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USDOE, RECOMMENDED VALUES AND TECHNICAL BASES FOR AIRBORNE RELEASE FRACTIONS (ARFS), AIRBORNE RELEASE RATES (ARRS), AND RESPIRABLE FRACTIONS (RFS) AT DOE NON-REACTOR NUCLEAR FACILITIES - (USED AS A REFERENCE IN OU 3 RI/FS/PP APPENDIX H)

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DOE-HDBK-0013-93
July 1993

DOE HANDBOOK

Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) at DOE Non-Reactor Nuclear Facilities

U.S. Department of Energy
Washington, D.C. 20585

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4-29-94
Forward To Bill Tapp, FERMCO
ACK

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INFORMAL NOTE

4/25/94

Date: April 21, 1994

To: Sharon Fauver, EM-424

Forward to Allen Harris, FN
SKF

From: Rick Khan, EM-23 Rick Khan

Subject: Release Fractions Information

During the conference call on April 20, 1994, FERMCO requested information to estimate the releases from the storage silos in OU-4 for accident conditions. Attached is a copy of a DOE Handbook for you to forward to FERMCO for consideration.

If you have any questions please call me at 3-7254.

Attachment: DOE HANDBOOK Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release rates (ARRs), and Respirable Fractions (RFs) at DOE Non-Reactor Nuclear Facilities, DOE-HDBK-0013-93, dated July 1993

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Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) at DOE Non-Reactor Nuclear Facilities

U.S. Department of Energy
Washington, D.C. 20585

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Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) for Materials from Accidents in DOE Fuel Cycle, Ex-Reactor Facilities

Revision 2

by

Jofu Mishima
ETM - Richland

DRAFT Date: April 21, 1993

DRAFT

ACKNOWLEDGMENT

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RECOMMENDED AIRBORNE RELEASE FRACTIONS AIRBORNE RELEASE RATES AND RESPIRABLE FRACTIONS FOR EVALUATION OF PUBLIC RISK SOURCE TERMS UNDER ACCIDENT CONDITIONS

SUMMARY

This document provides reasonable factors for estimating the radiological source terms in deterministic analyses of upper-bound (worst case) accident scenarios postulated for ex-reactor, fuel cycle facilities. These factors are the Airborne Release Fractions (ARF), or Airborne Release Rate (ARR), and the Respirable Fraction (RF). Factors are developed for different types of materials that can be involved in ex-reactor/fuel cycle process facility accidents: non-condensible gases, vapors, liquids, solids, and surface contamination. Factors are also developed for inadvertent nuclear criticalities that can produce radionuclides. The factors are based on experimental data; a distillation of the experimental conditions is used to support the recommendations of bounding factors for the situations considered. The recommended values for each type of material are briefly summarized below. The Summary Table (found at the end of this summary) provides a quick reference to the values recommended. The reader is strongly encouraged to use the table only as a reference, and thus a cross reference to the document sections that discuss each value is included.

NON-CONDENSIBLE GASES

Total release of non-condensible gases upon loss of containment is assumed. This includes any noble gases generated by inadvertent criticalities in solutions or released into moderator from small diameter pieces of solid or powder. (The expectation is that if the surface to volume ratio is large and the gases generated do not have to migrate through great distances, most of the gases will be released into the moderator and be released into the ambient environment.) If the criticality occurs in large pieces of solid where the surface to volume ratio is small and any gases generated would have to migrate a large distance through the solid to reach the surface, most of the gas will not be released even when heated to high temperature. Even a reduction of material released of a factor of two is not significant when the uncertainty of the estimates is considered. Use of an ARF of 1E+0 is recommended to maintain consistency with releases most realistically anticipated.

VAPORS

Under accident conditions where volatile forms of materials (e.g., iodine, or tritiated water) can be generated, an ARF of 1E+0 is assumed. In the case of criticalities in solutions or moderated/reflected materials, the LeakPath Factor (LPF) of 0.25 assumed in the NRC Reg Guides (NRC April 1977, April 1979, July 1979) is applied to be consistent with these Reg Guides.

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LIQUIDS

Experimentally derived data were available that reflect the response of two types of liquids (aqueous and combustible, organic liquids) to the five accident stresses covered (thermal stress, explosion generated forces, venting of pressurized gases over the material, free-fall spill/crush-impact/shock-vibration, and aerodynamic entrainment). The responses are further subdivided by different level of impact generated by the mechanism (e.g., shock and blast effects for explosive releases) and the varying responses of subcategories of some types of materials (e.g., solutions, slurries and viscous solutions of aqueous liquid in free-fall spill). The ARF/RF values for the aqueous liquids for all mechanisms are based upon experimentally derived data. However, for combustible, organic liquids only the response to thermal stress has been determined experimentally. Because the effects of surface tension and viscosity do not appear to be great, the response of combustible, organic liquids to the other mechanism is assumed to be the same as for aqueous liquids.

