# LEVEL

JUN 2 3 1981

DISTRIBUTION STATEMENT

# TASC

ONE JACOB WAY/READING, MASSACHUSETTS 01867/(617) 944-6850

TR-3135-1

# PROCEDURES TO CALCULATE RADIOLOGICAL AND TOXICOLOGICAL EXPOSURES FROM AIRBORNE RELEASES OF DEPLETED URANIUM

October 1980

DTIC
ELECTE
JAN 2 3 1981
C

Prepared for:

U.S. Army
ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
Dover, New Jersey

Prepared by:

Daniel A. Ensminger
Sharon A. Bucci

THE ANALYTIC SCIENCES CORPORATION
One Jacob Way
Reading, Massachusetts   01867

80   12   11   056

THE ANALYTIC SCIENCES CORPORATION

## PREFACE

This document was prepared for the ARRADCOM
Depleted Uranium Task Force as part of a continuing
effort to evaluate the potential hazards associated
with the use of depleted uranium munitions. Support
for this effort was provided by the Office of the Proj-
ect Manager, Tank Main Armament Systems, XM1 Tank
System Program, Army Contract Nos. DAAK10-78-C-0364
and DAAK10-80-R-0060. The technical monitor was Dr.
Ernest W. Bloore, DU Task Force Chairman, U.S. Army
Armament Research and Development Command, Dover,
New Jersey.

The authors wish to thank Army personnel
for their helpful and thoughtful comments during the
preparation of this document, especially Dr. E.W.
Bloore and Mr. E.F. Wilsey, Armament Research and
Development Command; COL J.W. Thiessen, Army Envi-
ronmental Hygiene Agency; and Mr. R.C. McMillan,
Mobility Equipment Research and Development Command.

ii

## TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

## LIST OF FIGURES

## LIST OF TABLES

## SUMMARY

The 105mm Armor-Piercing, Fin-Stabilized, Discarding Sabot-Tracered (APFSDS-T), Kinetic Energy XM774 and M735A1 cartridges, developed by the U.S. Army Armament Research and Development Command (ARRADCOM), are intended for use in tanks equipped with an M68 gun. These cartridges, both containing a depleted uranium (DU) penetrator, will provide improved penetration effectiveness over the currently fielded M392 and M728 series of armor-piercing, spin-stabilized, discarding sabot rounds and the M735 APFSDS-T cartridge.

A concern of using these munitions is centered on potential radiation and toxicity exposures which may result from scheduled or accidental releases of the DU penetrator to the air as fine particles. Depleted uranium metal is formed as a by-product of the uranium enrichment process, and contains a very small percentage, by weight, of the lighter, faster decaying $^{234}U$ and $^{235}U$ isotopes. Thus the activity of DU is much less than that of natural uranium, although chemically both metals have similar properties.

A number of efforts have been conducted within the Army to obtain a clearer understanding of expected radiological and toxicological exposures resulting from airborne dispersions of DU material under given release conditions. Although the fundamental approach is similar in each evaluation, variations in procedures and assumptions impede direct comparison of results and, in general, limit the applicability of the information to the overall question of consequences from airborne releases of DU munitions. Consequently, there is a need to establish uniformity in the methods and assumptions used to determine these exposures.

In this report, the framework for calculating radiation and toxicity exposures is outlined. Section I provides a detailed treatment of the Gaussian diffusion model typically used to simulate the transport of material dispersed into the air from a point-source release. Employing the model for given release conditions, the following concentrations of DU can be determined at various distances downwind of the source: (1) instantaneous, average, or integrated concentration of material in the air and (2) concentration of material deposited on the ground from the passing cloud. Instantaneous (puff) and continuous (plume) release modes are described for both constant and random wind conditions, addressing the requirements, application, and pertinent considerations for the use of each. Also discussed is the isotopic composition of the DU source term, the effect of atmospheric stability on airborne dispersion, general guidelines for model use, and a general treatment for estimating the contribution of resuspended materials to air concentrations.

In Section II, methods and criteria are presented for determining the radiological and toxicological insult from either occupational or general populace exposures to airborne uranium material. Measures of exposure include: whole-body dose, critical-organ dose, radiological concentration of DU in air -- for evaluating radiation insult, and concentration of soluble DU in air -- for assessing chemical toxicity burden. T'e effects of solubility or radiological exposures are discussed. All measures reflect the internal buildup of uranium within the body or its organs and, where applicable, external irradiation. Equations for determining exposure are described in detail, with the relevant contributions due to inhalation, resuspension, and/or deposition identified in each expression.

Maximum limits for chronic exposures to depleted uranium are presented in Section III. These limits, based on health and safety standards recommended by the International Commission on Radiological Protection and the U.S. Nuclear Regulatory Commission, are discussed both for monitored personnel in restricted areas (occupational limits) and for individuals in the population (general populace limits). Estimates of exposure should be compared to these recommended maximum limits to determine compliance with prescribed standards and to identify the critical (or limiting) exposure for a given release condition.

## SECTION I
## MODELS FOR DETERMINING AIR AND GROUND
## CONCENTRATIONS OF RELEASED DEPLETED URANIUM


This section provides a detailed description of the models used to determine concentrations of materials released to the air and ground from depleted uranium (DU) rounds used in conventional munitions. Section I,A discusses the source terms for depleted uranium used when modeling these releases. Section I,B gives an in-depth treatment of meteorological transport and deposition models. Section I,C describes the modeling of air concentrations from resuspended materials. The calculations shown here are an important adjunct to the computation of radiological and toxicological hazards resulting from the release of depleted uranium to the environment.


A. SOURCE TERMS


It is necessary to determine the number of curies for each isotope of uranium in the DU round before calculating air and ground concentrations. However the weight fractions of the uranium isotopes in DU will vary depending on the amount of $^{234}U$ and $^{235}U$ that is extracted during the enrichment process. Consequently, the specific activity of the overall DU mixture will also vary.


Differing values for the isotopic composition of DU appear in the literature, indicating different $^{235}U$ enrichment goals at the time of processing. Three such compositions are summarized in Table 1, Columns 1-3. The isotopic distribution


1

TABLE 1

ISOTOPIC COMPOSITIONS AND SPECIFIC ACTIVITIES
OF DEPLETED URANIUM

T-3811

| ISOTOPE | WEIGHT FRACTION | | | |
|---|---|---|---|---|
| | BARTLETT, et al (REF. 1) | WAITE, STOETZEL, AND GILCHRIST (REF. 2) | PORTSMOUTH ENVIRONMENTAL STATEMENT (REF. 3) | LEVY (REF. 4) |
| $^{234}U$ | $3.4 \times 10^{-6}$ | $5 \times 10^{-6}$ | -- | $8 \times 10^{-6}$ |
| $^{235}U$ | $3 \times 10^{-3}$ | $2.5 \times 10^{-3}$ | $2.0$ to $2.5 \times 10^{-3}$ | $2 \times 10^{-3}$ |
| $^{236}U$ | -- | -- | -- | $3.2 \times 10^{-5}$ |
| $^{238}U$ | $9.97 \times 10^{-1}$ | $9.975 \times 10^{-1}$ | $9.98 \times 10^{-1}$ | $9.98 \times 10^{-1}$ |
| Specific Activity of DU Mixture (Ci/kg) | $3.6 \times 10^{-4}$ | $3.7 \times 10^{-4}$ | $3.4 \times 10^{-4}$ | $3.8 \times 10^{-4}$ |

in Column 4 is considered to be a production goal for DU
in the future. This composition of DU includes the isotope
$^{236}U$, which is extracted during the enrichment of reproc-
essed fuel and not found in nature.

The specific activity of the DU mixtures in Table 1
vary from $3.4 \times 10^{-4}$ Ci/kg to $3.8 \times 10^{-4}$ Ci/kg. 10 CFR 20* recom-
mends that a value of $3.6 \times 10^{-4}$ Ci/kg be used for the specific
activity of DU, but does not specify a corresponding isotopic
composition. Using the isotopic composition in Column 1 of
Table 1, an overall specific activity of $3.6 \times 10^{-4}$ Ci/kg is
obtained. However, this calculation employs an 0.3% weight
fraction for $^{235}U$, which is at the high end of the 0.2%-0.3%
range observed in the literature.

---

*10 CFR 20 refers to Title 10 (NRC) Code of Federal Regulations,
 Part 20 (Reference 5).

A weight fraction of 0.25% for $^{235}U$ is concluded to be a more balanced choice when defining the composition of DU since 0.25% is the midpoint in the observed range of values for this isotope. Using the weight fraction of 0.25% for $^{235}U$ and a specific activity of $3.6 \times 10^{-4}$ Ci/kg for DU, weight fractions for $^{234}U$ and $^{238}U$ can be determined analytically by solving the following simultaneous equations:

$$x + 0.0025 + y = 1$$

$$(6.05)\ x + (2.14 \times 10^{-3})(0.0025) + (3.33 \times 10^{-4})\ y = 3.6 \times 10^{-4}$$

where

> x and y denote the weight fractions of $^{234}U$ and $^{238}U$ respectively

and

> 6.05, $2.14 \times 10^{-3}$, and $3.33 \times 10^{-4}$ are the specific activities (per unit mass) of the $^{234}U$, $^{235}U$, and $^{238}U$ isotopes respectively (Ci/kg)

Thus an "average" isotopic composition of DU having a specific activity of $3.6 \times 10^{-4}$ Ci/kg contains 0.00037% $^{234}U$, 0.25% $^{235}U$, and 99.75% $^{238}U$. These weight fractions are considered representative for the varying isotopic composites of DU that may be used in the fabrication of future DU rounds and thus, in this document, are used as fixed parameter values in the equations for estimating exposures from the release of DU to the air and ground.

Table 2 contains weight fractions for the average isotopic composition of DU in the M735A1 and XM774 penetrators and the corresponding activity per penetrator for each of the three uranium isotopes in DU. Note in the column, percent of activity per penetrator, that $^{238}U$ is the dominant contributor to radiological dose from exposure to DU.

3

### TABLE 2
### ISOTOPIC COMPOSITION OF DEPLETED URANIUM
### IN XM774 AND M735A1 PENETRATORS

T-3812a

| ROUND | TOTAL MASS OF DU PER PENETRATOR (kg/round) | ISOTOPE | WEIGHT FRACTION | SPECIFIC ACTIVITY PER UNIT MASS ISOTOPE (Ci/kg) | ACTIVITY PER PENETRATOR* (Ci/round) | PERCENT ACTIVITY PER PENETRATOR |
|---|---|---|---|---|---|---|
| M735A1 | 2.18 | $^{234}U$ | $3.7 \times 10^{-6}$ | 6.05 | $4.88 \times 10^{-5}$ | 6.2 |
| | | $^{235}U$ | $2.5 \times 10^{-3}$ | $2.14 \times 10^{-3}$ | $1.17 \times 10^{-5}$ | 1.5 |
| | | $^{238}U$ | $9.975 \times 10^{-1}$ | $3.33 \times 10^{-4}$ | $7.24 \times 10^{-4}$ | 92.3 |
| XM774 | 3.40 | $^{234}U$ | $3.7 \times 10^{-6}$ | 6.05 | $7.61 \times 10^{-5}$ | 6.2 |
| | | $^{235}U$ | $2.5 \times 10^{-3}$ | $2.14 \times 10^{-3}$ | $1.82 \times 10^{-5}$ | 1.5 |
| | | $^{238}U$ | $9.975 \times 10^{-1}$ | $3.33 \times 10^{-4}$ | $1.13 \times 10^{-3}$ | 92.3 |

$$\text{*Activity Per Penetrator} = \text{Total Mass Per Penetrator} \times \text{Weight Fraction} \times \text{Specific Activity Per Unit Mass Isotope}$$

## B.  MODELS OF METEOROLOGICAL TRANSPORT AND DEPOSITION

Models describing the transport of particles in the air enable the following estimates to be computed:

- Instantaneous, average, or integrated concentration of material in the air

- Concentration of material deposited on the ground from the passing cloud.

Gaussian diffusion models, wherein the shape of the cloud of released material is assumed to follow a two- or three-dimensional Gaussian distribution, are conventionally used to describe the transport and diffusion of materials dispersed into the air (References 6 and 7).  Such models are shown in the literature to be fundamental solutions to Fick's equation

4

for diffusion in the atmosphere (Reference 7). A basic assumption of these meteorology models is that the material released to the air is composed of gases and/or particles (less than 20 μm in diameter - Reference 8) that follow the motions of the atmosphere. This implies that the particles have negligible settling velocity and that the gas is neither positively nor negatively buoyant.

Key parameters in these Gaussian diffusion models include: effective release height of the pollutant, Pasquill atmospheric stability class, mean wind speed at the height of release, directional wind frequency (wind rose), lateral and vertical dispersion, and cloud depletion. Conservative values for these parameters should be used whenever adequate site-specific data are not available.

