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ARTICLE *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · SEPTEMBER 2008

Impact Factor: 5.33 · DOI: 10.1021/es00002a003

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RG-0108F
29160 PDF

INDUSTRIAL REGULATIONS

Toxic Emissions Indices for Green Design and Inventory

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The Toxics Release Inventory (TRI) is the most comprehensive and widely reported information on hazardous discharges to the environment in the United States. Unfortunately, the fledgling nature of the TRI may lead to simplistic interpretations of the results. In particular, TRI summaries typically report total releases of toxic chemicals by weight, implicitly assuming that a discharge of substance A is equivalent to an equal weight discharge of substance B. In contrast, various indices of the toxicity to humans of the chemicals reported in the Inventory indicate that the most harmful are more than 1,000,000 times more toxic than the least harmful. Thus, the simple rankings and time trends of facilities, industries, counties, and states as sources of toxic releases can be misleading because they have neglected relevant toxicological data. We contrast the one-to-one ranking of the TRI data with a ranking based on relative toxicity, using "threshold limit value" (TLV) indices. The weighting scheme presented here is a useful first step for correcting the TRI but is certainly not definitive. Additional study is needed of uncertainties and limitations of this proposed approach. Future applications may be found in green engineering design and manufacturing changes.

The usual government response to environmental pollution has been discharge control and remediation of toxic spills. With few exceptions, federal pollution control focuses on end-of-the-pipe discharge control. More recently, the U.S. Environmental Protection Agency has given attention to pollution prevention and waste minimization (*1*); policies and guidelines are being developed to encourage or require polluters to reduce their generation of toxic wastes. One such tool is the Emergency Planning and Community Right-to-Know Act (EPCRA) of 1986, also known as Title III of the Superfund Amendments and Reauthorization Act (SARA). In parallel with the European Community (Seveso Decree), Section 313 of SARA requires various manufacturing firms to report the total annual environmental discharges of some 370 chemicals and chemical categories by plant; these data are published by EPA as the annual Toxics Release Inventory (TRI) (*2*). Recent legislation (the Pollution Prevention Act of 1990) has amended the rule to require reporting how wastes are treated on site and the amount transferred to publicly owned treatment works (POTW).

Plants required to report TRI data are limited to manufacturing firms defined by the Department of Commerce's Standard Industrial Classification or "SIC" codes 20-39 (*3*); facilities that manufacture or process more than 25,000 pounds, or otherwise use 10,000 pounds of TRI chemicals; and plants with more that 10 full-time employees. At present, plants are required to report on only 370 chemicals and chemical categories. Although these are probably the most commonly used toxic substances, the vast majority of chemicals is ignored; 60,000 chemicals are reported to be in commercial use (*4*).

Perhaps the greatest limitation of the TRI data is their accuracy. Companies are not required to monitor discharges but rather only to estimate them by "professional judgment." As a result, the discharge data are likely to be in error for some chemicals in some plants by several orders of magnitude. Applying mass balance methods in which input, products, and emissions are made consistent would be an improvement (*5*). While requiring the use of monitoring or other documented methods to improve the accuracy of reported discharges may require statutory change, EPA can pursue other improvements to the TRI on its own. For example, the reporting threshold could be lowered for highly toxic chemicals and chemical categories, with all industrial sectors reporting regardless of the size of the facility. For better data, EPA has added 286 hazardous pollutants to the TRI list (*6*).

Another problem has been the focus on discharges rather than the environmental fate of chemicals, which results in exposure to humans and environmental damage. For example, emitting a pound

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of sulfuric acid into urban air has quite different implications for health than injecting it deep underground, in a place where it is unlikely to contact humans, plants, or animals.