Aqueous Liquids

Thermal Stress

Heating of Aqueous Solution in Flowing Air without Surface Rupture of Bubbles. Bounding ARF/RF values of 3E-5/1.0 for the airborne release of the bulk liquid during the heating of aqueous solutions in flowing air without noticeable surface breaking of the bubbles of the bulk liquid appear to be conservative based upon the experimental data available. Median values of 6E-7/1.0 are also estimated from the existing data.

Boiling (continuous surface breaking of bubble of the bulk liquid with <30% of the volume of the liquid as bubbles) of Aqueous Solutions in Flowing Air. A bounding ARF for the airborne release from the bubble-burst at the surface for aqueous solutions of 2E-3 exceeds all measured values reported. In the absence of a measured size distribution for the airborne droplets, a conservative value of 1.0 for the bound is assumed. A median value of 1E-3 is selected for the ARF values measured.

Explosive Release

Shock Effects. For detonations or deflagrations in or contiguous to a pool of aqueous liquid, a bounding ARF of the mass of inert material airborne equal to the calculated TNT Equivalent with an RF of 1.0 is recommended.

Blast Effects. For detonations and deflagration at a distance where the pressure impulse is essentially equal to a flow parallel to the surface of the liquid, an ARF of 4E-3/hour (1E-6/second) for the time the pressure pulse is over the liquid. A RF of 1.0 is conservatively assumed.

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Venting of Pressurized Liquids

Depressurization of Free Volume Above Liquid Surface, below boiling point of the liquid. The bounding ARF/RF values based upon the maximum experimental measurement for this situation are the same as those for the release during the boiling of an aqueous solution, 2E-3/1.0, since in both situations droplets are formed from surface rupturing of bubbles of heated liquid. Lesser values (1E-3/0.4) may be applicable for concentrated heavy metal nitrate solutions such as UNH. The median values are 3E-4/0.9 for solutions and 2E-4/0.3 for the concentrated heavy metal salt solution. The average values are 5E-4/0.9 for solutions and 3E-4/0.5 for concentrated heavy metal salt solutions.

Depressurization of Liquid via a Breach Under the Liquid Surface Level, below boiling point. Bounding ARF/RF values of 1E-4/1.0 are estimated using the mass fraction of droplets 10 micrometers and less in diameter formed by commercial spray nozzles designed to produce small drops (3.25-mm diameter orifice at 200 psig upstream pressure) under conditions that will exceed those anticipated for most accident situations.

Venting of Superheated Aqueous Solutions, >30°C over boiling point of solvent or liquid. For superheats less than 100°C above the boiling point of the liquid (<240 psig pressure), bounding ARF/RF values are 1E-1/0.7. The ARF appears to increase with decreasing source size and volumes. The values used in the experiments for these parameters are much below those anticipated under most accident situation (100 ml). At higher temperatures (pressures), there may be sufficient heat to evaporate all the solvent resulting in aerosolization of all the solute. Such situations are not covered. For the superheat range covered, the median ARF/RF are 2E-2/0.7 with average values of 4E-2/0.7.

Free-Fall Spill

Free-Fall Spill of Aqueous Solutions, Fall Distance 3 m or less. Based on the maximum measured ARF/RF from experiments involving spills of both dilute and concentrated solutions onto a stainless steel floor, the recommended bounding values for free-fall spills of aqueous solutions equal to or less than 3 m are 2E-4/0.7 for aqueous solutions with values of 2E-5/0.3 for concentrated solutions of heavy metal salts. The median values for the two types of aqueous solution are 4E-5/0.7 and 1E-6/0.3, respectively.

Free-Fall Spills of Slurries, Fall Distance 3 m or less, <40% solids. Based upon the maximum measured ARF/RF from experiments involving spills of slurries of relatively large, cohesionless powders onto a stainless steel floor, the recommended bounding ARF/RF are 5E-5/0.8 with median values of 2E-5/0.7.

Free-Fall Spills of Viscous Solutions, Fall Distance 3 m or less, viscosity >8 centipoise. Based upon experiments involving spill of concentrated sucrose solutions onto a stainless steel floor, the recommended bounding values are 3E-5/0.7 with median values of

6E-6/0.8. The bounding ARF is consistent with the bounding ARF measured for heavy metal solutions airborne from free-fall spill of equal distance listed above.

