



UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

Oct. 16

162
JRC
JRG
JYK
KSD
file

December 21, 1992

NOTE TO COMMISSIONER ASSISTANTS

OCM/IS

- Dennis Rathbun
- Karen Cyr
- Rebecca Nease
- Jim Johnson
- Chuck Casto
- Dan Martin
- Janice Dunn-Lee
- Bob McOsker
- Gerry Schuetze
- Donna Smith
- Carol Augustino
- Darlene Wright

OCM/KR

- Myron Karman
- Mort Fleishman
- Jack Scarborough
- Seth Coplan
- Lil Van Cise
- Patty Whitten

OCM/FR

- Steve Crockett
- Regis Boyle
- Beth Doolittle
- Jack Guttmann
- Jeanne Shoemaker
- Joanne Field

OCM/JC

- Jos Gray
- Dave Trimble
- Kevin Connaughton
- Kitty Dragonette
- Janet Kotra
- Gigi Rammling
- Ann Haikalis


OCM/GdeP

- Neil Jensen
- Eileen McKenna
- Joel Lubenau
- Kay Whitfield
- Evelyn Williams
- Jeanne Mullikin
- Connie Shum

FROM: James L. Blaha, AO/OEDO

SUBJECT: RISK COMPARISON

Enclosed is a prepublication copy of a paper which will appear in the Journal of Hazardous Materials. It provides a future risk estimate for hazardous waste which may be compared with human intrusion risks for high-level waste disposal.


James L. Blaha, AO/OEDO

Enclosure:
As stated

- cc: J. Taylor, EDO
- J. Sniezek, DEDR
- H. Thompson, DEDS
- J. Blaha, AO/OEDO
- R. Bernero, NMSS
- SECY
- OGC

9401060060 931116
PDR COMMS NRCC
CORRESPONDENCE PDR

**Future Risk From A Hypothesized RCRA Site Disposing Of
Carcinogenic Metals Should A Loss Of Societal Memory Occur**

**David Okrent* and Leiming Xing
Dept. of Mechanical, Aerospace and Nuclear Engineering
48-121 Engineering IV
University of California, Los Angeles
Los Angeles, CA 90024**

Abstract

The future risk of a hypothesized RCRA site disposing of carcinogenic metals, Arsenic, Chromium, Nickel, and Cadmium, is assessed. Societal memory is assumed to be lost regarding the site. A human intrusion scenario on the site and a residential scenario 1 kilometer down-gradient of the groundwater flow direction from the site are assumed, starting at 1000 years after the site closure. For the human intrusion scenario, the exposure pathways considered are fruit and vegetable intake, soil ingestion, and dermal contact with soil. The quantitative results obtained for the three pathways are as follows: lifetime excess cancer risk due to fruit and vegetable intake is 0.30; risk due to dermal contact with the soil is 0.13; and risk due to soil ingestion is 2.9×10^{-3} . For the residential scenario, only qualitative discussion of exposure via groundwater is presented due to the large uncertainties.

The U.S. EPA attention to and requirements concerning long-term risk from RCRA sites containing metal carcinogens, which never change due to radioactive decay, stand in sharp contrast to the stringent requirements over 10,000 years posed by EPA for geologic disposal of high level radioactive wastes, and the long-term requirements posed by the U.S. Nuclear Regulatory Commission for low level radioactive waste disposal sites.

* To whom the proofs are to be sent.

I. Introduction

Toxic metals are usually considered persistent in the environment in that, unlike radioactive isotopes, metals do not decay in the environment. This raises a serious concern about whether and how we can dispose of the wastes containing such toxic metals, given that society chooses to use them. As is well known, in 40 CFR 191 (remanded), EPA poses stringent requirements, including loss of societal memory, over 10,000 years for geologic disposal of high level radioactive wastes, despite the presence of markers at the site[1]. Also, the U.S. Nuclear Regulatory Commission (USNRC) requires long-term risk assessment for low level radioactive waste disposal sites[2]. This paper is to address the disparity between the EPA regulation regarding carcinogenic metals and the requirements posed on high level radioactive wastes.