A final problem has been a simplistic interpretation of the TRI data. Published summaries typically report discharges by weight. For example, one pound of sulfuric acid emission is simply added to one pound of acetone or formaldehyde, even though the toxicity of these chemicals varies significantly, as shown in Table 1. Although total releases have declined from 4.85 billion lb in 1988 to 3.16 billion lb in 1992 (for a consistent list of chemicals reported in both years) (2), no one knows whether the overall toxicity of the discharges has decreased. In this paper, we demonstrate a method to weight TRI discharges by their toxicity.

The public concern that led to the TRI reporting requirement also led to extensive press coverage of the TRI data. Every year, the news media have reported the national totals and the local top polluters. Recently, *Fortune* magazine published a story naming 10 corporations that lead in being environmentally responsible and 10 that are "laggards," with rankings based in part on the TRI data (7). This exposure has caused company executives and boards to show growing concern for their environmental performance.

A company could, however, reduce discharges of a relatively nontoxic chemical by 1000 lb while increasing the discharges of a highly toxic chemical by 100 lb and wind up doing net damage to the environment and human health, even though their TRI numbers indicated great progress. Without toxicological expertise, the company might not know this was a harmful decision. Even if they knew, the pressure to reduce their TRI discharges, combined with limited financial and engineering resources, could compel them to take easy actions.

Approaches to toxicity weighting

Several prototype toxic weighting systems have appeared. They are limited by lack of data and subjective input requirements. A prototype indexing system that rank orders TRI chemical releases in terms of their relative toxicity (both noncarcinogenic and carcinogenic) is described by Forman (8) for Maryland. The toxicity indices used are the oral reference dose (RfD) and cancer potency (CPF).

Davis et al. (9) present a release weighted effects model in which the sum of a health effects score and an environmental effects value is multiplied by exposure parameters to arrive at a hazard value; this value is multiplied by a weighted release amount. The health effects values are based on lethal doses for rodents and fish. The three exposure parameters involve BOD half-life, hydrolysis half-life, and biocon-

TABLE 1

Toxicity of Toxics Release Inventory (TRI) chemicals: Major chemical company #1

Using 1990 total releases and transfers and total air emissions data, the Carnegie Mellon University Equivalent Toxicity (CMU-ET) and toxicity ratio are calculated. The vast majority of toxic chemicals discharged were not very toxic, and more than 40% of the mass of released chemicals was in the least toxic threshold limit values (TLV) range.

Chemical	Total releases and transfers (10^4 lb/yr)	Total air emissions (10^4 lb/yr)	TLV (mg/m^3)
Acetone	[illegible]	864	1780
Ethylene glycol	281	9	none
Ethylene	278	278	none
Toluene	101	32	188
Methanol	[illegible]	63	262
Propylene	84	84	none
Naphthalene	79	32	52
Vinyl acetate	59	37	35
Hydrochloric acid	48	47	none
Polychlorinated biphenyls	[illegible]	0	none
Anthracene	[illegible]	0.02	none
Benzene	30	26	32
n-Butyl alcohol	27	15	none
Chloromethane	27	27	103
Glycol ethers	24	17	none
Biphenyl	[illegible]	0.08	1.3
Sulfuric acid	[illegible]	2	1
Methyl ethyl ketone	17	11	590
Ethylene oxide	16	15	1.8
1,2,4-Trichlorobenzene	[illegible]	0.03	none
Methyl isobutyl ketone	[illegible]	15	205
1,3-Butadiene	[illegible]	1	22
Ammonia	[illegible]	8	17
Styrene	12	2	213
Ethylbenzene	[illegible]	0.59	434
Cyclohexane	[illegible]	6	1030
Butyraldehyde	[illegible]	8	none
Acetaldehyde	[illegible]	8	none
Propylene oxide	[illegible]	8	48
1,4-Dioxane	[illegible]	4	90
Formaldehyde	[illegible]	0.52	0.37
2-Methoxyethanol	[illegible]	3	16
Propionaldehyde	[illegible]	3	none
2-Ethoxyethanol	[illegible]	3	18
1,2-Dichloroethane	[illegible]	3	40
Total	2372	1641	

Total releases and transfers		Total air emissions	
EPA-TRI (10^4 lb)	2372	EPA-TRI (10^4 lb)	1642
EPA-TRI$_{TLV}$ (10^4 lb)	[illegible]	EPA-TRI$_{TLV}$ (10^4 lb)	1173
CMU-ET (10^4 lb)	[illegible]	CMU-ET (10^4 lb)	17
Toxicity Ratio	0.04	Toxicity Ratio	0.01

Emissions data are taken from Reference 17; TLVs from Reference 12.