Free-Fall Spills of Aqueous Solutions, Slurries and Viscous Solutions, Fall Distance Greater than 3 m. The empirical correlation for ARF and drop size distribution parameter presented in the text from Ballinger et al. (January 1988) are recommended.

Aerodynamic Entrainment (Resuspension)

There appear to be very large differences in suspension rates under experimental test conditions as well as an order of magnitude uncertainty in measurements for individual conditions. On this basis, conservative values are applied.

Indoors, on Heterogeneous Surface (stainless steel, concrete), low airspeeds. Based on the maximum measured suspension of plutonium from shallow pools of concentrated nitrate solution on stainless steel from a very limited number of experiments, the bounding values recommended for aerodynamic entrainment of aqueous solutions by nominal air velocities passing parallel over the surface are ARR 4E-7/hr; RF 1.0.

Indoors, on Heterogeneous Surfaces, Covered with Debris or Under Static Conditions. Based upon reasoned argument that the presence of debris over the liquid restricts access of airflow to the surface, the recommended bounding values are ARR 4E-8/hr; RF 1.0.

Outdoors, from Large Pools/Ponds, Windspeeds to 30 mph. Based upon a model to describe the entrainment of spray formed by the whitecaps on the surface of large bodies of water subjected to airflow, the recommended bounding values are ARR 4E-6/hr; RF 1.0.

Outdoors, on Soil, Windspeeds to 50 mph. Based upon the suspension of uranium from a concentrated acidic solution spilled on soil in wind tunnel experiments, the recommended bounding values are ARR 9E-5/hr; RF 1.0.

Combustible Organic Liquids

Thermal Stress

The values recommended for combustible organic liquids are based on experimental data for combustion of small and large pools, organic over aqueous liquids, and gasoline over aqueous or air-dried heavy metal salts. For volatiles under all conditions, the bounding ARF/RF values are 1.0/1.0.

Indoors, Quiescent Burning Small Surface Area Pools. The small surface area pool values are from experiments using solvent only traced with some fission products

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(I 131, Cs-137, Ce-144, Zr-95) and uranium. The bounding ARF/RF values are 1E-2/1.0; median values are 6E-3/1.0.

Indoors, Vigorous Burning Large Pools. The large pool data are from experiments involving airborne release during the combustion solvent traced with cesium, thorium and cerium or strontium. The bounding ARF/RF values are 3E-2/1.0.

Indoors, Burning Solvent Over Aqueous Phase. The experimental data for combustion of combustible organic material over an aqueous phase were small scale experiments with and without external heat. The rapid evolution of the aqueous phase under the organic phase terminated combustion in many of these experiments. The bounding values are 1E-1/1.0; median values are 1E-2/1.0.

Outdoors, Aqueous Solution or Air-Dried Salts Under Gasoline Fire. Release fraction values for the suspension of material by the burning of gasoline over aqueous solutions or air-dried salts are based on experimental data obtained in wind tunnel experiments. The bounding values are 5E-3/0.4.

Outdoors, Aqueous Solution or Air-Dried Salt Under Gasoline Fire on Heat-Conducting Surface. The recommended bounding ARF/RF values are 2E-1/0.3.

The recommended ARF/RF values for explosive release, venting of pressurized liquid (either above or below the liquid surface), venting of superheated solution, free-fall spill, and aerodynamic entrainment (resuspension) are assumed to be the same as those for aqueous solutions.

SOLIDS

Some experimental data are available on the response to the five accident stresses considered of three types of solids: pyrophoric metal (plutonium and uranium which undergo self-sustaining oxidation at elevated temperatures), solids that undergo brittle fracture (aggregates such as concrete/ceramic oxide fuel pellets and glasses such as vitrified high-level waste), and powders. An extensive body of experimental data exists for the response of the pyrophoric metals to thermal stress. A correlation has been derived for the shock effects (fragmentation) on metals. None is available for their response to the other stresses although the aerodynamic entrainment is inferred from experimental data on the release during room temperature corrosion. The only experimental data for solids that undergo brittle fracture relate to fragmentation due to crush-impact forces. Experimental data on the response of powders to all mechanisms but shock effects are available.

