# APPENDIX E - Discussion of the Source Term Equation Parameters

## E.1 Introduction

The airborne pathway or inhalation will dominate the exposure to airborne contaminants. The following is a discussion of factors/parameters that need to be determined for particulate releases. Some of the factors/parameters will collapse to unity or one for special cases (for example, gaseous releases)[12]. The source term is the quantity or amount of DU available for aerosol production as a result of hard target perforation or a fire involving DU munitions modified by factors estimating its availability for suspension.

## E.2 Discussion of Source Term Equation Parameters

The airborne source term may be estimated by the following five-component linear equation[12]:

$$\text{Source Term} = \overbrace{\underbrace{MAR * DR * ARF * RF}_{\text{Initial Respirable Source Term}}}^{\text{Initial Source Term}} * LPF$$

Where:

MAR = Material-at-Risk (Ci or grams)

DR = Damage Ratio

ARF = Airborne Release Fraction (or Airborne Release Rate for continuous release)

RF = Respirable Fraction

LPF = Leakpath Factor

The initial source term and initial respirable source term are products of the first three factors and first four factors, respectively.

- **Material-at-Risk**

The MAR is the quantity of various materials (in grams or Ci of activity) available to be acted on by a given physical stress. The MAR is a value representing the maximum quantity of the material present for the situation or scenario being analyzed. Different MARs may be assigned for different situations, as it is only necessary to define the material in those discrete physical locations that are exposed to a given stress. For example, a MAR could be a single or multiple DU round that could penetrate a vehicle or DU munitions involved in a vehicle fire or a fire in a storage facility/area.

- **Damage Ratio**

The DR is the fraction of the MAR actually perforated (armor) or consumed (penetrator) by the scenario-generated conditions. A degree of interdependence exists between the definitions of MAR and DR.

The DR is estimated based upon the analysis of the response of structural materials for containment (for example, Abrams tank or BFV) to the type and level of stress/force generated by the event. Standard engineering approximations are typically used to estimate the DR. These approximations often include a degree of conservatism due to simplification of phenomena to obtain a usable model, but the purpose of the approximation is to obtain a realistic understanding of potential effects.

- **Airborne Release Fraction**

The ARF is the coefficient used to estimate the amount of material suspended in air as an aerosol and thus available for airborne transport as a result of the physical stresses from a specific release scenario. For discrete events, the ARF is a fraction of the source material so released. For mechanisms that continue to act to suspend radionuclides (for example, aerodynamic entrainment or mechanical resuspension), a release rate is required to estimate the potential airborne release from postulated incident conditions. Generally, impact puff airborne release rates (ARRs) are based upon measurements over some extended period to encompass most release situations for a particular mechanism. The ARRs are average rates for the broad spectrum of situations and, as such, the most typically meaningful time unit to reflect average conditions is 1 hour. There is evidence (discussed later in the subsection on the aerodynamic entrainment of surface contamination) that in some situations (for example, aerodynamic entrainment of sparse powder deposits on a heterogeneous surface) the rate of release is not uniform with time. Even in the situations where the ARRs are relatively uniform, the source may be reduced by the removal of particles from the surface-by-surface winds. Thus, the overall rate at which material is released into the air will decrease with time, unless the source of material is continuously replenished. Studies have shown a mean ARF of $1 \times 10^{-4}$ and a 95 percent confidence level of $4 \times 10^{-4}$ for uranium metal in air under static conditions[42].

This report specifically deals with ARFs and ARRs, although ARFs will connote both concepts in generic discussions for the sake of simplicity. The ARFs are based primarily upon field-measured values for the specific material (for example, DU) or surrogates subjected to the particular type of stress under controlled conditions. Attention is given to the parameters, if known, that may have a significant influence upon suspension by the specific mechanism and the uncertainty in the measurement as indicated by the variability of the results. Those applying the data must be aware of the range of stresses represented by the measured ARFs and must seek to define the conditions to determine, in a gross sense, whether or not the stresses induced by the postulated events are bounded by the parameters as evaluated in this report.

- **Respirable Fraction**

The RF is the fraction of airborne material that can be transported through air as particles and inhaled into the human respiratory system. In the field of chemical toxicology and radiation protection, it is commonly assumed that particles with an AED greater than about 10 μm are not so-called "respirable" that is, capable of being inhaled into the alveolated airways of the respiratory tract. The AED is defined as the diameter of a unit density sphere that has the same terminal settling velocity in air as the particle of interest. This characteristic of a particle's size determines the particle's deposition behavior under the influence of aerodynamic forces.