Different release modes (instantaneous or continuous) and durations (short-term or long-term) require different models for analysis, although all have the same Gaussian basis. For evaluating instantaneous point-source releases, puff models are employed; for analyzing continuous point-source releases, plume models are used. The following sections provide greater detail on the use of each type of model.

### 1. Instantaneous Releases

The Gaussian puff model simulates the diffusion and transport of instantaneous point-source releases of material to the air. A puff, once formed, dissipates with the speed and direction of the wind at the time of release. As the puff moves, it expands about its center.

Figure 1a illustrates the passage of a single puff of particles in the direction of the prevailing wind uniformly

a) PASSAGE OF A SINGLE PUFF – – SIDE VIEW



b) SAMPLE ISOPLETHS OF GROUND CONCENTRATION AFTER PASSAGE OF THE PUFF – – OVERHEAD VIEW
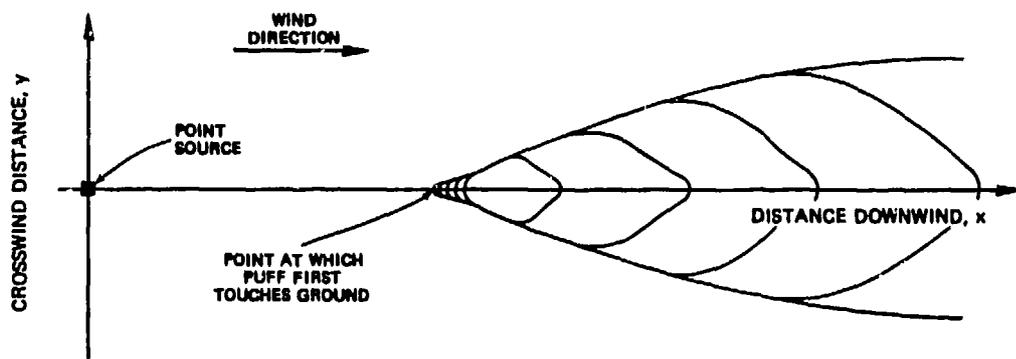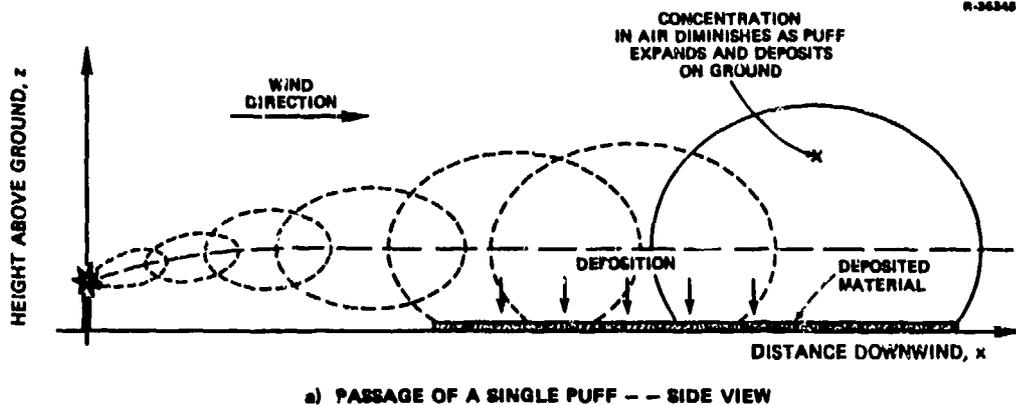
Figure 1    Passage of a Single Puff

over time. The concentrations of airborne material in the
puff diminish as distance downwind increases due to continual
expansion of the puff and deposition of material on the ground.
The concentration on the ground (Figure 1b) is seen to peak
sharply near the point at which the puff first touches the
ground and then to diminish monotonically as distance downwind
increases.

Puff Model with Constant Wind Direction - A Gaussian
puff model in which the wind direction is fixed is used for
modeling:

- All· single, instantaneous emissions

- All multiple, instantaneous emissions from the same source where

    - the wind direction is known to be constant for all releases, or

    - the releases occur over a period of less than eight hours in duration, and no specific data on wind direction are available.

The first quantity obtained from modeling instantaneous releases is the instantaneous concentration, which is a measure of the activity of radionuclides per unit volume of air at a fixed (x,y,z) coordinate and at a fixed point in time. It is important to note that at a fixed location instantaneous concentration varies as the puff passes.

The instantaneous concentration of material in air at ground level[*], $\chi$, normalized per unit activity released, $Q_0$, is calculated as follows (References 6 and 7):

$$\frac{\chi(x,y,0,t)}{Q_0} = \frac{Q_x/Q_0}{\sqrt{2}\ \pi^{3/2}\sigma_{xI}\sigma_{yI}\sigma_{zI}} \ \exp\ -\ \frac{1}{2}\ \left[ \left( \frac{(x-\bar{u}t)^2}{\sigma_{xI}^2} + \frac{y^2}{\sigma_{yI}^2} + \frac{h^2}{\sigma_{zI}^2} \right) \right] \quad (1)$$

where

        x,y,z = positions in ᶜ Cartesian coordinate sys-- tem (Figure 1) oriented so tnat the x-axis is in the direction of the horizontal wind vector, the y-axis is crosswind, and the z-axis is vertical (m)

        t = time elapsed since emission (sec)

---

[*]Reference 7 shows that the concentration in the air is greatest at ground level (z=0) for all distances downwind after the puff touches the ground. This is a conservative assumption for most downwind distances considered in a typical analysis.

$\chi(x,y,0,t)$ = instantaneous concentration of material in a puff at time t, measured at ground level at a distance x meters downwind and y meters crosswind ($Ci/m^3$)

$Q_0$ = total activity of radionuclides released to the air in the form of airborne particles (Ci)

$Q_x/Q_0$ = depletion factor, or fraction of material remaining in the puff at a distance x meters downwind of the source. The remaining material is deposited on the ground by the turbulent action of the lower atmosphere. See Section I,B,3.

$\sigma_{xI}, \sigma_{yI}, \sigma_{zI}$ = standard deviation of the instantaneous distribution of material in a puff in the x, y, and z directions (m). See Table 5, Section I,B,3. In general, $\sigma_{xI} \cong \sigma_{yI}$ (Reference 8).

$\bar{u}$ = average value of wind speed in the x direction (m/sec)

$h$ = effective height of release above ground (m). This is the height attained by the cloud after release. Since no credit is given for this rise, the effective release is set equal to the actual release height.

In order to obtain the instantaneous concentration at a fixed point, the relative (normalized) instantaneous concentration, $\chi(x,y,0,t)/Q_0$, from Equation 1 at that point is multiplied by the total activity in the puff, $Q_0$. Note from Equation 1 that maximum instantaneous concentration occurs along the puff centerline (i.e., y=0) at the center of the puff (i.e., $x=\bar{u}t$).

The _integrated concentration_ represents the summation of instantaneous concentrations at a fixed (x,y,z) coordinate over the duration of the passing puff ($Ci-sec/m^3$). All radiological and toxicological measures of internal exposure from the inhalation of radionuclides use the integrated concentration

8

at $(x,y,z)$ to represent the number of curies inhaled during passage of the cloud. For this reason, <u>integrated concentration is a more functional measure than instantaneous concentration</u>.

An analytic expression for integrated concentration, $\Psi$, normalized per unit activity released is:

$$\frac{\Psi(x,y,0)}{Q_0} = \int_{t=0}^{\infty} \frac{\chi(x,y,0,t)}{Q_0} \, dt$$

$$= \frac{Q_x/Q_0}{\pi \sigma_{yI} \sigma_{zI} \bar{u}} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_{yI}^2} + \frac{h^2}{\sigma_{zI}^2}\right)\right] \tag{2}$$

where

$\Psi(x,y,0)$ = integrated concentration of material from puff passage, measured at ground level at a distance x meters downwind and y meters crosswind $(Ci\text{-}sec/m^3)$

and $\chi(x,y,0,t)$, $t$, $Q_0$, $Q_x/Q_0$, $\sigma_{yI}$, $\sigma_{zI}$, $\bar{u}$, and $h$ are as defined in Equation 1.

To obtain the integrated concentration from the passage of one or more puffs, the relative (normalized) integrated concentration, $\Psi(x,y,0)/Q_0$, from Equation 2 is multiplied by the number of curies contained in all passing puffs, $Q_0$. Note from Equation 2 that maximum integrated concentrations occur along the puff centerline (i.e., $y=0$).

<u>Puff Model with Random Wind Direction</u> - For modeling multiple, instantaneous emissions from the same source that

- are somewhat uniformly spaced in time, and

- occur over a period of greater than eight hours in duration,

9

it is valid to spatially average concentrations to account for random changes in wind direction (Reference 9). To obtain an estimate of integrated concentration over a period which is very long compared to that over which the mean wind speed is computed, the technique of _sector-averaging_ is used. This involves (1) integrating Equation 2 with respect to y from $-\infty$ to $\infty$, (2) multiplying the result by the frequency with which the wind blows toward a given 22.5 degree compass sector, and (3) dividing by the width of that sector at the distance of interest (Reference 7).

The sector-averaged integrated concentration, normalized per unit activity released, is:

$$\frac{\Psi(r,0)}{Q_0} = \frac{f_c}{\pi r/8} \int_{y=-\infty}^{\infty} \frac{\Psi(x,y,0)}{Q_0} \, dy$$

$$= \frac{2.032 \cdot f_c \cdot (Q_x/Q_0)}{\sigma_{zI} \cdot \bar{u} \cdot r} \; \exp \left[ - \frac{h^2}{2\sigma_{zI}^2} \right] \qquad (3)$$

where

$(r,z)$ = positions in a cylindrical coordinate system oriented so that r measures distance downwind within a sector and z measures distance above the ground (m)

$\Psi(r,0)$ = sector-averaged integrated concentration of material from passing puffs, measured at ground level at a distance r meters downwind in a sector $(Ci\text{-}sec/m^3)$

$f_c$ = fraction of time the wind blows toward a given compass sector for a given wind speed and atmospheric stability condition

$\pi r/8$ = arc length of a 22.5 degree sector at downwind distance r (m)

10

2.032 = a constant factor from the averaging calculation, equal to $\dfrac{2}{\sqrt{2\pi}} \times \dfrac{1}{\pi/8}$

$\dfrac{\Psi(x,y,0)}{Q_0}$ = relative (normalized) integrated concentration for the puff model with constant wind direction ($sec/m^3$) (See Equation 2)

and $Q_0$, $Q_x/Q_0$, $\sigma_{zI}$, $\bar{u}$, and h are as defined in Equations 1 and 2.

The integrated concentration resulting from the passage of several instantaneous releases that are randomly spaced over a period of eight hours or more is obtained by multiplying the relative (normalized) integrated concentration, $\Psi(r,0)/Q_0$, from Equation 3 by the number of curies contained in all passing puffs, $Q_0$. Note that the concentration in the puffs are contained along the centerline (i.e., y=0) of the winds blowing into the defined sector and that $\Psi(r,0)$ is uniform across each sector at any given downwind distance r from the source.

The fraction $f_c$ in Equation 3 generally represents a joint frequency distribution of wind direction, wind speed, and atmospheric stability class (wind rose). When wind-rose data are available, the <u>critical sector</u> -- that having the highest sector-averaged integrated concentration of any sector -- can be identified. When site-specific data are lacking, conservative values for $f_c$ (and other model parameters) are used. Section I,B,4 treats this subject in greater detail.

<u>Deposition from Instantaneous Releases</u> - Dry deposition is defined as the removal of small particles from the passing cloud onto the ground due to nongravitational forces such as surface impact, adsorption, and electrostatic attraction. The areal density of material deposited on the ground by one or

11

more puffs at a given distance downwind is the product of the ground-level integrated concentration at that distance and the deposition velocity. The deposition velocity represents the average downward rate of movement of the particles in a puff due to the action of turbulent eddies near the ground (Reference 7). This can be expressed as:

$$\omega(x,y,0) = Q_0 \cdot \frac{\Psi(x,y,0)}{Q_0} \cdot v_d \tag{4}$$

for puff models with constant wind direction, or

$$\omega(r,0) = Q_0 \cdot \frac{\Psi(r,0)}{Q_0} \cdot v_d \tag{5}$$

for puff models with random wind direction, where

$\omega$ = areal density of material deposited on the ground $(Ci/m^2)$

$Q_0$ = total activity emitted in single or multiple instantaneous releases from the same source (Ci)

$v_d$ = deposition velocity[*] (m/sec)

and $\Psi(x,y,0)/Q_0$ and $\Psi(r,0)/Q_0$ are determined from Equations 2 and 3, respectively.