Pyrophoric Metals

Thermal Stress: Plutonium

The accident situations that appear to provide mechanisms for the airborne release of significant quantities of airborne plutonium appear to be adequately categorized by the three stress regimes defined by Carter and Stewart: 1) ignition and burning (melting); 2) partial disruption of molten plutonium (e.g., free-fall of molten drops, violent surface reactions, sparking); and 3) vapor formation from molten plutonium (e.g., explosive ejection of fine drops, very small quantities of plutonium metal subjected to very high temperatures). In some accident scenarios, the most severe stress imposed upon the metal may be simple exposure to the room atmosphere or temperature less than required for ignition. ARFs/Rfs are provided for airborne release during room temperature oxidation (corrosion) and oxidation at elevated temperatures (greater than room temperature but a temperature less than self sustained oxidation) in air.

Airborne Release of Particulates Formed by Room Temperature Oxidation (Corrosion). Based upon the experimental measured values, the bounding ARRs, Rfs recommended for the four situations covered are:

unalloyed plutonium:	(dry air) 2 micrograms Pu/cm^2-hr, 0.7
	(100% RH) 7 mg Pu/cm^2-hr, 0.7
delta-phase metal:	(dry air) 0.07 microgram Pu/cm^2-hr, 0.7
	(100% RH) 0.6 mg Pu/cm^2-hr, 0.7

Airborne Release of Particulates Formed by Oxidation at Elevated Temperature, Greater than Room Temperature but Less than Self-Sustained Oxidation (Ignition). For static oxidation at elevated temperatures less than ignition temperatures, ARF/RF values of 3E-5/0.04 are recommended. The material-at-risk is the amount of oxide present under the specific accident conditions. If oxidation is not complete, Table 4.2-2 from Stewart (1963) showing plutonium oxidation rates or Haschke's (July 1992) value (0.2 g PuO_2/cm^2 metal surface exposed per min. = 10.56 g Pu/cm^2 metal surface exposed per hour)(July 1992) can provide a basis for such estimations.

Airborne Release of Particulates Formed by Self-Sustained Oxidation (Molten Metal with Oxide Coat), Self-Induced Convection. For situations involving the self-sustained oxidation in air of metal pieces under self-induced convection, Mishima's values of 5E-4/0.5 exceed the combined value (ARF X RF) for all other measured values and are recommended for this situation.

Airborne Release of Particulates from Disturbed Molten Metal Surfaces (Flowing Metal, Actions Resulting in Continual Surface Renewal), High Turbulence at Surface, Violent Airborne Reaction. For situations where ignited-molten plutonium is disturbed by direct impact of high air velocities such as during free-fall, sparking, energetic surface

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reaction as during the conversion of hydride to oxides, the 95% confidence limit ARF/RF values recommended by Carter and Stewart (September 1970), 1E-2/1.0, still appear to bound the experimentally measured values reported.

Airborne Release of Particulates from Oxidation of Small (Hundreds of Micrometers in Diameter) Molten Metal Drops Passing Through Air or Explosive Reaction of Entire Metal Mass. For the violent ejection of molten metal and vapor formation from droplets, Raabe et al. measured an ARF of 4E-1 (and RF of 1.0 estimated from MMD reported) from exploding wire experiments. Carter and Stewart (September 1970) reported 1E+0/0.5 from small molten metal drops falling through air. These values appear to bound the experimental data; the latter values of 1E+0/0.5 are recommended as the bound.

Thermal Stress: Uranium (Plus Recommended Solubility Class of Released Material)

Airborne Release of Particulates During Complete Oxidation of Metal Mass, >500°C, Gas Flow 0 - 2 m/s. Based upon the experiments performed by Carter and Stewart (September 1970) heating uranium in an upflow of air with the oxide generated allowed to sluff away during the oxidation process, the mean value designated by the authors is chosen. The measured values were only for airborne particles <10 micrometers AED or less. The value for solubility class in simulated lung fluids is from the solubilities for the sintered oxides recovered from the burn tests performed as part of the hazard classification tests on armor-defeating munitions.

The 95% confidence level airborne release value for oxidation of uranium metal at flow velocities <100 cm/s reported by Carter and Stewart (September 1970) is exceeded by the value reported by Elder and Tinkle (December 1980) during the oxidation of staballoy penetrators during laboratory experiments. The ARF X RF values obtained for experiments at temperature less than 900°C were less than 1E-3.

Bounding ARF/RF values of 1E-3/1.0 are recommended for this category with median values of 1E-4/1.0. The solubility classification for the oxides formed is >95% "Y" class with remainder in "D" class.

