Journal of Hazardous Materials, 27 (1991) 327-337
Elsevier Science Publishers B.V., Amsterdam

A relative risk index for prioritization of inactive underground storage tanks

Venkatesh Chidambariah[a], Curtis C. Travis[a,*], John R. Trabalka[b] and Janice K. Thomas[a]

*Office of Risk Analysis, [a]Health and Safety Research Division, and [b]Environmental and Health Protection Division, Oak Ridge National Laboratory**, P.O. Box 2008, Oak Ridge, Tennessee 37831-6109 (USA)*

(Received October 30, 1990; accepted in revised form March 20, 1991)

Abstract

A relative risk index (RRI) is proposed for ranking the relative health risk potential of mixed liquid wastes in underground storage tanks (USTs) that are scheduled for remedial action. The RRI is defined as the number of reference volumes in the liquid volume of a tank. A reference volume is the amount of liquid a person must ingest over a lifetime to incur either a 10^{-6} lifetime cancer risk or a noncarcinogenic reference dose level exceeding one. The RRI accounts for contaminant concentration, contaminant toxicity, and the tank's liquid volume. The higher the number of reference volumes in a tank, the higher the relative risk potential of the tank. The RRI may be incorporated into any of the existing hazard ranking systems used for UST remediation.

1. Introduction

The use of USTs for storing petroleum products and hazardous waste has been a widespread practice in the United States. The U.S. Environmental Protection Agency (EPA) estimates that approximately three to five million underground storage tanks are located in the U.S., and that approximately 10% of these tanks store hazardous waste [1]. EPA is responsible for registration and regulation of USTs and has published interim status standards for owners and operators who use tank systems for storing or treating hazardous waste (40 CFR, Part 265, Subsection J—Tank Systems). These regulations require that tank systems from which there have been leaks or spills, or that are unfit for use, be removed from service immediately. The magnitude of the task of completing tank integrity examinations and the costs associated with immediate removal and replacement of several thousand tanks have prompted the

*To whom correspondence should be addressed.

**Operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under Contract No. DE-AC05-84OR21400.

0304-3894/91/$03.50

development of hazard ranking systems to prioritize tank removal. The use of such ranking systems helps ensure that tanks with the greatest potential for adverse impact on the environment and on human health receive first priority for further testing or closure.

Several states have developed distinct hazard ranking systems to prioritize leaking underground storage tanks for closure or interim corrective measures. EPA's Office of Policy, Planning, and Evaluation (OPPE), in cooperation with the Office of Underground Storage Tanks (OUST), has published a compendium of state priority-setting systems for use as a guideline for other states in developing their own priority systems for responding to leaking USTs [2,3]. In general, the following factors are considered in most hazard ranking systems used to prioritize tanks for remedial action:

(a) Leaking characteristics of the tank (e.g., rate, volume lost, structural integrity)
(b) Impact on water supplies (groundwater, surface water)
(c) Potential for explosion
(d) Presence of toxic vapors
(e) Toxicity
(f) Contaminant characteristics (e.g., mobility, persistence) in affected media
(g) Effect of contaminants on the environment.

This paper presents a risk-based methodology for incorporating toxicity into existing hazard ranking systems. Toxicologic properties of contaminants, their concentrations in the waste, and the liquid volumes in the tanks are combined into a single unitless metric to determine the relative health risk potential of a tank. This index is particularly applicable for ranking the relative risk potential of USTs containing complex mixtures of liquid waste, i.e., carcinogenic and noncarcinogenic chemicals and radionuclides, in varying quantities and varying levels of toxicity, and in varying liquid volumes in the tanks. This method provides the means for combining these disparate UST-content data into a single relative risk index (RRI) for each tank. The RRI can be incorporated into existing hazard ranking systems that contain other prioritization factors.

Only contaminants in the liquid phase are considered in this assessment because liquid contaminants have the greatest potential for migration in the event of a leak and therefore have the greatest potential for adversely impacting the environment and human health.