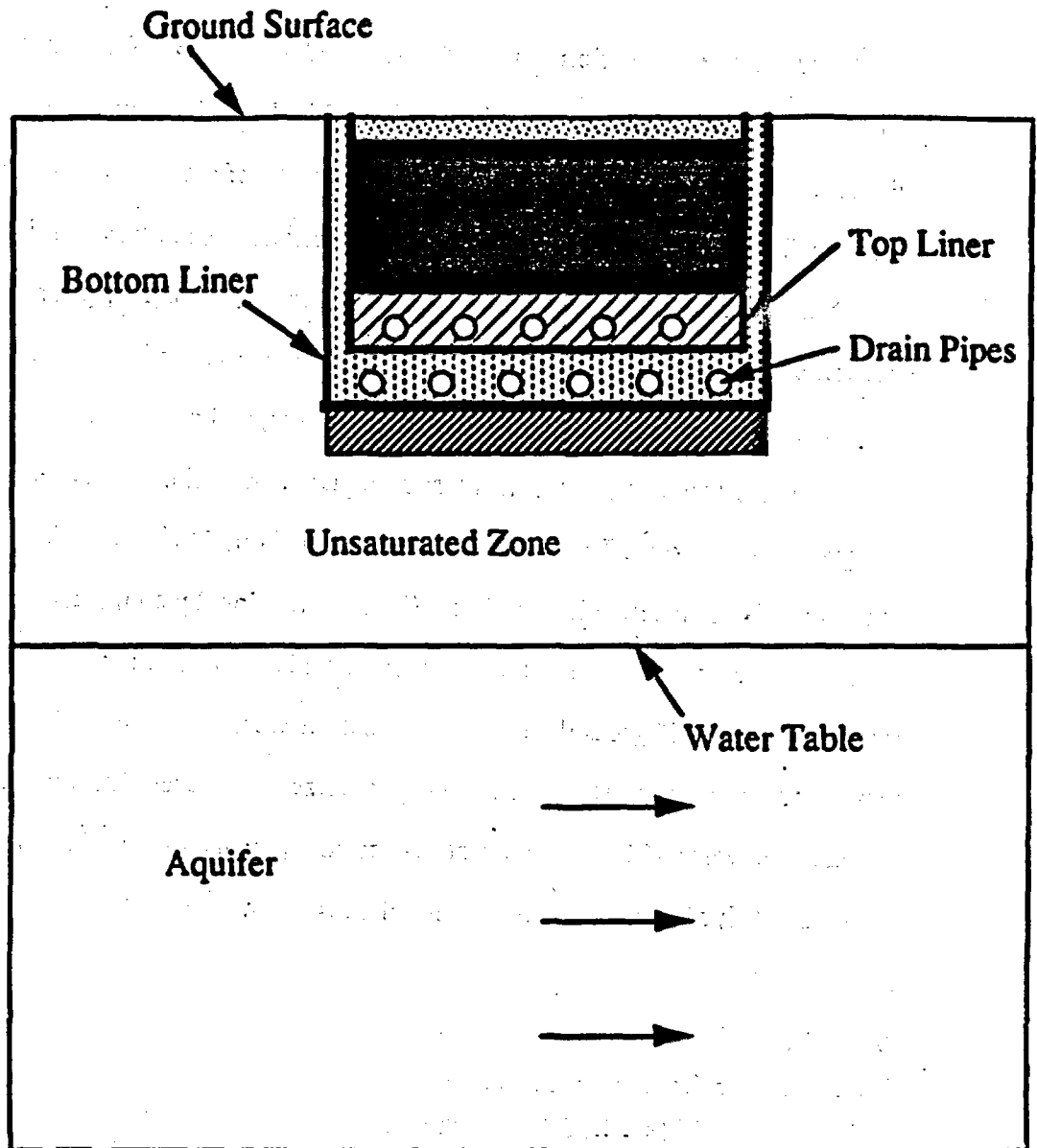
Four metals with potential carcinogenicity are the focus of this paper. These are arsenic, cadmium, chromium, and nickel. The future risks of a hypothesized Resource Conservation and Recovery Act (RCRA) site which disposed of these metals are assessed herein using similar scenarios and assumptions to those of a high level or a low level radioactive waste disposal site risk assessment[2]. Among the important assumptions, societal memory is assumed lost regarding the hypothesized RCRA site; human intrusion may occur at the site; and there may be a residential scenario down gradient of the groundwater flow direction.

Section II is a description of the hypothesized RCRA site. Section III is a review of toxicity and current usage of four carcinogenic metals. Section IV discusses the waste treatment and treatment standards imposed by EPA. Section V hypothesizes a RCRA site inventory that meets the current EPA requirements. Section VI assumes scenarios for the future risk analysis; these include the human intrusion scenario and residential scenario. Section VII discusses models of several exposure pathways as well as presents qualitative discussion on groundwater contamination. Section VIII presents results for the human intrusion scenario. Section IX is a discussion concerning the implications of this analysis.

II. Site Description

Figure 1 shows a hypothesized RCRA site. This site is assumed to be used to dispose of wastes containing several carcinogenic metals and their compounds. These wastes need to be treated before being disposed of. After treatment, different kinds of containment, such as Above Grade Mound, Above Grade Vault and Above Grade Building as well as Below Grade Landfill[3], can be used to hold the wastes. The difference between above grade and below grade containment is that the below grade containment holds the wastes below the ground surface. In this analysis, it is assumed that the RCRA site uses a Below Grade Landfill with double liners and leachate collection system. The basic design features of the hypothesized site are similar to those of the waste sites reported by the Minnesota Waste Management Board[3]. As shown in figure 1, the lowermost layer is recompacted clay with at least 3 feet thickness. This layer of clay has low permeability. On top of the clay is a secondary flexible membrane liner which is at least 30 mils (0.03 inch) thick[3]. Above the liner is the secondary leachate collection system which is able to drain off fluid which would reach the liner. Above the secondary leachate collection system is the primary flexible membrane liner. It is also required to be at least 30 mils thick. On the top of this liner lies the primary leachate collection system. The primary leachate collection system is covered by a permeable membrane over which the waste is placed. Above the wastes, there are vegetative caps. The caps might consist of three layers, as used in a low level radioactive waste site[2]. The bottom layer is a low-permeability clay, the middle layer a silt loam, and the top layer is the original undisturbed soil. The total thickness of these layers might be 2 meters.

About the location of the hypothesized site, the EPA requirement is the following according to Wagner[4]: "Currently, the only location restrictions are: The facility must be at least 200 feet from an active (during the last 10,000 years) Holocene fault; Facilities in a 100-year flood plain must be designed to prevent washout from 100-year floods."



Legend:






- | | | | |
|---|---------------------------|---|---------------------------|
|  | Caps |  | Wastes |
|  | Drainage Materials |  | Drainage Materials |
|  | Recompacted Clay | | |

Fig. 1 A Hypothesized RCRA Site

"More stringent location standards, as mandated by HSWA (Hazardous and Solid Waste Amendments), are expected to be issued in 1992. The purpose of these standards will be to create national requirements for the location of the hazardous waste management facilities. These requirements will contain restrictions based on proximity to populations, vulnerable hydrogeology, seismic zones, 100-year flood plains, poor foundation areas, subsidence-prone areas, landslide-prone areas, wetlands, and karst terranes (limestones areas with fissures, sink-holes, underground streams, and caverns)."

While not violating the current site requirements, the site is assumed on a local topographic high point. The water table is located about 24 meters below the land surface. The aquifer is 25 meters thick and is confined from below by an impermeable bedrock.

Table 1 lists the geological parameters which could be used to characterize the hypothesized site if groundwater contamination were to be studied. The choice of this parameter set is consistent with a hypothesized site used for disposal of low-level radioactive wastes[2]. The characteristics are permissible under the current RCRA regulations [4]; of course, a wide variety of sites are in actual use.

