

**COMPARATIVE EVALUATION
OF CHEMICAL RANKING
AND SCORING METHODOLOGIES**

EPA Order No. 3N-3545-NAEX

Prepared by

University of Tennessee
Center for Clean Products and Clean Technologies

Gary A. Davis, Principal Investigator
Mary Swanson, Senior Research Associate
Sheila Jones, Research Assistant

April 7, 1994

Printed on Recycled Paper

TABLE OF CONTENTS

LIST OF TABLES	iii
LIST OF FIGURES	iii
LIST OF ACRONYMS	iv
SECTION 1: INTRODUCTION	1
SECTION 2: METHODS	3
2.1 SUMMARY OF SYSTEMS	3
2.2 DETAILED DESCRIPTION OF SYSTEMS	8
2.3 DESCRIPTION OF IMPORTANT ELEMENTS AND APPLICATIONS OF RANKING SYSTEMS	9
2.3.1 Purpose and Application of Chemical Ranking and Scoring Systems	10
2.3.2 Human Health Criteria and Endpoints	12
2.3.3 Criteria and Endpoints for Environmental Effects	22
2.3.4 Measures of Exposure	24
2.3.5 Missing Data, Data Selection Approach	29
2.3.6 Aggregation and Weighing	31
2.3.7 Other Issues	33
SECTION 3: DISCUSSION	38
3.1 RISK ASSESSMENT PRINCIPLES APPLIED TO CHEMICAL RANKING AND SCORING	38
3.2 SIMILARITIES AND DIFFERENCES AMONG SYSTEMS REVIEWED	39
3.2.1 Most Common Effects and Exposure Endpoints Used	39
3.2.2 Ranking versus Categorization	39
3.2.3 Quantitative versus Qualitative Endpoints	41
3.2.4 Assigning Scores to Endpoint Data	41
3.3 GENERAL STRENGTHS AND WEAKNESSES OF EVALUATED SYSTEMS	44
SECTION 4: CONCLUSIONS	46
REFERENCES	49
APPENDIX A SUMMARIES OF RANKING AND SCORING SYSTEMS	A-1
APPENDIX B RANKING AND SCORING SYSTEMS IDENTIFIED	B-1
APPENDIX C DETAILED TABLES OF CRITERIA, ENDPOINTS, AND DATA APPROACH USED BY EACH EVALUATED SYSTEM	C-1

LIST OF TABLES

<u>Table No.</u>		<u>page</u>
1.	Chemical Ranking and Scoring Systems Evaluated	4
2.	Endpoints Used for Scoring Environmental and Human Health Effects	16
3.	Endpoints Used for Scoring Exposure	26
4.	WP Factors (WP) Scores for Several Systems	42
B-1	Overview of Purpose and Developers/Users of Ranking and Scoring Systems Evaluated	B-1
B-2	Overview of Purpose and Developers/Users of Additional Ranking and Scoring Systems Identified	B-2
C-1	Toxicity Criteria and Endpoints Used in Evaluated Systems	C-1
C-2	Overview of Exposure Criteria and Endpoints Used in Evaluated Systems	C-26
C-3	Overview of Data Selection Approach Used in Evaluated Systems	C-33

LIST OF FIGURES

<u>Figure No.</u>		<u>page</u>
1.	Comparison of Scoring for Several Systems	43
2.	Development of a Chemical Ranking and Scoring System	47

LIST OF ACRONYMS

AALAC: ambient aquatic life advisory concentration
ARET: Accelerated Reduction/Elimination of Toxics
ADI: allowable daily intake
ATSDR: Agency for Toxic Substances and Disease Registry
AWQC: aquatic water quality criteria
BAF: bioaccumulation factor
BCF: bioconcentration factor
BP: boiling point
BUA: Beratergremium für Umweltrelevante Altstoffe
CAG: carcinogen assessment group
CCHTE: chemical category human toxicity estimate
CFC: chlorofluorocarbon
CMR: Critical Materials Register
DfE: Design for the Environment
EC: European Communities
EC₅₀: the median effect concentration; the concentration at which 50% of the test population exhibit a specified response during a specified time period
ED₁₀: estimated dose associated with a lifetime increased cancer risk of 10%
EEC: European Community Commission
ELU: Environmental load units
EMPLL: Effluent Monitoring Priority Pollutants List
EPA: United States Environmental Protection Agency
EPS: environmental priority strategies
ERRP: ecological risk reduction potential
GWU: George Washington University
HA: health advisory
HEAST: Health Effects Assessment Summary Tables
HHSATR: human health structure activity team rank
HPV: high production volume
HRRP: human risk reduction potential
HRS: Hazard Ranking System
HWQC: human health water quality criteria
IARC: International Agency for Research on Cancer
IC₅₀: inhibitory concentration for 50% test population
IRIS: Integrated Risk Information System
ITC: Interagency Testing Committee
K_{ow}: octanol-water partition coefficient
LC₅₀: median lethal concentration; the concentration at which 50% of the test population die during a specified time period
LCA: life cycle assessment
LD₅₀: lethal dose for 50% test population
LD₁₀: lethal dose to some value < 50%

LIST OF ACRONYMS, continued

LET: lethality
LOAEL: lowest observable adverse effect level
MATC: maximum acceptable toxicant concentration
MED: minimum effective dose
MOE: Ministry of the Environment (Ontario)
NA: not applicable
NAAQS: national ambient air quality standard
NEL: no effect level
NFPA: National Fire Protection Association
NOAEL: no observable adverse effect level
NOEC: no observable effect concentration
NOEL: no observable effect level
NOx: nitrous oxides
NPL: National Priority List
NTP: National Toxicology Program
OECD: Organization for Economic Cooperation and Development
PGR: population growth rate
 q_1^* : cancer potency slope factor
QSAR: quantitative structure-activity relationship
RfC: reference concentration
RfD: reference dose
RQ: reportable quantity
SAR: structure-activity relationship
SARA: Superfund Amendments and Reauthorization Act
SATR: structure activity team rank
SIDS: screening information data set
SRS: Site Ranking System
TD₁₀: total dose resulting in a sublethal effect
TPQ: threshold planning quantity
TRI: Toxics Release Inventory
TSCA: Toxic Substances Control Act
TSCA CSSC: TSCA chemical scoring system category
UCR: unit cancer risk
URF: unit risk factor
UT: University of Tennessee (Knoxville, Tennessee)
VOC: volatile organic compound
WMS: Wet Milieugevaarlijke Stoffen
WOE: weight of evidence

SECTION 1: INTRODUCTION

Between 60,000 and 100,000 of the over 8,000,000 chemicals listed by the Chemical Abstracts Services Registry are commercially produced and are potential environmental pollutants. Some kind of risk-based evaluation for these chemicals is often required to evaluate the impacts of chemical use or releases, for regulatory action, and to set priorities for pollution prevention. The time and resources, however, are not reasonably available to test *all* of these chemicals for their potential health and environmental effects. During the last decade there have been vast improvements in the methods used to test chemicals for toxicity and environmental fate and to interpret these data within a risk assessment framework. We have not, however, developed generally accepted and widely used tools to better enable us to set priorities and focus limited resources on selecting those chemicals for study that would yield the greatest environmental benefits.

Risk-based ranking and scoring systems can be used to focus attention and resources on the largest potential hazards. Risk-based chemical ranking and scoring combines an assessment of both the toxic effects of chemicals (human and/or environmental) and the potential exposure to those chemicals to provide a relative evaluation of risk. Along with toxicity and exposure, ranking and scoring systems may include other environmental impacts (e.g. ozone depletion) and some measure of economic impact and/or societal value.

Although numerous ranking and scoring systems have been or are being developed, there is currently no scientific consensus on risk ranking methods. Chemical risk ranking has received the most attention, and several systems have been used, for example, to determine which chemicals should be included in various regulatory pollutant lists. To facilitate development of a framework for overall human health and environmental risk ranking, this report presents an evaluation of existing chemical ranking and scoring systems. Approximately fifty systems are compared and evaluated in terms of:

- the purpose and application of the ranking and scoring system;
- the human health criteria and endpoints included;
- the criteria and endpoints included for environmental effects;
- whether measures of exposure are included;
- the data selection approach¹ and handling of missing data;

¹ "Data selection approach" is a term used here to describe the methods used to build a comparable data set for a specific measurable characteristic across a set of chemicals of interest. As an example, to characterize the bioconcentration potential for a set of 100 organic compounds, measured bioconcentration factors are selected first for all chemicals where this information is available. For all other chemicals, a bioconcentration value is estimated from the octanol-water partitioning coefficient or from water solubility data.

- the use of aggregation and weighing of different health and environmental impacts;
- methods of accounting for chemical potency and severity of effects; and
- inclusion of other impacts or issues.

An evaluation of the important issues inherent to the development of any consensus ranking and scoring system is presented, and important similarities and differences among the systems evaluated are discussed.

In this document, following the introduction, Section 2 presents the methods used by the evaluated systems. This includes a list and summary of the systems, a more detailed description of the systems, and a description of important elements and applications of ranking systems. Section 3 contains a discussion, based on the analysis of systems in Section 2, of the application of risk assessment principles to chemical ranking and scoring, similarities and differences among the systems, and general strengths and weaknesses of the evaluated systems. Section 4 presents conclusions and suggestions for future work.

SECTION 2: METHODS

2.1 SUMMARY OF SYSTEMS

Fifty-one ranking and scoring systems have been reviewed for this report (listed in Table 1). A summary is provided for each of these in Appendix A. The systems selected for evaluation span a wide range of methodologies and levels of complexity (from simple and straight-forward to fantastically elaborate). Evaluating this variety of systems is intended to provide a representative sampling of the approaches to chemical ranking and scoring and the issues involved in developing a standardized (or consensus) framework.

It is necessary to distinguish *chemical* ranking and scoring systems from other risk ranking systems such as those that primarily rank sites (e.g. potential sites for listing on the National Priorities List) or issues (e.g. risk from hazardous waste sites versus air pollution, etc.). The majority of ranking and scoring systems that we have evaluated are based on a chemical-specific approach, which involves ranking, scoring, or categorizing a list of chemicals based on chemical-specific attributes. A system is considered a *chemical* ranking or scoring system if it meets the following criteria:

- it ranks or scores a list of chemicals;
- it results in a relative ranking or scoring, not quantitative measure(s) of risk;
- it includes measures of either toxicity alone or toxicity and exposure; or
- if it is a subsystem of a site or issue ranking method, the approach ranks sites or issues based on an initial chemical-specific evaluation.

Thirteen of the fifty-one systems reviewed here did not meet these conditions. The following systems reviewed did not meet the criteria of a chemical scoring or ranking system as defined above:

- *CERCLA Hazard Ranking System (HRS)* (EPA 1990): a site ranking system;
- *Modified Hazard Ranking System* (Hawley & Napier, 1985): a site ranking system;
- *A Groundwater Pollution Priority System* (Hutchinson & Hoffman): a site ranking system;
- *EPA Unfinished Business Report* (Morgenstern et. al., 1987): used to rank environmental issues which pose societal risks;
- *Coastal Hazardous Waste Site Review* (Beckvar & Harris, 1985): a site ranking system;
- *Site Ranking System (SRS) for Chemical and Radioactive Waste* (Rechard et. al., 1988, 1991): a site ranking system;
- *Evaluating Contamination Potential of Surface Impoundments* (Silka & Swearingen, 1978): a site ranking system;

TABLE 1. List of Ranking and Scoring Systems Evaluated

System no. ^a	System Name or Title	Reference
1	TRI Environmental Indicators Methodology (draft)	Abt Associates, Inc., 1992
2	ATSDR, "CERCLA Section 104 Third Priority List"	ATSDR, 1992
3	Existing Chemicals of Environmental Relevance	Behret, 1989a
4	Existing Chemicals of Environmental Relevance II, Selection Criteria and Second Priority List	Behret, 1989b
5	Review of Region VII TRI Strategy	Bouchard, 1991
6	Candidate Substance List for Bans or Phase-outs	Socha et al, 1992
7	Criteria Identifying High Risk Pollutants	BNA, 1991
8	A Classification System for Hazardous Chemical Wastes	Crutcher & Parker, 1990
9	CERCLA Hazard Ranking System (HRS)	EPA, 1990
10	Identifying Chemical Candidates for Sunsetting: George Washington University	Foran & Glenn, 1993
11	Existing Chemicals: Systematic Data Collection and Handling for Priority Setting	Gjøs et al., 1989
12	Substances and Preparations Dangerous for the Environment: A System for Classification, Labeling and Safety Data Sheets	Gustafsson & Ljung, 1990
13	Notes on Ranking Chemicals for Environmental Hazard	Halfon & Reggiani, 1986
14	Application of the Hazard Ranking System to the Prioritization of Organic Compounds Identified at Hazardous Waste Remedial Action Sites	Hallstedt et al., 1986
15	Modified Hazard Ranking System (mHRS); A Ranking System for Hazardous Waste Sites with Mixed Radioactive and Hazardous Wastes	Hawley & Napier, 1985
16	A Groundwater Pollution Priority System (GWPPS)	Hutchinson & Hoffman, 1983
17	The Great Lakes Water Quality Agreement (GLWQA) Annex 1, Lists 1,2,3	IJC, 1989