2. Methodology

The calculation of RRI involves three steps: (1) determining the lifetime doses via the ingestion pathway for each chemical and radionuclide; (2) determining the reference volume for complex mixtures in each tank; and (3) determining the number of reference volumes in each tank. Data needed to calculate RRI for each UST include (1) the concentrations of the contaminants of concern in the tank liquid; (2) the toxicity of the contaminants as determined by the cancer potency factors (for radionuclides and carcinogenic chemicals) and reference doses (for noncarcinogenic chemicals and noncarcinogenic effects of carcinogens); and (3) the liquid volume of the tank.

When complex mixtures of liquid waste exist, risk from simultaneous exposure to multiple contaminants must be considered. The calculation of the RRI is compatible with EPA guidelines for a health risk assessment of chemical mixtures [4] and with EPA guidance for calculating exposure to multiple substances at Superfund sites [5].

EPA's guidance for calculating exposure to multiple carcinogens and multiple noncarcinogens is based on the assumption of dose additivity. Cancer risk from exposure to multiple carcinogenic contaminants is estimated as

$$\mathrm{Risk_T} = \sum \mathrm{Risk}_i$$

where $\mathrm{Risk_T}$ denotes the total cancer risk, expressed as a unitless probability; and Risk_i the risk estimate for the ith contaminant.
A cancer risk range of 10^{-6} to 10^{-7} has been set as a site remediation goal for Superfund sites [5]. A 10^{-6} lifetime risk for carcinogens is used as the acceptable remediation level in these calculations.

For exposure to mixtures of noncarcinogenic contaminants, the hazard index (HI) is calculated as the sum of the hazard quotients,

$$\mathrm{HI} = \sum \mathrm{E}_i/\mathrm{RfD}_i$$

where E_i is the exposure level (mg/kg·day) for the ith contaminant; and RfD_i the reference dose (mg/kg·day) for the ith contaminant.
The exposure level and reference dose should represent the same exposure period (i.e., chronic, subchronic, or shorter-term). A sum equal to one is considered acceptable while a sum greater than one indicates there may be a concern for potential health effects. In complex mixtures, it is possible for the hazard index to exceed unity even if no single contaminant exposure exceeds its RfD. Additionally, EPA recommends that RfDs for noncarcinogenic effects of carcinogenic contaminants be included in the calculation of the noncarcinogenic hazard index [5].

While the relative risk methodology presented in this paper is an extension of the EPA methodology for assessing risks of exposure to chemical mixtures [5], the concept of "reference volume" is a new concept that combines in a single measure both the toxicity and the volume of the constituents in a UST. It also provides the waste manager a methodology for comparing radionuclides and chemicals on a common scale. EPA recommends caution when adding risk due to multiple contaminant exposure in a traditional baseline risk assessment. However, in a UST priorization scheme where only the *relative risk* between USTs is of consequence, that caution is not warranted.

2.1 Lifetime dose

The first step in computing relative risk is to determine lifetime doses (LD). The lifetime dose is defined as the total dose (mg) that a person would ingest over a lifetime if that person's daily intake equals the reference dose level for noncarcinogens or the 10^{-6} risk lifetime level for carcinogens. Reference doses (RfD) for noncarcinogenic chemicals, cancer potency factors (CPF) for nonradioactive carcinogenic chemicals, and cancer slope factors (CSF) for radionuclides are defined in the Superfund Health Assessment Document [6]. A more detailed description of LDs follows.

2.1.1 Noncarcinogenic chemicals

For noncarcinogenic chemicals, LD is defined as the total dose a person would ingest over a lifetime if that person's average daily intake exceeds the reference dose. The LD is a product of reference dose (mg/kg·d), reference body weight (70 kg), and average lifetime exposure (70 y):

$$\text{LD (mg)} = \text{RfD(mg/kg·d)} \times 70\ \text{(kg)} \times 70\ \text{(y)} \times 365\ \text{(d/y)}.$$

