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A Method for Calculating the Consequences of Explosive Radiological Releases

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Westinghouse
Hanford Company Richland, Washington

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A METHOD FOR CALCULATING THE CONSEQUENCES OF EXPLOSIVE RADIOLOGICAL RELEASES

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ABSTRACT

Radiological releases resulting from detonations are a primary concern of analysts when they are dealing with radiological sabotage. Calculating the consequences of these explosive releases is an integral part of the risk assessment process. This paper presents a method for relating the consequences of a release to the resultant doses by using the appropriate radiological guidelines. The doses are calculated as the product of dose conversion factors and building source terms. The uses of relative activities and committed dose equivalent factors, organ weighting factors, and meteorological data for calculating the dose conversion factors are discussed. Material at risk, release fractions, respirable fractions, and leak path factors, which are used to compute the building source terms, are also addressed.

INTRODUCTION

The central concept of quantifying consequences to the public based on appropriate radiological guidelines and the calculated doses received by offsite personnel is general and can be applied to the full spectrum of radiological releases. The concept of computing doses to personnel as the product of dose conversion factors and building source terms is also universal.

However, the detailed calculations of dose conversion factors depend on the types of doses being calculated. The dose conversion factors for inhalation doses, ingestion doses, and immersion doses are each calculated in a different manner. Similarly, the detailed calculations of building source terms depend on the release mechanism. The calculations of building source terms for detonations, deflagrations, and criticalities are different.

This paper focuses on the calculations of dose conversion factors for inhalation doses and building source terms for detonations because these are the primary concerns of analysts dealing with radiological sabotage. The formula and data needed to perform these calculations are discussed in the following sections.

CONSEQUENCE VALUES

Consequences can be quantified in terms of the calculated doses received by personnel and appropriate radiological guidelines in a variety of ways. For example, consequence values can be calculated using equation 1.

$$C = SF \cdot (CD / GD) \quad (1)$$

where:

C = Consequence value
SF = Scaling factor
CD = Calculated dose (rem)
GD = Guideline dose (rem).

The scaling factor is a constant chosen to force a certain multiple of the guideline dose to correspond to a certain consequence value. For example, in the *Site Safeguards and Security Plan Preparation Guide*¹ the scaling factor is SF = 0.1 which forces 10 times the guideline dose to correspond to a consequence value of 1.

The calculated dose is discussed at length in the next section of this paper.

Appropriate radiological guidelines can be chosen from a variety of sources. For example, guideline doses for the organs and tissues of interest can be chosen from *Reactor Site Criteria*² and *General Design Criteria*³ as shown in Table 1.

Consequence values are calculated for each organ or tissue of interest using equation 1 and Table 1. The highest value calculated for a particular release is generally taken to be the consequence value for that release.

Table 1. Guideline Doses.

Organ or tissue	NRC guideline dose (rem)	DOE guideline dose (rem)
Whole-body	25	25
Thyroid	300	300
Bone surface	--	300
Lung	--	75
Any other organ	--	75

CALCULATED DOSES

The calculated doses are computed as the product of the dose conversion factors and building source terms as shown in equation 2. The dose conversion factors represent the dose received by personnel for each unit mass of radioactive material released. The dose conversion factors are usually expressed in units of rem per gram (rem/g) or rem per kilogram (rem/kg). The building source terms represent the masses of radioactive materials released and are usually expressed in units of grams (g) or kilograms (kg).

$$D = DCF \cdot BST \quad (2)$$

where:

D = Dose (rem)
 DCF = Dose conversion factor (rem/g)
 BST = Building source term (g).

Distinct dose conversion factors must be calculated for each material and organ or tissue of interest. These factors can generally be calculated without a site visit because the required site-specific input data are as follows:

- A list of the stoichiometries and chemical forms of all releasable radioactive materials
- A list of all isotopes that are present in each releasable radioactive material and their mass fractions
- The distances from potential release points to the site boundaries
- Site-specific meteorological data.

Building source terms must be calculated for each location and material of interest. Calculation of these source terms generally requires a large amount of site, building, and room-specific data, including the following:

- List of the types, locations, and amount of all releasable radioactive materials
- Measurements of the respirable fractions for all dispersible powders

- Descriptions of the compositions, sizes, types, and weights of all radioactive material containers
- Descriptions of all storage configurations
- Room dimensions and the compositions and thicknesses of ceilings, floors, and walls for all affected areas
- Amounts and types of explosives or trinitrotoluene equivalents of the explosive energies involved in the releases.

DOSE CONVERSION FACTORS

The dose conversion factors are computed as the product of the relative activities, committed dose equivalent factors, organ weighting factors, relative concentration, and breathing rate as indicated in equation 3.

$$DCF = RA \cdot CDEF \cdot OWF \cdot RC \cdot BR \quad (3)$$

where:

DCF = Dose conversion factor (rem/g)
 RA = Relative activities (Ci/g)
 CDEF = Committed dose equivalent factors (rem/Ci)
 OWF = Organ weighting factors
 RC = Relative concentration (s/m³)
 BR = Breathing rate (m³/s).

The relative activities are expressed in units of radioactivity per unit mass of material, usually curies per gram (Ci/g). Relative activities are calculated for each nuclide in a material as the product of the specific activity of the nuclide and the mass fraction of the nuclide in the material as shown in equation 4.

$$RA = SA \cdot MF \quad (4)$$

where:

RA = Relative activity (Ci/g)
 SA = Specific activity (Ci/g nuclide)
 MF = Mass fraction (g nuclide/g material).

