

ANL/EA/CP--86212
Conf-950542--1

A SIMPLIFIED MODEL TO ESTIMATE RADIOLOGICAL DOSES FROM INCINERATION
OF RADIOACTIVE WASTE^a

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ABSTRACT

A simplified calculational model permits a rapid yet realistic estimate of small, but potential radiological doses to onsite workers and the offsite public as a result of transportation, handling, storage, incineration, and maintenance of waste containing trace amount of radioactive materials which is to be processed at a treatment, storage, and disposal (TSD) facility. The model was developed on the basis of previous detailed studies of eight TSD facilities and builds in the essential features of a TSD facility. The model would provide an understanding of the potential human exposure associated with the radioactive contents in the chemical wastes. The main features of the model are as follows.

- Doses to facility workers are modeled on a reference facility. The reference facility is characterized by the above operations and a set of selected key parameters and their associated representative values. Each operation is treated as a module and can be included in or excluded from the dose calculation. Worker doses can be calculated by using the representative values of the reference facility; the only required input parameter is then the activity of the waste shipment. Worker doses can also be calculated by the model by using site-specific information.
- The radiological dose to a maximally exposed offsite individual is proportional to the released activity and dependent on the individual's distance from the point of release and the effective stack height. The radiological dose to the general population is proportional to the released activity and dependent on the population density and effective stack height. A series of radionuclide-dependent constants were determined by empirical best fits to the TSD data for both the individual and the general population.

^a Work supported by the U.S. Department of Energy, Assistant Secretary for Environmental Management, under contract W-31-109-Eng-38.

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The model uses computer spreadsheets to calculate the worker external and internal doses, a maximally exposed offsite individual dose, and general population doses. These doses can be calculated rapidly upon receipt of information about waste shipments to a TSD facility.

INTRODUCTION

This paper describes a simplified model that can be used to estimate the potential worker and public radiation doses resulting from the transportation, handling, storage, incineration, and maintenance of chemical waste containing trace amount of radioactive materials which is to be treated at commercial treatment, storage, and disposal (TSD) facilities. The model incorporates the essential features of a TSD facility and will permit a rapid yet realistic dose evaluation. The model would provide an understanding of the low human health risks associated with the potential radioactive contents in the wastes.

In May 1991 the U.S. Department of Energy (DOE) Headquarters learned that past practices at DOE field facilities resulted in minute amounts of known or likely radioactive contamination in some hazardous and polychlorinated biphenyl (PCB) wastes. These wastes were shipped to various commercial TSD facilities not licensed to receive radioactive materials. To assess the radiation exposures to commercial hazardous waste workers and the associated offsite public, detailed dose assessments were performed for eight TSD facilities. The detailed dose assessments concluded that:

- The resulting doses are extremely small. They are orders of magnitude below federal limits and guidelines^b and orders of magnitude below the average dose from natural background radiation in the United States.
- Many TSD facilities are similar in their major operations.

Based on the experience and insight gained from the detailed studies of the eight TSD facilities, a simplified model was developed for determining doses to onsite workers and the offsite public from waste operations, including incineration at other TSD facilities. Because of the generic nature of the model, it was determined that the model can be possible applicable for other TSD facilities. The model currently can be applied to wastes containing uranium (U-234, U-235, U-238), plutonium (Pu-239, Pu-241, Pu-238, Pu-240, Pu-242), americium (Am-241), cesium (Cs-137), technetium (Tc-99), strontium (Sr-90), and tritium. As the need arises, other radionuclides will be incorporated into the model.

The model spreadsheets calculate individual worker external and internal doses, a maximally exposed offsite individual dose, and general population doses. These doses can be calculated rapidly upon receipt of information about waste shipments to a TSD facility.

^b Because TSD facilities are not licensed as radiation facilities, the allowable regulatory limits apply equally for the TSD facility workers as well as offsite public.