2.1.2 Nonradioactive carcinogenic chemicals

For nonradioactive carcinogenic chemicals, LD is defined as the total dose a person would ingest over a lifetime if that person's average daily intake of carcinogens produced a 10^{-6} lifetime risk level. Here, LD is a product of the acceptable lifetime cancer risk (10^{-6}), the reference body weight (70 kg), and average lifetime exposure (70 y), divided by the oral cancer potency factor (CPF):

$$\text{LD (mg)} = \frac{10^{-6} \times 70\ \text{(kg)} \times 70\ \text{(y)} \times 365\ \text{(d/y)}}{\text{CPF (mg/kg·d)}^{-1}}$$

2.1.2 Radionuclides

For radionuclides, LD is defined as the total dose of radioactivity a person would ingest over a lifetime if that person's average daily dose produced a 10^{-6} lifetime risk level. In this case LD is the acceptable lifetime cancer risk level (10^{-6}) divided by the oral cancer slope factor (pCi^{-1}):

$$\text{LD (pCi)} = \frac{10^{-6}}{\text{CSF (pCi}^{-1})}.$$

2.2 Reference volume

The second step in computing relative risk is to determine a *reference volume* for the complex mixture found in the liquid of the tank. A reference volume is the volume of liquid from the tank that a person must ingest over a lifetime so that the hazard index from such an exposure would equal one, or the lifetime cancer risk would be 10^{-6}.

Before the reference volume for a complex mixture can be determined, a critical volume for each contaminant must be computed. The critical volume is the volume (V_i) of a liquid containing the *i*th contaminant that a person must ingest to receive the lifetime dose (LD_i) for that contaminant. The critical volume is computed as the *i*th contaminant's lifetime dose divided by its concentration (C_i) in the liquid:

$$V_i = LD_i / C_i.$$

Concentrations for chemicals are expressed in mg/L. Concentrations for radionuclides are expressed in pCi/L. The critical volumes for noncarcinogens and carcinogens exhibiting noncarcinogenic effects are used to compute the noncarcinogenic reference volume (NRV) and the critical volumes for nonradioactive carcinogens and radionuclides are used to compute the carcinogenic reference volume (CRV).

The noncarcinogenic reference volume (NRV) is defined as the volume of liquid containing a complex mixture of noncarcinogens, and carcinogens exhibiting noncarcinogenic effects, that a person must ingest to reach a noncarcinogenic hazard index of unity. Thus,

$$\mathrm{NRV} = \left(\sum \frac{1}{V_i}\right)^{-1},$$

where V_i is the critical volume for the *i*th noncarcinogenic contaminant.

The carcinogenic reference volume (CRV) is defined as the volume of a complex mixture of radioactive and nonradioactive carcinogens that a person must ingest to have a total lifetime cancer risk of 10^{-6}. Thus,

$$\mathrm{CRV} = \left(\sum \frac{1}{V_i}\right)^{-1},$$

where V_i is the critical volume of the *i*th radioactive or nonradioactive carcinogenic contaminant. Because procedures differ for calculating carcinogenic and noncarcinogenic effects, the NRV and the CRV are not added together. The smaller, or most potent, of these two reference volumes is used as the reference volume for a tank.

2.3 Relative risk

The last step in computing relative risk is to determine the number of reference volumes found in the liquid volume of a tank. This step takes into account both the toxicity and lifetime doses of the contaminants (i.e., the reference volume) and the volume of the contaminants in the liquid of the tank. To calculate relative risk for a UST, liquid volume of the tank is divided by the reference volume. The higher the number of reference volumes in a tank, the greater the relative risk of the liquid waste:

$$\text{Relative risk} = \frac{\text{Liquid volume}}{\text{Reference volume}}$$

3. Application

Radioactive and hazardous chemical wastes have been produced from normal facility operations at Oak Ridge National Laboratory (ORNL) since its inception in 1943; low level liquid radioactive and chemical wastes have often been stored on-site in underground storage tanks. Approximately 40 of these tanks have been declared inactive and remediation of the inactive tanks is required by U.S. Environmental Protection Agency (EPA) regulations. The relative risk index was developed in conjunction with an overall risk-based hazard ranking system to prioritize the inactive tanks for further evaluation for interim corrective measures. This intermediary step to remediation was taken prior to receiving sufficient sampling data necessary to conduct a comprehensive risk assessment [7]. One of the 40 inactive USTs located at ORNL is used to illustrate the methodology described above.