EPA-TRI is total emissions per year, in pounds (10^4 lb). EPA-TRI$_{TLV}$ is total releases for which TLVs are known, in pounds (10^4 lb). CMU-ET is the equivalent weight of toxic releases, in pounds (10^4 lb). Toxicity ratio is CMU-ET divided by EPA-TRI$_{TLV}$.

centration. The hazard value is weighted by natural log of the air and water releases.

O'Bryan and Ross (*10*) develop a scoring system based on 11 parameters for hazard and exposure identification. The parameters include oncogenicity, lethal doses, and exposure potential. Welch and Ross (*11*) developed a scoring system for environmental effects of toxic chemicals based on lethal dose amounts, mobility, persistence, and expert opinion.

By measuring a range of toxic effects, these proposals have merit. However, the data on toxicity are so limited for most measures that the index covers only a minority of the released chemicals. Despite their merits, these indices are unable to characterize the toxicity of most TRI releases.

Proposed weighted TRI releases

We propose the use of threshold limit values (TLV), an index based on health effects and the broadest group of chemicals that have been tested. For example, carcinogenicity has been tested for only about 1100 chemicals (*11*). We base our index on the occupational health rules and guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH). The ACGIH TLV indices are designed to protect workers against a wide variety of health effects, from acute toxicity to carcinogenicity. The ACGIH TLV-TWA (time-weighted average) (*13*) is a concentration in air that must not be exceeded during any 8-hour work shift of a 40-hour work week. Although the TLV values were designed for protection from inhalation, we assume that they can be used to approximate the toxicity from all routes of exposure. In our tables, we show both the results of applying the TLV weights only to air discharges and of applying them to all discharges.

The range of TLV values associated with the TRI chemicals is quite large. For example, the chemicals shown in Table 1 have TLV values of 0.37 to 1780 mg/m^3. Also subject to reporting requirements is beryllium, whose TLV is 0.002 mg/m^3, more than one million times more toxic than is Freon 113, whose TLV is 7670 mg/m^3. The vast majority of toxic chemicals discharged were not very toxic. More than 40% of the mass of released chemicals was in the least toxic TLV range (1780 mg/m^3); only 0.9% of the mass had a TLV of < 1 mg/m^3. Note that reporting is required only for chemicals discharged in quantities greater than 10,000 lb per year.

The ACGIH TLV-TWA has the same meaning as the Occupational Safety and Health Administration's (OSHA) permissible exposure limit–time-weighted average (PEL-TWA). Indeed, nearly all of OSHA's PELs were adopted from the ACGIH TLV index. ACGIH's values are more current than the PELs' because they are revised much more frequently than the OSHA PELs, reflecting more recent scientific studies. Unlike PELs, TLVs are recommendations to employers and do not have the force of law.

EPA summaries of TRI chemical releases usually sum the emissions (X_i): ΣX_i. Below, we call this the EPA-TRI index, and it is given in units of pounds. On a particular list of discharged chemicals there are a number that do not have TLV values; the sum of these discharged chemicals is the EPA-TRI_{NONE} index, in pounds. Summing the releases of chemicals that have a TLV toxicity measure, we obtain the EPA-TRI_{TLV} index, reported in pounds. Consequently,

$$\text{EPA-TRI}_{TLV} + \text{EPA-TRI}_{NONE} = \text{EPA-TRI} \qquad (1)$$

We propose that TRI releases (X_i) be multiplied by a toxic weighting factor (w_i) to obtain an equivalent weight of releases:

$$\Sigma\ (X_i \times w_i) \text{ for all } i = 1 \text{ to } n \qquad (2)$$

where n is the number of TRI chemicals on a particular discharges list. The weighting factor is defined as:

$$w_i = TLV_{Reference}/TLV_i \qquad (3)$$

where $TLV_{Reference}$ denotes a reference TLV. For the sake of easy calculation, we use a reference TLV of 1 mg/m^3 over 8 hours. Sulfuric acid, phosphoric acid, and a number of other chemicals on the TRI list have this toxicity value. Thus, our index can be thought of as equivalent to pounds of sulfuric acid discharged. The resultant Carnegie Mellon University-Equivalent Toxicity (CMU-ET) is reported in units of pounds:

$$\text{CMU-ET} = \Sigma\ (X_i \times TLV_{Reference}/TLV_i) \text{ for all } i = 1 \text{ to } n \qquad (4)$$

The use of inverse hazard values for weights, as in Equation 4, to indicate the effect of a mixture of chemicals is common. EPA proposes an inverse weight to calculate hazard values for mixtures of chemicals with different maximum acceptable exposure levels (*14*). McKee and Scala (*15*) use an inverse combination rule (or harmonic mean formula) to determine joint additive toxicity of mixtures based on lethal dose amounts. Fathi-Afshar and Yang (*16*) use a measure identical to the CMU-ET in a study of toxic mixtures in petrochemical plants.

We define the "toxicity ratio" of a set of toxic discharges as the equivalent toxicity weight (CMU-ET) divided by the actual TRI weight for chemicals for which TLV indices exist: CMU-ET/EPA-TRI_{TLV}. With the CMU-ET index, it is used in the examples below to compare facilities, industries, and states.

Comparing releases and toxicity

We illustrate the use of the CMU-ET and the toxicity ratio on three analysis levels: company, industry, and state. In each example, we report total releases and transfers (if any) and total air emissions data. Other examples appear in Reference 17.

Unfortunately, the TLVs are missing for many chemicals on the SARA 313 discharges list. Taking all the chemicals and chemical categories on the TRI list in 1992 (*2*), only 59% of chemicals and 78% by weight of total TRI releases possess TLV values; no other toxicological database has nearly as good a coverage.

Missing values could be treated in several ways. For now, we omit these chemical emissions. We found that none of our conclusions were changed by a different approach that weighted unknown chemicals by the average toxicity score of chemicals whose weights were known.

Chemical industry. Tables 1 and 2 show the CMU-ET and the toxicity ratio of two major U.S. chemical companies, using total releases and transfers and total air emissions data of the top 35 chemicals on the companies' 1990 discharges list (*18*). Reflecting the 10,000-lb minimum TRI reporting requirement noted above, discharges and equivalent releases are shown to the nearest 10,000 lb.

The ACGIH TLVs (TLV-TWA) were not available for 12 chemicals out of the top 35 of the first manufacturer (about 35% of total discharge mass). Seven of the second company's TRI chemicals are missing TLV indices (about 26% of total discharge mass).

The EPA-TRI scores indicate that the second company releases and transfers almost six times as much mass in its top 35 chemicals as does the first company with its top 35. For both manufacturers, these 35 chemicals make up 99% of their total discharges and transfers. For both companies, the CMU-ET is much lower than the EPA-TRI_{TLV}, indicating that the discharges are less toxic than an equivalent amount of sulfuric acid (or any chemical that has a toxicity value of 1 mg/m^3 over 8 h).

Not only the second firm's total releases and transfers, but also its CMU-ET index and toxicity ratio are larger than those for the first company. If we take total air emissions only, the second manufacturer's CMU-ET index and toxicity ratio are again larger. Thus, an equivalent weight of releases is more toxic for the second company than for the first company. The second firm needs to work on reducing both the total weight and toxicity of its discharges.