The entire cloud is eventually depleted onto the ground at an infinitely large downwind distance. Note that the spatial profile of the ground concentration $\omega$ follows the Gaussian pattern of the integrated air concentration $\Psi$ at ground level

---

[*]Based on the assumptions of neutral buoyancy and negligible settling of particles for the Gaussian diffusion model, the value of 0.01 m/sec (Reference 10 and Section 5.3, Reference 7) is an acceptable estimate of deposition velocity.

(see Figure 1). The areal density of deposited radionuclides is of primary importance in computing external radiological dose and in computing concentrations of resuspended material in air (Section I,B).

## 2. Continuous Releases

A continuous Gaussian plume results from the addition of an infinite number of overlapping puffs carried in the direction of the wind (Reference 7). The advective transport of these puff elements and the diffusion of the elements about their individual centers cause dispersion of the plume (Reference 6). The activity of material released is expressed in terms of a release rate (Ci/sec) and the downwind material distribution is measured in terms of the average concentration (Ci/m$^3$) over the period of release.

Figure 2 illustrates the Gaussian distribution of a plume in the horizontal and vertical directions. The plume width is seen to expand as distance downwind increases. Ground concentration under the plume (not shown) peaks near the point at which the plume first touches the ground and then diminishes monotonically as distance downwind increases.

Plume Model with Constant Wind Direction - A plume model having a fixed wind direction is used to compute concentrations from continuous releases of less than eight hours in duration and when no specific data on wind direction are available. The short-term average concentration, the most important measure associated with the constant-wind plume model, is defined as the average concentration of the diffusing puff elements at each downwind location.

R-45524
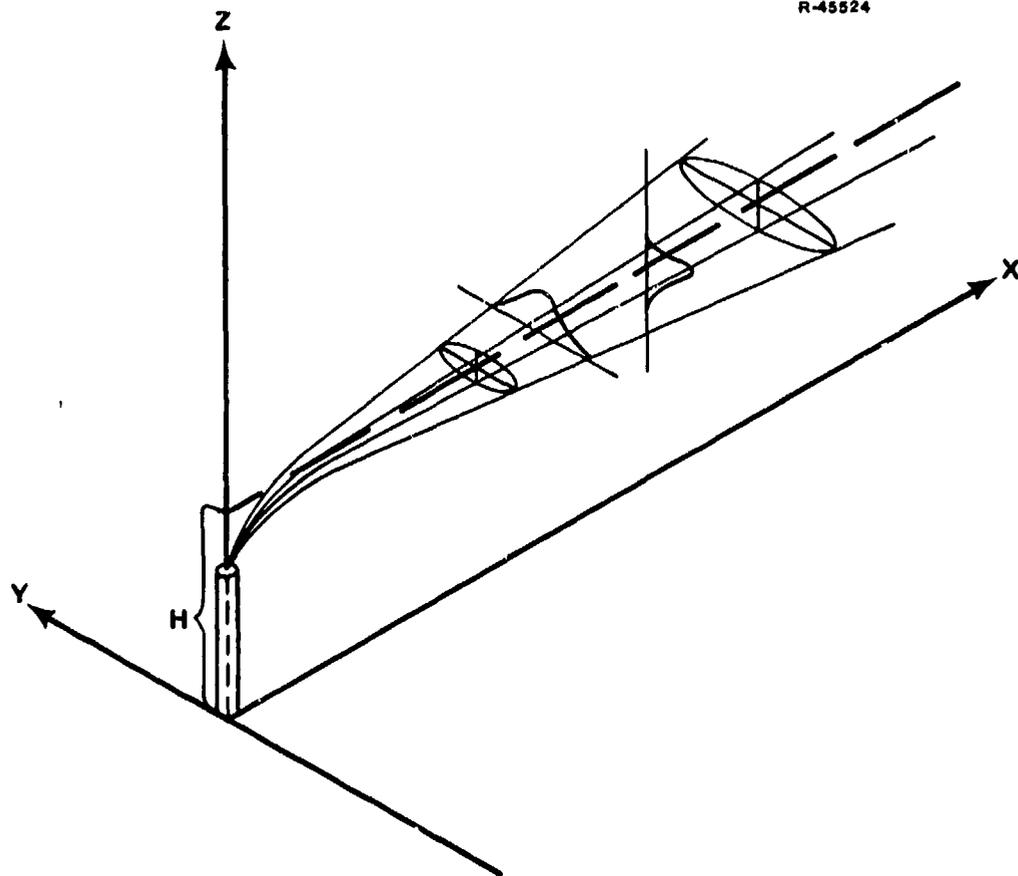
Figure 2    Gaussian Plume Distribution
(Adapted from Reference 8)

An analytic representation for the short-term average concentration of material in air at ground level[*] normalized per unit rate of activity released is:

$$\frac{\bar{\chi}(x,y,0)}{Q_0'} = \frac{Q_x'/Q_0'}{\pi \sigma_y \sigma_z \bar{u}} \; \exp\left[ -\; \frac{1}{2}\left( \frac{y^2}{\sigma_y^2} + \frac{h^2}{\sigma_z^2} \right)\right] \tag{6}$$

where

$\bar{\chi}(x,y,0)$ = short-term average concentration of material in a plume, measured at ground level at a distance x meters downwind and y meters crosswind $(Ci/m^3)$

*See footnote on p. 7.

$Q_0'$ = release rate of material to the air (Ci/sec)

. $Q_x'/Q_0'$ = depletion factor, or fraction of material remaining in the plume at a distance x meters downwind from the source. The remainder is deposited on the ground by the turbulent action of the lower atmosphere. See Section I,B,3.

$\sigma_y, \sigma_z$ = steady-state standard deviations of the plume in the y and z directions (m). See Table 6, Section I,B,3

$\bar{u}$ = average value of wind speed in the x direction (m/sec)

h = effective height of release above the ground (m). Since no credit is given for plume rise, the effective release is set equal to the actual release height

The short-term average concentration resulting from a continuous release of eight hours or less in duration is determined by multiplying the relative (normalized) average concentration, $\bar{\chi}(x,y,0)/Q_0'$, from Equation 6 by the constant release rate, $Q_0'$. Note from Equation 6 that short-term average concentrations are highest along the plume centerline (i.e., y=0).

Plume Model with Random Wind Direction - For continuous releases of greater than eight hours in duration, it is valid to spatially average the short-term plume concentration (Equation 6) to account for random changes in wind direction (Reference 9). To obtain an estimate of long-term average concentration over a period of release greater than eight hours in duration, a sector-averaging procedure, analogous to that presented in Section I,B,1 for the puff model, is used.

The long-term average concentration normalized per unit rate of activity released is:

15

$$\frac{\bar{\chi}(r,0)}{Q_0'} = \frac{f_c}{\pi r/8} \int_{y=-\infty}^{\infty} \frac{\bar{\chi}(x,y,0)}{Q_0'} \, dy$$

$$= \frac{2.032 \cdot f_c (Q_x'/Q_0')}{\sigma_z \cdot \bar{u} \cdot r} \quad \exp \left[ -\frac{h^2}{2\sigma_z^2} \right] \qquad (7)$$

where

$\bar{\chi}(r,0)$ = long-term average concentration of material in a plume, measured at ground level at a distance $r$ meters downwind in a sector $(Ci/m^3)$

$f_c$ = fraction of time the wind blows toward a given 22.5-degree compass sector for a given wind speed and atmospheric stability condition

$\pi r/8$ = arc length of a 22.5-degree sector at downwind distance $r$ (m)

$2.032$ = a constant factor from the averaging calculation, equal to $\dfrac{2}{\sqrt{2\pi}} \times \dfrac{1}{\pi/8}$

$\dfrac{\bar{\chi}(x,y,0)}{Q_0'}$ = relative (normalized) short-term average concentration for the plume model with constant wind direction (see Equation 6)

and $Q_0'$, $Q_x'/Q_0'$, $\sigma_z$, $\bar{u}$, and $h$ are as defined in Equation 6.

The long-term average concentration resulting from a continuous release of greater than eight hours in duration is determined by multiplying the relative (normalized) average concentration, $\bar{\chi}(r,0)/Q_0'$, from Equation 7 by the constant release rate, $Q_0'$. Average concentrations from long-term continuous releases are uniform across each compass sector at any given downwind distance $r$ from the source.

16

A site-specific wind rose may be used to represent the long-term joint frequency distribution of wind direction, wind speed, and atmospheric stability class (i.e., $f_c$ in Equation 7). When wind rose data are available, the critical sector (that having the highest long-term average concentration of any sector) can be identified. When site-specific data are lacking, conservative values for $f_c$ (and other model parameters) are used. Section I,B,4 treats this subject in greater detail.

Deposition from Continuous Releases - Dry deposition depletes material from the plume in a manner analogous to that presented for the puff (Section I,B,1). The areal density of material deposited on the ground at a given point (receptor) is a function of the integrated concentration, duration of exposure to the passing plume, and deposition velocity. Integrated concentration from a continuous release is obtained by multiplying the average concentration, $\bar{\chi}(x,y,0)$ or $\bar{\chi}(r,0)$, by the duration of exposure to the plume, T. If the receptor is present during the _entire_ passage of the plume, then $T = Q_0/Q_0'$ and the integrated concentration becomes simply the product of relative average concentration times total activity released (i.e., $\bar{\chi}/Q_0'$ times $Q_0$). More generally, deposition from continuous releases can be expressed as:

$$\omega(x,y,0) = Q_0' \cdot \frac{\bar{\chi}(x,y,0)}{Q_0'} \cdot T \cdot v_d \qquad (8)$$

for the plume model with constant wind direction, or

$$\omega(r,0) = Q_0' \cdot \frac{\bar{\chi}(r,0)}{Q_0'} \cdot T \cdot v_d \qquad (9)$$

for the plume model with random wind direction, where

17

$\omega$ = areal density of material deposited on the ground $(Ci/m^2)$

$Q_0'$ = release rate of material to the air (Ci/sec)

$T$ = duration of exposure of the ground to the passing plume (sec). Note that for computing deposition from passage of the <u>entire</u> plume, $T = Q_0/Q_0'$, where $Q_0$ is the total <u>number</u> of curies released

$v_d$ = deposition velocity[*] (m/sec)

and $\bar{\chi}(x,y,0)/Q_0'$ and $\bar{\chi}(r,0)/Q_0'$ are determined from Equations 6 and 7, respectively.

Note that the spatial profile of the ground concentration $\omega$ follows the distribution of the average air concentration $\bar{\chi}$ at ground level. The areal density of deposited radionuclides is of primary importance in computing external radiological dose and in computing concentrations of resuspended material in air (see Section I,C).

3. <u>Atmospheric Stability, Standard Deviations, and Depletion Factor</u>

Stability conditions in the lower atmosphere effect the expansion of the cloud as it moves downwind from the point of release and the amount of material remaining in the cloud (or conversely, depositing on the ground) at downwind distances. A number of factors influence stability including wind speed, time of day, incoming solar radiation, and cloud cover. A common method for determining atmospheric stability is to measure the vertical temperature difference between the release height

---

[*]See footnote on p. 12.

and the 10-meter level above ground (Reference 11). Stability classes using the temperature difference method are given in Table 3. When temperature decreases with height at a fast rate, the atmosphere is in <u>unstable</u> equilibrium and vertical motions are enhanced. When temperature increases rapidly with height (inversion), vertical motions are damped or reduced (stable equilibrium).

TABLE 3

CLASSIFICATION OF ATMOSPHERIC STABILITY
(Temperature Difference Method)

| STABILITY CLASSIFICATION | | TEMPERATURE CHANGE WITH HEIGHT ($°C/100m$) |
|---|---|---|
| Extremely unstable | A | $<-1.9$ |
| Moderately unstable | B | -1.9 to -1.7 |
| Slightly unstable | C | -1.7 to -1.5 |
| Neutral | D | -1.5 to -0.5 |
| Slightly stable | E | -0.5 to 1.5 |
| Moderately stable | F | 1.5 to 4.0 |
| Extremely stable | G | $>4.0$ |

Source: Reference 11.

Another method which has wide application for determining the degree of turbulence in the lower atmosphere was introduced by Pasquill (Reference 12). The stability of the atmosphere is estimated from the wind speed at a height of about 10 meters and from the incoming solar radiation during the day or the cloud cover during the night (Reference 8). Stability categories using Pasquill's method are given in Table 4. This stability classification is representative of

TABLE 4

KEY TO STABILITY CATEGORIES
(Pasquill Method)

A - Extremely unstable conditions    D - Neutral conditions[†]

B - Moderately unstable conditions    E - Slightly stable conditions

C - Slightly unstable conditions    F - Moderately stable conditions

T-3813

| SURFACE WIND SPEED (at 10m), m/sec | DAYTIME ISOLATION | | | NIGHTTIME CONDITIONS | |
|---|---|---|---|---|---|
| | STRONG | MODERATE | SLIGHT | THIN OVERCAST OR $\geq$ 4/8 CLOUDINESS[††] | $\leq$ 3/8 CLOUDINESS |
| <2 | A | A-B | B | | |
| 2 | A-B | B | C | E | F |
| 4 | B | B-C | C | D | E |
| 6 | C | C-D | D | D | D |
| >6 | C | D | D | D | D |

†Applicable to heavy overcast, day or night.