TABLE 1. List of Ranking and Scoring Systems Evaluated

System no. ^a	System Name or Title	Reference
18	Chemical Scoring by a Rapid Screen of Hazard (RASH) Method	Jones et al., 1987
19	Systematic Approach for Environmental Hazard Ranking of New Chemicals ("Schmallenberg")	Klein et al., 1988
20	WMS Scoring System	Könemann & Visser, 1988; Timmer et al., 1988
21	Benchmark Comparisons	Laskowski et al., 1982
22	Michigan Critical Materials Register (MCMR)	Michigan DNR, 1987
23	USEPA Unfinished Business Report: A Comparative Assessment of Environmental Problems	Morgenstern et al., 1987
24	Chemical Scoring System for Hazard and Exposure Identification	O'Bryan & Ross, 1988
25	Effluent Monitoring Priority Pollutant List (EMPLL)	Environment Ontario, 1987, 1988
26	Coastal Hazardous Waste Site Review	Beckvar & Harris, 1985
27	Site Ranking System (SRS) for Chemical and Radioactive Waste	Rechard et al., 1988; Rechard et al., 1991
28	A Practical Method for Priority Selections and Risk Assessment Among Existing Chemicals	Sampaolo & Binetti, 1986, 1989
29	UT Chemical Ranking System (draft)	Davis et al., 1993
30	A Manual for Evaluating Contamination Potential of Surface Impoundments	Silka & Swearingen, 1978
31	The EPS Enviro-Accounting Method	Steen & Ryding, 1992
32	Defense Priority Model (FY 1993 Version)	U.S. DOD, 1991
33	Hazardous Air Pollutants: Proposed Regulations Governing Constructed, Reconstructed and Modified Major Sources	EPA, 1993b (40 CFR 63)
34	Ranking System for Clean Water Act Section 307(a) List of Priority Pollutants	Poston & Prohammer, 1985; Cornaby et al, 1986

TABLE 1. List of Ranking and Scoring Systems Evaluated

System no. ^a	System Name or Title	Reference
35	CERCLA Section 102 Reportable Quantity Ranking Process	EMS, 1985; EPA, 1989c
36	The Source Category Ranking System	Radian Corp., 1990
37	Sax Toxicity Ratings (or Hazard Index)	Sax & Lewis, 1989
38	Examination of the Severity of Toxic Effects and Recommendations of a Systematic Approach to Rank Adverse Effects	Environ 1986
39	Screening Procedure for Chemicals of Importance to the Office of Water	EPA, 1986
40	Measuring Air Quality: The New Pollutants Standards Index	EPA, 1978
41	Ranking the Relative Hazards of Industrial Discharges to POTWs and Surface Waters	Abt Assoc., 1991
42	Targeting Pollution Prevention Opportunities Using the 1988 TRI	ICF, 1990
43	EPA Design for the Environment Program Use Cluster Scoring System (also called: Chemical Use Clusters Scoring Methodology)	EPA, 1993a
44	Screening Methodology for Pollution Prevention Targeting	EPA (date unknown)
45	Toxic Chemical Release Inventory Risk Screening Guide	EPA, 1989a
46	TSCA's TRI Chemical Risk Assessment Pre-Screening Methodology	EPA (date unknown)
47	Priority Setting of Existing Chemicals ("Schmallenberg")	Weiss et al., 1988
48	Multi-Media Environmental Pollutant Assessment System (MEPAS), formerly the Remedial Action Priority System (RAPS)	Whelan et al., 1987; Droppo et al., 1989; Strenge et al., 1989; Whelan et al., 1992
49	Canadian Accelerated Reduction/Elimination of Toxics (ARETS) Scoring Protocol	CLC, 1992; Canadian ARET, 1993
50	Risk Assessment Guidance under CERCLA, screening chemicals of potential concern	EPA, 1989d

TABLE 1. List of Ranking and Scoring Systems Evaluated

System no. ^a	System Name or Title	Reference
51	EC Proposal for Priority Setting of Existing Chemical Substances (Draft)	van der Zandt & van Leeuwen, 1992

(a) System numbers are used as a shorthand method of tracking the systems. They were based on a preliminary alphabetical list of references, but at this time are essentially an arbitrarily assigned number.

- *The EPS Enviro-Accounting Method* (Steen & Ryding, 1992): developed for life cycle impact assessment;
- *Defense Priority Model* (U.S. DOD, 1991): a site ranking system;
- *Examination of the Severity of Toxic Effects* (Environ Corp., 1986): not chemical specific;
- *Ranking the Relative Hazards of Industrial Discharges to POTWs and Surface Waters* (Abt Assoc., 1991): a site ranking system;
- *Targeting Pollution Prevention Opportunities Using the 1988 TRI* (ICF, 1990): a site ranking system; and
- *Multi-media Environmental Pollutant Assessment System (MEPAS)* (Whelan et. al., 1987; Droppo et. al., 1989; Strenge et. al., 1989; Whelan et. al., 1992): a site ranking system.

For the sake of completeness, and to illustrate the diversity among what are called risk ranking systems, these thirteen systems are also summarized in Appendix A.

2.2 DETAILED DESCRIPTION OF SYSTEMS

Descriptions of the fifty-one systems have been distilled into two-page summaries (Appendix A) that include the following information:

- system name or title;
- publication references;
- the intended user of the system;
- the purpose or application;
- chemicals addressed or used for demonstration;
- summary of method or algorithm;
- an outline of the criteria, subcriteria and endpoints used; and
- data selection approach.

Several other surveys of existing (primarily *chemical*) ranking and scoring systems have been identified:

- Waters et. al. (1993) describes seventeen ranking and scoring systems, including nine methods for ranking existing sites and eight "various chemical and substance ranking methodologies";
- Foran and Glenn (1993) analyze eight "existing chemical scoring systems" in detail, and include summary tables of effects criteria, endpoints, and scoring methods for the screening systems analyzed;

- ICF (1993) provides detailed summaries and comparisons of five chemical scoring systems with brief descriptions of fifteen additional systems in a bibliography;
- Abt Associates, Inc. (1992) summarizes, in some detail, twenty-one U.S. Environmental Protection Agency (EPA) ranking systems. An additional thirteen "ranking and indexing efforts" from outside of the EPA are described briefly. All of the systems surveyed make use of TRI data;
- The Organization for Economic Cooperation and Development (OECD, 1986) describes fifteen ranking and scoring systems in some detail and lists an additional fifty "known priority ranking systems" by system name, developer, and intended user of the system. Full references for the fifty systems were not included;
- Environ Corp. (1986) describes thirty-four "chemical ranking schemes", including eleven from the EPA, eight from other federal agencies, four state ranking schemes, two "degree of hazard" ranking schemes, three from international agencies, two "other ranking schemes", and four carcinogen ranking schemes; and
- Hushon and Kornreich (1984) summarize thirty-four "existing chemical scoring systems" in a table that includes the system title, purpose, developer(s), user(s), criteria used for scoring, algorithms used, substances scored, and references.

When all of the systems described by these authors are included, a total of 147 ranking and scoring systems have been identified. A complete listing of these is provided in Appendix B, with the system name, the developers and intended users of the system, the purpose or application of the system, and the system approach (where the information was available).

2.3 DESCRIPTION OF IMPORTANT ELEMENTS AND APPLICATIONS OF RANKING SYSTEMS

Important components of any chemical ranking and scoring system include:

- the purpose and application of the ranking and scoring system;
- the human health criteria and endpoints included;
- the criteria and endpoints included for environmental effects;
- whether measures of exposure are included;
- the data selection approach and handling of missing data; and
- the use of aggregation and weighing of different impacts.

Other issues addressed include major ecological impacts, chemical mixtures, application to life cycle assessment (LCA), and economic and social considerations. These are discussed below with examples of various approaches used by the evaluated systems.

2.3.1 Purpose and Application of Chemical Ranking and Scoring Systems

Chemical ranking and scoring systems are typically used as screening tools for a rapid assessment of relative chemical hazards. They consider the toxic effects of chemicals and some measure of exposure, but are not intended to serve the same purpose as a quantitative risk assessment.

The purpose or intended use of the ranking and scoring system affects all of the aspects of the system, including the human health and environmental impacts considered, the use of aggregation and weighing, and how missing data are handled. Chemical ranking and scoring systems have been developed for the broad purposes of regulatory action, priority setting, and impact evaluations. Each of these is discussed below.

Regulatory Action

The need for the regulation of chemicals of concern has been the driving force behind the development of many of the chemical ranking and scoring systems evaluated. Examples of this application are described below:

The *CERCLA Section 102 Reportable Quantity Ranking Process* (EMS, 1985; EPA, 1989) established reportable quantities (RQs) through a scoring process that takes into account environmental and human health hazards of chemicals on the CERCLA list. RQs are threshold quantities at which certain chemical releases must be reported to the EPA.

The *Michigan Critical Materials Register (CMR)* (MDNR, 1987) ranking process results in a list of chemicals that may threaten water quality in Michigan. Chemicals included in the register are considered to pose a high degree of environmental concern, and companies must report their use and discharge of these chemicals.

The *Ontario Ministry of the Environment (MOE) Candidate Substance List for Bans or Phase-outs* (Socha et. al., 1992) is a ranking system that identifies chemical substances for release reduction, bans, or phase-outs.

The *George Washington University (GWU) scoring system* (Foran and Glenn, 1993) is intended to serve as a tool for pollution prevention in the Great Lakes region through the identification of chemical substances for Sunsetting (bans or phase-outs) and other activities.

Priority Setting

Several ranking and scoring systems have been developed specifically for assessing chemical hazards for priority setting for non-regulatory purposes. For example:

The *EPA Design for the Environment Program (DfE) Use Cluster Scoring System* (EPA, 1993) is aimed at measuring potential health and environmental risks of chemicals that are used in industry clusters (i.e., certain common industrial processes) as a way of evaluating the benefits of substitutes for those chemicals. The relative risk scores are provided to industry as a means of encouraging the voluntary adoption of pollution prevention measures.

The *Wet Milieugevaarlijke Stoffen (WMS) Scoring System* (Könemann and Visser, 1988; Timmer et. al., 1988) was developed by the Directorate General for Environmental Protection of the Netherlands Ministry of Housing, Physical Planning, and the Environment. It was intended for use in industry, government, and academia for the selection of a limited number of chemicals as priorities for further investigation.

The *Agency for Toxic Substances and Disease Registry (ATSDR) System* (ATSDR, 1992): The Superfund Amendments and Reauthorization Act (SARA) of 1986 required the ATSDR to prepare a list, in order of priority, of the hazardous substances commonly found at National Priority List sites that pose the most significant potential human health threats. Substances on this priority list become candidates for the preparation of toxicological profile reports prepared by ATSDR.

The *University of Tennessee (UT) Center for Clean Products and Clean Technologies chemical ranking system* (Davis et. al., 1993) prioritizes chemicals for safe substitutes assessments. The system has also been used for impact evaluation, as discussed below, and for scoring of TRI releases from chemical production facilities.

Impact Evaluation

Other scoring systems have been developed to evaluate the potential impacts of chemical releases.

The *Toxics Release Inventory (TRI) Environmental Indicators Methodology* (Abt Assoc., 1992) is intended to evaluate TRI releases and derive a value to indicate the overall impacts of those releases by all facilities and to each environmental medium. Annual calculations of the indicator numbers allow a comparison of potential TRI impacts from year to year.

The *UT ranking system* (Davis et. al., 1993) has been modified to allow a comparative assessment of the potential hazard or risk posed by aggregate TRI chemical releases and transfers from an entire state or from facilities (Kincaid and Bartmess, 1993). The modified system was used to assess, on a relative basis, the potential impacts from chemical releases for the five states with greatest releases (Tennessee, Texas, Louisiana, Indiana, and Ohio) and is being used to score TRI releases from chemical production facilities.

The *New Pollutant Standards Index* (EPA, 1978) was developed for use by local and state air pollution control agencies to provide a simple method for reporting daily air pollutant concentrations and to inform the public about the potential health effects associated with these concentrations. The index is calculated from a measured air pollutant concentration and its national ambient air quality standard, and is characterized with terms such as "good" or "unhealthful".

Another aspect of impact assessment is within the field of life cycle assessment (LCA). The methods for conducting life cycle impact assessment are currently being developed (SETAC, 1993). Chemical ranking and scoring methods with a focus on impact assessment have the potential to be applied to this emerging technology. LCA is discussed further in section 2.3.7.

2.3.2 Human Health Criteria and Endpoints

In order to assess the potential or actual hazard associated with a particular chemical substance, chemical ranking and scoring systems may include criteria for scoring the toxicity of a chemical to terrestrial mammals, non-mammalian terrestrial species, aquatic organisms, and/or plants. The toxicity of chemicals to these organisms is used to evaluate potential effects to human health and the environment. Acute, subchronic and chronic mammalian toxicity data are often used as surrogates for human health effects. Ecological effects typically include acute, subchronic and chronic toxicity to terrestrial mammals, non-mammalian terrestrial species, aquatic organisms and plants. Although some ranking and scoring systems include bioaccumulation and/or persistence in the environmental effects category, these are discussed within the framework of this paper as factors affecting exposure.

Overview of Human Health Effects

Human health effects include many responses in humans caused by chemical exposure. Epidemiological data may be used to characterize health effects, but laboratory mammalian toxicity data are most often included in chemical ranking and scoring systems. The numbers and types of endpoints used to assess potential health effects vary significantly.

Criteria for evaluating health effects often include toxicity resulting from varying durations of exposure. Those effects resulting from acute, sub-chronic and chronic exposure are commonly included in chemical ranking and scoring systems. A brief description of each of these types of effects is listed below:

Acute Effects. Acute toxicity tests usually involve a single dose and a 14-day observation period. These tests are most commonly conducted on the mouse or rat, but other species, such as the dog or rabbit, may be used. Acute effects are often characterized by lethality, commonly reported as the mammalian median lethal dose or concentration (LD₅₀ or LC₅₀). This is the dose or concentration required to elicit lethality in 50% of the animals tested. Non-lethal acute effects are sometimes included as well. Skin or eye irritation and sensitization are examples of such effects. Routes of administration commonly preferred include oral, dermal and inhalation exposure. Some systems use data from other routes of exposure in the absence of preferred data.

