eqn. 5) is, for example, a combination of a weight factor [3] and a rating factor (S_r). The PHL model makes more use of quantitative data than most of the models reviewed although some ratings (e.g. S_r) are ordinal. Two disadvantages are apparent in the PHL Model. Firstly the parameters used in the model appear to be defined on a rather ad hoc basis and some consideration of the application of the parameters in a real sense would be desirable. Secondly the weight factors are obscured by the combination approach used and, since different weight factors may be appropriate in different situations, these should appear explicitly in the combination step. Despite these comments the PHL model provides an interesting approach to the indexing problem and some of the parameters used, Bd (eqn. 7) for example, may prove to be generally useful.

The landfill site ranking model proposed by Pavoni and Hagerty is also interesting in terms of the parameters used. However, little or no consideration appears to have been given to the means by which the hazardous material and landfill site ratings could be combined as a basis for decisions on whether or not to landfill a given material at a given site. Indeed it may be argued that, if sufficient information exists to rank both the material and the site with any degree of confidence, it may be more appropriate to calculate the likely contamination which will arise from the deposition of waste at the site than to use an indexing approach. This point is fundamental to the application of rating systems largely based on quantitative data.

BNW model

This model adopts a very simple approach and uses only three or four parameters to index a material. Its main failing is that, by selecting the minimum concentration known to cause harm as a parameter, any other information about environmental behaviour is discarded. Furthermore, Klee demonstrates [22] that the use of 'minimum concentration known to cause harm' as a parameter in indexing system is mathematically unsound and may lead to absurd results in some cases. Another disadvantage of the BNW model is the arbitrary nature of the weighting factor, *K*, used in eqn. 24. The combination of concentration, environmental mobility and annual production in the BNW model results in an index which relates to 'the volume of the sector of the environment of interest critically degraded each time period by a given waste stream' [22].

U.S. Coast Guard system

This system is ordinal in nature and does not attempt to combine indices for different aspects of behaviour. Thus it has little direct application in the context of this review. The U.S. Coast Guard index does, however, provide a good example of the way in which an ordinal system, based to some extent on qualitative data, may be usefully applied to the management of hazardous substances. Each index has some physical meaning and all are assessed on a normalised scale of 0—5. By not attempting to combine indices the system ignores the thorny issues involved in devising overall Hazard Index ratings.

Other indexing systems

Among the other indexing systems reviewed the Chemical Reaction Hazard Index (see p. 373) provides an example of a one parameter ordinal index derived from quantitative data. The index suffers from the disadvantage that the appropriate data and computer programme must be available to produce a rating by calculation. However, since the final rating is ordinal some compounds could be included on a qualitative assessment basis. Unfortunately the conversion of the results of computer calculations to an ordinal rating reduces the quality of information contained in the index.

The indexing systems for landfill sites which were reviewed provided examples of the following:

(i) the use of laboratory experiments in devising a parameter for indexing leachate quality [10];
(ii) the use of 'analogue methods' to relate measured values to an index where no simple arithmetic relation exists between the measured value and the index [11];
(iii) development of a computer model which uses borehole data to map a site according to contaminant attenuation capacity.

None of these models attempts to combine indexes for landfill sites with indexes for materials as part of a decision model. They do, however, illustrate some of the approaches which can be adopted in the site rating step of a decision model.

The remaining indexing systems reviewed earlier included examples of:

(i) indexing systems which define the response to an accident involving a material; without necessarily indicating the properties of the material;
(ii) use of indexing methods in economic analyses of environmental impact;
(iii) the assessment of environmental quality by indexing aspects of the environment and combining scores by a weighted root mean square approach.

The use of indices to define appropriate responses in accident situations raises the problem of using hazard indices based on the properties of a material to derive 'response indices' or 'economic impact indices'. While it may be fairly realistic to derive 'response indices' from the properties of a material it is unlikely that its economic impact will be easily assessed from such information. The Canadian Environmental Quality Index uses a combination method not considered above (see p. 378). Use of the root mean square approach is another method of combining indices so that the final result is dominated by extreme values of individual sub-indices. Thus, to some extent this combination method provides an alternative to the disjunctive model described above (see p. 380).

The Hazard Index models reviewed in this paper illustrate the many problems and pitfalls to be encountered in this field. However, they also provide examples of novel and useful approaches to some of these problems. The development of a model satisfactory and acceptable to all those involved in waste management is an impossible task but by drawing on existing information and experience it should be possible to develop a generally useful model. The two major problems in constructing a general model will be:

(i) the accumulation and economic storage of data in a useful and accessible form;
(ii) the handling of the data to evaluate alternatives as an aid in making management decisions.