METHODOLOGY

The model consists of two components: one to calculate the onsite worker doses and the other to calculate offsite public doses. The division was necessary due to the different calculation methods employed for the determination of each dose.

Worker Dose Assessment

The worker-dose model was developed in the following three steps:

Step 1 — Establishment of a Reference Facility. First, the data from the eight TSD sites were analyzed to identify major operations that may contribute significantly to the worker dose. The reference facility model incorporates all these major operations such as transportation, handling, storage, incineration, and maintenance of radioactive waste. Next, each operation was subdivided into operational steps. For example, a transport operation was divided into loading, driving, resting, and unloading steps. Last, key parameters involved in each operational step were determined (e.g., geometry, materials, distance, shielding, exposure times). Realistic yet conservative values for these key parameters were also chosen based on observations during site visits of the eight previously analyzed TSD facilities. Best engineering judgment was also used to determine these values.

Step 2 — Calculation of the Reference Facility Doses and Derivation of Scaling Parameters. Step 2 began with the derivation of specific dose equations for each operation from a general dose equation. These specific equations were then mathematically simplified to be the product of two parts. The first part is a series of parameters that are defined for a reference facility, thus permitting the calculation of the reference facility doses for a unit source term (so-called normalized doses). The second part is a set of variables (so-called scaling factors). The studies show that the only scaling factor is the activity of the waste shipped to that facility. Doses to a worker resulting from waste operations at a TSD facility are linearly proportional to the activity of the waste; therefore, the worker doses at a TSD facility are equal to the waste activity multiplied by the normalized dose of the reference facility.

Step 3 — Application to Other TSD Facilities. A spreadsheet was developed to apply the reference facility model to other TSD facilities. Inputs to the spreadsheet are: (1) the activity of contaminated shipments and (2) the applicable operations for the TSD facility under study. Each waste-treatment operation is treated as a module. The dose associated with each applicable operation is the product of the waste activity and the corresponding normalized dose. These are summed to yield the total worker doses. The outputs for the spreadsheet are the worker doses (both external and internal) for a specific TSD facility under study.

The model also includes some flexibilities by allowing the user to adjust for site-specific information.

Offsite Public-Dose Assessment

A different approach was employed to calculate offsite public doses. A simplified model was developed on the basis of detailed dose assessments previously performed for five sites. The model permits the calculation of offsite public doses (for individual and population) from operations at additional TSD sites from knowledge of a few key site-specific parameters and the characteristics of the DOE waste received. The previous detailed dose assessments indicated that incinerator stack emissions dominate the public doses.

The empirical formulas were then used to develop spreadsheets for incinerator operations.

ONSITE WORKER DOSE ANALYSIS

Reference Facility

Waste handling and treatment operations are similar for commercial TSD facilities. On the basis of previous detailed studies of eight TSD facilities, the major operations that may contribute to the radiation exposure of workers and the offsite public are transport from a DOE generator, unloading/sampling/check-in, storage, incineration, transport of incineration residues offsite, and incinerator maintenance. A reference facility is established that includes the above seven major operations. As an example, Table I lists the operational steps and the values of the key parameters (e.g., source geometry, shielding, distance, exposure duration) associated with the incineration operation and the incinerator maintenance operation.

PLACE TABLE I HERE

It is assumed that three groups of workers are involved in these six operations:

- Truck drivers are involved in transport from DOE generator and transport of incineration residues offsite.
- Receiving workers are involved in unloading/sampling/check-in and storage.
- Incineration workers are involved in incineration, transport of incineration residues onsite, and incinerator maintenance.

In addition, all workers would be exposed to the stack emissions.

Worker External Dose Analysis

The external radiation dose (D^{ex}) can be expressed as follows:

$$D^{ex} = \Sigma \Sigma D^{ex}_{ij}, \quad (\text{Eq. 1})$$

$$D^{ex}_{ij} = R^{ex}_{ij}(g, d, \rho, sh) \times S_i \times P_j \times T_j \times N_j,$$

where:

D^{ex}_{ij} = external radiation dose (mrem). External doses are presented in terms of the dose equivalent.