Committed dose equivalent factors represent the doses committed to the various organs of the body for each radionuclide of interest. Committed dose equivalent factors in units of rem/microcurie (rem/μCi) can be obtained directly from *Internal Dose Conversion Factors for Calculation of Dose to the Public*.⁴

Organ weighting factors are tissue- or organ-specific factors, which represent the fraction of the total health risk resulting from uniform whole-body irradiation that could be contributed to each tissue or organ. When calculating dose

conversion factors for specific organs or tissues these factors are set equal to 1. When calculating the whole-body dose conversion factor the values are taken from publication 26, *Recommendations of the International Commission on Radiological Protection*.⁵ These factors are given in Table 2.

Table 2. Weighting Factors for Organ and Tissues.

Organ or tissue	Weighting factor
Gonads	0.25
Breasts	0.15
Red bone marrow	0.12
Lungs	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder ^a	0.30

^aRemainder refers to the five other organs with the highest dose (e.g., liver, kidney, spleen, thymus, adrenals, pancreas, stomach, small intestine, or upper and lower large intestine). The weighting factor for each organ is 0.06.

The relative concentration, expressed in units of seconds per cubic meter (s/m^3), represents the dispersion of the radioactive materials between the points of origin and entry into the body. Calculations of the relative concentrations are usually based on centerline plume concentrations from a Gaussian diffusion model⁶ as indicated in equation 5.

$$RC = 1 / (\pi \cdot \sigma_y \cdot \sigma_z \cdot u) \quad (5)$$

where:

- RC = Relative concentration (s/m^3)
- σ_y = Horizontal dispersion standard deviation (m)
- σ_z = Vertical dispersion standard deviation (m)
- u = Wind velocity (m/s).

The horizontal and vertical dispersion standard deviations are functions of the distance between points of origin and entry into the body, and the Pasquill stability classes of the atmosphere. A full discussion of Pasquill stability classes as well as formula for calculating the dispersion standard deviations is given in *The Change of Concentration Standard Deviations with Distance*.⁷ Site-specific data on Pasquill stability classes and wind velocities can generally be obtained from environmental impact statements, safety analysis reports, or local weather stations.

The breathing rate represents the volumetric rate of inhalation expressed in units of volume per unit time. Typically the breathing rate used is from the standard human as described in publication 2, *Recommendations of the International Commission on Radiological Protection*.⁸

$$BR = 3.47 \cdot 10^{-4} \text{ m}^3/\text{s} \quad (6)$$

where:

BR = Breathing rate.

BUILDING SOURCE TERMS

The building source terms are computed as the product of the material at risk, release fractions, respirable fractions, and leak path factors as indicated in equation 7.

$$BST = MAR \cdot RF \cdot f_{RESP} \cdot LP \quad (7)$$

where:

- BST = Building source term (g)
- MAR = Material at risk (g)
- RF = Release fraction
- f_{RESP} = Respirable fraction
- LP = Leak path factor.

The material at risk is the mass of radioactive material available for release and can be based on the actual inventory or mass limits in the region affected by the explosion. It is generally expressed in grams (g).

The release fraction represents that fraction of the material at risk which will become airborne as a result of the release. If the material being released is a dispersible powder, then the release fraction is calculated using an equation developed by Halverson and Mishima.⁹ If the released material is not a dispersible powder, then the release fraction is calculated using the Steindler and Seefeldt model¹⁰ incorporated into the computer code DETIN.¹¹

The respirable fraction represents that fraction of the airborne material which is small enough to be inhaled into the lungs. This fraction is typically taken to be that fraction of the airborne particulates which have aerodynamic equivalent diameters of 10 microns or less. If the material being released is a dispersible powder, then this fraction is determined by laboratory analysis. If the material is not a dispersible powder, then the DETIN code¹¹ is used to calculate the respirable fraction.

The leak path factor represents that fraction of the respirable airborne material that leaks from the containment structure to the environment. It is a strong function of many important factors such as structural compositions and configurations, pressures and temperatures of the rooms involved, characteristics of the flow paths, and the energy released by the event.

The leak path factor is calculated using computer codes such as the EVENT code¹² or BLAST, a code being developed in the Security Applications Center. Both codes treat explosion-induced gas-dynamic transient within structures using a lumped-parameter method, which ignores spatial variations in flow properties. Both codes treat the

gases as ideal gases. The BLAST code contains data on the gas and energy generation rates of about three dozen different explosives.

CONCLUSION

This paper has presented a method for calculating the consequences of explosive radiological releases. The consequence values are proportional to the ratio of calculated doses to guideline doses as indicated in equation 1. The calculated doses are the product of dose conversion factors and building source terms as shown in equation 2. The dose conversion factors for inhalation doses are calculated using equation 3, and the building source terms for detonations are calculated using equation 7.

The formula and techniques employed in the calculations have been highlighted in this paper and are detailed in the references.

Although, this paper has focused on inhalation dose conversion factors and detonation building source terms, dose conversion factors for immersion and ingestion doses and building source terms for deflagrations and criticalities can also be used in equations 1 and 2 to determine the consequences of radiological releases.

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