Sub-chronic Effects. The most common test duration is 90 days for these tests, but the exposure time may vary. The main goal of these studies is to determine the no-observed-effect-level (NOEL) and to identify the specific organs affected after repeated doses of the test substance. These tests are usually conducted on the rat or the dog by an oral route of administration, but other species and routes may be used (Klaassen and Eaton, 1993).

Chronic Effects. These are long-term (longer than 3 months) studies designed to assess the cumulative toxicity of chemicals (Klaassen and Eaton, 1993). Chronic test data are often utilized in chemical scoring systems. Chronic health effects may be evaluated on the basis of a wide variety of toxicological endpoints. Carcinogenicity, mutagenicity, teratogenicity, reproductive toxicity, and other chronic toxic effects are often included in chemical scoring systems. General chronic effects may be characterized by RQs, reference doses (RfDs), threshold planning quantities (TPQs), the minimum effective dose (MED), or other measures.

A brief description of chronic effects often assessed in chemical ranking and scoring is provided below:

Carcinogenicity. Chemical carcinogens are substances which cause cancer in humans or other animals. Carcinogenicity is often evaluated on the basis of weight-of-evidence classifications developed by the EPA and/or strength-of-evidence classifications by the International Agency for Research on Cancer (IARC). Weight-of-evidence classification considers all long-term animal and relevant human studies as well as metabolism, pharmacokinetic and mechanistic information, structure-activity relationships (SARs) and other studies involving biochemical or physiological function. Strength-of-evidence classification may refer to the magnitude of conviction about the results of an experiment. For example, the National Toxicology Program (NTP) classifies each carcinogenic bioassay according to the amount and type of data from an experiment (Scala, 1993). The strength-of-evidence scheme developed by IARC excludes mechanistic information relating to the relevance to humans of bioassay data which show evidence of carcinogenesis in animals. This scheme does not consider all relevant data. For these reasons, the IARC classification scheme is considered to be based on strength-of-evidence rather than weight-of-evidence (Ashby et. al., 1990).

Sometimes one or both of the EPA and IARC classifications are combined with a measure of potency, usually the slope factor (q_1^*) or the ED_{10} in chemical ranking and scoring systems. Potency refers to the relationship between the dose and the response. The slope factor is an upper bound estimate of the probability of a response per unit intake of a chemical over a lifetime. It is used to estimate the probability of an individual developing cancer resulting from a lifetime exposure to a carcinogen (EPA 1989b). This is the potency factor normally used in EPA risk assessments. The ED_{10} is the estimated dose associated with a lifetime cancer risk increase of 10 percent. This is used in establishing RQs under CERCLA Section 102.

Mutagenic Effects. Mutagenesis occurs when chemicals cause changes in the genetic material which can be transmitted during cell division (Klaassen and Eaton, 1993). Several procedures, both *in vitro*

and *in vivo*, have been developed to test chemicals for possible mutagenicity. Tests for mutagenicity are often used to screen for potential carcinogenesis because the initiation of chemical carcinogenesis is believed to be a mutagenic occurrence (Klaassen and Eaton, 1993). Like carcinogenicity, mutagenicity is often evaluated according to weight-of-evidence classification which is sometimes combined with a measure of potency and/or severity. Mutagenic effects may also be of interest in terms of genetic alterations in the next generation.

Reproductive Toxicity. This refers to the occurrence of adverse effects, resulting from exposure to chemical or physical agents, on the male or female reproductive system. These may include effects on fertility, gestation, or lactation, among others (Klaassen and Eaton, 1993). These effects are usually scored according to some type of weight-of-evidence and/or potency and severity.

Teratogenic Effects. Teratogenicity occurs when exposure to some chemical or physical agent induces defects during the development of an organism from conception to birth (Klaassen and Eaton, 1993). Teratogenicity is sometimes considered separately from other reproductive effects. Likewise, these effects are often scored on the basis of weight-of-evidence and/or some measure of potency and/or severity.

Neurotoxicity. This includes adverse effects on the nervous system caused by chemical exposure which may be structural and/or functional and may include behavioral changes and learning disabilities.

Several chemical ranking systems include toxicity scoring criteria based not on specific toxicological endpoints, but on indices that combine or scale one or more toxicological endpoints, such as:

- RQ: A hazardous substance, under CERCLA, released in a quantity above this amount must be reported to the National Response Center, the State Emergency Response Commission and the Local Emergency Planning Committee;
- RfD: An estimated daily exposure to the human population that is likely to be without appreciable risk or adverse effects in a lifetime, expressed in mg/kg/day; and
- TPQ: The amount of an extremely hazardous substance present at a facility above which the emergency planning notification must be provided to the State Emergency Response Commission and the Local Emergency Planning Committee.

Endpoints Used for Human Health Effects

Member countries of the OECD have undertaken the investigation of approximately 600 high production volume (HPV) chemicals. A data set has been established which is necessary to provide an initial screening of health and environmental risks. The Screening Information Data Set (SIDS) is the minimum information needed for deciding whether or not a HPV chemical should be considered of low current concern, considered for further information gathering or testing, or a candidate for further review with possible action to reduce risks posed by the chemical (Auer, 1992). This represents an effort to standardize, on an international basis, the basic experimental data needed to characterize the potential health and environmental effects of chemicals.

The SIDS database (Auer, 1992) includes the following toxicological data:

- acute toxicity;
- repeated dose toxicity;
- genetic toxicity (two endpoints, generally point mutation and chromosomal aberrations); and
- reproductive toxicity (including fertility and developmental toxicity).

The endpoints used to score human health and ecological effects are presented in Appendix C and in Table 2. (The use of criteria and endpoints is discussed further in section 3.2.1.) Although most chemical ranking and scoring systems evaluated were designed with human health protection in mind, most of them do not clearly distinguish between endpoints included to assess human health from those used to characterize toxicity to other terrestrial mammals. Often a score for 'general toxicity' is determined. The manner in which systems evaluate health effects varies dramatically among the many different systems. As can be seen, the specific endpoints selected to represent health effects are numerous.

The *Nordic System* (Gjøs et. al., 1989) scores health effects based on data pertaining to acute mammalian toxicity, irritation, sensitization, general toxicity, genotoxicity, carcinogenicity and reproduction damage/teratogenicity.

The *EPA DfE Use Cluster Scoring System* (EPA, 1993) assigns a human health hazard ranking for chemicals. This system assigns a score on the basis of criteria such as the RfD, RQ, or the TPQ, among others. The carcinogenic properties of each chemical are also scored and the higher of the two scores is selected as the human health hazard potential score.

TABLE 2. Endpoints Used for Scoring Environmental and Human Health Effects

Endpoint	System Number for Method Using this Endpoint^a
Plant Toxicity	(8 systems)^b
phytotoxicity in higher plants (qualitative)	28
qualitative effects (algae)	28, 47
aquatic, terrestrial IC ₅₀	17
EC ₅₀	6, 22, 25, 47, 49
NOAEL/NOAEC	6, 25, 49
Aquatic Toxicity	(26 systems)
AWQC (acute or chronic)	1, 9, 42, 45
AALAC (ambient aquatic life advisory concentration)	1, 9
NOAEL	1, 6, 10, 25, 49
acute LC ₅₀	1, 2, 3, 4, 5, 6, 9, 10, 11, 12, 17, 19, 20, 22, 24, 25, 28, 29, 34, 35, 39, 49
acute LD ₅₀	17
acute EC ₅₀	3, 4, 10, 11, 12, 17, 19, 20, 22, 24, 28,
subchronic or chronic EC ₅₀	6, 25, 34, 49
subchronic or chronic MATC	6, 22, 25, 34, 49
NOEL/NOEC	20, 24, 29
aquatic toxicity RQ	41, 42
population growth rate (PGR) (algae)	5
lethality (LET) (algae)	5
acute and prolonged fish, Daphnia toxicity	47
Terrestrial (non-mammal) Toxicity	(8 systems)
subchronic or chronic effects	6
acute LC ₅₀	22
acute LD ₅₀	10, 22, 28
chronic NOAEL	10
severity and effective dose	22
subchronic or chronic NOEL	25, 49
acute toxicity (bird, earthworm)	47

TABLE 2. Endpoints Used for Scoring Environmental and Human Health Effects

Endpoint	System Number for Method Using this Endpoint^a
unspecified	11
Mammalian Toxicity^c	(19 systems)
acute LD ₅₀	2, 3, 4, 6, 7, 10, 11, 12, 17, 19, 20, 24, 25, 28, 29, 34, 35, 49
acute LC ₅₀	2, 3, 4, 6, 7, 11, 12, 17, 24, 25, 28, 35, 49
subacute NOEL/NEL	19, 20, 28
subchronic or chronic NOAEL	6
skin or eye irritation	19, 28
skin or eye sensitization	19, 28
severity and effective dose	24
subchronic or chronic NOEL	25, 49
subchronic or chronic LOAEL	17
subchronic or chronic LD ₁₀ and TD ₁₀	34
acute, subchronic, and chronic toxicity (rat)	47
General Ecological Effects	(7 systems)
ecological disruption	10
ecosystem recovery potential	23
ecological effects benchmarks	32
AWQC	43
aquatic toxicity RQ	43
team rank chemical category	43
ecotoxicity	44
ecological effects RQ	45
effect on fertility (mammals, birds, plants, etc)	47
Systemic (Non-carcinogenic) or General Health Effects	(30 systems)
acute LD ₅₀ and LC ₅₀	9, 29, 37
NOAEL and LOAEL	1, 43
LOEL	7
10-day health advisory (HA)	5
max. concentration level	8

TABLE 2. Endpoints Used for Scoring Environmental and Human Health Effects

Endpoint	System Number for Method Using this Endpoint^a
severity and effective dose	10
number of "highly toxic" chemicals	16
potency, relative potency	18, 23
other toxic effects	35
type of effect	35, 36, 37, 38
unspecified	46
chronic MED	1, 2, 35
RfD/RfC	1, 5, 7, 9, 23, 33, 42, 43, 45, 48, 50
chronic toxicity severity rating (R _v)	2
systemic mammalian toxicity	10
irritation	11, 47, 51
sensitization	11, 47, 51
general acute or chronic toxicity	5, 8, 11, 33, 36, 44, 51
chronic ADI	27, 32
RQ (acute, chronic, cancer)	33, 41, 42, 43, 45
NAAQS	40
TPQ	42, 43, 45
neurotoxicity	29, 44
Toxic Substances Control Act chemical scoring system category (TSCA CSSC)	43
HWQC	43
chemical category human toxicity estimate (CCHTE)	43
human health structure activity rank (HHSATR)	43
Carcinogenicity/Mutagenicity/Genotoxicity^c	(36 systems)
<u>carcinogenicity</u>	
weight, amount, or type of evidence; or probability	1, 2, 4, 6, 7, 9, 10, 17, 20, 22, 24, 25, 29, 33, 35, 39, 43, 44, 49
potency or slope factor (q ₁ * or CPF)	1, 9, 42, 43, 50
ED ₁₀	1, 9, 10, 33, 35
qualitative potency or effects	2, 3, 4, 23, 25, 34, 48, 49

TABLE 2. Endpoints Used for Scoring Environmental and Human Health Effects

Endpoint	System Number for Method Using this Endpoint^a
CERCLA hazard rank	7
carcinogen (yes or no)	11, 20, 47
URF (unit risk factor)	5, 7, 45
UCR	27
cancer potency RQ	41, 43
EEC guidance	28
unspecified endpoint	36, 51
number of carcinogens	16
<u>mutagenicity</u>	
weight, amount, or type of evidence	1, 4, 17, 22, 51
severity or dose	1
effects	3, 4, 34
EEC guidance	28
bacterial or short-term tests	19, 20
mutagen (yes or no)	29, 47
<u>genotoxicity</u>	
weight, amount, or type of evidence	1, 17, 24
severity or dose	1
genotoxin (yes or no)	11
Developmental/Reproductive Toxicity	(19 systems)
unspecified	36, 44
weight, amount, type of evidence	1, 10, 22, 24, 51
severity, dose	1, 10
teratogenic effects	6, 34
effective dose	6, 17, 22, 25, 49
LOEL	7
developmental or reproductive toxin (yes, no)	11, 29, 39, 47
teratogen, EEC guidance	28
teratogenesis and fetotoxicity	38

TABLE 2. Endpoints Used for Scoring Environmental and Human Health Effects

Endpoint	System Number for Method Using this Endpoint^a
Physical Hazard and Other Properties	(15 systems)
ignitability, flash point	2, 11, 22, 28, 35, 37
boiling point	2, 11, 28, 35, 51
reactivity, explosivity	2, 11, 22, 28, 35, 37
corrosivity	22
odor/taste and appearance	22
pH	22
molecular weight	28, 48
melting point	28
relative density	28
vapor pressure	28, 48, 51
surface tension	28
water solubility	28, 48
fat solubility	28
oxidizing properties	28
ecological risk reduction potential (ERRP)	43
human health risk reduction potential (HHRRP)	43
radionuclide dose factors	15, 48
welfare effects (recreation, aesthetics etc.)	23
gross alpha	16
Sax toxicity rating	14, 16
presence on CAA Amendments list	42
low Kow	51
other dangers not covered by specific criteria	12

(a) refer to Table 1 for the corresponding systems

(b) the number of systems listed in parentheses indicates how many of the evaluated systems consider some endpoint in the listed category

(c) criteria could apply to ecological and/or human receptors, depending on the system. Often, this distinction is not clear in the system documentation.