Computer and office equipment industry. The CMU-ET and the toxicity ratio of the computer and office equipment industry's (SIC codes 3571 to 3579) total releases and transfers and total air emissions in 1987 and 1990 are shown in Table 3 (*18*). Two chemicals on the 1987 TRI discharges list, sodium hydroxide (solution, 720,000 lb) and sodium sulfate (3,750,000 lb), were not reportable in 1990. To make the list of chemicals reportable in both years consistent, we ignored the two substances. Seven chemicals on this discharges list do not have ACGIH TLV-TWA indices. In both years, Freon 113 was the largest weight of chemical release, with 7.1 million lb and 3.9 million lb of releases and transfers, respectively, and a relatively low toxicity rating (as indicated by a high TLV index of 7670 mg/m^3).

In both years, the CMU-ET score is smaller than the EPA-TRI_{TLV} figure, indicating that the discharges are less toxic than the equivalent amount of sulfuric acid. The total discharges, that is EPA-TRI, were reduced by 49%, from 16.5 million lb in 1987 to 8.4 million lb in 1990. The CMU-ET equivalent weight of releases was reduced by 38%, from 2.6 million lb to 1.6 million lb. However, there was not a significant change in the toxicity ratio from 1987 to 1990, in terms of total releases and transfers as well as in terms of total air emissions. Therefore, reducing the mass of emissions did not lead to a reduction in the average toxicity of releases.

States. The TRI can be used to rank facilities, industries, counties, and states on the basis of the pounds of toxic chemicals discharged to the environment each year. EPA simply sums the total releases of the TRI chemicals and ranks states on this basis, that is, using the EPA-TRI index. A more meaningful ranking would be to account for the toxicity of the discharges. Table 4 shows the CMU-ET and the toxicity ratio of two states for 1991 (*19*).

TABLE 2

Toxicity of TRI chemicals: Major chemical company #2

With the use of 1990 total releases and transfers and total air emissions data, the CMU-ET and toxicity ratio are calculated.

1990	Total releases and transfers (10^4 lb)	Total air emissions (10^4 lb)
EPA-TRI	13,562	726
EPA-TRI_{TLV}	10,080	700
CMU-ET	2644	78
Toxicity ratio	0.26	0.11

Emissions data are taken from Reference 17; TLVs from Reference 12.

EPA-TRI is total emissions per year, in pounds (10^4 lb). EPA-TRI_{TLV} is total releases for which TLVs are known, in pounds (10^4 lb). CMU-ET is the equivalent weight of toxic releases, in pounds (10^4 lb). Toxicity ratio is CMU-ET divided by EPA-TRI_{TLV}.

TABLE 3

Toxicity of TRI chemicals: Computer and office equipment industry

With the use of 1987 and 1990 total releases and transfers and total air emissions data, the CMU-ET and toxicity ratio are calculated. The mass of emissions was reduced by 49% between 1987 and 1990; unfortunately, this improvement wasn't reflected in the average toxicity of these releases. The toxicity ratio was constant or even rose slightly.

	Total releases and transfers (10^4 lb)		Total air emissions (10^4 lb)	
	1987	1990	1987	1990
EPA-TRI	1647	840	1126	668
EPA-TRI_{TLV}	1509	773	1104	659
CMU-ET	256	156	10	6
Toxicity ratio	0.17	0.20	0.01	0.01

Emissions data are taken from Reference 17; TLVs from Reference 12.

EPA-TRI is total emissions per year, in pounds (10^4 lb). EPA-TRI_{TLV} is total releases for which TLVs are known, in pounds (10^4 lb). CMU-ET is the equivalent weight of toxic releases, in pounds (10^4 lb). Toxicity ratio is CMU-ET divided by EPA-TRI_{TLV}.