Development of a Hazard Index model for waste management

Availability of data and generation of new information

The types of data which might be considered appropriate for use in Hazard Index calculations cover a wide range of properties. A preliminary list for hazardous substances may be drawn up as follows under three headings:

A. Intrinsic properties

(i) solubility
(ii) vapour pressure
(iii) form or viscosity
(iv) molecular weight
(v) decomposition temperature
(vi) calorific value
(vii) chemical composition

B. Interactive properties

(i) adsorption behaviour
(ii) degradation (biological interactions)
(iii) chemical reactivity (precipitation or solubilisation by other materials)
(iv) corrosivity (oxidising or reducing properties, ability to solubilise other materials)
(v) flammability (flash point, lower flammable limit)
(vi) combustibility (temperature and residence time for incineration)

C. Environmental effects

(i) toxicity in air (TLV)
(ii) toxicity in water (MPC, human or fish toxicity)
(iii) ingestion toxicity (LD_{50})
(iv) contact toxicity (skin or eye irritant)
(v) colour
(vi) odour (odour threshold)
(vii) oxygen demand
(viii) disease transmission potential
(ix) annual production
(x) treatment costs

It is more difficult to formulate a list of parameters to describe management alternatives but a preliminary attempt under four headings is as follows:

A. Landfill sites

(i) site capacity (volume)
(ii) permeability at site
(iii) absorption capacity at site
(iv) proximity of aquifer to site
(v) dilution capacity of aquifer
(vi) amenity value of site
(vii) site capacity for air polluting materials

B. Incineration

(i) Operating temperature
(ii) residence time
(iii) capacity of incinerator
(iv) gas treatment capability

C. Discharge to water

(i) dilution capacity of water body
(ii) amenity value of water body
(iii) sensitivity of water population to pollutants

D. Transport

(i) container capacity
(ii) robustness of container
(iii) probability of spill for transport method
(iv) environmental sensitivity to spill (route and population which might be affected)
(v) security of loading/unloading procedure

While the above lists represent only a preliminary consideration of the Hazard Indexing problem they illustrate the bulk of data which might be required. A total of 23 parameters have been listed for the properties of materials and a further 19 for various aspects of waste management. Some of the parameters are likely to be known [25, 26] e.g. solubility, vapour pressure and Threshold Limit Values; but others such as absorption behaviour, biodegradability and size absorption capacity may have to be measured. In some cases standard measurement techniques might need to be developed, in others only a qualitative assessment may be possible. The development of test procedures needs to allow for the investigation of all defined wastes as well as individual compounds. Thus absorption tests, for example, may have to be based on analysis for total dissolved solids or dissolved organic carbon when an ill defined or mixed waste is being studied. Development work may also be necessary on analytical techniques for use with difficult or ill defined materials.

In order to apply data on a material's behaviour sensibly, some understanding must be obtained of the sensitivity of the data to outside influences such as pH and temperature. If, for example, the solubility of a material changes by a factor of 5 between pH 4 and pH 5 then there will be a large uncertainty about its solubility in a landfill site of changing pH. Any experimental work should therefore identify materials and parameters which are especially sensitive to external conditions, and attempt to quantify variations in behaviour. A fundamental study of some representative compounds and substrates could be used to define the patterns of behaviour possible in some detail. A less thorough study of the bulk of the compounds might then serve to establish their 'behaviour type'.

The use of what might be termed 'modelling experiments' to investigate the interaction of materials with refuse in the laboratory may provide a preliminary basis for Hazard Index calculations. However, although experiments of this type provide an indication of overall behaviour in landfill they do not yield any specific data on adsorption, solubility, evaporation or other parameters. The meaning of the results obtained in such modelling experiments is thus open to debate and data on adsorption, solubility and volatility obtained under controlled 'clean' conditions, are needed to support the results of any such modelling experiments.

In conclusion it may be said that a large portion of data relating to the properties of materials is either available or could be obtained by standard test methods. Data on adsorption, degradability, combustibility and some aspects of chemical reactivity may largely have to be determined experimentally and standard test methods need to be developed. Information about waste management options should largely be available from landfill site surveys, incinerator operating specifications, etc., but again some experimental work on adsorption or permeability may be necessary in certain cases. Information on bulk aspects of landfill behaviour such as permeability of refuse, diffusion rates of vapour through refuse and gas evolution rate is needed.