The *CERCLA HRS* (EPA, 1990) evaluates human health effects based on acute toxicity and two categories of chronic toxicity, which include cancer and non-cancer toxicological responses. The non-cancer score is based on the RfD, and the score for carcinogenicity is based on the q_1^* . The higher of the two chronic toxicity scores is the score assigned for human toxicity. Acute toxicity data are used to score human toxicity only in the absence of RfD and q_1^* data.

The *Ontario MOE Candidate Substances List for Bans or Phase-outs system* (Socha et. al., 1992) includes mammalian acute lethality, sublethal effects on mammals and chronic effects such as teratogenicity, genotoxicity/mutagenicity and carcinogenicity for evaluating human health effects.

Not only is there a wide variation of endpoints selected for assigning a score or scores in the area of human health effects, but the preference given to these endpoints may vary as well. For example, the *HRS* (EPA, 1990) prefers chronic toxicity data over acute data, whereas many other scoring systems include both. Often, the purpose or application of the system affects the choice of criteria to be considered.

Potency and Severity of Effects

Potency. The dose required to elicit a toxic effect is referred to as potency. Data regarding the potency of chemicals in test organisms are more frequently used to assess acute rather than chronic effects to terrestrial and aquatic plants and animals. For acute toxicity endpoints such as lethality, the dose required to elicit the effect (i.e. potency) is commonly reported (e.g. LC_{50}). Data regarding the potency of chemicals required to elicit chronic effects such as mutagenicity or carcinogenicity, however, are often limited.

Many ranking and scoring systems assign scores, particularly for carcinogenicity, based only on the weight of evidence that the chemical causes the effect in humans. Examples include:

- *Michigan CMR* (MDNR, 1987);
- *German Existing Chemicals of Environmental Relevance List I and II* (BUA; Behret, 1989a,b); and
- *The MOE Candidate Substance List for Bans or Phase-outs* (Socha et. al., 1992).

It is helpful to distinguish between a highly potent carcinogen and a moderately potent one, but the availability of potency data is limited. A few systems include both weight-of-evidence and potency data. For example, *GWU* (Foran and Glenn, 1993) assigns a score according to a matrix which includes a weight-of-evidence classification as well as the potency factor ($1/ED_{10}$) that has been used to assign reportable quantities for carcinogens by the CERCLA Section 102 program. In the *EPA DfE Use Cluster Scoring System* (EPA, 1993) weight-of-evidence is combined with the reportable quantity potency factor or the q_1^* . The *CERCLA HRS* (EPA, 1990) assigns values based on weight-of-evidence and the q_1^* or an estimate based on the ED_{10} .

Severity. Severity is a function of both the *type* and *magnitude* of the effect. The type of effect (e.g. a specific biochemical effect) reflects the mechanism of action as well as the target organ of a particular chemical. The magnitude of the effect (e.g. the percent change from normal of the biochemical effect) reflects the dose-response properties associated with a chemical (Environ, 1986).

Currently, there is no widely accepted method for incorporating severity into chemical ranking and scoring systems and many systems do not include measures of severity at all. This may yield misleading results. For example, two chemicals may have exactly the same NOEL of 0.3 mg/kg/day for neurotoxicity. Assigned scores based on the NOEL would be the same for these two chemicals, even though at similar doses one may cause a temporary narcotic effect and the other long-term irreversible brain damage. Below are examples of two systems that do include severity when scoring substances:

The *Toxic Substances Control Act (TSCA) System* (O'Bryan and Ross, 1988) includes severity in several parameters. For example, for nonlethal acute toxicity, the dose score is multiplied by the severity score to arrive at a final score in this category. The severity of effects are scored according to whether the effect is life-threatening or severe, moderately serious, mild, or no effects are observed at high doses.

The *Michigan CMR* (MDNR, 1987) also includes severity in several parameters. For example, a score for "other toxicity" (chronic or subchronic) to terrestrial animals includes severity ranging from adverse effects to severe effects. Examples of each effect classification are provided to guide decisions in response to the question of how severe is the effect. For example, "moderate effects" include effects such as degenerative or necrotic changes with no apparent decrement of organ functions; or reversible, slight changes in organ function.

2.3.3 Criteria and Endpoints for Environmental Effects

Overview of Environmental Effects

Ecological effects resulting from chemical exposure may occur in populations of organisms from many trophic levels. These include both terrestrial mammalian and non-mammalian species, aquatic organisms, and plants. Most ranking systems evaluate ecological effects through the use of toxicity test data. Typically, surrogate species are selected for use in the evaluation of the potential environmental hazards of chemicals.

When including toxicity information in a chemical ranking and scoring system, it is important to specify the following information regarding the endpoints to be considered (EPA, 1989d):

- organism tested or observed;
- nature of the effect;
- concentration or dose needed to produce the effect;
- duration of exposure needed to produce the effect; and

- environmental conditions under which the effects were observed.

Similar to tests used for evaluating human health effects, the durations for testing chemicals of ecological concern include acute, sub-chronic and/or chronic exposure periods. Observations include lethality as well as sub-lethal effects. Lethal doses directly disrupt important physiological functions and result in death. Sub-lethal toxicity may have long-term physiological or behavioral impacts on a population.

Terrestrial effects. Terrestrial organisms commonly considered by chemical ranking and scoring systems to be important receptors include mammals, non-mammals and plants. Most scoring systems do not make a distinction between mammalian toxicity and human health effects. At least two of the chemical ranking and scoring systems examined use the same endpoint for human health effects as was used to characterize terrestrial mammalian toxicity (rodent acute toxicity). Terrestrial non-mammalian data are usually derived from tests on avian species such as the mallard duck or ring-neck pheasant. Data for terrestrial plants are sometimes included, but such data are limited. Other organisms may be included as surrogates, but unfortunately, there is not a large data base of information regarding the effects of chemicals on most terrestrial organisms.

Aquatic effects. The aquatic receptors of interest in most chemical ranking and scoring systems include non-mammalian aquatic organisms and plants. The most common surrogates for evaluating the toxic potential of chemicals include fish, *Daphnia* and algae. There is a fairly large data base of information regarding the toxicity of chemicals to these organisms. The majority of available data are from short-term toxicity tests performed on these species, but in reality there is often greater concern regarding the effects of long-term exposure and effects. Additionally, the types of organisms most often tested are not necessarily those about which there is the most concern. Due to standardized test methods and data availability, however, it is reasonable to include these commonly tested organisms in chemical ranking and scoring systems.

The endpoints most frequently included in ranking and scoring systems for aquatic toxicity are the LC_{50} and the EC_{50} . The LC_{50} describes lethality and the EC_{50} describes the concentration at which there are observed effects in 50% of the test population. The effects may be behavioral or physiological and may indicate immobilization or changes in growth and reproduction, among others. Other endpoints, such as the no-observable-adverse-effect-level (NOAEL) or regulatory standards such as ambient water quality criteria (AWQC) may be included.

In the absence of data, there are over fifty high-quality quantitative structure-activity relationships (QSARs) for estimating biological effects in these three organisms (Clements, 1993). QSARs are discussed further in section 2.2.5.

Endpoints used for Environmental Effects

Endpoints used for environmental effects for each system are presented in Appendix C and are summarized in Table 2. (The use of criteria and endpoints is discussed further in section 3.2.1.) The following examples illustrate some of the types of data used to evaluate ecological effects:

The *Schmallenberg System* (Klein et. al., 1988; Weiss et. al., 1988) was developed by a group of French and German officials and scientists and uses many endpoints to assess ecological effects, including acute, subacute and chronic effects in algae, plants, earthworms, birds and fish.

The *GWU system* (Foran and Glenn, 1993) includes acute and chronic toxicity to aquatic organisms as well as terrestrial and avian species.

The *EPA Toxics Release Inventory Environmental Indicators Methodology* (Abt Assoc., 1992) scores ecological effects based on a matrix of aquatic toxicity and bioaccumulation. Aquatic toxicity is scored according to the LC₅₀, life cycle/chronic NOAEL, or other measures such as the Acute or Chronic Ambient Water Quality Criteria (AWQC). Bioconcentration is based on the water solubility, log K_{ow}, or bioconcentration factor (BCF).

The *EPA DfE Use Cluster Scoring System* (EPA, 1993) scores ecological hazard based on the AWQC (acute and chronic) or Aquatic Toxicity Reportable Quantities.

The *Michigan Critical Materials Register* (MDNR, 1987) scores acute and chronic effects on aquatic organisms (fish, invertebrates, amphibians), acute and chronic effects on terrestrial animals, and plants.

The SIDS database (Auer, 1992) includes the following ecotoxicological data:

- acute toxicity to fish;
- acute toxicity to daphnids;
- acute toxicity to algae; and
- terrestrial toxicity (if significant exposure in terrestrial environment or if aquatic toxicity testing is not possible).

2.3.4 Measures of Exposure

As stated earlier, chemical ranking and scoring systems span a wide range of complexity. The simplest level is to use toxicity data alone. When exposure is considered, the systems become more complex. In fact, the level of complexity is primarily a function of the degree of sophistication used to estimate exposure. In a quantitative risk assessment, a dose to each receptor from each potential pathway is estimated on a site-specific basis using measured or modeled concentrations for each potentially contaminated environmental medium. This approach represents a high degree of sophistication and is not used in most chemical ranking and scoring systems. In a simpler approach, production or use volume or TRI emission data are often used as surrogates for dose. An intermediate level of

sophistication might employ a multimedia fate and transport model to estimate the distribution of chemicals in the environment based on release data.

Many factors affect the potential for exposure to a chemical. These factors generally relate to properties of the chemical, characteristics of the human or environmental receptors of concern, amount of the chemical available for exposure, and the behavior (fate, transport) of the chemical in the environment. Appendix C and Table 3 present the measures of exposure used by the ranking systems evaluated. This is also discussed further in section 3.2.1. Examples of the use of these various measures for exposure follow.

The *WMS Scoring System* (Könemann and Visser, 1988; Timmer et. al., 1988) assigns scores for environmental exposure according to use volume, percentage release to the environment, degradation in air, soil and/or water, relative occurrence in these media and bioconcentration. Exposure via products is also scored, and this includes use patterns, exposure frequency and intensity of exposure.

The *GWU system* (Foran and Glenn, 1993) assesses exposure according to the bioaccumulation, persistence, and release or production volume.

The *Michigan CMR* (MDNR, 1987) scores chemical exposure according to bioaccumulation, persistence, and a few physicochemical properties such as flammability, reactivity, and corrosivity.

The *Effluent Monitoring Priority Pollutants List (EMPPPL)* (Environment Ontario, 1987, 1988) includes environmental persistence, bioaccumulation and detection in the environment.

The *German Beratergremium für Umwelrelevante Altstoffe (BUA) System* (Behret, 1989a,b) includes bioaccumulation, persistence and production volume.

The *EPA Toxics Release Inventory Environmental Indicators Methodology* (Abt Assoc., 1992) uses facility-specific data and generic fate, transport, and exposure models to estimate a "surrogate dose", or the amount of chemical an individual might be exposed to. A separate evaluation is conducted for each release pathway allowing comparisons across media. The level of uncertainty is included in the scoring for exposure. Exposure of aquatic life is obtained by estimates of the ambient water concentration.