††The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

Source: Reference 12.

atmospheric conditions in open country or rural areas, but is less reliable for urban areas. Differences are due primarily to the influence of the city's larger surface roughness and heat island effects upon the stability regime. The greatest difference in atmospheric stability between rural and urban areas occurs on calm clear nights. On such nights conditions over rural areas are very stable; but over urban areas, conditions are slightly unstable or neutral to a height several times the average building height, with a stable layer above (Reference 12).

The <u>standard deviations</u> ($\sigma_{yI}$, $\sigma_{zI}$, $\sigma_y$, and $\sigma_z$) for puff and plume expansion increase with increasing distance downwind from the source. The rate at which these dispersion

coefficients increase with downwind distance is a function of the turbulent nature of the atmosphere. This relationship is commonly modeled using a power-law function (e.g., $\sigma = ax^b$), where the coefficients a and b vary with atmospheric stability. Power function coefficients for determining puff and plume dispersion are given in Tables 5 and 6 respectively. (Typical analytic and graphic relationships for puff and plume standard deviations can be found in References 7, 8, 13, and 14). For stable (E, F, or G) atmospheric conditions, the $\sigma$'s increase at a relatively slow rate; for neutral (D) and unstable (A, B, or C) conditions, the $\sigma$'s increase at a moderate and fast rate, respectively.

TABLE 5

STANDARD DEVIATIONS FOR PUFF RELEASES

| STABILITY CLASS | $\sigma_{zI} = ex^f$ | | $\sigma_{yI} = gx^h$ | |
|---|---|---|---|---|
| | e | f | g | h |
| | $100 \leq x \leq 4000$ | $100 \leq x \leq 4000$ | $100 \leq x \leq 4000$ | $100 \leq x \leq 4000$ |
| A<br>B | 0.53 | 0.73 | 0.14 | 0.92 |
| C<br>D | C.15 | 0.70 | 0.06 | 0.92 |
| E<br>F | 0.05 | 0.61 | 0.02 | 0.89 |
| G | 0.03 | 0.61 | 0.013 | 0.89 |

Source: Reference 7 - Stability Classes A-F
Reference 14 - Stability Class G

Note: Variable x represents downwind distance (m) from source.

The <u>depletion factors</u> for puff and plume releases $(Q_x/Q_0$ and $Q_x'/Q_0')$ at a given downwind distance depend on the standard deviations, effective release height, wind speed, and

TABLE 6

STANDARD DEVIATIONS FOR PLUME RELEASES

T-4601

| STABILITY CLASS | $\sigma_z = ax^b$ | | | | | | $\sigma_y = cx^d$ | | | |
| | a | | | b | | | c | | d | |
| | x<500 | 500≤x<5000 | x≥5000 | x<500 | 500≤x<5000 | x≥5000 | x<10000 | x≥10000 | x<10000 | x≥10000 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 0.0383 | 0.000254 | 0.000254 | 1.281 | 2.089 | 2.089 | 0.495 | 0.606 | 0.873 | 0.851 |
| B | 0.1393 | 0.0494 | 0.0494 | 0.9467 | 1.114 | 1.114 | 0.310 | 0.523 | 0.897 | 0.840 |
| C | 0.112 | 0.101 | 0.115 | 0.910 | 0.926 | 0.911 | 0.197 | 0.285 | 0.908 | 0.867 |
| DD Day | 0.0856 | 0.259 | 0.737 | 0.865 | 0.687 | 0.564 | 0.122 | 0.193 | 0.916 | 0.865 |
| DN Night | 0.0818 | 0.253 | 1.297 | 0.8155 | 0.634 | 0.442 | 0.122 | 0.193 | 0.916 | 0.865 |
| E | 0.1094 | 0.2452 | 0.9204 | 0.7657 | 0.6358 | 0.4805 | 0.093 | 0.141 | 0.912 | 0.868 |
| F | 0.05645 | 0.1930 | 1.505 | 0.805 | 0.6072 | 0.3662 | 0.0625 | 0.0800 | 0.911 | 0.864 |
| G | 0.03387 | 0.1158 | 0.903 | 0.805 | 0.6072 | 0.3662 | 0.0417 | 0.0533 | 0.911 | 0.864 |

Source: Reference 13 - Stability Classes A-F
        Reference 14 - Stability Class G

Note: Coefficients are based on a 10-minute averaging time. Variable x represents
      downwind distance (m) from source.

deposition velocity. For stable conditions, the fraction of ma-
terial in the cloud deposited on the ground increases rapidly
as distance downwind increases; neutral and unstable conditions
are characterized by moderate and slow rates of deposition,
respectively, as distance downwind increases.

Depletion factors can be evaluated using the analyses
of Van der Hoven (Reference 7, Section 5.3-2)

$$Q_x/Q_0 = \exp\left[-\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{v_d}{\bar{u}}\right)\int_0^{x'}\frac{1}{\sigma_{zI}}\exp\left(-\frac{h^2}{2\sigma_{zI}^2}\right)dx\right] \quad (10)$$

for puff releases, or

$$Q_x'/Q_0' = \exp\left[-\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{v_d}{\bar{u}}\right)\int_0^{x'}\frac{1}{\sigma_z}\exp\left(-\frac{h^2}{2\sigma_z^2}\right)dx\right] \quad (11)$$

22

for plume releases, where x' is downwind distance and $v_d$, $\bar{u}$, $\sigma_{zI}$, h, and $\sigma_z$ are defined in Equations 1 and 6. When $Q_x'/Q_0'$ is set equal to 1, all the material released is assumed to remain in the cloud at each downwind distance, yielding con- servatively high estimates of the air concentration.

### 4. Guidelines for Model Use

In a specific application, when sufficient meteorolog- ical data are gathered, these values may be used to calibrate the released puff or plume (Sections I,B,1 and I,B,2). However appropriate data may not be available or may exist only in the form of long-term averages. As a result, guidelines have been established (References 6 and 9) to introduce an appropriate degree of conservatism into the calculations whenever there are uncertainties in the data, or whenever there is not sufficient information available to fully characterize site conditions.

NRC Regulatory Guide 1.3 (Reference 9) provides a framework for selecting a conservative model type and parame- ter values whenever sufficient site-specific data is not avail- able. The nature of a release, instantaneous or continuous, dictates whether the puff or plume model is used; the duration of the release determines whether the constant or random wind approach is used and the nature of the data, site-specific or NRC-recommended, that may be employed. These guidelines are summarized in Table 7 by release duration.

For releases of up to eight hours in duration, a con- stant wind model must be used. When releases are eight hours or more in duration, a random wind model employing sector-averaging may be used. NRC-recommended parameter values should be used with either a constant wind or random wind model for releases of up to 30 days. These parameter values will provide a conser- vative bound on the estimates of air concentration. (The use

23

## TABLE 7

## GUIDELINES FOR SELECTING GAUSSIAN DIFFUSION MODELS AND PARAMETER VALUES

T-3814a

| RELEASE DURATION | TYPE OF MODEL AND DATA TO USE | RELEASE HEIGHT, h | DEFAULT PARAMETER VALUES | | |
|---|---|---|---|---|---|
| | | | PASQUILL STABILITY CLASS(ES) | WIND SPEED BY STABILITY CLASS, $\bar{u}$ | WIND ROSE FACTOR, $f_c$ |
| 0-8 hours | • Constant wind | Ground-level | 100% F-stability | 1 m/sec | - |
| | • Recommended data | Elevated | Envelope of Pasquill categories (Figure A7, Reference 6) | 1 m/sec | - |
| 8-24 hours | • Random wind | Ground-level | 100% F-stability | 1 m/sec | 1.0 |
| | • Recommended data | Elevated | Envelope of Pasquill categories | 1 m/sec | 1.0 |
| 1-4 days | • Random wind<br><br>• Recommended data | Ground-level | 40% D-stability<br>60% F-stability | 3 m/sec (D-stability)<br>2 m/sec (F-stability) | 1.0 |
| | | Elevated | Maximum[†] of:<br><br>1) 40% A-stability<br>60% C-stability<br><br>2) 50% C-stability<br>50% D-stability<br><br>3) 33.3% C-stability<br>33.3% D-stability<br>33.3% E-stability<br><br>4) 33.3% D-stability<br>33.3% E-stability<br>33.3% F-stability<br><br>5) 50% D-stability<br>50% F-stability | 2 m/sec<br>(A-, B-, E-, and F-stability)<br><br>3 m/sec | 1.0 |
| > 4 days | Releases of 4-30 days:<br><br>• Random wind<br><br>• Recommended data<br><br>Releases of 30 days:<br><br>• Random wind<br><br>• Recommended or average long-term, site-specific data | Ground-level | 33.3% C-stability<br>33.3% D-stability<br>33.3% F-stability | 3 m/sec<br>(C- and D-stability)<br><br>2 m/sec<br>(F-stability) | 0.33 |
| | | Elevated | Maximum[†] of:<br>1) 40% A-stability<br>60% C-stability<br><br>2) 50% C-stability<br>50% D-stability<br><br>3) 33.3% C-stability<br>33.3% D-stability<br>33.3% E-stability<br><br>4) 33.3% D-stability<br>33.3% E-stability<br>33.3% F-stability<br><br>5) 50% D-stability<br>50% F-stability | 2 m/sec<br>(A-, B-, E-, and F-stability)<br><br>3 m/sec<br>(C- and D-stability) | 0.33 |

[†]Choose the combination that yields the highest concentration at a given downwind distance.

Source: Reference 9.

of average long-term, site-specific data cannot be employed effectively for short-term releases with any degree of certainty.)

When releases of 30 days or more are evaluated, either average long-term, site-specific data or the more conservative, NRC-recommended values may be used. Note from Table 7 that the use of recommended data sometimes involves fractional occurrences of two or more stability classes. This is done to more realistically simulate the day-to-day variation in stability class that occurs at any location.

In summary, Table 7 provides a framework for selecting the appropriate diffusion model and parameter values to insure that a conservative estimate of air concentration will be obtained when sufficient meteorological data are not available. However, when site-specific, meteorological data are measured in conjunction with a puff or plume release, these data may be used in the model regardless of the duration of release.

## C. RESUSPENSION OF SURFACE PARTICLES

Material from the passing cloud which is displaced by wind or by human activity forms a secondary source of material which contributes to the air concentration downwind both during and after passage of the cloud. Evaluation of airborne concentration of dispersed material should include concentrations due to both primary and resuspended sources. This section outlines a general analytic treatment of resuspension.

### 1. Resuspension Factor

The simplest model of air concentration due to resuspension of deposited material is one in which the resuspended

air concentration is expressed as the product of ground concentration and a _resuspension factor_ (References 10 and 15). The resuspension factor (ratio of local air concentration to local ground concentration) is used to convert the ground concentration into an estimate of average air concentration due to all potential resuspensions of the deposited material. The resuspended air concentration can be expressed in terms of Gaussian puff or plume model variables as:

$$\bar{\chi}_r(x,y,0) = K_r \cdot \omega(x,y,0) \tag{12}$$

for constant wind-direction models, or

$$\bar{\chi}_r(r,0) = K_r \cdot \omega(r,0) \tag{13}$$

for random wind-direction models, where

$\bar{\chi}_r$ = average concentration of resuspended particles in air at ground level $(Ci/m^3)$

$K_r$ = resuspension factor $(1/m)$

$\omega$ = areal density of material deposited during initial cloud passage $(Ci/m^2)$

Resuspension factors are determined largely by empirical measurements of average ground and air concentrations and are dependent on many site-specific factors such as:

- Surface conditions (degree of moisture, roughness, agriculture)

- Nature of particulates deposited (particle size, compound, isotope)

- Local meteorology (humidity, wind speed)

- Degree of agitation by motor or pedestrian traffic.

Most resuspension factors are based on measurements made in semi-desert regions, and their direct applicability to soils having other characteristics is questionable. For example, resuspension factors applicable to dry surfaces would most likely tend to overestimate the extent of resuspension in more humid environments. One reason for this is that material deposited on soil tends to mix with the surface layer and is transported below the surface by precipitation. However, the decrease in surface activity via leaching can be estimated in more humid environments using a nuclide-specific environmental loss factor. Such an approach has been taken in modeling efforts for the Liquid Metal Fast Breeder Reactor (Reference 15) and the WASH-1400 Reactor Safety Study (Reference 10). According to Reference 10, initial resuspension factors can range from $10^{-2}$/m to $10^{-10}$/m depending on the nature of the deposition surface, the degree to which the deposited material is agitated, and the degree to which upwind concentration distributions contribute to resuspended concentrations. Therefore, obtaining site-specific data is very important when using resuspension factors.