For consideration of chemical toxicity, various groups have presented other definitions of "respirable" particles at different times. The British Medical Research Council adopted a definition in 1952 classifying particles with a terminal velocity equal to that of a 5 μm diameter as respirable dust. The U.S. Atomic Energy Commission (AEC) defined respirable dust as insoluble particles that are part of inhaled dust which penetrate to the non-ciliated portions of the gas exchange region, with a 50 percent respirable cut-size of 3.5 μm AED. The ACGIH has adopted a definition that is almost identical to AEC's, differing only in the 2 μm AED fraction allowed. The USEPA defines inhalable dust as particles penetrating the upper respiratory airway and entering the thorax, with a 50 percent cut-off at 15 μm AED. The International Standards Organization-Europe defines inhalable dust as particles entering the nasal or oral passages, with a 50 percent cut-size of 10 μm AED. Accordingly, use of a 10 μm AED cut-size for respirable particles is considered conservative and may even be overly conservative, since the mass is a cubic function of particle diameter. (See Appendix D for a discussion on inhalability and respirability of particles. See Appendix J for a discussion of the respiratory tract models and uranium transport through the kidneys.)

The measurement of particle size distribution is complex, and different techniques can lead to different values. If the method used to measure particle size is optical/electron microscopy or spectrometry, the resulting particle size is a projected diameter measured by the plane that intercepts the light/electron beam or reflection from light scattered by the particle. The size represents the two-dimensional area intercepting the beam and, as with all projections of three dimensions into two, can result in considerable distortion. The projected diameter approximates the geometric diameter ($D_g$). Sieving, where the size measurement is termed geometric, linear or least linear diameter, also approximates the $D_g$. The measurement represents the smallest dimension of the particle that will pass through the openings in the sieve, Parkhurst et al., (1995b).

Aerodynamic separation techniques of inertial impaction by a cascade impactor measure the settling velocity of a particle and report size as an aerodynamic characteristic. Size is reported as an equivalent unit density/sphere with the same settling velocity or Stoke's Diameter ($D_{Stk}$). The AED specifically refers to particles with an equivalent sphere with a density of 1 g/cm$^3$. The AED is the parameter of interest for defining respirable particles (that is, $\leq$ 10 $\mu$m AED) as it normalizes materials of differing density.

The AED is related to $D_g$ by the equation:

$$AED = [D_g(\rho_p)^{0.5}(C_{c,e}/C_{c,a})^{0.5}]/\propto$$

Where:

| | | |
|---|---|---|
| AED | = | Aerodynamic Equivalent Diameter |
| $D_g$ | = | Geometric diameter |
| $D_p$ | = | Particle density (g/cm$^3$) |
| $C_{c,e}$ | = | Cunningham slip factor corresponding to the volume equivalent diameter |
| $C_{c,a}$ | = | Cunningham slip factor corresponding to the AED |
| $\propto$ | = | Aerodynamic shape factor |

The Cunningham slip factor is related to the potential for particle impact with the mean free path of air molecules. Above the sub-micron size range, all particles impact with air molecules and the ratio of both Cunningham slip factors can be ignored. The $\propto$ is not typically known and is assumed to be 1. Therefore, the AED may be estimated from $D_g$ by simply multiplying the $D_g$ by the square root of the particle density[9].

The RFs for particles made airborne under scenario-induced stresses are dependent upon a variety of factors. These include the bulk density (that is, how well the DU powder or dust at rest compacts), the presence of moisture, stress deagglomeration of the powder or subdivision of the solid/liquid, the efficiency with which the stress suspends the powder/fragments of solid over various particle size ranges, and the degree of immediate proximity of surfaces on which airborne particles may impact/settle. Data to evaluate these factors individually for all cases are not found in the literature. Measured RF data from the experimental studies are applied where available.

Measured RF data are from the same general sources used for the ARFs. To keep RFs at a reasonable bound rather than an ultraconservative level, the RF associated with the measured bounding ARF is generally selected rather than the highest RF value measured. However, the highest RF values are often associated with the smallest ARFs, and when used in conjunction with the bounding ARF, result in extremely conservative estimates of the RF released. When no measured RF is associated with the maximum measured ARF, but other measured RFs are available for the experimental set, the greatest RFs are generally used. In some cases where significant uncertainty may exist, RFs are arbitrarily set to a value of 1.0 percent or 100 percent for conservatism[9].

- **Leakpath Factor**

The LPF is the fraction of the material in the respirable aerosol that is transported through some containment, deposition or filtration mechanism. There can be many LPFs for some conditions (for example, the fraction transported from a package, such as a shipping container, to an enclosure; the fraction leaked from the enclosure to the immediate operating area around the enclosure; or the fraction leaked from the immediate operating area to the atmosphere). Where multiple leakpaths are involved, their cumulative effect is often expressed as one value that is the product of all leakpath multiples. Perforation(s) in the armor, open hatches, leaking seals, and EC/NBC System in operation are leakpaths for armored vehicles. The LPF is a calculated or standard value based upon:

- Established relationships among size of the particulate material, airborne transport mechanisms, and losses by deposition mechanisms; or
- Specified filtration efficiencies[9].