3.1 Sample tank characterization

The sample tank selected from the 40 inactive USTs located at ORNL contains a liquid volume of 77,044 gallons (308,000 L) of mixed liquid wastes including noncarcinogenic and carcinogenic chemicals and radionuclides. The specific contaminants of concern and their concentrations in the liquid volume of the tank are provided below in Table 1.

3.2 Calculation of lifetime doses (LD)

3.2.1 Noncarcinogenic chemicals

For the following noncarcinogenic UST chemicals, methyl ethyl ketone, chromium (VI), mercury, and lead, the LDs are:

(1) Methyl ethyl ketone

$$\text{LD (mg)} = 5.0\cdot10^{-2}\ (\text{mg/kg}\cdot\text{day}) \times 70\ (\text{kg}) \times 70\ (\text{y}) \times 365\ (\text{day/y}) = 89425\ \text{mg}$$

(2) Chromium (VI)

$$\text{LD (mg)} = 5.0\cdot10^{-3}\ (\text{mg/kg}\cdot\text{day}) \times 70\ (\text{kg}) \times 70\ (\text{y}) \times 365\ (\text{day/y}) = 8942.5\ \text{mg}$$

(3) Mercury

TABLE 1

Contaminants of concern and their concentrations in the liquid volume of the UST

Contaminants of concern	Concentration
Noncarcinogenic chemicals	
Methyl ethyl ketone	0.075 mg/L
Chromium (VI)	32.0 mg/L
Mercury	0.07 mg/L
Lead	1.05 mg/L[a]
Carcinogenic chemicals	
Trichloroethylene	0.082 mg/L
Tetrachloroethylene	0.507 mg/L
Carbon tetrachloride	0.004 mg/L
Radionuclides	
^{137}Cs	$5.4 \cdot 10^{8}$ pCi/L
^{90}Sr	$1.3 \cdot 10^{7}$ pCi/L

[a]Concentration for lead based on 50% of the detection limit for lead (<2.1 mg/L).

$$\text{LD (mg)} = 1.6 \cdot 10^{-4}\ \text{(mg/kg·day)} \times 70\ \text{(kg)} \times 70\ \text{(y)} \times 365\ \text{(day/y)} = 286.16\ \text{mg}$$

(4) Lead[1]

$$\text{LD (mg)} = 5.0 \cdot 10^{-2}\ \text{(mg/L)} \times 2\ \text{(L/day)} \times 70\ \text{(y)} \times 365\ \text{(day/y)} = 2555\ \text{mg}$$

3.2.2 Noncarcinogenic effects of carcinogens[2]

The LDs for noncarcinogenic effects of the UST carcinogens tetrachloroethylene and carbon tetrachloride are:

(5) Tetrachloroethylene

$$\text{LD (mg)} = 1.0 \cdot 10^{-2}\ \text{(mg/kg·day)} \times 70\ \text{(kg)} \times 70\ \text{(y)} \times 365\ \text{(day/y)} = 17{,}885\ \text{mg}$$

(6) Carbon tetrachloride

[1]No reference dose for lead has been determined. A reference dose was calculated using the maximum contaminant level (MCL) for lead in drinking water; calculation assumes 2 liters of water are ingested per day/per person. Although calculations based on the MCL may not accurately reflect a reference dose, the calculated dose is used as the default dose for purposes of assessing relative risk potential between USTs.

[2]No RfD for trichloroethylene found.

$$LD\ (mg) = 7.0\cdot 10^{-4}\ (mg/kg\cdot day)\times 70\ (kg)\times 70\ (y)\times 365\ (day/y) = 1252\ mg$$

3.2.3 Carcinogenic chemicals

Lifetime doses for carcinogenic effects of the UST carcinogens tri- and tetrachloroethylene, and carbon tetrachloride are:

(1) Trichloroethylene

$$LD\ (mg) = \frac{10^{-6}\times 70\ (kg)\times 70\ (y)\times 365\ (day/y)}{1.1\cdot 10^{-2}\ (mg/kg\cdot day)^{-1}} = 162.75\ mg$$