## 2. Bounding the Overall Concentration in Air

Another perspective on resuspension is gained through a mathematical analysis of the processes of deposition and resuspension. Horst's study (Reference 16) concluded that under very general conditions the air concentration due to both the depleted initial cloud and the resuspended cloud is less than or equal to that due to the initial cloud without allowing for depletion by deposition. In other words, a very conservative estimate of the air concentration or exposure from both initial cloud passage and resuspension may be made by simply computing the concentration due to the undepleted cloud. The only qualification to this conservatism is the

neglect of redeposition. However, it is likely that the impact of redeposition is small, since its net effect is to reduce the resuspended air concentration. Additionally, several model conservatisms would tend to more than offset the neglect of redeposition. For instance, losses due to leaching of weathered material, which can be substantial, are not considered. In addition, Horst calculates exposure to the resuspended air concentration over the entire period required to resuspend all of the deposited material. Since a single receptor may not be exposed for this extended period, this assumption is also conservative.

### 3. Methodology for Analysis of Resuspension

To summarize, two approaches are suggested in the literature for modeling resuspension. In the "constant factor" approach, the ground concentration at a given point is multiplied by a constant factor to obtain a resuspended air concentration. In the "bounding approach", the undepleted concentration of the original cloud is considered an upper bound for the concentration due to both the initial cloud corrected for depletion and resuspension of the deposited material. Based on these approaches, the following general methodologies may be used to account for resuspension:

- Whenever enough site-specific data can be collected for the areas adjacent to a release point, the "constant factor" approach is used. A value for the resuspension factor $(K_r)$ is selected based on the best match of site parameters with empirical data, and Equations 12 or 13 is used to compute the average concentration due to resuspended particles. A corresponding duration of exposure is assumed for the particular measure being computed. Air concentrations from the initial cloud and areal densities of deposited materials are computed using the procedures described in Section I,B.

28

- If site-specific data are lacking, the "bounding approach" is used to provide an upper limit on exposure due to inhalation of both the initial cloud and the resuspended cloud. The required computations for the integrated or average concentration due to primary inhalation and resuspension involve the use of Equations 2 or 3 (for puff models) or Equations 6 or 7 (for plume models) without the $Q_x/Q_0$ or $Q'_x/Q'_0$ depletion factors.

Whenever the impact of resuspension is to be evaluated, the first technique is preferred because it does not produce overly conservative results. However, this procedure can only be applied effectively when site-specific data are available.

SECTION II.

METHODS FOR CALCULATING RADIOLOGICAL AND
TOXICOLOGICAL EXPOSURE MEASURES

In this section the equations used to calculate expo-
sure measures from releases of DU to the air and ground are
presented, along with general criteria for their use. The
calculations are based primarily on procedures outlined in
References 5, 7, 9, and 17. Although the discussion in this
section focuses on chronic exposures, the following equations
may also be used to evaluate acute exposures.

Throughout this section, two classes of exposure are
considered: occupational exposure and exposure to the general
populace. Occupationally exposed persons must be 18 years of
age or older and must submit to frequent monitoring for radio-
logical or toxicological insult. Members of the general popu-
lace, on the other hand, are not monitored and include children,
for whom lower dose limits are prescribed. Additional differ-
ences between these two groups include different rates of re-
spiration, different potential exposure times to harmful sub-
stances (i.e., 40 hours per week for occupational exposures
versus 168 hours per week for general populace exposures), and
different periods of time over which the exposure measures are
to be computed.

All exposure measures described in the following sec-
tions consider the effects of internal buildup of inhaled uranium
within the body or its organs. Additionally, dose calculations
for the whole body and critical organs incorporate irradiation
from external sources. The effect of radioactive decay on

30

concentration is negligible due to the long half-lives of the uranium isotopes, and thus is not included explicitly in the equations.

## A.  CRITERIA FOR DETERMINING THE LIMITING EXPOSURE MEASURE

Radiation dose and chemical toxicity are important measures of human exposure to depleted uranium.  A radiation dose can occur from either internal or external exposures, while toxicological effects are produced solely by concentrations of DU within the body.  In any situation, it is necessary to consider such factors as the isotopic composition and solubility of the DU compounds as well as the potential pathways of exposure (internal and/or external) before deciding whether radiation or toxicity is the more critical concern.

Depleted uranium may be released to the air and ground in the form of either soluble or insoluble compounds.  The most important aspect of solubility is its potential for translocating and concentrating inhaled uranium compounds within the various body organs.  The maximum amount of insoluble DU that may be inhaled is governed by the dose of radiation received by the lungs, which is the point of entry into the body.  When compounds of DU are soluble, chemical damage to the kidney is of greater concern than radiological damage to the lungs. (Radiation effects from inhaled soluble compounds of uranium dominate only when the mixture is highly enriched in $^{235}$U (Reference 18).)

Thus, initial assessments of DU contamination should include an evalution of all possible exposures.  For assessing potential hazards from insoluble DU, radiation dose from both

internal and external sources and average radiological concen-
tration in air are determined; for assessing risks from soluble
DU, an estimate of chemical toxicity is computed. From these
determinations, the limiting exposure(s) will become evident;
all future evaluations for the same operating conditions need
focus only on the critical measures(s).


B.   RADIATION DOSE

### 1.   Whole-Body and Critical-Organ Dose

The organs and tissues of the body respond to radia-
tion in varying degree. The effect of radiation on body or-
gans depends on both the magnitude of the dose delivered and
the essential function performed by the organ. Thus, some
organs and tissues are more susceptible to the circumstances
under which they are irradiated and are said to be critical.

In the case of whole-body irradiation, the critical
organs and tissues are taken to be the blood-forming organs,
the gonads, and the lenses of the eyes. Any dose to the whole
body from internal or external sources is assumed to uniformly
affect these organs. When irradiation is more or less limited
to portions of the body, the critical organ is that organ most
likely to be permanently damaged either because of its inherent
radiosensitivity, or because of a combination of radiosensitivity
and localized high dose. The critical body organ is generally
one of the following: lung, gastro-intestinal (GI) system
(lower large intestine), bone, or kidney. Other portions of
the body may receive radiation (primarily from external sources),
but are not usually considered to be critical. These include
the skin, forearms and hands, and ankles and feet (Reference 19).

32

Whole-body dose is computed as the sum of (1) internal dose to the whole body from inhalation of radionuclides, (2) external gamma dose from deposited radionuclides, and (3) internal whole-body dose from the inhalation of resuspended radionuclides. Critical-organ dose is computed as the sum of (1) internal dose to the critical organ from inhalation of radionuclides, (2) external gamma dose from deposited radionuclides, and (3) internal critical-organ dose from the inhalation of resuspended radionuclides. The calculations shown here are for dose from <u>insoluble</u> compounds of uranium only, for which the lung is the critical organ. The effect of solubility on whole-body and critical-organ dose is discussed in Section II,B,2.

Whole-body and critical organ doses, averaged annually for both workers and members of the general populace, are calculated using the following expression:

$$D_{jk\ell} = \left[ f_a \cdot f_b \cdot N_\ell \cdot B_k \cdot \sum_i (A_i \cdot DFI_{ij}) \right] \cdot F \qquad \text{(inhalation)}$$

$$+ \left[ f_a \cdot M_\ell \cdot v_d \cdot T_{k\ell} \cdot \sum_i (A_i \cdot DFD_{ij}) \right] \cdot F \qquad \text{(deposition)}$$

$$+ \left[ f_a \cdot M_\ell \cdot v_d \cdot K_r \cdot T_{k\ell} \cdot B_k \cdot \sum_i (A_i \cdot DFI_{ij}) \right] \cdot F \qquad \text{(resuspension)}$$

$$(14)$$

where

$D_{jk\ell}$ = total radiological dose to organ j of a person in population class k during period $\ell$ (rem)

i = radionuclide index (1=$^{234}$U, 2=$^{235}$U, 3=$^{238}$U)

j = body organ index (1=whole body, 2=critical organ)

k = population class index (1=occupational, 2=general populace)

33

$\ell$ = index of the averaging period used (1=annual, 2=quarterly, 3=weekly, 4=user specified)

$f_a$ = fraction of available DU that is dispersed to the air as aerosols (particles <20 μm AED)

$f_b$ = fraction of aerosolized DU that is respirable (particles $\leq$ 3 μm AED)

$N_\ell$ = amount of DU available for release to the air during averaging period $\ell$ (kg)

$B_k$ = breathing rate for a person in population class k ($m^3$/sec)

$A_i$ = number of curies of radionuclide i per unit mass of DU (Ci/kg)

$DFI_{ij}$ = fifty-year dose commitment factor for organ j from inhalation (chronic or acute) of radio-nuclude i in insoluble form (rem/Ci)

$F$ = normalized concentration of material in the passing cloud at a ground-level receptor ($\Psi/Q_0$ for puffs or $\bar{\chi}/Q_0'$ for plumes -- see Section I) (sec/$m^3$)

$$M_\ell = \frac{\begin{bmatrix} \text{Amount of DU} & \text{Amount of DU} \\ \text{accumulated} & \text{accumulated} \\ \text{through beginning} & + \quad \text{through end} \\ \text{of final averaging} & \text{of final averaging} \\ \text{period } \ell & \text{period } \ell \end{bmatrix}}{2} \quad (\text{kg})$$

When the actual duration of release $\leq$ the averaging period, $M_\ell = N_\ell$.

$v_d$ = deposition velocity (m/sec)

$T_{k\ell}$ = duration of exposure of persons in population class k to air or ground concentrations in averaging period $\ell$ (sec)

$DFD_{ij}$ = dose factor for external exposure (chronic) of organ j one meter above a uniformly dis-tributed areal density of radionuclide i $\left(\dfrac{\text{rem/sec}}{Ci/m^2}\right)$

$$K_r = \text{resuspension factor} = \frac{\begin{array}{l}\text{concentration of}\\\text{respirable}\\\text{DU in the air}\end{array}}{\begin{array}{l}\text{concentration of}\\\text{aerosolized}\\\text{DU on the ground}\end{array}} \quad (1/m)$$

(See Section I,C)

Values for several of the above parameters are given in Table 8, p. 41.

### 2. Impact of Solubility on Radiation Doses

The radiation dose calculations presented in Section II,B,1 are based on the Reference Man model and parameters for insoluble uranium described by the International Commission on Radiological Protection (ICRP) (Reference 19). A recent study (Reference 20) revealed that approximately 40% of the airborne respirable DU particles were observed to dissolve in simulated lung fluid within seven days. Therefore it is necessary to consider the possible effects of solubility on the radiation dose calculations in Section II,B,1.

It is possible to bound the range of radiation doses by examining two extreme cases: complete solubility and complete insolubility. Figure 3 is a block diagram of the ICRP Reference Man model for internal radiation dosimetry. It can be seen that the major difference between pathways for soluble and insoluble compounds that have been inhaled is the rapid entry of soluble compounds into the bloodstream. For soluble compounds, essentially all material (25% of the total amount inhaled) reaching the lungs quickly enters the bloodstream. For insoluble compounds, about half of the insoluble material (12.5% of the total amount inhaled) remains in the lungs for a time period (characteristic time, $T_B$, of 120 days) before entering the bloodstream. The other half is expelled from the
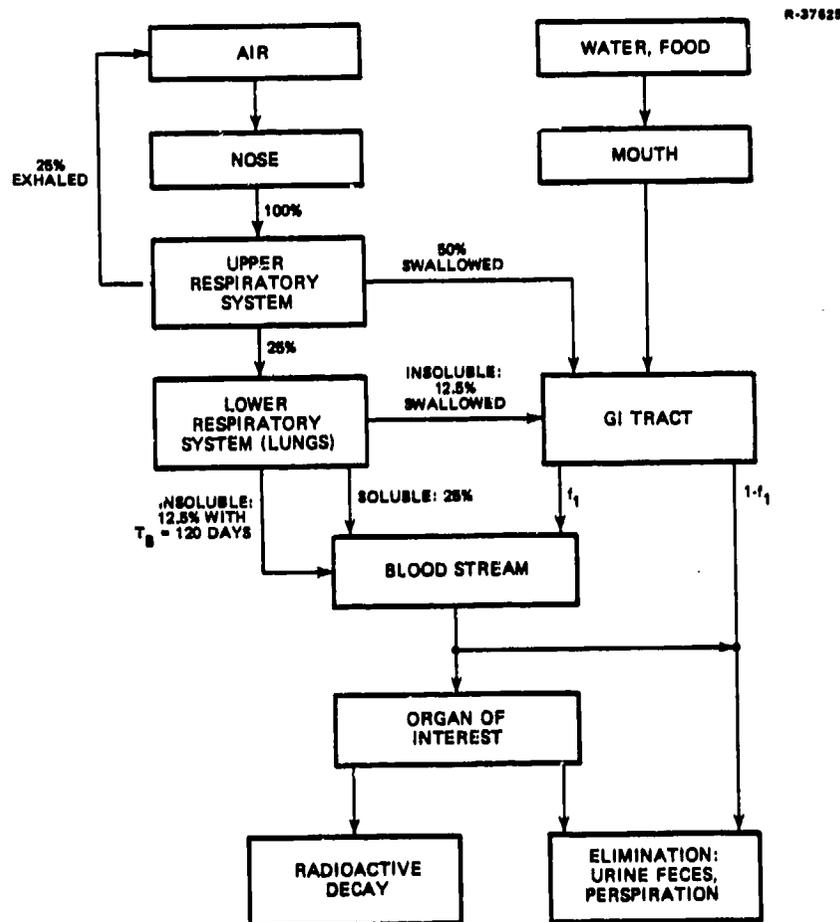
Figure 3    ICRP Reference Man Model for Internal
            Radiation Dosimetry

lungs and enters the GI tract through swallowing.  None of the
swallowed insoluble material and only a small portion of the
soluble material reaching the GI tract enters the bloodstream.
ICRP (Reference 19) gives a value of 0.01 for $f_1$ in Figure 3,
i.e., the transfer coefficient from the GI tract to the blood
for soluble compounds.  Thus for insoluble compounds, 12.5% of
the total matter inhaled eventually enters the bloodstream --
compared to [25% + (50%)(0.01)] $\cong$ 25.5% when the material is
soluble.