TABLE 1
Parameters for the Hypothesized Site
 (Adapted from Table 4-1 of Reference [2])

Average Annual Infiltration	25 cm/year
Thickness of Unsaturated Zone	24 m
Saturated Hydraulic Conductivity of Unsaturated Zone	115.3 m/year
Porosity of Unsaturated Zone	0.52
Thickness of Aquifer	25 m
Hydraulic Conductivity of Aquifer	115.3 m/year
Hydraulic Gradient of Aquifer	0.02
Porosity of Aquifer	0.52
Average Pore Velocity of Aquifer	4.44 m/year
Longitudinal Dispersivity of Aquifer	2 m
Transverse Dispersivity of Aquifer	0.2 m

Actual sites would vary in their characteristics from that of the hypothesized site. For example, porosity might be 0.35. However, such differences are not important herein since these site characteristics were not used in these calculational results. A groundwater source was not modeled quantitatively in the risk assessment.

III. Toxicity and Current Usage of Several Carcinogenic Metals

The contaminants considered in the sites are several metals and their compounds. Four metals which are carcinogenic are listed in Table 2 [5]. In the EPA weight-of evidence classification system for carcinogenicity, A stands for human carcinogen, and B1 stands for probable human carcinogen. Arsenic, chromium (6), and nickel (subulfide) are considered by EPA to be sufficient for them to be labeled as carcinogens. For cadmium, EPA considers human evidence as to its carcinogenicity to be limited; hence cadmium is ranked lower (category B1) in Table 2.

TABLE 2

**Carcinogenic Group of Metals
(Adapted from Reference [5])**

Metal	EPA Group	Description
As	A	Carcinogen,sufficient human evidence.
Cd	B1	Carcinogen,limited human evidence.
Cr(6)	A	Carcinogen,sufficient human evidence.
Ni(subulfide)	A	Carcinogen,sufficient human evidence.

Annual production of these four metals are listed in Table 3 [6]. It can be seen that the amount of metals used is large. After the the technologically useful lifetime of those products containing these metals, one or more RCRA sites is needed to dispose of them. Recycle of all the metals is impractical. The costs to separate and encapsulate the vast tonnage of most of these widely used carcinogens would be very large, even more so for existing wastes.

TABLE 3
Annual Production of the Four Metals
(Data Collected from References [6])

Metal	Total World Annual Production (Metric Tons)	Year of Production
As	60,000 tons	1975-1977
Cd	12,000 tons	1980
Cr	8,600,000 tons	1976
Ni	660,000 tons	1973

The cancer potency factor of these four metals are listed in Table 4 [5]. It is usually expressed as excess lifetime cancer risk after 70 - year exposure to a chemical at an administered dose of 1 mg per kg of body weight per day. The cancer potency factor is also known as the slope factor, which is usually, but not always, the upper 95th percent confidence limit of the slope of the dose-response curve and is expressed as $(\text{mg/kg-day})^{-1}$.

Several aspects of these four metals are discussed in the following.

1. Arsenic

From both the biological and toxicological point of view, arsenic compounds may be classified into three major groups [6]: 1) inorganic arsenic compounds; 2) organic arsenic compounds; and 3) arsine gas. Arsenic penta-oxide is highly soluble in water while arsenic

TABLE 4**Cancer Potency Factor of the Four Metals
(Adapted from Reference [5])**

Metal	Cancer potency factor (mg/kg/day)⁻¹
As (A)	15.0
Cr (6) (A)	42
Ni (A)	1.7
Cd (B1)	6.3

trioxide is only slightly soluble in water. Interchanges in valence state may occur in water solutions, depending on the PH of the solution as well as the presence of other substances which can be reduced or oxidized.

Epidemiological studies have indicated that exposure via ingestion to inorganic arsenic compounds in drugs and drinking water is causally related to the development of skin cancer in humans. Exposure to arsenic trioxide by inhalation is clearly related to the development of lung cancer in certain smelter workers[5]. Trivalent inorganics are, in general, considered to be more toxic than pentavalent ones. Although evidence regarding carcinogenicity is mostly available for trivalent forms, pentavalent ones are also classified as carcinogenic in the absence of firm evidence to the contrary. One of the reasons is that there is a possibility of reduction of pentavalent to trivalent arsenic within the human body.

The major current uses of arsenic[6] are as pesticides, e.g., lead arsenate, calcium arsenate, and sodium arsenite, herbicides, and cotton desiccants. Elemental arsenic is utilized as an additive in the production of several alloys to increase hardness and heat resistance. Gallium arsenide, an artificial crystal, has become an important material in the manufacture of integrated circuits.

2. Chromium (6)

The epidemiological study of workers in the chromate - production industry has provided sufficient evidence for increased respiratory cancer by exposure to chromium compounds [5]. Hexavalent chromium is more easily absorbed via both lung and GI tract than trivalent chromium. Chronic adverse effects are caused by hexavalent compounds which are the most toxic to human. There has been no evidence of carcinogenic effects of trivalent compounds in experimental animals via either inhalation or ingestion. Therefore, the EPA concluded only hexavalent chromium is carcinogenic. In the environment, the trivalent form is known to be predominant, because it is the most stable oxidation state. Hexavalent chromium is the second most stable form, which can be readily reduced to trivalent chromium in the presence of organic matter.

The principal industrial consumers of chromium are the metallurgical, refractory and chemical industries[6]. The U.S. figures for consumption by these industries were 60%, 20% and 20% respectively.

3. Nickel

The epidemiological evidence in the nickel refining industry has been strongest for human carcinogenicity of nickel via inhalation[5]. Based on the combination of human and animal evidence, nickel refinery dust is considered as a human carcinogen. In addition, the fact that the major compound of this refinery dust is nickel subsulfide has caused nickel subsulfide to be considered as a human carcinogen. For nickel carbonyl, the human evidence of carcinogenicity is inadequate to evaluate, but the animal evidence is sufficient. The carcinogenic potential of other compounds is under further investigation. The fact that soluble nickel compounds have not produced any increase in tumors in animal oral studies shows carcinogenic evidence via ingestion is inadequate.

About 40% of the nickel produced is used in steel production [6]. Nickel is also used in the production of other alloys, for which reason nickel can be found in coins and household utensils. Electroplating using nickel sulfate accounts for 20% of the nickel

produced. Nickel hydroxide is used in nickel-cadmium batteries. Nickel carbonate serves in electronic components, such as vacuum tubes and transistor cans.