(2) Tetrachloroethylene

$$LD\ (mg) = \frac{10^{-6}\times 70\ (kg)\times 70\ (y)\times 365\ (day/y)}{5.1\cdot 10^{-2}\ (mg/kg\cdot day)^{-1}} = 35.77\ mg$$

(3) Carbon tetrachloride

$$LD\ (mg) = \frac{10^{-6}\times 70\ (kg)\times 70\ (y)\times 365\ (day/y)}{1.3\cdot 10^{-1}\ (mg/kg\cdot day)^{-1}} = 13.77\ mg$$

3.2.4 Radionuclides

The LDs for cesium-137 and strontium-90 are:

(4) ^{137}Cs

$$LD\ (pCi) = 10^{-6}/2.8\cdot 10^{-11}\ (pCi^{-1}) = 3.6\cdot 10^{4}\ (pCi)$$

(5) ^{90}Sr

$$LD\ (pCi) = 10^{-6}/3.3\cdot 10^{-11}\ (pCi^{-1}) = 3.0\cdot 10^{4}\ (pCi)$$

3.3 Calculation of critical volumes

From the above calculated lifetime doses and the characteristic concentrations of the compounds in the UST, the critical volumes are calculated.

3.3.1 Noncarcinogenic chemicals

(1) Methyl ethyl ketone

$$V_1 = 89425\ mg/0.075\ mg/L = 1{,}192{,}333\ L$$

(2) Chromium (VI)

$V_2 = 8942.5 \text{ mg}/32 \text{ mg/L} = 279.45 \text{ L}$

(3) Mercury
$V_3 = 286.16 \text{ mg}/0.07 \text{ mg/L} = 4080 \text{ L}$

(4) Lead
$V_4 = 2555 \text{ mg}/1.05 \text{ mg/L} = 2433.3 \text{ L}$

3.3.2 Carcinogens with noncarcinogenic effects

(5) Tetrachloroethylene
$V_5 = 17{,}885 \text{ mg}/0.507 \text{ mg/L} = 35{,}276 \text{ L}$

(6) Carbon tetrachloride
$V_6 = 1252 \text{ mg}/0.004 \text{ mg/L} = 313{,}000 \text{ L}$

3.3.3 Carcinogenic chemicals

(1) Trichloroethylene
$V_1 = 162.75 \text{ mg}/0.082 \text{ mg/L} = 1984.76 \text{ L}$

(2) Tetrachloroethylene
$V_2 = 35.77 \text{ mg}/0.507 \text{ mg/L} = 70.55 \text{ L}$

(3) Carbon tetrachloride
$V_3 = 13.77 \text{ mg}/0.004 \text{ mg/L} = 3442.5 \text{ L}$

3.3.4 Radionuclides

(4) ^{137}Cs

$$V_4 = \frac{3.6 \cdot 10^4 \text{ (pCi)}}{5.4 \cdot 10^8 \text{ (PCi/L)}} = 6.7 \cdot 10^{-5} \text{ L}$$

(5) ^{90}Sr

$$V_5 = \frac{3.0 \cdot 10^4 \text{ (pCi)}}{1.3 \cdot 10^7 \text{ (PCi/L)}} = 2.3 \cdot 10^{-3} \text{ L}$$

3.4 Calculation of reference volumes

3.4.1 Noncarcinogenic reference volume

$$\begin{aligned} \text{NRV} &= [\textstyle\sum 1/V_i]^{-1} \\ &= [1/V_1 + 1/V_2 + 1/V_3 + 1/V_4 + 1/V_5 + 1/V_6]^{-1} \\ &= [1/1{,}192{,}333 \text{ L} + 1/279.45 \text{ L} + 1/4080 \text{ L} + 1/2433.3 \text{ L} + 1/35{,}276\text{L} \\ &\quad + 1/313{,}000 \text{ L}]^{-1} \\ &= [4.271 \cdot 10^{-3} \text{ 1/L}]^{-1} \end{aligned}$$

$= 234.15\ \mathrm{L}$

Note that NRV is mostly determined by the Cr (VI) critical volume value.