Radiation doses to all organs other than the lungs and lower large intestine result from the transport of radionuclides through the blood. Since about twice the amount of uranium enters the bloodstream when the inhaled material is soluble rather than insoluble, doses to organs other than the lungs and lower large intestine will be about twice as large for soluble uranium compounds as for insoluble compounds. The dose to the lungs and lower large intestine, on the other hand, will decrease. Consequently, the whole-body dose, which is a weighted sum of the radiation doses to all the organs, can be no more than twice as large when soluble compounds are inhaled instead of insoluble compounds*.

When the inhaled compounds are insoluble, the lung is the critical organ. It can be shown from the ICRP model and the dose commitment factors in Reference 21 that the radiological dose (amount × dose commitment) to any organ from inhaled soluble compounds of uranium is always less than the dose to the lungs from insoluble compounds. Therefore, the critical-organ dose will not be larger for soluble compounds than for insoluble compounds. Since radiological dose to the lung from soluble compounds of uranium is small, another organ will become the critical organ.

C. EXPOSURE TO CONCENTRATIONS OF DEPLETED URANIUM IN AIR

The average concentration of DU in air to which a person is exposed for a period of time is a general measure used to estimate exposure to depleted uranium. This measure

---

*Note that the whole-body dose due to inhalation of airborne and resuspended insoluble uranium compounds is only a portion of the total whole-body dose for occupational and general populace exposures. The remainder dose is supplied by gamma radiation from radionuclides deposited on the ground. Therefore this factor-of-two bound on whole-body dose is conservatively high.

is determined separately for occupational and general populace exposures. Various forms of this measure have been established to consider both (1) the radiological properties of soluble and insoluble uranium and (2) the toxicological properties of soluble uranium. Average concentrations are based on both material in the passing cloud and material that is deposited by the cloud and subsequently resuspended.

### 1. Radiological Concentrations

The average radiological concentration of DU in air to which an individual is exposed over a period of time ($\mu Ci$/ $m\ell$) determines the inhalation dose commitment for the critical organ. An equivalent measure is the total intake of radioactive material ($\mu Ci$) during the period, which is obtained by multiplying the average concentration by the amount ($m\ell$) of air inhaled in the period. Separate maximum permissible concentration ($MPC_a$) limits are specified for radiological concentrations of soluble and insoluble compounds of uranium in air for both occupational and general populace exposures (Section III,B,1). It should be noted that the use of $MPC_a$ standards alone is only valid if there are no significant contributions from external sources of radiation (Reference 19). This topic is discussed in greater detail in Section III,B,1.

The average radiological concentration in air is computed quarterly for occupational exposures and annually for general populace exposures using the following equation:

$$c_{k\ell}^{R} = \left[ \frac{f_a \cdot f_b \cdot N_\ell \cdot 1 \cdot \sum_i A_i}{T_{k\ell}} \right] \cdot F \qquad \text{(inhalation)}$$

$$+ \left[ f_a \cdot M_\ell \cdot v_d \cdot K_r \cdot 1 \cdot \sum_i A_i \right] \cdot F \quad \text{(resuspension)} \quad (15)$$

where

$C_{k\ell}^{R}$ = average radiological concentration of DU in air to which a person in population class k is exposed during averaging period $\ell$ ($\mu$Ci/m$\ell$)

1 = conversion factor $\left(\dfrac{\mu Ci/m\ell}{Ci/m^3}\right)$

and all other variables are as defined in Equation 14.

### 2. Toxicological Concentrations

Average Toxicological Concentration - When water-soluble compounds of uranium are airborne, chemical toxicity may be a more limiting factor than radiological activity (Section II,A). Accordingly, an additional measure for estimating exposure to airborne concentrations of uranium is the average concentration of soluble uranium in air (mg/m$^3$) to which a person is exposed in a work week (occupational exposure) or in a year (general populace exposure). Maximum permissible limits for toxic concentrations of soluble uranium in air are given in Section III,B,2 for both occupational and general populace exposures.

The average toxicological concentration in air is expressed as:

$$C_{k\ell}^{T} = \left[\frac{f_a \cdot f_b \cdot N_\ell \cdot 10^6}{T_{k\ell}}\right] \cdot F \qquad \text{(inhalation)}$$

$$+ \left[f_a \cdot M_\ell \cdot v_d \cdot K_r \cdot 10^6\right] \cdot F \qquad \text{(resuspension)} \qquad (16)$$

where

$C_{k\ell}^{T}$ = average toxicological concentration of soluble DU in air to which a person in population class k is exposed during averaging period $\ell$ (mg/m$^3$)

$10^6$ = conversion factor (mg/kg)

39

and all other variables are as defined in Equation 14. It is
important to note that for acute exposures (i.e., less than 1
work week), toxicological concentrations are averaged over the
actual duration of exposure. The use of weekly or annual averag-
ing periods are applicable for chronic exposures only.

Exposure to Inhaled Uranium - A second chemical toxi-
city measure for estimating exposures to airborne concentrations
of depleted uranium, the weekly exposure to soluble uranium, is
applicable to chronic occupational exposures only (Reference
5). However, this measure can be shown to be equivalent to
the average concentration measure in Equation 16.

D.  SUMMARY OF FIXED PARAMETER VALUES

Table 8 summarizes the values and sources for all
parameters in Equations 14, 15, and 16 that are fixed from
scenario to scenario. Values for normalized concentration
factors (F) are determined using the analytic procedures de-
scribed in Section I. Values for all other parameters assume
chronic exposure and depend on the specific case being analyzed.
When evaluating acute exposures, parameter values should be
adjusted accordingly.

## TABLE 8
### FIXED PARAMETER VALUES FOR CALCULATING CHRONIC EXPOSURE

T-3757a

| PARAMETER | RADIONUCLIDE, $i$ | ORGAN, $i$ | POPULATION CLASS, $k$ | AVERAGING PERIOD, $\ell$ | VALUE | UNITS | SOURCE |
|---|---|---|---|---|---|---|---|
| Breathing rate, $B_k$ | | | 1-Occupational | | $3.48 \times 10^{-4}$ | $m^3/sec$ | Reference 19 |
| | | | 2-General Populace | | $2.32 \times 10^{-4}$ | | |
| Source term, $A_i$ | $1-^{234}U$ | | | | $2.24 \times 10^{-5}$ | Ci/kg | Product of data in columns 4 and 5, Table 2, Section I, unless specified otherwise |
| | $2-^{235}U$ | | | | $5.35 \times 10^{-6}$ | | |
| | $3-^{238}U$ | | | | $3.32 \times 10^{-4}$ | | |
| Deposition Velocity, $v_d$ | | | | | $10^{-2}$ | m/sec | Reference 7 |
| Duration of exposure to concentrations, $T_{k\ell}$ | | | 1-Occupational | 1-Annual | $6.91 \times 10^6$ | sec | Assumed: 240 8-hour workdays |
| | | | | 2-Quarterly | $1.79 \times 10^6$ | | 62 8-hour workdays |
| | | | | 3-Weekly | $1.44 \times 10^5$ | | 5 8-hour workdays |
| | | | 2-General Populace | 1-Annual | $3.15 \times 10^7$ | | 365 24-hour days |
| Dose commitment factor for internal exposure (chronic or acute) to air concentrations, $DFI_{ij}$ | $1-234_U$ | 1-Whole Body | | | $6.46 \times 10^5$ | $\frac{rem}{Ci}$ | Reference 21 |
| | | 2-Critical Organ (Lungs) | | | $5.22 \times 10^7$ | | |
| | $2-235_U$ | 1-Whole Body | | | $6.07 \times 10^5$ | | |
| | | 2-Critical Organ (Lungs) | | | $4.90 \times 10^7$ | | |
| | $3-238_U$ | 1-Whole Body | | | $5.67 \times 10^5$ | | |
| | | 2-Critical Organ (Lungs) | | | $4.58 \times 10^7$ | | |
| Dose commitment factor for chronic external exposure to ground concentrations, $DFD_{ij}$ | $1-234_U$ | 1-Whole Body | | | $2.03 \times 10^{-6}$ | $\frac{rem/sec}{Ci/m^2}$ | Reference 21 |
| | | 2-Critical Organ (Lungs) | | | $2.03 \times 10^{-6}$ | | |
| | $2-235_U$ | 1-Whole Body | | | $3.65 \times 10^{-4}$ | | |
| | | 2-Critical Organ (Lungs) | | | $3.65 \times 10^{-4}$ | | |
| | $3-238_U$ | 1-Whole Body | | | $9.77 \times 10^{-4}$ | | |
| | | 2-Critical Organ (Lungs) | | | $9.77 \times 10^{-5}$ | | |

SECTION III

LIMITS FOR EXPOSURE TO DEPLETED URANIUM


In this section recommended limits for chronic exposure to depleted uranium are discussed. The following indices are considered for both occupational and general populace exposures:

- Whole-body dose

- Critical-organ dose

- Radiological concentrations of DU in air

- Toxicological concentrations of soluble DU in air.

Sections III,A and III,B present the limits against which the computed radiological and toxicological exposure measures are compared to assess compliance with recommended guidelines. These maximum exposure limits have been described according to procedures and criteria outlined by the U.S. Nuclear Regulatory Commission (10 CFR 20) (Reference 5) and the International Commission on Radiological Protection (Reference 19). A summary table appears in Section III,C.


A. LIMITS FOR RADIATION DOSE


1. Whole-Body Limits

10 CFR 20 sets the following occupational and general populace limits for whole-body dose:

42

- 5 rems/yr for occupational exposures

- 0.5 rems/yr for general populace exposures.

These limits are applicable for both soluble and insoluble uranium compounds. The general populace limit is lower because of the potential presence of children in the group (Reference 19).

Maximum exposures of 5 rems/yr to a worker may be exceeded only if (1) the dose received in any one calendar quarter does not exceed 3 rems and (2) the dose to the whole body, when added to the accumulated occupational dose to the whole body, does not exceed 5(N-18) rems, where N is the individual's age in years at his last birthday. Therefore, the 5 rems/yr value may be viewed as a conservative limit.[*]

## 2. Critical-Organ Limits

The following body organs receive dose commitments from both internal and external exposure to the isotopes in depleted uranium, and are considered the organs most likely to be critical (Section III,B,1). Recommended annual occupational radiation limits for these organs are also given (Reference 19).

| Organ | Annual Occupational Dose Limit (rem) |
|---|---|
| Bone | 30 |
| Kidney | 15 |
| Lungs | 15 |
| GI-Lower Large Intestine | 15 |

[*]In keeping with the spirit of 10 CFR 20, every effort should be made to maintain levels cf radiation exposure "as low as reasonably achievable" (ALARA).

The critical organ for insoluble DU compounds is the lungs; the recommended occupational limit for this organ is 15 rems/yr. When the DU compounds are soluble in body fluids, the critical organ, from the standpoint of radiological damage, will be an organ other than the lungs (see Section II,B,2). However, since the occupational limit of 15 rems/yr is the most stringent of the organ limits specified above, this measure is applicable for both insoluble and soluble compounds of uranium.

In deriving annual general populace exposure limits for the critical organ, one must again allow for the potential presence of children in the population. Accordingly, the occupational radiation limit for the critical organ should be reduced by approximately a factor of 10 to determine the general populace value (Reference 19). This results in a general populace limit of 1.5 rems/yr for the critical organ, which is relevant for both insoluble and soluble forms of uranium.