Table 3. Endpoints Used for Scoring Exposure

Endpoint	System Number for Method Using this Endpoint^a
Degradation or Transformation Potential	(25 Systems)^b
degradability in air, water, soil and/or sediment ($t_{1/2}$)	3, 4, 6, 9, 10, 20, 21, 22, 24, 25, 34, 48, 49
biodegradation	8, 19, 47
transformation	24, 45
oxidation	34
photolysis	9, 35, 47
hydrolysis	8, 9, 29, 34, 35
BOD 1/2 life, BOD ₅ /COD, BOD ₂₈ , BOD/ThOD	11, 12, 28, 29, 35
volatilization half-life	9
log K_{ow}	9, 43
qualitative degree of persistence/ expert judgement	16, 43
source existence (yrs)	16
EPA persistence rating scale	14
Mobility/Partitioning	(30 Systems)
adsorption (K_d , K_{oc})	8, 21, 34, 45
water solubility	1, 9, 11, 21
log K_{ow} (P , P_{ow})	1, 3, 4, 6, 9, 11, 12, 19, 20, 21, 22, 24, 25, 28, 34, 43, 47, 49, 51
BCF	1, 3, 4, 6, 9, 12, 17, 20, 22, 24, 25, 29, 39, 43, 49
BAF (some systems consider BCF=BAF)	10, 17, 22, 34
molecular weight (regarding bioconcentration)	11, 51
bioconcentration (yes/no)	45
vapor pressure	21
initial partitioning/transport	19, 24, 45, 47, 48, 51
evaporation	22
volatilization	9, 45
site-specific characteristics	16, 32
leaching potential	21
environmental transfer factors (e.g. soil to plants)	48

Table 3. Endpoints Used for Scoring Exposure

Endpoint	System Number for Method Using this Endpoint ^a
environmental spread/degree of mobility (qualitative)	28, 16
Estimated Dose, Environmental Occurrence, Concentration, or Releases (37 Systems)	
<u>Dose estimate</u>	
human exposure potential (mg/kg/day)	1
theoretical daily dose	2
estimated daily intake	32
<u>chemical concentration, frequency or occurrence</u>	
exposure to contaminant or medium containing contaminant	2
exposure via migration pathway	9
projected levels in various media/compartments	19, 46, 47,
estimated ambient concentrations	1, 7, 23
frequency of occurrence/application	2, 14, 21, 23, 34
occurrence in air/soil/water	3, 4, 20, 27, 39
measured concentrations	15, 26, 32, 40, 50
concentration of chemical introduced	21
<u>Use, production amounts, release or emission data</u>	
number of sites of discharge/use	34, 43
emission source data	36, 45
emissions estimates (rate,type,release height, temp.,flow rate,vent diameter)	36
TRI releases/transfers	5, 29, 42, 46
national emissions data (various sources)	7
release to environment (annual)	10, 24, 34, 41, 43, 44, 45
production volume	10, 11, 12, 19, 21, 24, 44, 51
import volume	11, 12, 51
waste volume	16
use volume	10, 20, 43
quantity on the market	28
release reduction potential	43

Table 3. Endpoints Used for Scoring Exposure

Endpoint	System Number for Method Using this Endpoint ^a
Exposure Frequency or Intensity (Receptor Characteristics) (11 Systems)	
use pattern	19, 20, 51
population size/number potentially exposed	1, 23, 24, 27, 28, 32, 43
land use	32
distance from site	32
presence of critical environments	32
intensity of exposure	20, 23, 24
length of exposure	23
probability of exposure	24
frequency of exposure	20, 23
plurality of exposure	28
geographical extent of exposure (ecological)	23

(a) refer to Table 1 for the corresponding systems

(b) the number of systems listed in parentheses indicates how many of the evaluated systems consider some endpoint in the listed category

The SIDS database (Auer, 1992) includes the following data to assess sources and levels of exposure:

- production ranges (metric tons per annum);
- categories and types of use;

and environmental fate and pathways:

- aerobic biodegradability;
- abiotic degradability (hydrolysis and photodegradation by estimation); and
- estimates of environmental fate, pathways and concentrations (including Henry's Law constant, aerosolization, volatilization, soil adsorption and desorption).

2.3.5 Missing Data, Data Selection Approach

Due to the extensive time and resources required to perform thorough testing of each of the thousands of chemicals in commerce, the available data necessary for complete assessment of the hazards of these chemicals are limited. Therefore, chemical ranking and scoring systems must somehow work in the absence of complete data sets for every chemical. An overview of the approaches for assigning values to criteria or endpoints used by the ranking systems evaluated can be found in Appendix C. Four general approaches were identified:

1. Assign one endpoint per criteria being assessed and estimate missing data (e.g. use oral LD₅₀ for rats for acute human toxicity criteria). In the *UT system* (Davis et. al., 1993) there is only one endpoint specified for each criterion, and missing data are estimated using QSARs, surrogate chemicals, or other structure-activity relationships (SARs).

2. Choose data from a hierarchy of endpoints, listed in order of preference, based on data quality, appropriateness of test, etc. The *Chemical Use Cluster Scoring Methodology* (EPA, 1993) uses a data hierarchy based on data quality for scoring the toxicity components. Preference is given to high quality data as specifically defined in the document. Data of medium or low quality may be used in the absence of high quality data. When scoring non-carcinogens, the RfD and RQ are classified as "high quality" data whereas chronic and sub-chronic NOAELs are "medium quality". If multiple data are available within the high quality classification, then the data yielding the highest score (i.e. most conservative or health-protective) is used.

3. Choose the most conservative value from a pool of different endpoints. The *GWU System* (Foran and Glenn, 1993) is an example of a system where a group of endpoints could be considered for a given criterion, and the data yielding the most conservative (health-protective) result are chosen. If multiple data are available for a particular criterion (e.g. acute mammalian toxicity), then the data resulting in the highest score are used. One drawback that should be noted for such a system is that it does not encourage further testing of compounds, because it is unlikely that a score for a chemical can be lowered by filling data gaps.

4. Assign cutoff (or trigger) values to a large number of criteria and select a chemical if one or a specified number of the criteria are met. Several systems designed to select chemicals for regulatory action or for further study do not provide an overall score for a chemical. Rather, a chemical is selected if it meets certain criteria. Examples of this type of system include the *Michigan CMR* (MDNR, 1987), where a chemical is selected for regulatory action if it receives a certain score; and the *Candidate Substance List for Bans or Phase-Outs* (Socha et. al., 1992), where certain cut-off values are used to determine if a substance is to be considered as "persistent", "bioaccumulative" and/or "toxic". The primary list consists of substances considered to be all three of these.

For approaches where required data are not available, it is necessary to somehow estimate the missing data. SARs, QSARs, default values, and/or ad hoc expert judgement have been used in the absence of experimental data. SARs and QSARs are often used in many chemical scoring and ranking systems to estimate chemical properties for which data are lacking. SARs qualitatively relate known data from a chemical with similar molecular or molecular fragment structure, and therefore similar expected biological activity or other properties, to the chemical with missing data. QSARs are obtained primarily through regression analysis which results in mathematical equations representing correlations. Chemical structure or physicochemical properties, such as molecular weight and octanol-water partitioning coefficients, are typically compared with chemical toxicity or fate (Hermans, 1989). The limitations of these methods must be weighed against the impact of missing data on the results of a chemical ranking or scoring system.

Examples of systems that use SARs QSARs for predicting the effects of chemical exposure are discussed below.

The *Schmallenberg system* (Klein et. al., 1988; Weiss et. al., 1988) defines the minimum data set required for priority-setting. Data on mutagenesis and acute aquatic toxicity are essential and may be estimated by QSARs when necessary. Other important missing data can be estimated from QSARs, but any information, even if it is semi-quantitative in nature is considered.

The *German (BUA) scoring system* (Behret, 1989a,b) assigns negative scores where data are unavailable. These scores are based largely on SARs. The use of negative scores occurred for only a few chemicals evaluated by this system.

The *UT system* (Davis et. al., 1993) requires a quantitative assessment for many of the endpoints included in the algorithm. This is obtainable through the use of expert judgement, SARs or QSARs for estimation.

The *EPA DfE Use Cluster System* (EPA, 1993) allows a score for human health hazard potential to be assigned by a structure activity team. Ecological hazard potential may be scored according to QSAR concentrations of concern.

Another approach to filling data gaps results in the assignment of default values in the absence of data or reliable QSARs or SARs. The *European Communities (EC) system* (van de Zandt and van Leeuwen, 1992) uses default values and flags the data to identify when default values are used.

A few systems use expert judgement to give qualitative or semi-quantitative scores to chemicals (e.g. high, med., low). An example of a system using this approach is the *EPA Unfinished Business Report* (Morgenstern et. al., 1987). The project was described as being based on "informed judgement". Quantitative information available within the EPA was collected on the various environmental problems addressed, but because the qualitative judgement was extensive, the study results were not considered to be scientifically "reproducible".

2.3.6 Aggregation and Weighing

The majority of the chemical ranking and scoring systems reviewed include human health and environmental effects as well as exposure parameters. The manner in which these parameters are combined to give an overall ranking or risk categorization varies tremendously and significantly affects the final result. Scores may be added, multiplied, divided or not combined at all. Scores may be weighted differently for human versus environmental effects (e.g. *Screening Methodology for Pollution Prevention Targeting*, EPA, date unknown), acute versus chronic effects (e.g. EPA, 1990) or exposure via water versus exposure via air (e.g. Klein et. al., 1988; Weiss et. al., 1988). Examples of various aggregation and weighing methods follow.

Chemical selection in the *Michigan CMR* (MDNR, 1987) is based on combinations of scores in the various parameters. For example, selection for the Register may occur if a chemical scores a "5" in two or more criteria. These criteria include all of the health, environmental and exposure parameters where none are considered more important than the others.

The Nordic system (Gjøs et. al., 1989) selects chemicals with a score of "high" in an effects category (health or environmental) regardless of the exposure score or chemicals with an effect score of "medium" and an exposure score of "high".

The *WMS Scoring System* (Könemann and Visser, 1988; Timmer et. al., 1988) calculates ten scores for ten different combinations of exposure and effects. Examples of such combinations include 1) Exposure via air *and* general toxicity for mammals, carcinogenicity, and mutagenicity; and 2) Exposure via products *and* general toxicity for mammals, carcinogenicity, and mutagenicity.

In the *MOE Candidate Substance List for Bans and Phase-outs* (Socha et. al., 1992) substances are selected on the basis of combinations of scores in toxicity, persistence and bioaccumulation. For example, a substance is placed on the primary list if it scores a "10" in any one of the seven toxicity categories *and* has a persistence of a half-life of 50 days *and* it has a bioconcentration factor of more than 500.

In the *ATSDR Priority List* (ATSDR, 1992) scores are assigned for each of three criteria: frequency of detection at National Priorities List (NPL) sites, toxicity, and potential for human exposure. The total score is simply the sum of the scores assigned for each of these parameters.

Once scores are obtained for each of the various exposure and effects parameters, chemicals may be placed into categories, such as selected or non-selected chemicals, or they may be ranked in order of priority.

Categorization may be accomplished by determining an overall concern score of high, medium or low, or by selecting chemicals according to combinations of numerical scores in the exposure and effects categories. For example:

The *Schmallenberg system* (Klein et. al., 1988; Weiss et. al., 1988) scores chemicals and places them in one of three categories: immediate action, observation, or no action.

The *GWU Method* (Foran and Glenn, 1993) assigns scores of high, medium or low in several toxicity categories, release and production, persistence, and bioaccumulation. A chemical is selected as a candidate for Sunsetting if 1) it scores "high" in any toxicity category and "high" in release and production (excluding pesticides) or 2) it scores "high" in any acute or chronic toxicity category and "high" in persistence or bioaccumulation (including pesticides).

The *WMS Scoring System* (Könemann and Visser, 1988; Timmer et. al., 1988) categorizes chemicals into three areas of priority by plotting an image point on a two-dimensional diagram. The image point is determined after each chemical has been assigned a rank for exposure and effects.

The *MOE Candidate Substances List for Bans or Phase-outs* (Socha et. al., 1992) assigns numerical scores for environmental transport, persistence and bioaccumulation as well as seven categories for toxicity. Specific combinations of scores in these categories result in the inclusion of the chemical on the primary or secondary list for appropriate action.

The scoring systems which are designed to rank chemicals often include an algorithm for combining individual scores for toxicity and exposure in order to determine an overall score which represents a relative indicator of hazard for each chemical. These ranking systems then prioritize chemicals in order of their potential hazard to human and environmental health. For example:

The *UT Method* (Davis et. al., 1993) uses an algorithm which includes both additive and multiplicative parameters to determine an overall hazard value for each chemical. The chemical rank indicates its hazard relative to the other chemicals that are scored.

The *ATSDR Method* (ATSDR, 1992) places 275 substances in order of hazard potential based on the total score. The total score is obtained by the following formula:

$$\text{Total score} = \text{NPL frequency} + \text{Toxicity} + \text{Potential for human exposure}$$

The *EPA DfE Use Cluster Scoring System* (EPA, 1993) arrives at an overall chemical score as follows:

$$\text{Chemical score} = \text{Human risk reduction potential} + \text{Ecological risk reduction potential} + \text{EPA interest level}$$

The average chemical score for the entire cluster is then added to the cluster score for pollution prevention potential to give an overall cluster score which forms the basis for prioritizing clusters.

Whether a method results in categorization or ranking of chemical substances will depend on the specific goals of the system. Systems developed for regulatory objectives frequently categorize chemicals by selecting those that pose the greatest potential threat for regulation and/or monitoring. Systems for prioritization for other purposes may rank chemicals in order to focus research or other activities on those chemicals highest on the list.

2.3.7 Other Issues

Other issues that can be considered in chemical ranking and scoring include:

- indirect ecological impacts, such as greenhouse gases, acid rain, eutrophication, and stratospheric ozone depletion;
- effect of chemical mixtures;
- application to life cycle assessment, specifically, life cycle impact assessment; and
- social or economic impacts.

Indirect Ecological Impacts

The release of chemicals into the environment can have direct effects on human health and the environment, but indirect effects may result as well. Certain substances are known to affect abiotic components of the environment and ultimately result in large scale ecological disruption. For example, a few substances (e.g. carbon dioxide) are considered "greenhouse gases" because they are believed to have the potential to change the global climate. Other examples of chemicals that may cause these indirect impacts are sulfur and nitrous oxides, which contribute to acid rain, chlorofluorocarbons (CFCs), which contribute to stratospheric ozone depletion, and nitrous oxides and volatile organic compounds (VOCs) which contribute to tropospheric (low atmosphere) ozone formation. Another example is eutrophication of surface waters caused by excess nutrient inputs.

Most chemical ranking and scoring systems do not include these types of indirect impacts as scoring criteria. The hazards posed by substances causing these effects have not been quantified in such manner that they can be easily included. This is not to say that the risks are not significant or that they should be ignored in chemical scoring. Ayres (1993), in an analysis of the relationship between natural resources and economic growth, concludes by asserting that "those activities that are most likely to interfere with natural climatological and nutrient cycling processes" should be of primary importance to both economic development and environmental protection policy.

Foran and Glenn (1993) list several reasons why there is no mechanism currently available for predicting or quantifying large scale ecological disruption. First, due in part to a lack of understanding of how hazardous compounds affect the structure and function of ecosystems it is difficult to predict the adverse impacts at an ecosystem or global level. Additionally, hazardous substances may interact with components of ecosystems, but due to a lack of understanding of the fate and transport characteristics of these substances, their effects on ecosystems are difficult to predict. It is important to have information about the use and release patterns of a chemical in order to predict large-scale ecological disruption, but this information is not generally available when a chemical is created and tends to change over time.