Airborne Release During Free-Fall of Molten Metal Drops. The median ARF X RF value for the free-fall of molten uranium metal droplets in air are as given by Carter and Stewart (September 1970). The bounding ARF X RF value recommended is an arbitrary increase of the 95% confidence level value assigned by Carter and Stewart to 1E-2 to be consistent with the comparable value for plutonium. Since the airborne material is cooled rapidly after formation, the solubility of the airborne oxides formed from plastic deformation and ignition of the thin film of metal generated by the impact of penetrators against hard targets of 50% "Y" class and 50% "D" class is recommended.

Bounding ARF/RF values for airborne release during free-fall of molten metal drops are 1E-2/1.0; median values are 2E-3/1.0. The recommended solubility class of released material is 50% "Y" class + 50% "D" class.

Airborne Release from Explosive Dispersal of Molten Uranium. The airborne release values for the explosive release of molten uranium indicate that, if the uranium is molten and subdivided in very small drops (as by the exploding wire technique) and ejected into air at sonic velocities (as by the electrodynamic thruster technique), all the uranium could be made airborne as a very fine particulate material (1.0 as particles/aggregates 10 micrometers AED and less). Bounding values are 1E+0/1.0. The solubility class of the airborne material is anticipated to be like the airborne material formed during the impact of staballoy penetrators against hard targets or armor (thin film formed by the plastic deformation of the metal in passage through the armor is ignited by frictional heat and rapidly cooled in the air). The maximum values reported for the type of situation is 50% "D" class + 50% "Y" class.

Explosive Release

Shock Effects. For detonations in or contiguous to metal, a bounding ARF X RF of the mass of inert material equal to the mass of the TNT Equivalent estimated.

Blast Effects. No significant airborne release is postulated for this configuration.

Venting of Pressurized Gases Over Metal

Use values for the venting of pressurized powders.

Free-Fall Spill/Crush Impact

No significant airborne release is postulated for this accident configuration.

Aerodynamic Entrainment (Resuspension)

Based upon assumption that the airborne release during corrosion of plutonium metal is equal to the aerodynamic entrainment (resuspension) of the corrosion product from the metal surface, the bounding ARF/RF values for this configuration are

unalloyed metal:	(dry air) 2 microgram metal/cm^2-hr, 0.7
	(100% RH) 7 mg metal/cm^2-hr, 0.7
delta-phase metal:	(dry air) 0.07 microgram metal/cm^2-hr, 0.7
	(100% RH) 0.6 mg metal/cm^2-hr, 0.7

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Solids That Undergo Brittle Fracture (e.g., Aggregates, Glass)

No data were available for thermal stress or explosive release.

Venting of Pressurized Gases over Solid

The entrainment of the material is a function of the characteristics of the flow over the particulate material that may be lying on the surface, the particles, and the surface. Some of the flow characteristics are dependent on the initial pressure and the size of the vent. No bounding ARF/RF can be recommended at this time.

Free-Fall Spill/Crush-Impact

The ARF X RF for the fragmentation of a solid that can undergo brittle fracture can be estimated by:

$$PULF = A\ P\ g\ h\ (J \text{ per } 10^7\ g\text{-}cm^2/s^2)$$

where: PULF = fraction pulverized into 10 Micrometer and less size range
A = empirical correlation, 2E-4 cm^3/J ($J = kg\text{-}m^2/s^2$)
P = specimen density, g/cm^3
g = gravitational acceleration, ~960 cm/s^2 at sea level
h = height, cm.

Aerodynamic Entrainment (Resuspension)

For the aerodynamic entrainment of any particles of the solid material lying on the surface, refer to values recommended for the aerodynamic entrainment of powders.

Powders

Thermal Stress

The recommended bounding ARF/RF for various plutonium compounds subjected to thermal stress (temperature < 1000°C, natural convection) are as follows:

non-reactive* compounds	6E-3/0.01
reactive* compounds (except PuF_4)	1E-2/0.001
PuF_4	1E-3/0.001

* See text for compounds tested.

The total mass of the RF size fraction for non-reactive compounds cannot exceed the mass in this size fraction in the source material.

Explosive Release

Shock Effects. No data available.

Blast Effects. The following bounding ARF/RF values are recommended:

Accelerated airflow parallel to surface = 5E-3/0.3.

Deflagration of limited volume of flammable mixture above powder (volume mixture less than 10% free volume above powder) = 1E-1/0.7.

Deflagration of large volume of flammable mixture above powder = 1E+0/1.0.

The respirable fraction is limited to the mass present in the source material.