## B.  LIMITS FOR EXPOSURE TO CONCENTRATIONS OF DU IN AIR

### 1.  Radiological Concentration Limits

For the purpose of limiting the exposure of individuals to concentrations of radioactive materials in air, maximum permissible concentrations ($MPC_a$'s) are established by isotope (soluble or insoluble) for both workers and members of the general populace in 10 CFR 20. The occupational $MPC_a$ is defined as an average concentration which, if inhaled uniformly for 40 hrs/week, 50 weeks/yr, for a continuous work period of 50 years, will impart the maximum allowable radiological dose to the critical organ of an individual (Reference 19). $MPC_a$'s for the general populace, are derived assuming 50 years of continuous exposure (168 hrs/week) and allowing for the potential

44

presence of children in the group; resulting exposure limits are about a factor of 30 lower than the occupational $MPC_a$'s (Reference 19). For the purpose of comparison against the prescribed $MPC_a$'s, radiological concentrations are averaged quarterly for occupational exposures and annually for general populace exposures (Section II,C,1).

Using the isotopic composition of DU and the $MPC_a$ for each uranium isotope, the maximum allowable radiological concentration for the DU mixture as a whole can be computed. 10 CFR 20 requires that the following condition be met:

$$c^R \cdot \sum_i \frac{f_i}{MPC_i} \leq 1 \qquad (17)$$

where

$\quad$ i = index of a uranium isotope

$\quad c^R$ = average radiological concentration of the DU mixture in air ($\mu Ci/m\ell$*)

$\quad f_i$ = the number of curies of isotope i per curie of DU$^\dagger$ (values are 0.062 for $^{234}U$, 0.015 for $^{235}U$, and 0.923 for $^{238}U$)

$\quad MPC_i$ = the maximum permissible radiological concentration of isotope i in air, as specified in Reference 5 (Tables I and II) for insoluble or soluble compounds ($\mu Ci/m\ell$*).

Using Equation 17, the maximum permissible radiological concentration for the DU mixture ($c^R_{max}$) is determined as follows:

---

*Note: 1 $\mu Ci/m\ell$ = 1 $Ci/m^3$.

$^\dagger f_i = \dfrac{\text{weight fraction} \times \text{specific activity of isotope i}}{\text{specific activity of DU}}$

45

$$C^R_{max} = \frac{1}{\sum_i \frac{f_i}{MPC_i}} \qquad (18)$$

Occupational and general populace values of $\bar{\chi}_{max}$ for both soluble and insoluble DU compounds are given in Table 9.

It is important to note that the use of $MPC_a$ standards alone is only valid if there are no significant contributions from external sources of radiation (Reference 19). For cases where external radiation exists, the following approach is taken:

- Whole-body and critical-organ doses from both internal and external sources are computed according to the procedures described in Section II,B and compared against the appropriate dose limits in Section III,A

- The $MPC_a$'s are reduced by the amount of the external radiation dose before these values are compared against the computed radiological concentrations in air. That is, $C^R_{max}$ in Equation 18 is adjusted as follows for occupational and general populace exposures:

$$(C^R_{max})_{adjusted} = (C^R_{max}) \times \left(1 - \frac{\text{annual external dose to the critical organ}}{\text{annual dose limit for the critical organ}}\right) \quad (19)$$

2. Toxicological Concentration Limits

When low-level radioactive compounds of uranium are soluble, chemical toxicity in the body becomes a greater limiting factor than radioactivity. Consequently, measures have

been provided in Appendix B of 10 CFR 20 for limiting the concentration of soluble uranium in air such that the maximum permissible toxicity burden to the critical organ (kidney) is not exceeded. For soluble mixtures of uranium isotopes, if the percent by weight of $^{235}$U is less than 5%, the average permissible concentration of uranium in the air breathed may not exceed:

- 0.2 mg/m$^3$/work week for occupational exposures

- 0.007 mg/m$^3$/year for general populace exposures.

It is important to note that these prescribed standards were established on the basis of <u>chronic</u> exposures. For acute exposures (i.e., less than 1 work week) to concentrations of soluble uranium in air, the average concentration limit should be adjusted to reflect the actual duration of release to provide a more equitable measure by which to compre the calculated toxicological concentration in air.* The use of concentration limits derived for chronic releases is a conservative standard by which to assess compliance for an acute release.

C.  SUMMARY OF EXPOSURE LIMITS

Table 9 summarizes all chronic exposure limits discussed in this section.

---

*To date, 10 CFR 20 acknowledges the need to adjust chronic limits for compatibility with acute releases, but does not indicate specific procedures for doing this.

## TABLE 9
### SUMMARY OF CHRONIC EXPOSURE LIMITS

T-3758

| EXPOSURE INDEX | OCCUPATIONAL LIMITS | | | GENERAL POPULACE LIMITS | | |
|---|---|---|---|---|---|---|
| | UNITS | INSOLUBLE DU | SOLUBLE DU | UNITS | INSOLUBLE DU | SOLUBLE DU |
| Whole-Body Dose | rems/year | 5 | 5 | rems/year | 0.5 | 0.5 |
| Critical-Organ Dose | rems/year | 15 | 15 | rems/year | 1.5 | 1.5 |
| Radiological Concentration of DU in Air | $\mu Ci/m\ell$ (averaged quarterly) | $1 \times 10^{-10}$ | $7.5 \times 10^{-11}$ | $\mu Ci/m\ell$ (averaged annually) | $4.9 \times 10^{-12}$ | $3.2 \times 10^{-12}$ |
| Toxicological Concentration of Soluble DU in Air | $mg/m^3$ (averaged weekly) | - | 0.2 | $mg/m^3$ (averaged annually) | - | 0.007 |

## REFERENCES

1.  Bartlett, W.T., et al., "Radiation Characterization and Exposure Rate Measurements from Cartridge, 105mm, APFSDS-T XM774," Pacific Northwest Laboratory, Richland, Washington, PNL-2947, November 1979. NOTE: On p. 7, the value for $^{234}U$ should have been shown as 0.00034%.

2.  Waite, D.A., Stoetzel, G.A., and Gilchrist, R.L., "Preliminary Environmental Survey of the B-3 Range and Ford's Farm Area," Pacific Northwest Laboratory, Richland, Washington, PNL-2976, May 1979 (Draft Report).

3.  "Final Environmental Statement -- Portsmouth Gaseous Diffusion Plant Expansion, Piketon, Ohio," U.S. Energy Research and Development Administration, Washington, D.C., ERDA-1549 (Section 9), September 1977.

4.  Wilsey, E., U.S. Army Armament Research and Development Command, Ballistic Research Laboratory, with Levy, L.M., National Lead Company of Ohio, August 3 and 7, 1979 (Telephone Communication).

5.  "Rules and Regulations -- Title 10, Chapter 1, Code of Federal Regulations - Energy -- Part 20: Standards for Protection Against Radiation," U.S. Nuclear Regulatory Commission, Revised September 1, 1978.

6.  "Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors," U.S. Nuclear Regulatory Commission, Washington, D.C., Regulatory Guide 1.111, Revision 1, July 1977.

7.  Slade, D.H. (Editor), "Meteorology and Atomic Energy, 1968," U.S. Atomic Energy Commission, Washington, D.C., TID-24190, 1968.

8.  Turner, D.B., _Workbook of Atmospheric Dispersion Estimates_, U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio, 1970.

9.  "Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss-of-Coolant Accident for Boiling Water Reactors," U.S. Atomic Energy Commission, Regulatory Guide 1.3, Revision 2, June 1974.

REFERENCES (Continued)

10.    "Reactor Safety Study:  An Assessment of Accident Risks
       in U.S. Commercial Nuclear Power Plants," U.S. Nuclear
       Regulatory Commission, Washington, D.C., WASH-1400
       (NUREG-75/014), October 1975.

11.    U.S. Nuclear Regulatory Commission, Office of Standards
       Development, "On Meteorological Programs," NRC Regula-
       tory Guide 1.23 (Safety Guide 23).

12.    Pasquill, F., "The Estimation of the Dispersion of Wind-
       borne Material," Meteorology Magazine, 90:1063, pp.
       33-49, 1961.

13.    Porter, R.A., Dispersion Equation Solutions by Calcula-
       tor -- A Guide for Air Pollution Engineers and Scientists,
       Texas Air Control Board, Austin, November 1975.

14.    U.S. Nuclear Regulatory Commission, Office of Standards
       Development, "Atmospheric Dispersion Models for Potential
       Accident Consequence Assessments at Nuclear Power Plants,"
       NRC Regulatory Guide 1.145, August 1979.

15.    "Proposed Final Environmental Statement, Liquid Metal
       Fast Breeder Reactor Program," U.S. Atomic Energy Com-
       mission, Washington, D.C., WASH-1535, December 1974.

16.    Horst, T.W., "The Resuspension of Material Dispersed by
       Atmospheric Diffusion from a Point Source," Battelle,
       Pacific Northwest Laboratories, Richland, Washington,
       BNWL-1964, December 1975.

17.    U.S. Nuclear Regulatory Commission, Office of Standards
       Development, "Calculation of Annual Doses to man from
       Routine Releases of Reactor Effluents for the Purpose
       of Evaluating Compliance with 10 CFR Part 50, Appendix
       I," NRC Regulatory Guide 1.109, Revision 1, October
       1977.

18.    International Commission on Radiological Protection,
       Recommendations of the International Commission on Ra-
       diological Protection (Evaluation of Radiation Doses
       to Body Tissues from Internal Contamination Due to Oc-
       cupational Exposure:  A Report by Committee 4 of the
       ICRP), ICRP Publ. 10, Pergamon Press, Oxford, 1968.

REFERENCES (Continued)

19.   International Commission on Radiological Protection,
      Recommendations of the International Commission on Ra-
      diological Protection (Report of Committee 2 on Permis-
      sible Dose for Internal Radiation), ICRP Publ. 2, Per-
      gamon Press, London, 1959.

20.   Glissmeyer, J.A., and Mishima, J., "Characterization of
      Airborne Uranium from Test Firings of XM774 Ammunition,"
      Pacific Northwest Laboratory, Richland, Washington,
      PNL-2944, November 1979.

21.   Soldat, J.K., Robinson, N.M., and Baker, D.A., "Models
      and Computer Codes for Evaluating Environmental Radia-
      tion Doses," Battelle, Pacific Northwest Laboratories,
      Richland, Washington, BNWL-1754, Revised Version,
      February 7, 1977.

DISTRIBUTION LIST

Office of Secretary of Defense
   (Health Affairs)
ATTN:  LTC B. Chase
Pentagon, Room E171
Washington, DC  20301

Honorable Percy A. Pierre
Assistant Secretary of the Army
   for Research, Development
   and Acquisition
Department of the Army
Washington, DC  20301


Office of Secretary of Defense
Office of Director of Defense
   Research and Engineering
ATTN:  Mr. J. Persh
Washington, DC  20301

Undersecretary of Defense for
   Research and Engineering
Deputy Undersecretary
   (Tactical Warfare Programs)
Department of Defense
Washington, DC  20310


Office of Assistant Secretary
   of Defense for Atomic Energy
ATTN:  Cmdr G. Cliff
Pentagon, Room 3E1069
Washington, DC  20301

Office of the Deputy Undersecretary
   of Defense, Research and Engineering
ATTN:  Mr. R. Thorkildsen
Pentagon
Washington, DC  20301


Office of the Undersecretary
   of the Army
Deputy Undersecretary (Operations) Research
ATTN:  Mr. D. Hardison
Department of the Army
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DASG-TSP-E, COL Wangeman
Washington, DC  20310


Director
Defense Advanced Research Projects Agency
ATTN:  Tech Info
1400 Wilson Blvd
Arlington, VA  22209

Headquarters
Department of the Army
ATTN:  DACS-DMT
Washington, DC  20310


Undersecretary of Defense for
   Research and Engineering
Deputy Undersecretary (Research and
   Advanced Technology)
ATTN:  Dr. A Bement
Department of Defense
Washington, DC  20301

Headquarters
Department of the Army
ATTN:  DAMA-ARX-A, Dr. M. Lasser
Washington, DC  20310

52

DISTRIBUTION LIST

Headquarters
Department of the Army
ATTN:  DAMA-CSS, Dr. J. Bryant
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DAMO-TRS, LTC Lyon
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DAMA-CSM, LTC German
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DAMO-DRI, MAJ Speedy
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DAMA-CSM-CA, Mr. Lippi
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DALO-TSP, LTC Deakery
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DAMA-WSW, LTC Hinson
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DALO-SMS, Ms. Ueckert
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DAMA-WSZ-A
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DACS-DPA, LTC Rogers
Washington, DC  20310