4. Cadmium

Epidemiological studies have suggested that occupational exposure to cadmium (primarily as the oxide) increases the risk of prostate, respiratory, and genito-urinary cancers in humans, although in some cases the excess risk was not statistically significant [5]. Significant evidence was reported for lung cancer from exposure to airborne cadmium oxide and fumes. All of these studies has provided limited evidence for carcinogenicity of cadmium in humans. There has been sufficient evidence that cadmium chloride via inhalation is carcinogenic in rats. However, there is no evidence that carcinogenic responses have been reported in either animals or humans via the ingestion of cadmium.

Cadmium is used in a number of industrial processes, but for most of its uses there are alternatives of lower toxicity[6]. In U. S. A., 60% of the cadmium produced or imported was used for plating, 11% in color pigments, 19% as stabilizers in plastics, 3% in accumulators, and 7% for other purposes.

IV. Wastes Treatment and Treatment Standards

As mentioned, the hazardous waste has to be treated before land disposal. Stabilization and Solidification are commonly used treatment methods. For inorganic wastes stabilization/solidification, there are two recommended methods which are used for setting Best Demonstrated Alternative Technology (BDAT) standards for many wastes[7]. These are cement-based stabilization/solidification and pozzolanic stabilization/solidification. Descriptions about these two technology are adapted from reference[7] as follows:

"Cement-based stabilization/solidification is a process in which waste materials are mixed with portland cement. Water is added to the mixture to ensure proper hydration reactions necessary for bonding the cement. The wastes are incorporated into the cement matrix and, in some cases, undergo physical-chemical changes that further reduce their mobility in the waste-cement matrix. Typically, hydroxides of metals are formed, which are

much less soluble than ionic species of the metals. The final product may vary from a granular, soil-like material to a cohesive solid, depending on the amount of reagent added and the types and amounts of wastes stabilized/solidified. The Cement-based stabilization/solidification has been applied to plating wastes containing various materials such as cadmium, chromium, copper, lead, nickel, and zinc, e.t.c. "

"Pozzolanic stabilization/solidification involves siliceous and aluminosilicate materials, which do not display cementing action alone, but form cementitious substances when combined with lime or cement and water at ambient temperatures. The primary containment mechanism is the physical entrapment of the contaminant in the pozzolan matrix. Examples of common pozzolans are fly ash, pumice, lime kiln dusts, and blast furnace slag. Pozzolans contain significant amounts of silicates, which distinguish them from the lime-based materials. The final product can vary from a soft fine-grained material to a hard cohesive material similar in appearance to cement. Pozzolanic reactions are generally much slower than cement reactions. Waste materials that have been stabilized/solidified with pozzolans include oil sludges, plating sludges containing various metals (aluminum, nickel, copper, lead, chromium, and arsenic), waste acid, and creosote. "

Both cement-based and pozzolanic stabilization/solidification aim at immobilizing the metals in the wastes, instead of removing the metals permanently. The choice of treatment technology as well as achievable standards are much waste type dependent.

The land disposal restrictions, codified in 40 CFR 268, place stringent controls on the land disposal of hazardous wastes[4]. Congress set forth a schedule of land disposal restrictions in HSWA. The statute automatically prohibited the land disposal of hazardous wastes if EPA failed to set a treatment standard by the statutory deadline. The statute also required EPA to make determinations on prohibiting land disposal, within the indicated time frames, for the following:

1. At least one-third of all ranked and listed hazardous wastes by August 8, 1988
2. At least two thirds of all ranked and listed hazardous wastes by June 8, 1989

3. All remaining ranked and listed hazardous wastes and all hazardous wastes identified by a characteristic by May 8, 1990.

Within the first third wastes, there are K101 and K102 wastes.

K101--Distillation tar residues from the distillation of aniline-based compounds in the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds. (40 CFR 268.10)

K102--Residue from the use of activated carbon for dechlorization in the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds. (40 CFR 268.10)

On August 17, 1988, EPA promulgated treatment standards for hazardous wastes listed in 40 CFR 268.10. For K101 and K102 wastes (Ash residues), the Best Demonstrated Available Technology chosen is stabilization[7]. EPA also established BDAT treatment standards. The BDAT standards for K101 waste are shown in Table 5. While these standards are derived based on BDAT, they are concentration standards. In other words, any technology satisfying this standard is acceptable. The BDAT standards for K102 wastes are the same as given in Table 5.

TABLE 5

BDAT Treatment Standards for K101 Waste[7]

(Nonwaste Waters)

(Low Arsenic Subcategory - Less than 1% total arsenic)

Constituent	Maximum for any single grab samples	
	Total Composition (mg/Kg)	TCLP(mg/l)
Ortho-nitroaniline	14	(1)
Cadmium	(1)	0.066
Chromium(total)	(1)	5.2
Lead	(1)	.51
Nickel	(1)	.32

(1) Not Applicable

In Table 5, TCLP is the Toxicity Characteristic Leaching Procedure (Federal Register 1986). It presumably represents the maximum leaching concentration of the waste. It can be seen from the table, for metals cadmium, chromium, and nickel, only TCLP is specified, nothing has been mentioned about the total composition in the wastes. As for arsenic, weight content less than 1% (10,000 ppm) is acceptable; the leachate concentration of arsenic must comply with the Toxicity Characteristic Level[4] of 5.0 mg/l.

V. The Waste Inventory of the Hypothesized RCRA Site

Based on the above discussion, we can hypothesize a RCRA site containing considerable amounts of Arsenic and other metals. For simplicity, it can be assumed that the waste consists mainly of distillation tar residues from the production of veterinary pharmaceuticals (i.e., K101 wastes), which can have up to 1% weight content of arsenic. Also, other kinds of waste which contains more of Chromium, Cadmium and Nickel have been mixed with the K101 waste. The stabilization process has been chosen to treat the mixture of these wastes. The treated wastes are assumed fine grained, soil-like in form and meet the TCLP standards as discussed above. So conceivably, one can have a RCRA site of the inventory as shown in Table 6. The arsenic inventory is less than the regulatory limit. This inventory does not violate the current EPA regulation.