The *GWU system* (Foran and Glenn, 1993) considers evidence for ecological disruption when selecting candidates for Sunsetting. The data available are mostly derived from studies of effects in natural ecosystems, but other chemical-specific studies may be considered as well. Laboratory studies or theoretical evaluations that suggest ecological disruption potential must be supported by predicted use and release patterns of the substance.

The *TRI Environmental Indicators Methodology* (Abt Assoc., 1992) has not yet included scoring criteria for these effects, but it notes a major EPA project aimed at determining the risks associated with CFCs and their alternatives. The model is complicated but could perhaps be used to evaluate the risks posed by the emissions of these substances. Methods are also suggested for developing an indicator for tropospheric ozone. This would involve identifying all VOCs reported in the TRI that are considered to be ozone precursors and to sum the releases of these compounds from each facility.

Alternatively, policy changes which would require reporting of VOCs and nitrous oxides (NO_x) as a group would help in the development of an indicator. The developers of the system are also examining models designed to determine the exposure resulting from particle deposition to evaluate the risks posed by airborne chemicals which are deposited into other media, such as surface water.

Because chemical ranking and scoring systems have focused on direct toxicity to humans and other organisms in the environment, indirect, large-scale impacts such as those discussed above have rarely been taken into account. Impact assessment approaches have been developed, and the challenge will be to incorporate these with the direct toxicological impacts. The field of life cycle assessment, discussed below in section 2.3.7.3 is one place where this challenge is being addressed.

Effect of Chemical Mixtures

The majority of toxicity tests are conducted for single chemicals, usually at high doses. Organisms in the environment, however, are more typically exposed to low levels of several chemicals rather than to one chemical at a time. Chemicals may interact with one another to elicit effects that are different from the combined effects of the individual chemicals. The effects may be additive, where the total effects approximately equal the sum of the individual chemical effects; synergistic, where the total effects are greater than the additive effects; or antagonistic, where the total effects are less than the additive effects. Other types of chemical interaction can also occur that result in unanticipated effects. There are limited data regarding the effects of chemical mixtures. One data source developed by the EPA (MIXTOX) contains summary information from and literature citations on studies of toxicological interactions, primarily for binary mixtures (EPA, 1992).

The chemical ranking and scoring systems evaluated do not consider the effects of chemical mixtures. Because they are not usually site-specific, they are designed to evaluate the general potential harm from substances on a chemical by chemical basis without regard to the effects of mixtures. It is difficult to predict the effect of chemical mixtures on humans and environment. If incorporation of mixture toxicity into chemical ranking and scoring systems is a goal, however, there is some evidence to suggest that real world situations involving many organic chemicals are likely to result in approximate additive toxicity (McCarty and MacKay, 1993).

Life Cycle Assessment

Recently, much attention has been focused on the methodology of LCA, a holistic approach to evaluating the human health and environmental burdens associated with a product or process life cycle. LCAs are tools for evaluating the effects on the environment associated with products, processes or activities (SETAC, 1993). A full LCA includes a quantitative inventory of resource and energy inputs and pollutant outputs and some form of impact assessment. A life cycle impact assessment is a process for assessing the potential and actual effects of environmental loadings identified in the inventory (SETAC, 1993). Chemical ranking and scoring could become an essential element in the development of tools for assessing the impacts to health and the environment from chemical releases throughout the life cycle of products.

LCA has several uses, although its uses are more limited if some form of impact assessment is not included. LCA can be used for internal product improvements, for designing new products, for setting public policy on products and materials, and for environmental labeling. Clearly, the different uses of LCA create different needs for impact assessment. An LCA used for internal product improvement, for example, might simply use the inventory component and operate on a "less-is-best" approach. An LCA used for setting public policy on materials or products would need to include some framework for assessing and comparing the significance of environmental releases and resource and energy use of the different products and materials being compared.

One of the systems evaluated was developed for life cycle impact assessment. The *EPS-Enviro-Accounting Method* (Steen and Ryding, 1992) was developed to assess the health and ecological effects associated with the entire life-cycle of a product, process, or activity. The main objective of the *EPS Method* is to provide one overall economic measure of resource depletion and potential health and environmental impacts throughout a life cycle.

In this system, values are assigned to impacts on the environment in terms of five 'safe-guard subjects' (human health, biodiversity, production, resources & aesthetic values) according to willingness to pay to restore them to normal status. Emissions, use of resources, and other human activities are then valued according to their estimated contribution to the changes in these safeguard subjects. The information on environmental impacts originates from LCA-based inventory of the materials/process under study.

Economic Considerations

Chemical ranking and scoring systems are usually designed to be fairly quick and simple, limiting the time and resources required for assessment to a minimum. It is usually beyond the scope of these systems to determine potential economic impacts caused by releases of a particular chemical.

One system that does include economic considerations is the *EPS Enviro-Accounting system* (Steen and Ryding, 1992) which is intended for life cycle impact assessment. Impacts on five safeguard subjects are valued on a relative scale which is based on the willingness to pay for avoiding undesired effects. Environmental load units (ELUs) which are standard monetary values, are assigned accordingly to score impacts. As another example, the *Unfinished Business Report* (Morgenstern et. al., 1987) considers monetary estimates of damage when categorizing environmental problems as they relate to welfare effects.

Social Values

Economic impacts can be included under the broader category of social welfare or social values. SETAC (1993, p. 20) outlines a variety of "social welfare impact categories"; some of these issues or impacts possibly relevant to chemical ranking and scoring include:

- demographic impacts, including fertility and mortality, morbidity, migration;
- sociopolitical impacts, including legal, governmental;
- social impacts, including quality of life;
- community impacts, including land use, physical appearance of community, community satisfaction;
- sociocultural impacts, including social justice, aesthetics, environmental values; and
- psychosocial impacts, including anxiety or stress.

Only a few systems include social considerations, per se, in the scoring or selection criteria. One example, The *Michigan Critical Materials Register* (MDNR, 1987) includes aesthetic considerations such as taste, odor and appearance as criteria for scoring chemicals within one parameter. The *Unfinished Business Report* (Morgenstern et. al., 1987), although not specifically a chemical ranking system, ranks issues related to social welfare such as recreation, losses in aesthetics and non-user values. The *EPS Enviro-Accounting method* (Steen and Ryding, 1992) includes aesthetic values as one of the five safeguard subjects for which impacts are evaluated.

SECTION 3: DISCUSSION

3.1 RISK ASSESSMENT PRINCIPLES APPLIED TO CHEMICAL RANKING AND SCORING

Chemical ranking and scoring systems are typically intended to be fairly simple and quick methods for determining the health and environmental hazards posed by the use and release of chemical substances. Although not intended to provide a quantitative assessment of risk, the majority of the systems reviewed do rely on the basic principles of risk assessment for chemical ranking and scoring.

Chemical risk is a product of both toxicity and exposure. Most chemical ranking and scoring systems include measures of both toxicity and exposure and, in this way, are similar to quantitative risk assessment methods. The major difference is the extent to which the exposure assessment is performed.

Exposure assessment in a quantitative risk assessment involves an analysis of contaminant releases, identification of exposed populations, identification of all potential exposure pathways, and estimation of exposure point concentrations and contaminant intakes. The exposure assessment results in an estimate of the magnitude, frequency and duration of actual or potential human exposures through various pathways expressed as a total dose. None of the chemical ranking and scoring systems reviewed include a detailed site-specific quantitative risk assessment, although the *(TRI) Environmental Indicators Methodology* (Abt Assoc., 1992) approaches this level of detail.

The system developed by Jones et. al. (1988) is one of the few systems that does not include any exposure assessment. The stated purpose of the system, however, is to estimate only the relative toxicological potency for hazardous substances rather than overall hazard. Another example is the method developed by the EPA (1993b) for demonstrating the relative hazard of emissions under section 112(g) of the Clean Air Act. As required, offsetting emission decreases must be considered "more hazardous" than emission increases. For categorizing emissions, toxicity criteria alone are considered. The Sax Toxicity Ratings (Sax and Lewis, 1989) is also based only on chemical properties posing a physical hazard and toxicological characteristics. The other systems reviewed include some measure of exposure, although the endpoints used to characterize exposure vary significantly.

The final step in a baseline risk assessment is risk characterization. Here, chemical toxicity data are combined with potential exposure levels for the receptors of interest at a site to arrive at a quantitative estimate of the risk that receptors will suffer adverse effects. Such site-specific characterization is not generally performed in chemical ranking and scoring, but most of the systems reviewed do combine toxicity and exposure in some manner to score, select, or prioritize chemicals. As discussed in Section 2.3.6, the manner in which toxicity and exposure are combined for an overall assessment also varies significantly.

3.2 SIMILARITIES AND DIFFERENCES AMONG SYSTEMS REVIEWED

3.2.1 Most Common Effects and Exposure Endpoints Used

The effects and exposure categories specified by the systems were difficult to compare. They were divided, as best could be done, into categories of commonly recognized criteria for presentation in Tables 2 and 4 and in Appendix C. More information is available in Appendix A, where the criteria, subcriteria, and endpoints as defined by each system are outlined. Some criteria and endpoints were commonly used in many systems while others were unique to a particular system. The most commonly listed endpoints for major classes of effects criteria include:

- *carcinogenicity, mutagenicity, genotoxicity*, most often characterized by the weight, type, or amount of evidence that a chemical would elicit that effect;
- *systemic (non-carcinogenic) or general health effects*, most commonly characterized by chronic or subchronic Rfd or RfC values;
- *aquatic toxicity*, most often quantified by acute LC₅₀ and EC₅₀ data;
- *mammalian toxicity*, most often quantified by acute LD₅₀ and LC₅₀ data;
- *developmental/reproductive toxicity*, again most often measured by the weight, type, or amount of evidence;
- *physical hazard*, most often characterized by ignitability, boiling point, and reactivity;
- *plant toxicity*, most commonly measured by EC₅₀ data;
- *terrestrial non-mammalian toxicity*, most often characterized by acute LD₅₀; and
- *general ecological effects*, with no specific endpoint used by more than one system.

The most commonly listed endpoints for major classes of exposure criteria include:

- *degradation or transformation potential*: most commonly measured by half-life in the environment and some type of BOD data;
- *mobility and partitioning*, most often characterized by Kow and BCF;
- *estimated dose, environmental occurrence, concentration, or amount released*, most commonly measured by annual releases to environment and production volume; and
- *exposure frequency or intensity*, relates to potential receptors and usually is measured by population size or number potentially exposed.

The classes of criteria are listed in both cases in decreasing order from the most to the least often included as components of the evaluated systems.

3.2.2 Ranking versus Categorization

As mentioned in Section 2.3.6, there are two major types of chemical ranking and scoring systems; those that rank chemicals and those that categorize chemicals. Examples of categories that may be used include substances of high, medium or low concern or selected chemicals, non-selected chemicals

and chemicals for further review. Ranking systems, however, usually derive overall scores and rank chemicals relative to one another based on these scores.

In developing a consensus framework for chemical scoring, a decision must be made whether to use the system to rank chemicals, select or categorize chemicals, or rank and select chemicals. To a certain extent, this decision depends on the purpose of the system, but one disadvantage for a system that only categorizes or selects chemicals is that those selected substances cannot be further prioritized. For example, suppose such a system were used to choose a subset of chemicals that are considered to be of high concern from a regulatory perspective. If 200 chemicals meet the criteria to be considered high concern, there may need to be a means of further prioritizing these substances before regulatory policy decisions could be made. van de Zandt and van Leeuwen (1992) suggest that a ranking system is preferable to classification methods for this reason.

Three of the systems reviewed assign chemical scores which are not used to rank or categorize the chemicals. For example, the *TRI Environmental Indicators Methodology* (Abt Assoc., 1992) scores TRI chemicals to reflect the impacts of the releases and transfers. These numbers can then be compared from one year to the next to monitor changes in impacts. Chemicals are not ranked or selected.

Several systems assign chemical scores and rank the substances according to relative hazard. The priority list of substances prepared by the ATSDR (1992) is the result of ranking and scoring, in order of priority, chemicals commonly found at NPL sites.

Chemical ranking may be used for selecting chemicals for further review, regulatory action or some other activity. An example is the *Ranking System for the Clean Water Act* (Poston and Prohammer, 1985; Cornaby et. al., 1986) in which chemicals were ranked and then selected as candidates for possible inclusion on or deletion from the Priority Pollutant List. There are seven systems reviewed which result in both ranking and selection of chemicals.

Thirteen of the systems evaluated resulted in the selection or categorization of chemicals, mostly for regulatory purposes (ten systems), without first ranking them. An example of such a system is that developed by ICF (1990) for the EPA which selects chemicals as "High Priority Pollutants" if certain exposure and effects criteria are met. Another example is the *Michigan CMR* (MDNR, 1987) which is derived from scoring chemicals for various exposure and effects criteria. Chemicals are then selected for inclusion in the Register if they receive a score a "5" (the maximum score) in two or more criteria or score an additive level of "15" or greater for all criteria. Chemicals are chosen for more detailed scrutiny if other similar criteria are met.