R^{ex}_{ij} = external radiation dose rate (mrem/h), calculated for a specific activity of 1 pCi/g and dependent on the source geometry (g) (e.g., a drum, a tank, a bin), the source distance (d), source density (ρ), and the source shielding (sh), as given in Table I, for example.

S_i = ratio of specific activity to 1 pCi/g, $(A/M)/(1 \text{ pCi/g})$, where A is the activity of the waste and M is the mass.

P_j = process factor for waste treatment, such as mixing with other materials (note that $P = 1$ for untreated waste).

T_j = duration of the operation (h).

N_j = number of operations performed.

The subscript i denotes the various isotopes, and the subscript j denotes the various operational steps identified in Table I, for example. The external dose for each individual worker is summed across all isotopes and all applicable operations.

The dose rate (R^{ex}) was calculated by using the code MicroShield (1). Note that the dose rate (R^{ex}) is calculated separately for each isotope. The external doses consider the contribution of those daughter radionuclides in secular equilibrium with the parent radionuclides.

Equation (1) can be simplified and reexpressed as follows:

$$D^{ex}_{ij} = A_i \times D^{ex,o} \times C_j, \quad (\text{Eq. 2})$$

where:

A_i = activities of the i'th isotope in the waste shipped to a TSD facility.

$D^{ex,o}$ = worker doses calculated for the reference facility with 1 Ci of activity (so-called normalized doses) using the default values of the parameters as given in Table I, for example.

C_j = correction factors for the j'th operation. These corrections are calculated by using site-specific information that supersedes the default values.

The key assumptions used to calculate the worker external doses are summarized in Table II. Computer spreadsheets were developed to facilitate the dose calculations. The activities (A) in the

waste are inputs to be supplied by the users to the spreadsheets. The normalized doses ($D^{ex,0}$) were built into the spreadsheets. The correction factors (C) will be calculated by the spreadsheets if the users consider that the default values given in Table I are not adequate. The users, however, need to supply site-specific information for calculating the correction factors.

PLACE TABLE II HERE

Worker Internal Dose Analysis

TSD workers may be exposed to internal radiation as a result of inhalation of contaminated air due to the handling and processing of slightly radioactive wastes. Internal exposure due to ingestion is not likely for TSD workers because of work practices (i.e., designated eating areas, changing rooms, showers) and the use of personal protective equipment. A screening calculation revealed that even if these practices and procedures were ignored, doses from ingestion would be much lower than those calculated for the inhalation pathway. Therefore, only the inhalation pathway was considered for detailed evaluation. The radioactive isotopes in the wastes could have become airborne by the following four scenarios:

- Normal stack releases from incineration of wastes.
- Sampling drums containing wastes.
- Maintenance of the incinerator system.

The internal exposure (D^{in}) due to inhalation is calculated by:

$$D^{in} = \sum \sum D_{ij}^{in},$$

$$D_{ij}^{in} = CON_{ij} \times BR \times T_j \times N_j \times 1/PF_{ij} \times DCF_i, \quad (\text{Eq. 3})$$

where:

- D_{ij}^{in} = internal radiation dose (mrem). Internal doses are presented in terms of the committed effective dose equivalent (CEDE).
- CON = airborne radioactivity concentration (Ci/m^3).
- BR = breathing rate (m^3/s). BR is taken to be the standard value of $11.7 \times 10^{-3} \text{ ft}^3/\text{s}$ ($3.33 \times 10^{-4} \text{ m}^3/\text{s}$).
- T = exposure time.
- N = number of operations.
- PF = respiratory protection factor.
- DCF = dose-conversion factor (rem/Ci).

The subscript i denotes the various isotopes, and the subscript j denotes the various operational steps such as those identified in Table I. For each individual, the internal dose is summed across all isotopes and all applicable operations.