Methods of handling data and assigning indices

This is undoubtedly the most difficult aspect of developing a Hazard Index Model and poses many problems for which there are no unique solutions. The first problem arises in deciding how to store the data for the indexing system. If the data is to be used in index calculations it should all appear on a common scale of say 0 to 1 or 0 to 10. However, the ranges of effect observed for different parameters may be of very different magnitudes. To give an example calorific value expressed in units of 1,000 BtU/lb may range from 0 to 20, while LD_{50} for rats in mg/kg body weight may range from less than 1 to well over 1,000. Thus while calorific value might be linearly indexed on a scale of 0 to 10, LD_{50} might be better indexed as a reciprocal on a logarithmic scale of 1 to 10 so that an LD_{50} of 0.001 mg/kg gave an index of 10 and 1,000,000 mg/kg gave an index of 1. The question also arises whether a parameter, such as LD_{50}, is linearly related to a value judgment of hazard. It may be that for all practical purposes an LD_{50} of 1,000 mg/kg is no worse than one of 1,000,000 mg/kg. However, if the probability of ingesting 0.001 mg of a substance were 100 times greater than that of ingesting 0.01 mg, an LD_{50} of 0.001 mg might be considered 100 times worse than an LD_{50} of 0.01 mg. Clearly considerable thought will need to be given to this aspect of the information storage.

Some of the difficulties to be encountered in combining indices to obtain an overall rating have been discussed above (see p. 379). One approach might be to express indices in a form which gathers together those properties which will govern the behaviour of a substance in a given situation. For example an air toxicity index may serve to rank materials by the factor by which their saturated vapour concentration exceeds their TLV. This ordering might then by maintained as vapour disperses in the atmosphere from a source so that combination of the site parameters with the air toxicity index would provide an evaluation of the air borne hazard at a landfill site. However, it can be argued that if so much is known about the problem it would be as easy, and more reliable, to apply a deterministic approach to calculate likely distances over which TLV was exceeded.

Because of the uncertainties attached to many aspects of environmental behaviour it may be more sensible to apply probability distributions rather than weighting factors to indices in any combination step. Probability distributions could be assigned by deciding upper and lower limit values for the aspect under consideration, along with its most likely expected value. The result of the combination step would itself be a probability and would allow a more informed decision to be made. This approach would be mathematically more complex than a simple weighting method but provided only 5 to 10 indices were to be combined the task should be feasible.

Different combination models could be developed to cover different aspects of waste management and their development will need to draw on information from the Landfill Research Programme and other sources. Use of a centralised computer facility would allow the use of fairly sophisticated combination and evaluation techniques as part of the decision model. Information could be obtained from a data bank of indices for materials and from questions about the management problem under consideration. A combination and evaluation model would then be used to process the data and compare the results, as far as possible, with prior experience. This would give an estimate of the suitability of the waste for disposal or treatment method under consideration. Alternatively details of the waste material might be used to define the landfill or incineration conditions required for safe disposal as a prelude to selection of a suitable site or incinerator.

Conclusion

It is often extremely difficult to make even a semiquantitative evaluation of the relative environmental impact of two materials of widely differing properties. In cases where the properties of the materials and the situation in which they may arise are known in some detail, it may be possible to make a direct quantitative comparison on the basis of calculations of their relative behaviour. However, such cases are rare and this approach is unlikely to be practicable when many different materials are to be considered. The use of an indexing system and an appropriate set of combination and evaluation models can provide a rational means of evaluating relative environmental impact where definitive calculations cannot be used to determine a materials behaviour.

The first step in using such an indexing approach is to draw up a list of the materials or wastes of interest and the management or disposal options to be considered. The properties of the materials or wastes which are relevant to the evaluation process should be obtained either from the existing literature or by measurements in the laboratory. It then remains to construct a combination model appropriate to the management situation under consideration. The Additive Utility Model described in p. 379 is probably the most generally useful combination method but other options may be more appropriate in certain cases. The normalised indices for each material and the relative utility range for each property, or 'criterion', are derived from the data as outlined previously and the overall index calculated using the combination model. These overall indices should then reflect the actual properties of the material in combination with the relative importance attributed to each property by means of the 'relative utility range' or weighting factor.

Provided that the combination model is mathematically sound, the use of an indexing and combination approach allows great versability in quantifying valve judgements about aspects of a materials environmental behaviour. Indeed such an approach is probably the only simple but rational means of assessing the combined effects of several widely differing properties when deterministic calculations of behaviour are not possible.

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