TABLE 6

Inventory of the Hypothesized RCRA Site

Metal	Weight Content (mg/kg)	Maximum Allowed Leachate Concentration (mg/l)
Arsenic	1,000	5.0
Cadmium	100	0.066
Chromium	100	5.2
Nickel	100	0.32

VI. Scenarios for Future Risk Assessment

It should be acknowledged that EPA indeed considers the near future situation of a RCRA site. For example, EPA currently requires that a site is not in a seismic active region and it should not be in a 100 year flood plain. Also, leachate collection and post-closure monitoring for groundwater contamination should last for 30 years.

However, in contrast to the stringent standards EPA imposed on the geological disposal of high level radioactive wastes[1] as well as the long term consideration of low level radioactive waste disposal[2], the requirement of long term risk assessment for RCRA site disposal of persistent carcinogenic metals is lacking. The authors believe there is an inconsistency in current regulation practices. Thereby in this text, an effort is made to do a future risk assessment of the hypothesized RCRA site given that the societal memory has been lost in a distant future, e.g., a thousand years later.

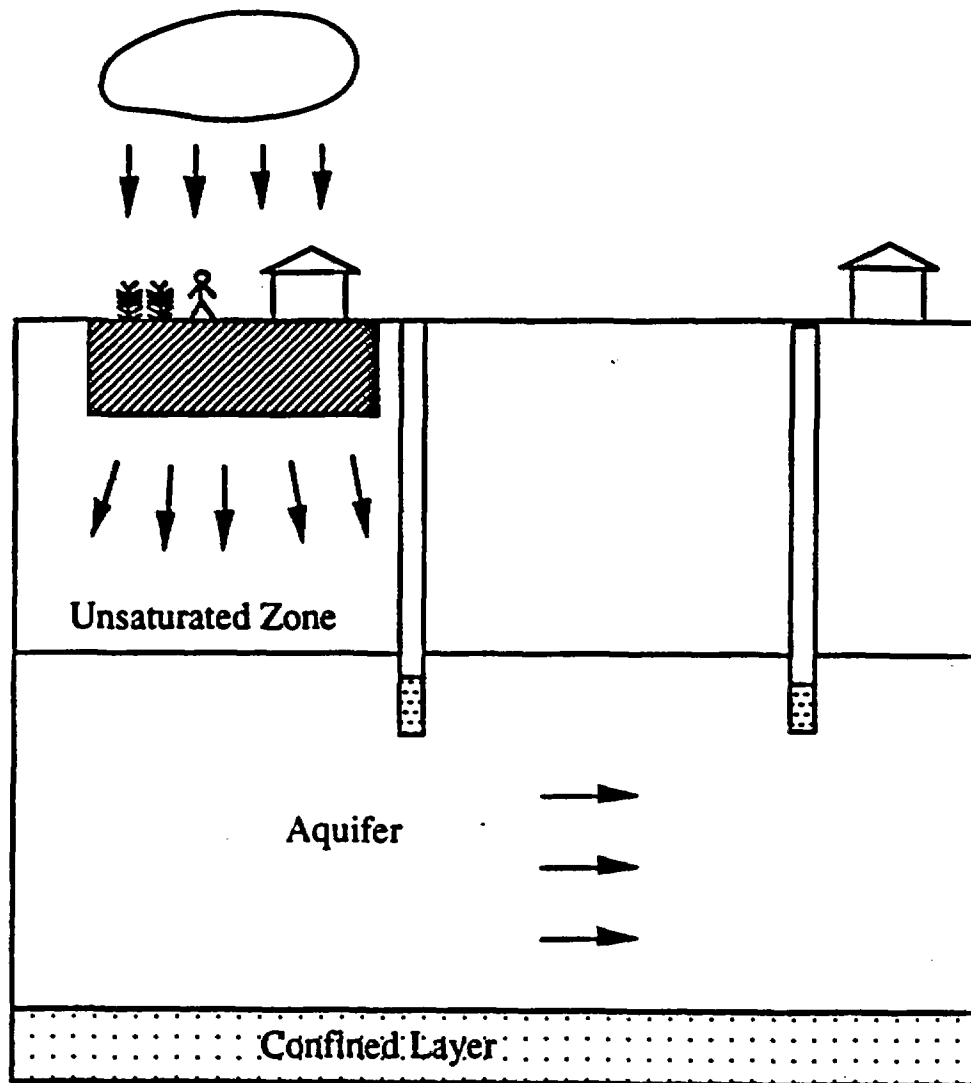
Two scenarios are considered in this study. One is a human intrusion scenario, the other is a residential scenario down-gradient of the site.

1. Human Intrusion

A human intrusion scenario similar to that analyzed for a low-level radioactive waste disposal site[2] is considered. It is assumed that 1000 years after the site closure, a group of farmer families intrude the site. During this 1000 years, there is a thousand-year flood which washes out the caps of the site. The farmers excavate the disposal facility area and build houses directly on the site as shown in Figure 2. The farmers dig wells just down gradient of the waste disposal facility. The ground water serves for their family's drinking water and is also used to irrigate the fruits and vegetables in case the weather is dry. The families consume part of the fruits and vegetables produced on the site. The farmers contact the soil during various activities.

2. Residential Scenario (1000 m down-gradient of the site)

It is assumed that present day precipitation and infiltration data do not change dramatically in the future. The precipitation at the site will cause percolation of water



Mixture of Soil and Wastes

Fig. 2 Intrusion and Residential Scenarios

through the cover system of the facility into the disposal units. The double liners and leachate collection system are assumed to lose functionality after 100 years of site closure. The wastes might be transported down into the aquifer and be further transported in the aquifer.

Suppose at 1000 years a community resides 1000 meters down-gradient of the groundwater flow direction from the site and people use groundwater as their drinking water. The cancer risk should be considered.