3.2.3 Quantitative versus Qualitative Endpoints

Chemical ranking and scoring systems are basically quantitative in nature, oftentimes resulting in ranking or selection based on numeric cut-off values for various criteria. The assignment of scores for specific endpoints, however, is not always based on quantitative data. Many of the systems reviewed include a

combination of both qualitative and quantitative endpoints. Particularly for chronic health effects, such as carcinogenicity, qualitative data are essential. A large number of the systems which include carcinogenicity as a scoring criterion utilize weight-of-evidence and/or strength-of-evidence information. Sometimes, as in the *GWU system* (Foran and Glenn, 1993), these qualitative data are combined with quantitative potency estimates where available. Qualitative data are also used frequently in the absence of quantitative data for certain criteria. For example, the *BUA system* (Behret, 1989a,b) assigns negative scores where qualitative information is utilized in the absence of a desired quantitative endpoint. When there is no data such as the K_{ow} or bioconcentration factor (BCF) regarding bioaccumulation, then a score of -1 is assigned if there is no suspicion of bioaccumulation or a -2 if bioaccumulation potential is suspected. Qualitative data, such as SARs, are frequently used to fill data gaps.

3.2.4 Assigning Scores to Endpoint Data

For those systems where there is agreement on which particular endpoint to use, there still exists a variety of approaches to assign corresponding numerical scores. To illustrate this, BCF is used as an example of an endpoint included in several systems and scored in a variety of ways. Table 4 presents the numerical scores assigned to BCF or log BCF by eight systems. For comparison purposes, all BCF data are converted to log BCF and the scores are normalized on a scale of 0 to 1 corresponding to the minimum and maximum value assigned by the system. This information is also presented graphically in Figure 1.

A few items are worthy of note. First, there is a noticeable lack of agreement; the eight systems represented here use seven different schemes to assign values to BCF data. Second, the majority of systems use some kind of step function to assign values to endpoint data (i.e. if log BCF is between 3 and 4, then assign a value of x). One exception is the *UT system*, which uses a continuous linear function with upper and lower bounds. The systems that use step functions use different numbers of steps. The *BUA system* has only two; it simply assigns a minimum score if the log BCF is less than 2 and a maximum score if it is greater than 2. Several others use five steps. Finally, it can be seen that different systems assign varying levels of significance to BCF values. The *BUA system* considers a log BCF of 2.1 to be of maximum significance, while, for this same BCF value, the *Michigan CMR* assigns a relatively low value and the *UT system* assigns a mid-range score.

Similar evaluations could be useful for all endpoints included in a chemical ranking and scoring system, but are beyond the scope of this report.

TABLE 4. Bioconcentration Factor (BCF) Scores for Several Systems

System name (System no.)	BCF	Log BCF	Score	Normalized score ^a
Candidate Substance List for Bans or Phase-outs (6); Effluent Monitoring Priority Pollutant List (EMPPL) (25); Canadian Accelerated Reduction/Elimination of Toxics (ARET) Scoring Protocol (49)	>15,000	>4.2	10	1.0
	500 - 15,000	2.7 - 4.2	7	0.7
	20 - 500	1.3 - 2.7	4	0.4
	≤20	≤1.3	0	0
Michigan Critical Materials Register (MCMR) (22)	≥100,000	≥5	S(sufficient)	1.0 ^b
	10,000 - 99,999	4 - 5	5	0.71
	1,000 - 9,999	3 - 4	3	0.43
	100 - 999	2 - 3	1	0.14
	<1 - 99	<2	0	0
WMS Scoring System (20)		>3	2	1.0
		1.5 - 3	1	0.5
		<1.5	0	0
Chemical Scoring System for Hazard and Exposure Identification (TSCA) (24)	≥1000	≥3	9	1.0
	200 - 1,000	2.3 - 3	7	0.78
	100 - 200	2 - 2.3	5	0.56
	10 - 100	1 - 2	3	0.33
	<10	<1	0	0
TRI Environmental Indicators Methodology (1)	>10,000	>4	50,000	1.0
	1,000 - 10,000	3 - 4	5,000	.79
	100 - 1,000	2 - 3	500	.57
	10 - 100	1 - 2	50	.36
	1 - 10	0 - 1	5	.15
	<1	<0	0.5	0
Existing Chemicals of Environmental Relevance (BUA) I & II (3,4)	>100	>2	2	1.0
	<100	<2	0	0
UT Method (29)		>4	2.5	1.0
		1 - 4	0.5logBCF+0.5	(calc)
		≤1	1	0.4

(a) normalized on a scale from 0 to 1 by dividing each score by the maximum score for that system

(b) normalized assuming a maximum score of 7

Figure 1

3.3 GENERAL STRENGTHS AND WEAKNESSES OF EVALUATED SYSTEMS

A detailed critique of all fifty-one systems reviewed is beyond the scope of this report. Instead, a general discussion is presented for consideration either in choosing an existing system, or in developing a new or hybrid system. Van de Zandt and van Leeuwen (1992) suggest that a priority setting system should be:

- quick to use as a screening tool to identify priority substances for further review;
- systematic and computerized;
- transparent, with methodologies described in detail for clarity to the user
- flexible;
- accurate, avoiding too many false positives or negatives and working with available data to give consistent results;
- based on a scientifically justifiable framework and generally accepted methodologies; and
- based on exposure and effects, with emphasis on long-term effects.

These aspects, along with a few additional issues we have identified, are discussed below:

Ease of use, complexity. The EPA chemicals of potential concern selection process is simple and straight forward when concentration data are available. The required toxicity data, however, are readily available for only a limited number of chemicals. The *TRI indicators methodology* is very complex and amounts to practically conducting a quantitative risk assessment at every facility that reports TRI releases. The time and resources required is an important deciding factor in choosing or developing a method. Also, the mathematical or mechanical processes of scoring and ranking should be straight forward enough so that the system is *transparent* to the user. It should be easy to understand the results given a basic knowledge of the chemicals and data used.

Flexibility. A system should have enough flexibility so the user can augment or simplify it, add or subtract components, add new data as they become available, or change the weighing for various criteria while the system maintains its integrity. The *UT system* is an example of a relatively flexible system.

Availability of data. Many systems require data that either are not readily available or frequently require estimation methods. As much of the required data as possible should be peer-reviewed. The *Use Cluster Scoring System* (EPA, 1993) draws on a number of possible endpoints, arranged in a hierarchy for high, medium and low quality data. This data selection approach allows the user to draw from a much wider range of data, and should result in fewer instances of missing data.

Comparability to other systems. Ranking and scoring results, especially when regulations are involved, should be comparable across regulatory programs and across industries. Ideally, they should also be

comparable on an international basis. One example where international comparability could be important is where trade issues are involved. Three of the evaluated systems (the *Canadian Substance List for Bans or Phase-outs*, the *EMPPL system*, and the *ARETS Scoring Protocol*) use the same scoring criteria, based on the MOE scoring criteria, although their selection processes differ slightly. Otherwise, there is little consistency among the evaluated systems.

Number of chemicals the existing system has been demonstrated on. Some systems may seem like a good idea, but may disintegrate under the pressure of a large number of chemicals. A few of the evaluated systems were presented only in theory, with no demonstration using real chemical data. Others have been demonstrated or used on hundreds of chemicals. For example, over 700 chemicals were ranked by the *CERCLA 104 Priority List system* (ATSDR, 1992), and van de Zandt and van Leeuwen (1992) addressed 2000 HPV chemicals in the *Priority Setting of Existing Chemical Substances system*.

Applicability to various classes of chemicals. Ions, metals and radionuclides pose problems that are very different from organic compounds. For example, many QSAR or SAR estimation methods do not apply to inorganic chemicals. The *CERCLA HRS system* (Hallstedt et. al., 1986) was intended only for ranking organic compounds, but has been modified to include radionuclides in the site ranking process (Hawley & Napier, 1985).

Reproducibility or subjectiveness of scoring methods. Results from a panel of experts or when qualitative estimations are used may not be reproducible at different times or when applied by different users. For example, the *WMS Scoring System* relies on a panel of experts to score chemicals; if used in another application, different experts could arrive at different scores for the same chemicals. In addition, a system should be based on scientific principles and an understanding of risk assessment methodologies.

Completeness. All potential and important effects should be included in a system. The following components should be included, or the decision not to include a component should be made clear:

- the purpose and application of the ranking and scoring system;
- the human health criteria and endpoints included;
- the criteria and endpoints included for environmental effects;
- whether measures of exposure are included;
- the data selection approach and handling of missing data;
- the use of aggregation and weighing of different health and environmental impacts;
- methods of accounting for chemical potency and severity of effects; and
- inclusion of other impacts or issues.

SECTION 4: CONCLUSIONS

This review of various chemical ranking and scoring systems demonstrates that there is currently no consensus regarding an appropriate framework for evaluating adverse impacts to human health and the environment from exposure to chemical substances. There is much variation in the degrees of sophistication, the types and numbers of endpoints incorporated, the data selection approach and the manner of weighing and/or combining scores to arrive at a final assessment.

Clearly, the purpose for which the ranking or scoring tool is intended will affect these factors. Although the intended purpose of a ranking or scoring system can influence its design, it would be useful to develop a standard framework for chemical ranking and scoring that is flexible enough to be adapted for most purposes. A standardized system for ranking and scoring chemicals is desirable for several reasons. It could assist business and regulatory agencies to target their pollution prevention efforts; enable environmental policy and business decisions to be made on similar, objective, and scientifically-based methods; provide consistency nationally across regulatory programs as well as internationally; make use of and build on previous experience gained from the development of existing systems; allow new information to be incorporated while maintaining system integrity; and save on time and expense incurred by continuing to develop new systems from scratch with every new application.

Due to the large variation among ranking systems in terms of criteria, endpoints, data selection approaches, and scoring methods, one logical way to approach a consensus on methods would require the following steps (illustrated in Figure 2):

- Develop a consensus on the overall framework for chemical ranking and scoring, including its component parts: criteria, endpoints, data selection approach, and scoring formula;
- Work toward agreement on the component parts, such as:
 - which criteria should be included in any chemical ranking and scoring system
 - which endpoint(s) should be used to measure or score that criteria
 - what data selection approach should be used to select or estimate data for the criteria
 - how should criteria scores be weighted and combined to reach an overall score or rank for each specific chemical (if an overall score per chemical is the goal)

Figure 2

- what level of sophistication in exposure estimation is appropriate - from total amounts produced, used or released, to multimedia environmental fate models, to site-specific models including estimates of dose over time
- Reassemble these elements into the agreed-upon framework, providing flexibility to use some or all of the components for specific purposes.

The process of developing the consensus framework should involve all of the significant stakeholders - government agencies, chemical manufacturers and users, environmental and consumer groups, and academic researchers. This will create greater acceptance of the results.

Given the current interest in chemical ranking and scoring, and the many potential applications, an effort to develop a consensus framework for chemical ranking and scoring would be an important contribution to reducing chemical risk.

REFERENCES

- Abt Associates, Inc. (1991). *Ranking the Relative Hazards of Industrial Discharges to POTWs and Surface Waters*. Prepared for U.S. Environmental Protection Agency, Office of Policy Analysis.
- Abt Associates, Inc. (1992). *Toxics Release Inventory Environmental Indicators Methodology*. (Draft Report). By Abt Associates, for U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington, DC.
- Agency for Toxic Substances and Disease Registry (ATSDR) (1992). *Support Document: The CERCLA 104 Priority List of Hazardous Substances That Will Be The Subject of Toxicological Profiles*. U.S. Public Health Service, Department of Health and Human Services, Washington DC.
- ARET Criteria Sub-Committee (1993). *ARET Criteria Sub-Committee Report*, revision date September 27, 1993.
- Ashby, J. et. al. (1990). A Scheme for Classifying Carcinogens. *Regulatory Toxicology and Pharmacology*, 12, 270-295.
- Auer, C.M. (1992). Memorandum, "The OECD "SIDS" Program", June 17, 1992 (updated from OECD document S6/CK/BIAC91.181/4.9.91) Director, Existing Chemicals Assessment Division. U.S. Environmental Protection Agency, Office of Pesticides and Toxic Substances, Washington, DC.
- Ayres, R.U. (1993). Cowboys, Cornucopians and Long-Run Sustainability. *Ecological Economics*, 8, 189-207.
- Beckvar, N. & L. Harris (1992). *Coastal Hazardous Waste Site Review, September, 1992*. Hazardous Materials Response and Assessment Division, NOAA, ORCA, Seattle, WA.
- Behret, H. (Ed.) (1989a). *Existing Chemicals of Environmental Relevance*. GDCh-Advisory Committee on Existing Chemicals of Environmental Relevance. VCH, New York.
- Behret, H. (Ed.) (1989b). *Existing Chemicals of Environmental Relevance II, Selection Criteria and Second Priority List*. GDCh-Advisory Committee on Existing Chemicals of Environmental Relevance. VCH, New York.
- Bouchard, D. (1991). *Review of Region VII TRI Strategy*. (Memo, EPA Region VII).