Venting of Pressurized Powders

For venting of pressurized powder or the venting of pressurized gases through a powder, <3.4 MPa, the bounding values are 1E-1/0.5. Median values are 5E-2/0.4.

Free-Fall Spill of Powders/Shock-Impact

For the free-fall spill of cohesionless powders, the following bounds were determined:

Fall distance <3 m, air velocity normal to powder flow <1 m/s = bounding 2E-3/0.3; median 3E-4/0.5.

Fall distance >3 m, air velocity normal to powder flow <1 m/s = Calculations are outlined that can be applied if the ARF/RF values exceed 2E-3/0.3) Earthquake

Air velocities normal to direction powder flow >1 m/s (suspension of soil dispersed into flowing air). Use the equation

Highwind

$$ARF = 0.0134\ U + 0.00543,\ RF\ 1.0$$

where U = windspeed, m/s. = 0.42 at 31 m/sec

Again, the mass airborne in the RF is limited by total mass of material in this size fraction in the source material.

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For the suspension of powder due to vibration of substrate from shock-impact due to falling debris, the bounding ARF/RF values are 1E-3/0.1.

Aerodynamic Entrainment (Resuspension)

Based upon the information on resuspension factors and rates found in the review articles and the outdoor rates, the long-term ARR suggested by Sehmel and Lloyd (1976) appears to be a reasonable bound, 4E-5/hr. Although ARRs appear to decrease with time, use of the initial ARR measured would be conservative. The ARR should be applied to the residual material-at-risk that is being depleted by the entrainment. Not including this depletion of the source with time also tends to overestimate the release. The resuspension tends to fluctuate as the level of stress fluctuates and the surface conditions respond to the previous stresses. After an event, the powder released may be exposed to primarily aerodynamic stresses within the facility or remnants of the facility until remedial action can be taken. The time interval of exposure would be hours rather than seconds. Thus, a bounding ARR of 4E-5/hr with a RF of 1.0 is recommended. Due to the decrease in aerodynamic stress if the powder is shielded by remnants and debris of the structure or exposed to static conditions within the structure and indication from a single experimental study, a bounding ARR/RF for powder under debris of 4E-6/hr with an RF of 1.0 is recommended. The bounding ARFs/RFs for aerodynamic entrainment due to the passage of vehicular traffic and from the shock-impact of falling debris are the maximum measured experimental values.

Homogeneous Bed of Powder Exposed to Ambient Conditions (Normal Process Facility Ventilation Flow or Less, or Atmospheric Windspeeds <2 m/s). The bounding ARR/RF for a homogeneous bed of powder exposed to ambient conditions (normal process facility ventilation flow or less, or atmospheric windspeeds <2 m/s) following an event would be 4E-5/hr, 1.0.

Homogeneous Bed of Powder Buried Under Structural Debris Exposed to Ambient Conditions or Under Static Conditions Within the Structure. The bounding ARR/RF for a homogeneous bed of powder buried under structural debris exposed to ambient conditions or under static conditions within the structure following an event would be 4E-6/hr, 1.0.

Entrainment of Powders from Road Surface by Vehicular Traffic. For entrainment of powders from road surface by passage of vehicular traffic, bounding values for ARR/RF would be 1E-2/passage, 1.0.

Suspension of Thick Beds of Powder by Impact of/Turbulence Generated By Falling Objects, Air Velocity <1 m/s. For the suspension of thick beds of powder by impact of turbulence generated by falling objects, air velocity <1 m/s, the bounding values would be 1E-2/0.2; median values would be 4E-4/0.2.

Again, for the preceding RF values, the total mass of material airborne in the size fraction is limited by the mass of material in that size fraction in the source material.

SURFACE CONTAMINATION

Three categories of surface contamination are addressed: sparse surface contamination (layer of contamination less than 2 D_p thick covering < 10% of surface area) on 1) combustible solid substrate and 2) non-combustible solid substrate and the particulate material accumulated on 3) the surface of the filter medium in HEPA filters. For surface contamination on solid combustible substrates, experimental data for releases under thermal stress are available. Values are recommended for shock and blast effects, venting of pressurized gases over the solid, shock-vibration and aerodynamic entrainment by analogy to the suspension of powder by these mechanisms. There are no experimental data directly applicable to the behavior of sparse contamination on non-combustible solids. Values are recommended by analogy to the behavior of solids or powders under these conditions. Indirect experimental data are available for the behavior of HEPA filters to a level of thermal stress, shock- and blast-effects, shock-impact after free-fall. The ARF/RF values for blast effects are used to bound the release of pressurized gases through the filter. No significant loss of accumulated materials due to aerodynamic entrainment is postulated.