Louisiana was ranked number 1 and Arizona number 21 on the list of states with the "biggest polluters." We took the first five components from the list of chemicals for these two states. In the case of Louisiana, we did not find a TLV-TWA for hydrochloric acid (5% of total releases), while for the same reason zinc and copper compounds, making up as much as 59% of total releases and 76% of total air emissions, were omitted for Arizona. Louisiana emitted 380 million lb in its top five chemicals, almost eight times more than Arizona, with 50 million lb of these five components. The CMU-ET index for Louisiana was also higher than for Arizona. However, the toxicity ratios for Arizona are higher than those for Louisiana.

This example indicates that a state may be a more serious polluter in terms of the toxicity of its discharges than its EPA rank may suggest. Clearly, the

TABLE 4

Comparing states: Louisiana and Arizona

The CMU-ET and the toxicity ratio for 1991 total discharges and emissions data. On the basis of mass, Louisiana is a worse polluter than Arizona. However, the toxicity ratios are much greater for Arizona. If the toxicity ratios applied to all discharges, the toxicity weighted total discharges and air emissions (CMU-ET) would be greater for Arizona than for Louisiana, indicating that a mass-based index is inaccurate and misleading.

	Total releases (10^4 lb)		Total air emissions (10^4 lb)	
1991	Louisiana	Arizona	Louisiana	Arizona
EPA-TRI	37,629	4985	5418	88
$EPA\text{-}TRI_{TLV}$	35,839	2022	4830	21
CMU-ET	23,020	11,017	398	122
Toxicity ratio	0.64	5.45	0.08	5.81

Emissions data are taken from Reference 17, TLVs from Reference 12.

EPA-TRI is total emissions per year, in pounds (10^4 lb). $EPA\text{-}TRI_{TLV}$ is total releases for which TLVs are known, in pounds (10^4 lb). CMU-ET is the equivalent weight of toxic releases, in pounds (10^4 lb). Toxicity ratio is CMU-ET divided by $EPA\text{-}TRI_{TLV}$.

mass-based ranking is not supportable as the basis of identifying the "most polluted" states.

Conclusion

The TRI is a powerful data source for evaluating the potential environmental and health effects of industrial plants. However, summarizing the data in terms of pounds of total discharges may be misleading. The use of equal weights for chemicals of widely differing toxicities can pressure companies into making abatement decisions that may increase health risks, even though the company is reducing its total weight of discharges.

The toxicity weighted emissions indices have substantial limitations. They must be interpreted carefully and used only to compare or track environmental performance over time and space. They should be thought of as first approximations to health effects because they deal with discharges, not environmental transport and human exposure; many chemicals have no toxicity weight and are ignored in our analysis; and the ACGIH TLV-TWA indices are only approximations to the health effects that would be expected from low-level exposure in the environment. Finally, the current data do not come from careful measurements but rather are general estimates for a number of large plants in a few specific industries. Despite these major limitations, in our judgment, a toxicity-based measure is a useful step in modifying the TRI to provide better information for company, government, and consumer environmental decisions.

Pollution prevention requires environmentally conscious decisions early in the design stage. The toxicity weighted emissions ranking might be used to decide on the relative "greenness" of a process or a product on the basis of expected discharges. It is capable of providing comparisons among alternatives from the local to the national level. Toxicity weighting should prove to be a useful tool for designers and corporate managers to lower the environmental burden of their products and companies. The CMU-ET and toxicity ratio indices are simple to use and interpret, even for people with no toxicological training.

Current rankings that mark industries and other participants in the environmental domain as "best performers" and "laggards" have major flaws. A meaningful, toxicity-based, transparent method would be superior. Future steps should include correcting the TRI so that human exposures can be estimated from the discharges. In addition, the TRI coverage should be expanded to more industries and more chemicals/chemical categories, along with improving the data accuracy.

Acknowledgments

Financial support from the IBM Environmental Research Program and the Green Design Consortium of Carnegie Mellon University's Engineering Design Research Center and Environmental Institute are gratefully acknowledged. Two reviewers, Dick Morgenstern, other EPA employees, and numerous industrial colleagues made helpful suggestions.

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