Equation (3) can be simplified and reexpressed as follows:

$$D_{ij}^{in} = A_i \times D_{ij}^{in,0} \times C_j, \quad (\text{Eq. 4})$$

where the definitions of terms are similar to those in the worker external doses analysis.

The key assumptions used to calculate the worker internal doses are summarized in Table III. Spreadsheets similar to those used for external dose calculations were developed.

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OFFSITE PUBLIC DOSE ANALYSIS

Empirical Model for Doses to Individual

An simplified model was developed based on the doses estimated for five TSD incinerator facilities previously studied. These studies utilized site-specific data modeled by the EPA CAP88-PC code (3). In this simplified model, the following parameters have been determined to be significant: (1) the total activity of all isotopes processed annually at a TSD facility and (2) vertical and horizontal atmospheric dispersion. Vertical dispersion is affected by release height as well as the location of the individual. This dependence reflects components of the Gaussian plume model. The simplified model for the offsite individual is as follows:

$$D_I = \sum_i \frac{C_i \text{ ECI } \text{RF}_i}{\text{RD} (1 - e^{-\text{RD}/L})} e^{-\frac{1}{2} \left(\frac{H_e}{A \text{ RD}} \right)^2} \quad (\text{Eq. 5})$$

where:

- D_I = dose to individual (mrem/yr).
- C_i = quantity of radionuclide I incinerated in 1 yr (Ci/yr).
- ECI = empirical derived constant for the individual from radionuclide I (mrem-m/Ci).
- RF_i = release fraction for radionuclide I.
- RD = distance of individual from the point of release (m).
- H_e = effective stack height (m).
- L = fixed lid height parameter (1,000 m).
- A = fixed vertical dispersion constant similar to D stability class (0.051).

The effective stack height, H_e , incorporates the actual physical height of the stack as well as the plume rise by taking into account the effluent stack gas velocity, stack diameter, and wind velocity.

The release fraction, RF_i , is estimated by subtracting the removal efficiency (RE) from 1 (i.e., 1-RE). On the basis of several TSD facilities studies, the RE ranged from 0 to 0.99,

depending on the filtration system at each facility. The value of RE should be adjusted to appropriate site-specific values.

The vertical dispersion constant (0.051) was derived by plotting estimated results from a uranium release in Equation 5 against those obtained from CAP88-PC calculation and adjusting the parameter until a best-fit correspondence was found. Uranium was used because it is the primary radionuclide contributing to the majority of the dose. Once this constant was calculated, the ECI factor for the radionuclides was calculated by using a least-squares regression to the calculated site doses from a 1-Ci release. These factors incorporate all pathways (i.e., dose from inhalation, air immersion, ingestion of food products, and ground-surface irradiation), as well as meteorological data.

The radionuclide empirical factors for calculating dose to the individual are summarized in Table IV.

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Simplified Model for Doses to the General Population

The model for calculating dose to the general population contains the following key parameters: the total activity of all isotopes processed annually at a TSD facility, the population density, and the effective stack height. The simplified model for the general population is as follows:

$$D_{\text{pop}} = \sum_i \frac{C_i \text{ ECP } RF_i \text{ PD}}{\left(1 + \frac{H_e}{25}\right)} \quad (\text{Eq. 6})$$

where:

- D_{pop} = dose to population within 50-mi radius (person-rem/year).
- C_i = quantity of radionuclide i incinerated in one year (Ci/yr).
- ECP = empirically derived constant for radionuclide i for the population from all pathways [(person-rem)/(Ci)(person/mi²)].
- RF_i = release fraction for radionuclide i .
- H_e = effective stack height (m).
- PD = population density parameter: $\text{ECD} \times \text{PD}_{0-20} + (1-\text{ECD})\text{PD}_{20-50}$.

where:

- ECD = empirically derived constant for population density: 0.89.
- PD_{0-20} = average population density within 20 mi of the facility (people/mi²).
- PD_{20-50} = average population density from 20 to 50 mi of the facility (people/mi²).