Surface Contamination on Combustible, Solid Substrate

The substrate will typically be composed of trash; materials that could be found are paper, rags, cardboard, plastic wrapping, sheets, bags, containers, glovebox windows, tools, casings, ion exchange resins, wood, or wall board.

Thermal Stress

In all cases, the mass airborne in the RF cannot exceed the mass in that size fraction in the source material.

Packaged Mixed Waste. For contaminated combustible materials heated/burned in packages with non-contaminated exterior surfaces, the bounding ARF/RF values of 5E-4/1.0 are recommended based on maximum experimentally determined ARF and conservative assumption of RF. The median values are 8E-5/1.0.

Uncontained Cellulosics (paper, cardboard, rags, wood). Based upon maximum experimentally determined ARF/RF for burning of unpackaged cellulosic materials, the following values are recommended: bounding 1E-2/1.0 and median 5E-4/1.0.

Uncontained Plastics. This situation applies to contaminated combustible materials burning in uncontained atmosphere (no packages). For all plastic materials except polystyrene, bounding values of 5E-2/1.0 are based upon maximum experimentally determined ARF and RF for polychloroprene and polymethylmethacrylate. For polystyrene,

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bounding values of 1E-2/1/0 are based upon maximum experimentally determined ARF and RF for very limited set (3) of experiments involving polystyrene contaminated with UNH solution.

Entrainment during Passage of Air Through Ash. For the burning of unpackaged contaminated combustible with air flowing through burning mass, the following bounding values were obtained based upon maximum experimentally determined ARF and conservative assumption of RF. The experimental bases are the burning of very small specimen sizes of combustibles with powder, solution and air-dried solution contaminants using airflows of 0.46 and 1.0 m/s. For powder the values are 4E-1/1.0; for solution or air-dried solution the values are 8E-2/1.0.

Explosive Releases

No applicable data were found; the values selected based upon reasoned judgment.

Shock Effects. No applicable data. The combustible materials considered can be fragmented by shock effects but many of them are extremely flexible. Particles are unlikely to be dislodged from porous surfaces. The release is bounded by the release of powder from surfaces due to vibration-shock of substrate. Ignition and burning may be the most significant response. The bounding ARF/RF values are 1E-3/1.0.

Blast Effects. The bounding ARF/RF values are based upon reasoned judgment that suspension/release by this mechanism is bounded by suspension of powders from surfaces by shock-vibration; the bounding values are 1E-3/1.0.

Venting of Pressurized Gases Over Contaminated, Combustible Waste

No applicable data were found.

Free-Fall Spill, Crush-Impact

Free-Fall Spill. No applicable data were found for free-fall spills.

Impact with Surface (Shock-Vibration Induced by Impact). Bounding ARF/RF of 1E-3/1.0 are based on reasoned judgement that suspension under these circumstances are bounded by suspension postulated for powders from surfaces by shock-vibration.

Aerodynamic Entrainment (Resuspension)

No applicable data were found; bounding ARRs/RFs quoted are based on reasoned judgment that entrainment under these conditions is bounded by suspension of powder under similar circumstances.

For nominal flow conditions indoors (normal process facility flows) and outdoors (<5m/s). the bounding ARR;RF are 4E-5/hr; 1.0.

For static conditions indoors (essentially no flow) or surface contamination buried under debris, the bounding ARR; RF are 4E-6/hr; 1.0.

Sparse Contamination on Non-Combustible Solid Substrate

Generally the substrate is composed of large, solid pieces associated with the structure, enclosures, and containers, but it could include glass/plastic equipment and containers.

Thermal Stress

Bounding values of 1E-2/0.001 were selected based on reasoned judgment that the suspension of surface contamination (most probably in the form of a sparse population of particles attached to the surface) under thermal stress is bounded by the suspension of reactive powders under thermal stress in a flowing airstream.

Explosive Releases

Shock Effects. Based upon the maximum mass of respirable particles predicted by the Steindler and Seefeldt (1980) correlation, the bounding value is the mass respirable particle released equal to mass TNT Equivalent estimated. The mass of substrate carrying surface contamination needs an assumption as to the depth of layer fragmented by detonation.

Blast Effects. Bounding ARF/RF of 5E-3/0.3 are based on reasoned judgment that suspension under these conditions would not exceed comparable values for loose powders under similar circumstances.