VII. Exposure Pathway Modeling

VII.1 Inventory Losses

We assume the site inventory can be approximated by an exponential loss equation as follows

$$m_i(t) = m_{0,i} e^{-\lambda t} \quad (1)$$

where $m_i(t)$ is the mass inventory of metal i at time t after the liners lose their functions. i refers to four metals arsenic, chromium, cadmium, and nickel. $m_i(t)$ accounts for all the forms of metal i . $m_{i0}(t)$ is the initial mass inventory of metal i . λ is the inventory loss rate, it can be expressed as

$$\lambda = \frac{\ln 2}{T_{1/2}} \quad (2)$$

where $T_{1/2}$ is the half time of inventory losses. The basic loss mechanism is leachate into the soil and then groundwater. If metal i changes from one chemical form to another, it is not counted as a loss.

It can be assumed that the total volume of the wastes does not change with time, so the metal concentration also observes an exponential law, i.e.,

$$C_{s,i}(t) = C_{s,i,0} e^{-\lambda t} \quad (3)$$

where $C_{s,i}(t)$ (mg/kg) is the concentration of metal i at time t . The value of $C_{s,i,0}$ has been listed in Table 6.

The loss rate λ depends on many factors, such as pH level of the soil, the infiltration rate, total metal inventory in the site, the area of the site, etc. In this analysis, we assume that after liners lose their functions, the initial leachate concentration does not exceed that given in column 3 of Table 6. This assumption gives a very small loss rate λ . As a result, the metal concentration at 1000 years does not change very much from the initial concentration; this is effectively the case with $\lambda=0$. We thus use the initial weight concentration in column 2 of Table 6 for $C_{s,i}$ in the human intrusion scenario. It is noted that the treatment of λ herein neglects the groundwater contamination, which might be an important pathway. A realistic value of the loss rate λ is needed for more elaborate models on this topic.

VII.2 Human Intrusion Scenario

In principle, there are four pathways considered for the human intrusion scenario. They are: ingestion of contaminated groundwater, ingestion of contaminated fruits and vegetables, dermal contact with contaminants in the soil, and ingestion of metals in the soil.

There are large uncertainties in modelling groundwater contamination for carcinogenic metals. These include the effect of retardation, uncertainties about the influence of chemical reactions, and uncertainties in geological configuration. The groundwater ingestion pathway is not modeled herein because: 1) we use a zero loss rate λ ; 2) the heavy metals are

believed to have low mobility in the ground. But groundwater contamination may be a significant contributor to risk for the human intrusion scenario.

1. Fruit and Vegetable Ingestion

Homegrown vegetables and fruits are classified into three groups, i.e., leafy vegetables, exposed produce, and protected produce[5]. Leafy vegetables present a broad, flat leaf surface for direct interception of depositing pollutant. Exposed produce such as tomatoes, apples, etc. present edible portions for direct deposition pathway, but edible portions generally have reproductive functions and are associated with significantly different soil-plant uptake parameters than leafy vegetables. Protected produce such as potatoes and citrus fruits do not have edible portions exposed to direct atmospheric deposition. Like exposed produce, edible portions are not vegetative in nature. Therefore, the soil-plant transfer coefficient of a pollutant for vegetative portions is applied to the soil-plant uptake for leafy vegetables while the transfer coefficient of the pollutant for reproductive portions is applied to the soil-plant uptake for exposed or protected produce.

Neglecting the atmospheric deposition, the concentration of contaminant in homegrown fruits and vegetables can be calculated as[5]

$$C_{Pi} = (B_V \text{ or } B_R)C_{Si} \quad (4)$$

where C_{Si} (mg/kg) is the contaminant concentration as calculated in (3). B_V is the soil-plant elemental transfer coefficient for vegetative portions (unitless), B_R is the soil-plant elemental transfer coefficient for reproductive portions (unitless). Table 7 [5] represents the soil-to-plant transfer coefficient for different metals.

TABLE 7

Soil-to-Plant Transfer Coefficient
(Adapted from Reference [5])

Pollutant	B_v	B_r
As	0.040	6.0×10^{-3}
Cd	0.55	0.15
Cr	7.5×10^{-3}	4.5×10^{-3}
Ni	0.060	0.060

The fruit and vegetable intake can be estimated as[5]

$$IT_{FVi} = \frac{C_{Pi} \times IR \times FI \times EF \times ED}{BW \times AT} \quad (5)$$

where IT_{FVi} is the fruit and vegetable intake of contaminant i (mg/Kg/day). C_{Pi} (mg/Kg) is contaminant concentration in fruits and vegetables as calculated in (4). IR (Kg/day) is the ingestion rate. Total daily consumption rate for each category of vegetable and fruit is assumed to be 38 g/day for leafy vegetables, 82 g/day for exposed produce and 153 g/day for protected produce, respectively[5]. Therefore, the ingestion rate for vegetative portions is 0.038 Kg/day (leafy vegetables and fruits), and the ingestion rate for reproductive portions is 0.235 Kg/day (sum of exposed produce and protective produce). FI is fraction ingested from a contaminated source. The home grown portion of total vegetable and fruit consumed is assumed to be 25% regardless of the category[5]. Therefore FI is taken 0.25 for both vegetative and reproductive portions. EF (days/year) is the exposure frequency, for which a value of 365 day/year is assumed. $ED = 70$ years is exposure duration; $BW = 70$ Kg is body weight; and $AT = 70 \text{ yrs} \times 365 \text{ days/yr}$ is the averaging time. It is noted that no allowance for contaminated water in this calculation.

To calculate the lifetime cancer risk, a proper dose-response model should be used. For extrapolating from high dose to low dose, "EPA's guidelines recommend that the linearized multistage model be employed in the absence of adequate information to the contrary. Among the other models available are the Weibull, probit, logit, one-hit, and gamma multihit models, as well as various time-to-tumor models." [8]

Since the intake in this analysis might be high, we choose the one-hit equation for risk calculation. The lifetime excess cancer risk due to fruit and vegetable intake can be calculated as [8]

$$R_{FVi} = 1 - e^{-IT_{FVi} \times SF_i} \quad (6)$$

where R_{FVi} is the cancer risk posed by metal i ; and SF_i is the slope factor for metal i , as shown in Table 4.