Headquarters
Department of the Army
ATTN: DAMO-RQD, LTC Ivey
Washington, DC  20310

Headquarters
Department of the Army
ATTN:  DAEN-ZE, COL Herndon
Washington, DC  20310

DISTRIBUTION LIST

Headquarters
Department of the Army
ATTN: SARDA, COL D. Brudvig
Washington, DC 20310

Project Manager
Production Base Modernization & Exp
ATTN: SARPM-PBM, Mr. C. Kolis
Dover, NJ 07801

Project Manager
XM1 Tank System
ATTN: DRCPM-GCM
Warren, MI 48092

Project Manager
M60 Tank
Michigan Army Missile Plant
ATTN: DRCPM-M60
Warren, MI 48090

Project Manager
XM1 Tank System
ATTN: DRCPM-GCM-SI, Mr. D. Bartle
Warren, MI 48090

Commander
US Army Materiel Development and
    Readiness Command
ATTN: DRCDR-DW, COL Collins
5001 Eisenhower Avenue
Alexandria, VA 22333

Project Manager
Tank Main Armament System
ATTN: DRCPM-TMA, COL D. Appling
Dover, NJ 07801

Commander
US Army Materiel Development and
    Readiness Command
ATTN: DRCQA, Mr. R. Fahy
5001 Eisenhower Avenue
Alexandria, VA 22333

Project Manager
Tank Main Armament System
ATTN: DRCPM-TMA 105 mm
     LTC M. Michlik
Dover, NJ 07801

Commander
US Army Materiel Development and
    Readiness Command
ATTN: DRCDMD
5001 Eisenhower Avenue
Alexandria, VA 22333

Project Manager
Division Air Defense Gun
ATTN: DRCPM-ADG
Dover, NJ 07801

Commander
US Army Materiel Development and
    Readiness Command
ATTN: DRCBSI
5001 Eisenhower Avenue
Alexandria, VA 22333

THE ANALYTIC SCIENCES CORPORATION

DISTRIBUTION LIST

Commander
US Army Materiel Development and
   Readiness Command
ATTN:  DRCDMA-ST
5001 Eisenhower Evenue
Alexandria, VA  22333

Director
DARCOM Field Safety Activity
ATTN:  DRXOS-ES, Mr. E. Olsen
Charlestown, IN  47111


Commander
US Army Materiel Development and
   Readiness Command
ATTN:  DRCSMA-ST, COL Vincent
5001 Eisenhower Avenue
Alexandria, VA  22333

Director
US Army Materials and Mechanics
   Research Center
ATTN:  DRXMR-X, Dr. E. Wright
Watertown, MA  02172


Commander
US Army Materiel Development and
   Readiness Command
ATTN:  DRCSG, COL R. Cutting
5001 Eisenhower Avenue
Alexandria, VA  22333

Director
US Army Materials and Mechanics
   Research Center
ATTN:  DRXMR-AR, Mr. S. Levin
Watertown, MA  02172


Commander
US Army Materiel Development and
   Readiness Command
ATTN:  DRCPA-E, Mr. Pace
5001 Eisenhower Avenue
Alexandria, VA  22333

Director
US Army Materiels Systems Analysis Agency
ATTN:  DRXSY
Aberdeen Proving Ground, MA  21005


Commander
US Army Materiel Development and
   Readiness Command
ATTN:  DRCSG-R, LTC Bell
5001 Eisenhower Avenue
Washington, DC  22333

Director
US Army Materiels Systems Analysis Agency
ATTN:  DRXSY-GS, Mr. W. Brooks
Aberdeen Proving Ground, MA  21005


Commander
US Army Materiel Development and
   Readiness Command
ATTN:  DRCSF-P, Mr. Taras
5001 Eisenhower Avenue
Alexandria, VA  22333

Director
US Army Materiels Systems Analysis Agency
ATTN:  DRXSY-GA, Mr. J. McCarthy
Aberdeen Proving Ground, MD  21005

55

## DISTRIBUTION LIST

Director
US Army Materiels Systems Analysis Agency
ATTN: DRXSY-GA, Mr. R. Smith
Aberdeen Proving Ground, MD 21005

Commander
US Army Armament Research and
   Development Command
ATTN: DRDAR-TD, Dr. R. Weigle
Dover, NJ 07801

Commander
US Army Armament Materiel
   Readiness Command
ATTN: DRSAR-MAD-C, Mr. P. Shaw
Dover, NJ 07801

Commander
US Army Armament Research and
   Development Command
ATTN: DRDAR-BL, Dr. Eichelberger
Dover, NJ 07801

Commander
US Army Armament Materiel
   Readiness Command
ATTN: DRSAR-ASR, LTC Counihan
Rock Island, IL 61201

Commander
US Army Armament Research and
   Development Command
ATTN: DRDAR-SC, Dr. D. Gyorog
Dover, NJ 07801

Commander
US Army Armament Materiel
   Readiness Command
ATTN: DRSAR-SF, Mr. B. Morris
Rock Island, IL 61201

Commander
US Army Armament Research and
   Development Command
ATTN: DRDAR-SCM, Mr. J. Corrie
Dover, NJ 07801

Commander
US Army Armament Materiel
   Readiness Command
ATTN: DRSAR-LEA, Mr. E. Beckman
Rock Island, IL 61201

Commander
US Army Armament Research and
   Development Command
ATTN: DRDAR-SCM, Dr. E. Bloore (10 cys)
Dover, NJ 07801

Commander
US Army Armament Research and
   Development Command
ATTN: DRDAR-CG, MG A. Light
Dover, NJ 07801

Commander
US Army Armament Research and
   Development Command
ATTN: DRDAR-LCU-D-T, Mr. Davitt
Dover, NJ 07801

DISTRIBUTION LIST

Commander
US Army Armament Research and
   Development Command
ATTN:  DRDAR-SF, Mr. Elliott
Dover, NJ  07801

Commander
US Army Armament Research and
   Development Command
ATTN:  DRDAR-LCB, Mr. P. Rummel
Watervliet, NY  12189

Commander
US Army Armament Research and
   Development Command
ATTN:  DRDAR-BLT, Mr. R. Vitali
Aberdeen Proving Ground, MD  21005

Commander
US Army Mobility Equipment Research
   and Development Command
ATTN:  DRDME-RZT, Tech Doc Ctr B/315
Fort Belvoir, VA  22060

Commander
US Army Armament Research and
   Development Command
ATTN:  DRDAR-BLT, Dr. W. Gillich
Aberdeen Proving Ground, MD  21005

Commander
US Army Mobility Equipment
   Research and Development Command
ATTN:  DRDME-VR, Mr. McMillian
Fort Belvoir, VA  22060

Commander
US Army Armament Research and
   Development Command
ATTN:  DRDAR-BLV, Mr. E. Wilsey
Aberdeen Proving Ground, MD  21005

Commander
US Army Environment Hygiene Agency
ATTN:  HSE-O
Aberdeen Proving Ground, MD  21005

Commander
US Army Armament Research and
   Development Command
ATTN:  DRDAR-BLP, Mr. R. Comer
Aberdeen Proving Ground, MD  21005

Director
US Army Human Engineering Laboratory
ATTN:  DRXHE-HE, Mr. Erickson
Aberdeen Proving Ground, MD  21005

Commander
US Army Armament Research and
   Development Command
ATTN:  DRDAR-AD-SA, Mr. Maryland
Aberdeen Proving Ground, MD  21005

Commander
US Army Logistics Center
ATTN:  ATCL-M, Mr. Thompson
Fort Lee, VA  23801

DISTRIBUTION LIST

Commander
US Army Missile Munitions
ATTN: ATSK-CD
Redstone Arsenal, Alabama  35809

Commander
US Army Tank Automotive Research
    and Development Command
ATTN: DRDTA-RWL
Warren, MI  48090

Commander
US Army Logistics Evaluation Agency
ATTN: DALO-LEI, Mr. Frye
New Cumberland Army Depot
New Cumberland, PA  17070

Commander
US Army Tank Automotive Research
    and Development Command
ATTN: DRDTA-RKA, Mr. V. Pagano
Warren, MI  48090

Director
US Army Ammunition Center
ATTN: SARAC-D, Mr. K. Croscost
Savannah, IL  61074

Commander
US Army Test and Evaluation Command
ATTN: DRSTE
Aberdeen Proving Ground, MD  21005

Commander
US Army Missile Command
ATTN: DRCPM-LCE, Mr. Crosswhite
Redstone Arsenal, AL  35809

Commander
US Army Test and Evaluation Command
ATTN: DRSTE-AR, Mr. Brown
Aberdeen Proving Ground, MD  21005

Commander
US Army Research Office
ATTN: Dr. G. Mayer
PO Box 12211
Research Triangle Park, NC  27709

Commander
US Army Test and Evaluation Command
ATTN: DRSTE-CE
Aberdeen Proving Ground, MD  21005

Commander
US Army Research Office
ATTN: Dr. E. Saibel
PO Box 12211
Research Triangle Park, NC  27709

Commander
US Army Test and Evaluation Command
ATTN: DRSTE-PP-E
Aberdeen Proving Ground, MD  21005

58

DISTRIBUTION LIST

Commander
US Army Test and Evaluation Command
ATTN: DRSTE-ST, Mr. J. Starkey
Aberdeen Proving Ground, MD 21005

Superintendent
US Naval Post Graduate School
ATTN: Director of Library
Monterey, CA 93940

Commander
US Army Training and Doctrine Command
Fort Monroe
Hampton, VA 23651

Commander
Naval Sea Systems Command
ATTN: SEA 62YD6, Mr. F. Wilczek
Washington, DC 20362

Director
US Army TRADOC Systems Analysis Activity
ATTN: ATAA-SA
White Sands Missile Range, NM 88002

Commander
US Naval Surface Weapons Center
ATTN: Code WR-32, Dr. S. Fishman
White Oak, MD 20910

Commander
US Army Foreign Science and
    Technology Center
ATTN: DRXST-CB, J. Bollendorf
7th Street, NE-Building 220
Charlottesville, VA 22901

Commander
US Naval Surface Weapons Center
ATTN: Code DG-52, W. Wishard
White Oak, MD 20910

Commander
Naval Facilities Engineering Command
Code 04N2, Mr. G. Hendrix
200 Stovall Street
Alexandria, VA 22333 (2 cys)

Commander
US Marine Corps Liaison Officer
Aberdeen Proving Ground, MD 21005

Commander
US Naval Ordnance Systems Command
ATTN: ORD-9132
Washington, DC 20360

Commander
US Air Force Headquarters
ATTN: SG-PA, LTC J. Bayer
Washington, DC 20314

## DISTRIBUTION LIST

HQ ADTC/SCV
ATTN:  MAJ R. Conrad
Eglin AFB, FL  32542

Union Carbide Corporation
Nuclea: Division
ATTN:  .ir. M. Sanders
PO Box Y
Oak Ridge, TN  37830


HQ ADTC/DLV
ATTN:  Dr. J. Cornette
Eglin AFB, FL  32542

Nuclear Regulatory Commission
Division of Fuel Cycle and Material Safety
ATTN:  Mr. E. Wright
Washington, DC  20555


Commander
US Air Force Tactical Air Command
ATTN:  SG-PA, LTC J. Coughlin
Langley AFB, VA  23665

University of California
Los Alamos Scientific Laboratory
ATTN:  Dr. D. Sandstrom, CMB-6
Los Alamos, NM  87544


National Lead Company of Ohic
ATTN:  Mr. L. Levy
Box 39158
Cincinnati, OH  45239

Air Force Materiel Laboratory
ATTN:  LTM S. Inouye
Wright-Patterson AFB, OH  45433


Rockwell International
Rocky Flats Plant
ATTN:  Mr. T. Crites, Bldg. 123
PO Box 464
Golden, CO  80401

Air Force Materiel Laboratory
ATTN:  XYD, CPT D. Schuur
Wright-Patterson AFB, OH  45433


The Analytic Sciences Corporation
ATTN:  Dr. S. Bucci
One Jacob Way
Reading, MA  01867

HQ, ADTC
ATTN:  CEEDO/CC Detachment 1
Tyndall AFB, FL  32403

DISTRIBUTION LIST

USA Ordnance Center and School
Aberdeen Proving Ground, MD 21005

Battelle Northwest Laboratories
ATTN:  Mr. R. Gilchrist
Battelle Blvd.
Richland, WA  99352

Director
DARCOM Field Safety Activity
ATTN:  DRXCS-ES, Mr. L. Foley
Charlestown, IN  47111

Commander
US Army Armament Materiel
    Readiness Command
ATTN:  DRSAR-CG
Rock Island, IL  61201

Commander
US Army Combined Arms Combat
    Development Activity
ATTN:  APCA-BC
Fort Leavenworth, KA  66027

Naval Nuclear Power Unit
Radiological Affairs Support Office
Port Hueneme, CA  93041