The empirically derived constant for population density (ECD) was determined by adjusting the

parameter until a best-fit correspondence was found between results from Equation 6 and CAP88PC.

The denominator in this equation represents the dependence of dose on stack height. It was derived by fitting the CAP88-PC stack height as a function of the dose for a specific site. This site was chosen because its stack height is in the center of the range of the stack heights for all of the TSD facilities.

The empirical constant, ECP, in Equation 6 was derived similar to ECI in Equation 5; however, the estimated population doses were plotted against the population dose estimates obtained from CAP88-PC calculations and the parameter was adjusted until a best-fit correspondence was found. The constants were obtained using a least-squares fit to the population doses resulting from the incineration of 1 Ci/yr at all of the TSD sites. These empirical constants incorporate all pathways (i.e., dose from inhalation, ingestion of food products, and ground-surface irradiation), as well as meteorological and population data. The ingestion pathway is most sensitive to site specific agricultural productivity. For sites that show a high dose resulting from strontium, technetium, or tritium using this model, it is suggested that CAP88-PC be used in place of this estimation method.

The empirical constants for calculating dose to the general population are summarized in Table IV.

CONCLUSIONS

A simplified model for estimating radiological doses at TSD facilities was developed based on the previous detailed studies of eight TSD facilities. This model for the worker and offsite public dose requires only a few key input parameters. If detailed site specific parameters are readily available, it is suggested that a more complete analysis be conducted. This would entail performing specific worker dose analysis and using CAP88-PC for offsite public dose analysis. The main conclusions of the model are:

- External and internal doses to workers can be easily and rapidly calculated by the model using built-in representative values. The calculation requires the activity of the waste shipment as the only input parameter. The results are generally in the 70 to 90 percentile confidence level and are therefore conservative. The model also provides an option to consider site-specific information by evaluating correction factors if users so desire. The input parameters will then include the activity of the waste shipment plus the selected site-specific information.
- An simplified model for doses received by the maximally exposed individual and the general population from TSD facilities was developed. This model was derived from CAP88-PC dose estimates calculated for five TSD incineration sites. Radionuclide-specific empirical constants, ECI and ECP, were developed by using least-squares regression to correlate detailed CAP88-PC estimates with the reference facility model estimates. Key parameters used in the reference model for calculating doses to individual are the total activity of all isotopes processed annually at a TSD facility and vertical and horizontal

atmospheric dispersion. The key parameters for calculating dose to the general population also include the total activity of all isotopes processed annually at a TSD facility, plus population density and effective stack height. For stack release sites, results determined by using the empirical model fall generally within 35% of those determined by using CAP88-PC for the maximally exposed individual, and 40% for the general population.

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TABLE I. Incineration operations of reference facility.

| Operation and Step | Source type | Time | Distance | Shielding ^a [in. (cm)] | No. of workers | Respirator type | Remarks |
|---|---|-----------------|----------------|-----------------------------------|----------------|-----------------|---|
| Incineration | | | | | | | |
| a. Operation of incinerator | | | | | | | Remote-control operation |
| b. Collect residues in bin | Bin 4 × 4 × 7 ft (1.2 × 1.2 × 2.1 m) | 30 min/ bin | 5 ft (1.5 m) | 0.25 in. (0.63 cm) | 2 | None | Residues (ash, slag, filter cake) from incineration of both solids and oil. Includes collection during operation and maintenance. |
| c. Transport bin to storage area by forklift | Bin as above | 10 min/ bin | 5 ft (1.5 m) | 0.25 in. (0.63 cm) | 2 | None | |
| d. Transport bin from storage area to dump truck shipment offsite | Bin as above | 10 min/ bin | 5 ft (1.5 m) | 0.25 in. (0.63 cm) | 2 | None | |
| e. Stack emissions with fumigation conditions | Airborne particulates | 21 h/yr | 197 ft (60 m) | None | NA | None | Internal dose only |
| f. Stack emissions with building wake effect | Airborne particulates | 1,040 h/yr | 328 ft (100 m) | None | NA | None | Internal dose only |
| g. Emergency venting of the kiln | Airborne particulates | | | | | | Internal dose only |
| Incinerator maintenance | | | | | | | |
| a. Remove slag from incinerator walls, floor | Incinerator 0.5 × 10 × 30 ft (0.15 × 3.0 × 9.1 m) | 16 h/ maint. | 1 ft (0.3 m) | 0 | 1 | FFAP | 4 maintenance operations/yr |