2. Ingestion of Metals in Soil

The intake of metal i , IT_{Si} (mg/kg-day), due to ingestion of soil can be expressed as [8]

$$IT_{Si} = \frac{C_{Si} \times IR \times CF \times FI \times EF \times ED}{BW \times AT} \quad (7)$$

where C_{Si} is the chemical concentration in soil (mg/kg) as calculated in (3); $IR = 100$ mg/day is the ingestion rate for the age group greater than 6 years old; $CF = 10^{-6}$ kg/mg is the conversion factor; FI is the fraction ingested from contaminated sources, a value of 0.1 is chosen for FI ; $EF = 365$ days/year is the exposure frequency. ED , BW and AT have the same meaning and values as before.

The risk due to soil ingestion can be calculated as

$$R_{Sli} = 1 - e^{-IT_{Sli} \times SF_i} \quad (8)$$

3. Dermal Contact with Metals in Soil

The absorbed dose due to dermal contact with chemicals in soil IT_{ADi} (mg/kg-day) can be calculated as[8]

$$IT_{ADi} = \frac{C_{Si} \times CF \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \quad (9)$$

where C_{Si} is the chemical concentration in soil (mg/kg) as calculated in (3); $CF = 10^{-6}$ kg/mg is the conversion factor; SA is the skin surface area available for contact (cm²/event), the 50th percentile body part-specific surface areas for males is 0.23 m² for arms, 0.082 m² for hands and 0.55 m² for legs, hence SA is assumed to be the sum of these areas, i.e., 8620 cm²; AF is the soil to skin adherence factor (mg/cm²). It is assumed that a layer of soil with particle size 0.01 mm forms on the skin, the soil density is assumed to be 2 g/cm³, the product of thickness and soil density gives an AF value of 2 mg/cm²; ABS is the absorption factor, a value of 0.1 is assumed; EF is the exposure frequency, a value of 100 events/year is assumed; ED, BW, and AT have the same values as discussed above.

The risk due to dermal contact with chemical i in soil R_{DCi} is

$$R_{DCi} = 1 - e^{-IT_{ADi} \times SF_i} \quad (10)$$

VII.3 Residential Scenario

For the residential scenario, it is assumed that the groundwater intake is the primary concern.

According to Wagner[4], RCRA section 3004(d) requires that petitioner for a RCRA site demonstrate, to a reasonable degree of certainty, that there will be no migration of hazardous constituents from the disposal unit or injection zone for as long as the waste remain hazardous. It seems to the authors that this requirement might not be met, given the current RCRA regulation imposed by EPA. First, carcinogenic metals are persistent, their toxicity might remain forever. Secondly, many compounds of these metals are soluble, thereby it is conceivable that the metal compound may be transported down into the aquifer by infiltration if some conditions are met (e.g., pH becomes small), and they might be transported further down gradient in the aquifer. Table 8 lists some metal compounds with high solubility.

In a report to the Congress[10], EPA assessed the potential health effects of the waste disposal sites of the U.S. coal power plants. These power plants generate fly ash, bottom ash, boiler slag, and flue gas desulfurization wastes which contains the carcinogenic metals we have discussed. According to the report, "while most of the laboratory results indicated that coal combustion wastes do not possess RCRA hazardous characteristics, in some instances, data on actual field observations indicates that migration of potentially hazardous constitutes from utility wastes disposal sites has occurred. For example, observed concentrations of contaminants found in ground water down gradient from the sites exceed the primary drinking water standards about 5% of the time".

Based on the above discussion, groundwater contamination down-gradient of our hypothesized site might be possible. However, due to large uncertainties about models and available data, a quantitative assessment of the residential scenario has not been performed in this analysis.

TABLE 8

Some Soluble Metal Compounds[9]

Name	Formula	Solubility (g/100cc)
Ortho-arsenic	$H_3AsO_4 \cdot 1/2H_2O$	302
Arsenic tri-iodide	AsI_3	6.0
Arsenic penta-oxide	As_2O_5	150
Arsenic trioxide	As_2O_3	3.7
Chromate	$(NH_4)_2CrO_4$	40.5
Dichromate	$(NH_4)_2Cr_2O_7$	30.8
Chromium chloride hexahydrate	$[Cr(H_2O)_4Cl_2]Cl \cdot 2H_2O$	58.5
Chromium sulfate	$Cr_2(SO_4)_3 \cdot 18H_2O$	120
Nickel bromide, trihydrate	$NiBr_2 \cdot 3H_2O$	199
Nickel perchlorate	$Ni(ClO_4)_2 \cdot 6H_2O$	222.5
Nickel chloride, hexahydrate	$NiCl_2 \cdot 6H_2O$	254.0
Nickel nitrate, hexahydrate	$Ni(NO_3)_2 \cdot 6H_2O$	238.5
Cadmium borotungstate	$Cd_5(BW_{12}O_{40})_2 \cdot 18H_2O$	1250
Cadmium chlorate	$Cd(ClO_3)_2 \cdot 2H_2O$	298
Cadmium nitrate	$Cd(NO_3)_2$	109
Cadmium sulfate hydrate	$CdSO_4 \cdot 8H_2O$	113

VIII. Results for Human Intrusion Scenario

This section presents the calculation result of lifetime cancer risk for the human intrusion scenario. The risk herein is a unitless probability for an individual to contract cancer by exposure to a dose of 1 mg/Kg-day averaged over a seventy year life span. Table 9 and Table 10 represent the risk calculation for fruit and vegetable intake. Table 9 shows the risk due to the vegetative portion intake and Table 10 shows the risk due to the

reproductive portion intake. Total risk for the vegetative portion is 0.13 and that for the reproductive portion is 0.17. Total risk due to fruit and vegetable intake is 0.30.

Table 11 represents the result for dermal contact with metals in soil. The total risk for this pathway is 0.13.

Table 12 represents the risk due to ingestion of metals in soil. The total risk of this pathway is 2.9×10^{-3} .

Combining all the pathways, except drinking of groundwater, the total risk of the human intrusion scenario is 0.43. It is clear that the risk for the human intrusion scenario is large, and might be significantly enhanced by contaminated groundwater.