3.4.2 Carcinogenic reference volume

$$\begin{aligned}\mathrm{CRV} &= [\Sigma\, 1/V_i]^{-1}\\ &= [1/V_1 + 1V_2 + 1/V_3 + 1/V_4 + 1/V_5]^{-1}\\ &= [1/1984.76\ \mathrm{L} + 1/70.55\ \mathrm{L} + 1/3442.5\ \mathrm{L} + 1/6.7\cdot 10^{-5}\ \mathrm{L} + 1/2.3\cdot 10^{-3}\ \mathrm{L}]^{-1}\\ &= [15360.17\ 1/\mathrm{L}]^{-1}\\ &= 6.5\cdot 10^{-5}\ \mathrm{L}\end{aligned}$$

Note that CRV is almost completely determined by the cesium-137 critical volume value.

3.5 Calculation of relative risk index (RRI)

$$\mathrm{RRI} = \frac{\text{Total liquid volume all USTs}}{\text{Carcinogenic reference volume}} = \frac{77{,}044\ \text{gal} \times 3.8\ (\text{L/gal})}{6.5\cdot 10^{-5}\mathrm{L}} = 4.5\cdot 10^{9}$$

3.6 Ranking of sample tank

The RRIs calculated for the 40 inactive USTs located at ORNL ranged from less than 10^2 to greater than 10^8. To ensure that the calculated RRIs for the tanks were compatible with other ranking criteria used during the ORNL tank ranking exercise, the range ($<10^2$, $>10^8$) of RRIs was divided into five groups and assigned scores as provided in Table 2 below:

The sample tank, with a RRI of $4.5\cdot 10^9$, received the highest priority in terms of relative risk for removal or remedial action. This ranking was combined with assigned scores for other ranking criteria to determine the sample tank's overall ranking.

TABLE 2

Ranking of RRIs calculated for the 40 inactive USTs located at Oak Ridge National Laboratory

Relative risk index	Score
$>10^8$	5
10^8 to 10^6	4
10^6 to 10^4	3
10^4 to 10^2	2
$<10^2$	1

4. Conclusions

An index is proposed for ranking the relative risk potential of mixed liquid wastes in underground storage tanks (USTs). Through the use of RRI, the relative risk potential of USTs containing wastes of various composition, toxicity, and volume can be ranked on a common scale. The use of the RRI should prove to be particularly valuable in the evaluation of the relative risk potential of tanks with complex waste mixtures.

References

1 A.D. Young, Jr., M.A. Barbara, J.P. Miller, R.W. Kane and W. Rogers, Underground Storage Tank Management: A Practical Guide, 2nd ed., Government Institutes, Inc. Rockville, MD, 1987.

2 U.S. Environmental Protection Agency, Compendium of State LUST Priority-Setting Systems, Prepared in conjunction with State UST Programs by the Office of Policy, Planning, and Evaluation, and the Office of Underground Storage Tanks, Washington, DC, 1989.

3 U.S. Environmental Protection Agency, Enhanced Ranking Systems, Office of Policy, Planning, and Evaluation, and Office of Underground Storage Tanks, Washington, DC, 1989.

4 U.S. Environmental Protection Agency, Guidelines for the Health Risk Assessment of Chemical Mixtures, 51 Federal Register 34014, September 24, 1986.

5 U.S. Environmental Protection Agency, Risk Assessment Guidance for Superfund. Volume I: Human Health Evaluation Manual. Interim Final, Office of Emergency and Remedial Response, Washington, DC, 1989.

6 U.S. Environmental Protection Agency, Superfund Health Effects Assessment Summary Tables and User's Guide. 4th Quarter FY89, Washington, DC, 1989.

7 V. Chidambariah, C.C. Travis, J.R. Trabalka and J.K. Garrett, A Risk-based Approach to Prioritize Inactive Low Level Liquid Radioactive Waste Underground Storage Tanks for Further Evaluation For Interim Corrective Measures, Office of Risk Analysis report, Oak Ridge National Laboratory, Oak Ridge, TN, June, 1990.