FFAP = full-face air-purifying (respirator); L = liter.

^a Steel shielding.

TABLE II. Major operations, scaling parameters, and key assumptions for calculating external doses to workers.

| Operations | Scaling parameters | Key assumptions |
|--|--------------------|--|
| 1. Transport of DOE waste to TSD facility | A | Shipment takes 30 h |
| 2. Unloading/sampling/check-in | A | |
| 3. Storage | A | Each shipment is stored for 20 working days |
| 4. Incineration (collection of slag, ash, and filter cake) | A | All wastes/residues are collected in the same type of container (i.e., a bin) |
| 5. Transport of residues offsite | A | All residues are transported in a dump truck |
| 6. Maintenance of the incinerator system | A | Respirable particulate concentration is 10 mg/m ³ Wall plateout removal rate is 1 ft ³ (0.028 m ³)/man-hr |

A = activity.

TABLE III. Major operations, scaling parameters, and key assumptions for calculating internal doses to workers

| Operations | Scaling parameters | Key assumptions |
|---|--------------------|--|
| 1. Transport from DOE generator | - | <ul style="list-style-type: none"> No internal dose |
| 2. Unloading/sampling/check-in | A | <ul style="list-style-type: none"> All drums are sampled and inspected Respirable particulate concentration in drum-head space is 10 mg/m^3 Tritium vapor pressure in drum-head space is taken to be equal to water [50 mm Hg at 100°F (38°C)] Unbounded water content is 1% for solid waste and 10% for liquid waste |
| 3. Storage | - | <ul style="list-style-type: none"> No internal dose |
| 4. Incinerator stack release | A | <ul style="list-style-type: none"> 95% removal efficiency for U-234, U-235, U-238, Pu-239, Sr-90, Cs-137, etc., and 0% for ^3H 1% fumigation |
| 5. Transport of incineration residues offsite | - | <ul style="list-style-type: none"> No internal dose |
| 6. Incinerator maintenance | A | <ul style="list-style-type: none"> Respirable particulate concentration is 10 mg/m^3 Wall plateout removal rate is 1 ft^3 (0.028 m^3)/man-hr |

A = activity.

TABLE IV. Radionuclide Empirical Constants (ECI and ECP in Equations 5 and 6) for Calculating Doses to the Individual and General Population

| Radionuclide | Individual Empirical Constants (ECI) ^a | General Population Empirical Constants (ECP) ^b |
|--------------|---|---|
| Am-241 | 5.7×10^4 | 1.1×10^1 |
| Cs-137 | 2.0×10^3 | 2.5×10^{-1} |
| H-3 | 9.5×10^{-2} | 1.5×10^{-5} |
| Pu-239 | 5.0×10^4 | 7.2 |
| Pu-241 | 8.2×10^2 | 1.1×10^{-1} |
| Sr-90 | 1.2×10^3 | 6.8×10^{-2} |
| Tc-99 | 2.3×10^2 | 1.8×10^{-2} |
| U-232 | 6.4×10^4 | 9.9 |
| U-234 | 1.8×10^4 | 2.8 |
| U-235 | 1.8×10^4 | 2.7 |
| U-236 | 1.7×10^4 | 2.6 |
| U-238 | 1.7×10^4 | 2.5 |

^a In units of (mrem-m/Ci)

^b In units of (person-rem)/(Ci)(person/mi²)

306
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