TABLE 9
Risk Due to Fruit and Vegetable Intake
Vegetative Portion

Metal	Soil Concentration (mg/Kg)	C_{pv} (mg/kg)	Intake (mg/kg-day)	Risk
As	1,000	40	5.43×10^{-3}	7.82×10^{-2}
Cd	100	55	7.46×10^{-3}	4.59×10^{-2}
Cr	100	0.75	1.02×10^{-4}	4.27×10^{-3}
Ni	100	6	8.14×10^{-4}	1.38×10^{-3}

TABLE 10

**Risk Due to Fruit and Vegetative Intake
Reproductive Portion**

Metal	Soil Concentration (mg/kg)	C_{pr} (mg/kg)	Intake (mg/kg-day)	Risk
As	1000	6.0	5.04×10^{-3}	7.28×10^{-2}
Cd	100	15	1.26×10^{-2}	7.63×10^{-2}
Cr	100	0.45	3.78×10^{-4}	1.58×10^{-2}
Ni	100	6.0	5.04×10^{-3}	8.53×10^{-3}

TABLE 11

Risk Due to Dermal Contact with Contaminants in Soil

Metal	Soil Concentration (mg/kg)	Absorbed Dose (mg/kg-day)	Risk
As	1000	6.75×10^{-3}	9.61×10^{-2}
Cd	100	6.75×10^{-4}	4.24×10^{-3}
Cr	100	6.75×10^{-4}	2.79×10^{-2}
Ni	100	6.75×10^{-4}	1.15×10^{-3}

TABLE 12

Risk Due to Ingestion of Metals in Soil

Metal	Soil Concentration (mg/kg)	Intake (mg/kg-day)	Risk
As	1000	1.43×10^{-4}	2.14×10^{-3}
Cd	100	1.43×10^{-5}	9.00×10^{-5}
Cr	100	1.43×10^{-5}	6.00×10^{-4}
Ni	100	1.43×10^{-5}	2.43×10^{-5}

IX. Discussion

While there is uncertainty in modeling the various pathways, this study indicates that the future risk for the human intrusion scenario for a hypothesized RCRA site is potentially intolerable, if one adopts the general rationale used in 40 CFR Part 191 for high level radioactive waste disposal[1]. The risk of the residential scenario has not been obtained quantitatively due to the large uncertainty, but potentially significant risk for this scenario can not be excluded. Although the risk calculated is one thousand years away in the future, as in 40 CFR 191, it is not assumed that the future generations would be more advanced in technology. Furthermore, societal memory regarding the site is assumed to be lost. This degree of conservatism is along the same lines as that chosen by U.S. EPA for high level radioactive waste disposal in a geological repository[1] and by the U.S. NRC for disposal of low level radioactive wastes[2].

In superfund cleanup programs, consideration of risk into the far future is also lacking. Doty and Travis[11,12] reviewed 50 EPA Records of Decisions made in fiscal year 1987. Among them, less than half (22) of the Records of Decisions documented quantitative future risk assessment. It is obvious that risk a thousand years away did not play a role in the superfund decision making process.

In summary, the U.S. EPA requirements concerning long-term risk from RCRA sites containing metal carcinogens which never change due to radioactive decay stand in sharp contrast to the stringent requirements over 10,000 years posed by EPA for high level radioactive waste disposal in 40 CFR 191 (remanded), and the long-term requirements posed by U.S. Nuclear Regulatory Commission for low level radioactive waste disposal sites.

Acknowledgement

This work was supported in part by the Toxic Substances Research and Teaching Program of the University of California. Dr. William E. Kastenberg and Mr. Don Browne

have offered beneficial comments on this paper. We would like to express our gratefulness to both of them.

References

- 1 EPA, Environmental Standard for the Management and disposal of Spent Nuclear Fuel, High-Level Waste, and Transuranic Radioactive Waste, Final Rule, Federal Register, 50, No. 182, Washington, D.C., 1985.
- 2 M.S. Y. Chu, M. W. Kozak, J. E. Campbell, B. M. Thompson, A Self-Teaching Curriculum for the NRC/SNL Low-Level Waste Performance Assessment Methodology, NUREG/CR-5539, SAND90-0585, January 1991.
- 3 Minnesota Waste Management Board, Stabilization and Containment Draft Report on Facility Development, May 28, 1987. Obtained through personal communication with Mr. Don Browne.
- 4 Travis P. Wagner, The Complete Guide to the Hazardous Waste Regulations, 2nd edition, Van Nostrand Reinhold, New York, Copyright 1991 by Travis P. Wagner.
- 5 Jinhong Lee, Health Risk Assessment of Incinerator Stack Emissions: Trace Metals, Ph. D. Dissertation for Doctor of Philosophy in Engineering, UCLA, 1990.
- 6 Lars Friberg et. al., Handbook on the Toxicology of Metals, Vol. II, Elsevier Science Publishers B.V., P. O. Box 1527, 1000 BM Amsterdam, 1986.
- 7 U.S. EPA, Stabilization/Solidification of CERCLA and RCRA Wastes, Physical Tests, Chemical Testing Procedures, Technology Screening, and Field Activities, EPA/625/6-89/022, May 1989.
- 8 U.S. EPA, Risk Assessment Guidance for Superfund, Vol. I, Human Health Evaluation Manual (Part A), Interim Final, EPA/540/1-89/002, Dec., 1989.
- 9 Robert C. Weast, Editor in Chief, et. al., CRC Handbook of Chemistry and Physics, 69th Edition, CRC Press, 1988-1989.
- 10 EPA, Report to Congress, Wastes from the Combustion of Coal by Electric Utility Power Plants, EPA/530-SW-88-002, PB88-177977, Feb. 1988.
- 11 Carolyn B. Doty and Curtis C. Travis, The Superfund Remedial Action Design Process, ORNL/M--780, DE 89 010160, 1989.
- 12 C. B. Doty and C. C. Travis, The Superfund Remedial Action Process: A Review of Fifty Records of Decisions, J. of Air & Wst. Mgt. Ass. 39(12) (1989) 1535-1543.