- Bureau of National Affairs, Inc. (BNA) (1991) Criteria for Identifying High Risk Pollutants, *Environment Reporter*, Washington, DC, pp. 463-465.
- Canadian Labor Congress (CLC) (1992). *A Critique of the Ontario Hazard Assessment System*. CLC Environment Bureau, Ottawa, Ontario.
- Clements, R.G, J.V. Nabholtz, D.W. Johnson & M. Zeeman (1993). The Use and Application of QSARs in the Office of Toxic Substances for Ecological Hazard Assessment of New Chemicals. In *Environmental Toxicology and Risk Assessment*, ASTM STP 1179.
- Cornaby, B.W. et. al. (1986). *Results of Implementation of a Chemical Ranking System*. Prepared by Battelle, for U.S. Environmental Protection Agency, Washington, DC.
- Crutcher, M.R., & F.L. Parker (1990). A Classification System for Hazardous Chemical Wastes. Superfund 90, Hazardous Materials Control Research Institutes, 11th Annual National Conference, 222-225.
- Davis, G.A. et. al (1993). Chemical Ranking for Potential Health and Environmental Impacts. University of Tennessee, Center for Clean Products and Clean Technologies, Knoxville, TN.
- Droppo, J.G., Jr. et. al. (1989). *Multimedia Environmental Pollutant Assessment System Application Guidance, Volume 2 - Guidelines for Evaluating MEPAS Input Parameters*. Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, WA.
- Environ Corporation (1986). *Examination of the Severity of Toxic Effects and Recommendation of a Systematic Approach to Rank Adverse Effects*. Prepared for U.S. Environmental Protection Agency, Office of Environmental Criteria and Assessment, Cincinnati, OH.
- Environment Ontario (1987). *The Effluent Monitoring Priority Pollutants List*. Ontario Ministry of the Environment, Hazardous Contaminants Coordination Branch. ISBN 0-7729-2784-7.
- Environment Ontario (1988). *The Effluent Monitoring Priority Pollutants List, 1988 Update*. Ontario Ministry of the Environment, Hazardous Contaminants Coordination Branch. ISBN 0-7729-5450-X.
- Environmental Monitoring and Services, Inc. (EMS) (1985). *Technical Background Document to Support Rule Making Pursuant to CERCLA Section 102* (Volumes 1-2). Prepared for U.S. Environmental Protection Agency.

- Foran, J.A. & B.S. Glenn (1993). *Criteria to Identify Chemical Candidates for Sunsetting in the Great Lakes Basin*. The George Washington University, Environmental Health and Policy Program, Department of Health Care Sciences, Washington, DC.
- Gjøvs, N., M. Møller, G.S. Hægh, & K. Kolset (1989). *Existing Chemicals: Systematic Data Collection and Handling for Priority Setting*. Center for Industrial Research, Oslo, Norway. Nordic Council of Ministers, Copenhagen.
- Gustafsson, L. & E. Ljung (1990). *Substances and Preparations Dangerous for the Environment: A System for Classification, Labelling and Safety Data Sheets*. Final Report from a Nordic Working Group, Nordic Council of Ministers, Copenhagen.
- Halfon, E., & M.G. Reggiani (1986). Notes on Ranking Chemicals for Environmental Hazard. *Environ. Sci. Technol.* 20, 1173-1179.
- Hallstedt, P.A., M.A. Puskar, & S.P. Levine (1986). Application of the Hazard Ranking System to the Prioritization of Organic Compounds Identified at Hazardous Waste Remedial Action Sites. *Hazardous Waste and Hazardous Materials*, 3(2), 221-232.
- Hawley, K.A., & B.A. Napier (1985). *A Ranking System for Hazardous Sites & With Mixed Radioactive and Hazardous Wastes*, Proceedings of the Fifth DOE Environmental Protection Information Meeting. U.S. Department of Energy, Office of Operational Safety, Pacific Northwest Laboratory, Richland, WA.
- Hermens, J.L.M. (1989). Quantitative Structure-Activity Relationships of Environmental Pollutants. In *Handbook of Environmental Chemistry*. Hutzinger, O. (Ed.), Volume 2E, Springer Verlag, Berlin, pp. 111-162,.
- Hushon, J.M. and M.R. Kornreich (1984). Scoring Systems for Hazard Assessment, in: *Hazard Assessment of Chemicals: Current Developments*, Volume 3, J. Saxena (Ed.). Academic Press, Inc., Orlando.
- Hutchinson, W.R., & J.L. Hoffman (1983). *A Ground Water Pollution Priority System* (N.J. Geographical Open File, Report No. 83-4). Division of Water Resources, Trenton, NJ.
- ICF Incorporated (1990). *Targeting Pollution Prevention Opportunities Using the 1988 Toxics Release Inventory*. Prepared for U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Pollution Prevention.
- ICF Incorporated (1993). *Summary and Comparison of Five Chemical Scoring Systems*. Submitted to: Chemical Manufacturers Association, Washington, D.C.

- International Joint Commission's (IJC) Binational Objective Development Committee (1989). *The Great Lakes Water Quality Agreement Standard Methods and Annex 1, Lists of Substances*.
- Jones, T.D., P.J. Walsh, A.P. Watson, B.A. Owen, L.W. Barnthouse, & D.A. Sanders (1988). Chemical Scoring by a Rapid Screen of Hazard (RASH) Method. *Risk Analysis*, 8(1), 99-118.
- Kincaid, L.E. & J.E. Bartmess (1993) Evaluation of TRI Releases in Indiana, Louisiana, Ohio, Tennessee and Texas. University of Tennessee, Center for Clean Products and Clean Technologies, Knoxville, Tennessee.
- Klaassen, C.D. & D.L. Eaton (1993). Principles of Toxicology. In *Casarett and Doull's Toxicology: The Basic Science of Poisons*, Fourth Edition. M. Amdur, J. Doull, C.D. Klaassen (Eds.). McGraw Hill, Inc., New York.
- Klein, W., W. Kördel, A.W. Klein, D. Kuhnen-Clausen, & M. Weiss (1988). Systematic Approach for Environmental Hazard Ranking of New Chemicals. *Chemosphere*, 17, 1445-1462.
- Könemann, H. & R. Visser (1988). Selection of Chemicals With High Hazard Potential: Part 1: WMS-Scoring System. *Chemosphere*, 17, 1905-1919.
- Landis, W.G., J.S. Hughes & M. Lewis (Eds.). American Society for Testing and Materials, Philadelphia, pp. 56-64.
- Laskowski, P.A., C.A.I. Goring, P.J. McCall, & R.L. Swann (1982). Principles of Environmental Risk Analysis: Terrestrial Environment. in *Environmental Risk Analysis for Chemicals*, R. Conway (Ed.), pp. 198-240. Van Nostrand Reinhold, New York.
- McCarty, L.S. & D. MacKay (1993). Enhancing Ecotoxicological Modeling and Assessment. *Environmental Science and Technology*, 27(9), 1719-1728.
- Michigan Department of Natural Resources (MDNR) (1987). *Critical Materials Register*. (Criteria and Support Documents).
- Morgenstern, R., D. Clay, G. Emison, R. Hanmer, & M. Williams (1987). *USEPA Unfinished Business: A Comparative Assessment of Environmental Problems, Volume 1*. U.S. Environmental Protection Agency, Washington, DC.
- O'Bryan, T.R. & R.H. Ross (1988). Chemical Scoring System for Hazard and Exposure Identification. *J. Toxicol. Env. Health*, 1, 119-34.

- Organization for Economic Co-operation and Development (OECD) (1986). *Existing Chemicals: Systematic Investigation, Priority Setting and Chemicals Reviews*. Paris, France.
- Poston, T.M. & L.A. Prohammer (1985). *A Ranking System for Clean Water Act Section 307(a) List of Priority Pollutants*. Prepared by Battelle for U.S. Environmental Protection Agency, Washington, DC.
- Radian Corporation (1990). *The Source Category Ranking System: Development and Methodology*. Prepared for U.S. Environmental Protection Agency, Office of Air Quality Planning Standards, Chemicals and Petroleum Branch, Research Triangle Park, NC.
- Rechard, R.P., G.G. Wilkinson, & J.D. Schreiber (1991). *User's Manual for SRS88: Site Ranking System for Chemical and Radioactive Waste* (SAND87-2815, UC-721). Sandia National Laboratories, Albuquerque, NM.
- Rechard, R.P., M.S.Y. Chu, & S.L. Brown (1988). SRS: Site Ranking System for Hazardous Chemical and Radioactive Waste. Sandia National Laboratories, Albuquerque, NM.
- Sampaolo, A. & R. Binetti (1986). Elaboration of a Practical Method for Priority Selections and Risk Assessment among Existing Chemicals. *Reg. Toxicol. & Pharmacol.*, 6, 129-154.
- Sampaolo, A. & R. Binetti (1989). Improvement of a Practical Method for Priority Selections and Risk Assessments Among Existing Chemicals. *Reg. Toxicol. & Pharmacol.*, 10, 185-195.
- Sax, N.I. & R.J. Lewis (1989). *Dangerous Properties of Industrial Materials*. Van Nostrand Reinhold, New York.
- Scala, R.A. (1993). Risk Assessment. In *Casarett and Doull's Toxicology: The Basic Science of Poisons*, Fourth Edition. M. Amdur, J. Doull, C.D. Klaassen (Eds.). McGraw Hill, Inc., New York.
- Silka, L.R., & T.L. Swearingen (1978). *A Manual for Evaluating Contamination Potential of Surface Impoundments*. (EPA 570/9-78-003). U.S. Environmental Protection Agency, Office of Drinking Water, Washington, DC.
- Society of Environmental Toxicology and Chemistry (SETAC) (1993). *A Conceptual Framework for Life-Cycle Impact Assessment*, J. Fava, et. al., Eds., A Workshop Report, February 1-7, 1992, Sandestin, Florida. Sponsored by SETAC and the SETAC Foundation for Environmental Education, Inc.

- Socha, A.C., T. Dickie, & R. Aucoin (1992). *Candidate Substances List for Bans or Phase-Outs*. Ontario Ministry of the Environment.
- Steen, B., & S.O. Ryding (1992). *The EPS Enviro-Accounting Method*. Swedish Environmental Research Institute (IVL), Göteborg, Sweden.
- Streng, D.C., S.R. Peterson, & S. Sager (1989). *Chemical to Base for the Multimedia Environmental Pollutant Assessment System (MEPAS): Version 1*. U.S. Department of Energy, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, WA.
- Timmer, M., H. Könemann, & R. Visser (1988). Selection of Chemicals With High Hazard Potential: Part 2: WMS-Scoring System. *Chemosphere*, 17, 1921-1934.
- U.S. Department of Defense (DOD)(1992). *User's Manual for the Defense Priority Model* (FY 93 version, Interim Draft). Prepared by Earth Technology Corporation and ERM Program Management Company, for U.S. Department of Defense, Office of Deputy Assistant Secretary of Defense (Environment), Washington, DC.
- U.S. Environmental Protection Agency (EPA)(1978). *Measuring Air Quality: The New Pollutants Standards Index*. U.S. Environmental Protection Agency, Office of Policy Analysis, Washington, DC.
- U.S. Environmental Protection Agency (EPA)(1986). *Screening Procedure for Chemicals of Importance to the Office of Water*. U.S. Environmental Protection Agency, Office of Health and Environmental Assessment, Washington, DC.
- U.S. Environmental Protection Agency (EPA)(1989a). *Toxic Chemical Release Inventory Risk Screening Guide* (Vol. 1). U.S. Environmental Protection Agency, Office of Toxic Substances, Washington, DC, EPA 560/2-89-002.
- U.S. Environmental Protection Agency (EPA)(1989b). *Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual*. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response. EPA/540/1-89/002.
- U.S. Environmental Protection Agency (EPA)(1989c). *Technical Background Document to Support Rule Making Pursuant to CERCLA Section 102* (Volume 3) U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response.

- U.S. Environmental Protection Agency (EPA)(1989d). *Risk Assessment Guidance for Superfund, Volume II, Environmental Evaluation Manual, Interim final*. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response. (EPA/540/1-89/001).
- U.S. Environmental Protection Agency (EPA) (Dec. 14, 1990). Hazard Ranking System; Final Rule. *Federal Register* 55 (241): 51532-51667 (40CFR Part 300).
- U.S. Environmental Protection Agency (EPA) (1992). *MIXTOX: An Information System on Toxicologic Interactions for the MS-DOS Personal Computer, Version 1.5, User's Guide*. U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office, Cincinnati, OH.
- U.S. Environmental Protection Agency (EPA) (1993a). *Chemical Use Clusters Scoring Methodology* (Draft). U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Chemical Engineering Branch, Washington DC.
- U.S. Environmental Protection Agency (EPA) (1993b). *Hazardous Air Pollutants: Proposed Regulations Governing Constructed, Reconstructed and Modified Major Sources* (40 CFR Part 63).
- U.S. Environmental Protection Agency (EPA) (date unknown). *Screening Methodology for Pollution Prevention Targeting*. U.S. Environmental Protection Agency, Office of Toxic Substances.
- U.S. Environmental Protection Agency (EPA) (date unknown). *TSCA's TRI Chemical Risk Assessment Pre-Screening Methodology*. U.S. Environmental Protection Agency, Office of Toxic Substances, Existing Chemical Assessment Division.
- Waters, R.D., M.R. Crutcher & F.L Parker (1993). Hazard Ranking Systems for Chemical Wastes and Chemical Waste Sites. In *Hazard Assessment of Chemicals, Volume 8*. J. Saxena (Ed.). Taylor and Francis, Washington, D.C.
- Weiss, M., W. Kördel, D. Kuhnen-Clausen, A.W. Lange, & W. Klein (1988). Priority Setting of Existing Chemicals. *Chemosphere*, 17, 1419-1443.
- Whelan, G. et. al. (1987). *The Remedial Action Priority System (RAPS): Mathematical Formulations*. U.S. Department of Energy, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, WA.
- Whelan, G. et. al. (1992). Overview of the Multimedia Environmental Pollutant Assessment System (MEPAS). *Hazardous Waste & Hazardous Materials*, 9 (2), 191-208.

van de Zandt, P.T.J., & C.J. van Leeuwen (1992). *A Proposal for Priority Setting of Existing Chemical Substances*. Netherlands Ministry of Housing, Physical Planning and the Environment.