Median and average (or arithmetic mean) values are estimated for the data. These estimates are made solely for the purpose of providing perspective on potential conservatism and should not be used as a basis for an ARF statistical distribution. Use of published experimental data from various sources to develop assumed statistical distributions of values for probabilistic assessments may introduce additional uncertainty.

The generation and suspension of particles are the result of the interaction of multiple physiochemical variables that have not been completely characterized. Accordingly, any data obtained are more accurately characterized as selected points from multiple distributions against multiple parameters than as different values from a common distribution. Even if this concern is neglected, there are still intractable problems in attempting to generate statistical distributions.

While the data are presumed to be bounding for the purpose intended, it is largely unknown whether the data values are truly 90th percentile, 99th percentile, or 99.9th percentile.

Furthermore, in many cases it is considered likely that incident-specific ARFs are actually distributed in a highly irregular manner (that is, multi-modal or truncated distributions). Assuming a typical distribution (that is, lognormal or Poisson), using standard deviations will produce seriously distorted values that may have little or nothing to do with reality.

The values for ARFs and RFs taken from actual measurements can be reasonably well defined. It is noted, however, that they are dependent upon the types and levels of stress imposed, the initial state (for example, physical form, chemical composition, particle size distribution, degree of dispersion of the material-of-concern), and the response of the material-of-concern and other materials present. In most cases, the materials chosen were selected to bound the behavior of materials under incident conditions for a specific location or process. The applicability of the incident conditions to the complete spectrum of normal processes and potential incident conditions is, however, uncertain.

The estimates of ARFs and RFs applicable to various incident-generated mechanisms for the suspension of material are based upon data for specific types and levels of stress/force. Care must be used in applying the ARFs/ARRs to ensure that the values chosen truly reflect the type and level of stress/force postulated for the event. For instance, the suspension of powder from a surface (commonly termed resuspension) is not applicable to situations where a readily dispersible powder is dropped into flowing gas in a dispersed fashion.

Before the ARFs and RFs presented can be properly applied, the conditions imposed and the response of critical items must be evaluated. The calculational methods to perform the engineering analysis are not part of the scope of this report, though many standard methods are applicable. However, in some cases (for example, the blast energy from the deflagration of flammable gas and oxidant mixtures in the free volume above the materials), standard engineering calculational methods are not available. Interpretation of information and data (for example, the fraction of the heat of combustion of reactants that translates into the shock wave) is required.

Once the forces and conditions imposed upon the material for dispersion/fragmentation and suspension are identified, the applicable ARF and RF can be selected. In most cases, precise correspondence between the incident conditions and experimental conditions during the measurement of the ARFs and RFs is not found. For conservative analysis, the data are applicable if the measurement conditions exceed those calculated for the event. In most cases, extrapolation beyond the data is valid for a limited range beyond the maximum (a factor of 2 to 5 dependent on the slope of the data and the range of incident conditions) imposed in this assessment.

A final emphasis is necessary regarding application of any field data. Special attention has been given to understanding suspension phenomena, ranges of relevant parameters covered in experimental studies, artifacts or limitations of the data that may have been induced by experimental conditions, and possible effects of relevant parameters that may not have been controlled or monitored. As noted, this has resulted in development of bounding ARFs and RFs.

For fires, the factor (ARF * RF) in the source term equation ranges from $5 \times 10^{-5}$ to $4 \times 10^{-4}$. The ARF and RF values of $1 \times 10^{-3}$ and 1.0, respectively, are assessed to be bounding for the thermal stress from a DU munitions fire. The bounding values selected for the parameter of lung solubility class for DU particles are > 95 percent Class Y (or Type S) with < 5 percent being Class D (or Type F). In the case of subsequent resuspension of surface-deposited DU (residual $DU_3O_8$), the release rate of respirable particles is < 0.01 of the overall ARF, Parkhurst et al., (1995b).

For bare DU and DU fragments in a fire with temperatures in the range of 500°C to 900°C, the "bounding" ARF ranges from $1 \times 10^{-7}$ to $4 \times 10^{-6}$, Parkhurst et al., (1999). During the BFV burn study, the ARF ranged between $1 \times 10^{-6}$ to $1 \times 10^{-5}$, Parkhurst et al., (1999). With an RF of 0.33, the factor (ARF x RF) would then be $3.3 \times 10^{-7}$ to $3.3 \times 10^{-6}$.

For blasts/explosions, there are no experimentally measured values available for the ARF and RF[12].

The source term estimate should provide information about the quantities (µCi or mg) of materials released in a form that is suitable for the pathway models used. There must be a connection between the source term analysis and the development of the pathway models so that the various source streams will be appropriate.