Venting of Pressurized Gases Over Contaminated, Non-Combustible Solid

No applicable data were found. A bounding value of 1E-1/0.5 is based on an assumption that any release is conservatively bounded by bounding ARF/RF postulated for powders.

Free-Fall Spill, Crush-Impact

No applicable data were found. Bounding values are based upon assumptions that release for various mechanisms bounded by airborne release of powder under similar circumstances.

Free-Fall Spill, Materials That Undergo and Do Not Undergo Brittle Fracture. No significant airborne releases postulated during free-fall.

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Impact, Shock-Vibration. For materials that undergo brittle fracture, the airborne release is bounded by the ARF/RF postulated for brittle fracture of solids: PULF = A P g h ($J/10^7$ g-cm^2/s^2).

For materials that do not undergo brittle fracture, the bounding ARF/RF values are the same as those postulated for powder by shock-vibration: ARF/RF 1E-3/1.0.

Aerodynamic Entrainment (Resuspension)

The bounding values are assumed to be bounded by the ARR/RF postulated for aerodynamic entrainment of powders.

Nominal conditions indoors (process facility ventilation flows) and outdoors (<5 m/s). The bounding ARR; RF are 4E-5/hr; 1.0.

Static conditions (1 m/s and less) or from surface contamination covered by debris. The bounding ARR; RF are 4E-6/hr, 1.0.

HEPA Filters

Thermal Stress

Based upon conservative extrapolation of the maximum experimental measurement of release of particles accumulated by the passage heated air through HEPA filters, bounding ARF/RF of 1E-4/1.0 are obtained.

Explosive Releases

Assume shock and blast effects in same direction as normal airflow through filters.

Shock Effects. Based on experimentally measured releases of accumulated particles from HEPA filters subjected to shock waves, bounding ARF/RF are 2E-6/1.0.

Blast Effects. Based on maximum measured release of accumulated particles by passage of high velocity air through filters, bounding ARF/RF are 1E-2/1.0.

Release of Pressurized Gases Through Filters

Releases are bounded by ARF/RF for blast effects; bounding ARF/RF are 1E-2/1.0.

Free-Fall Spill, Shock-Impact

No applicable experimental data for airborne release of particles during free-fall of HEPA filters were uncovered. No significant release is postulated during free-fall. Releases

on impact are bounded by conservative extrapolation of maximum releases measured for contained (in packages) and uncontained HEPA filters.

For enclosed (e.g packages, housing) HEPA with accumulated particles upon impact with hard unyielding surface, bounding ARF/RF are 5E-4/1.0.

For unenclosed HEPA filters with accumulated particles upon impact with hard, unyielding surfaces, bounding ARF/RF are 1E-2/1.0.

Aerodynamic Entrainment (Resuspension)

Since the filters are designed and manufactured to collect and retain particles in flowing air, no significant release of accumulated particle is postulated by passage of air across face of filter. Even if filter medium is exposed, no significant release of particles accumulated by nominal air velocities is postulated.

INADVERTENT NUCLEAR CRITICALITIES (NUCLEAR EXCURSIONS)

Under appropriate accident conditions, fissile and fissionable radionuclides may undergo a self-sustaining nuclear reaction (chain reaction) called an inadvertent nuclear criticality or a nuclear excursion. This accident scenario does not lend itself to discussion under the same categories of accident stress that were applied to gases, liquids, solids, and surface contamination. The fraction that is at-risk of airborne suspension depends upon the physical form of the fissionable materials involved. Accordingly, several modifications to the method used for determining the airborne release were made for four physical systems: solutions, fully moderated/reflected solids, dry solids, and large storage arrays. These modifications are discussed in detail in Chapter 6 of the document. The calculational methods are outlines in the Summary Table; bounding values for the factors involved in calculating the release fractions for nuclear excursions are summarized here.

For nuclear excursions, the material-at-risk is determined by the fraction of fission products generated by the criticality and the fraction of the fissile/fissionable material that may be suspended by the event generated conditions (primarily heat). [Since fissile materials (^{233}U, ^{235}U, ^{239}Pu) are also fissionable, both will be referred to as fissionable.] The amount of fission products and actinides produced by the excursion is a function of the total fissions from the criticality and the specific fissionable radionuclide involved and should be determined by an appropriate code such as ORIGEN2.

Values of ARF for fission product noble gases are assumed to be 1.0. For radioiodines and other radiohalogens that can be generated as vapors by accident conditions, the ARF is chosen to be 0.25. For salts in liquid evaporated (assume 100 liter for large volume solution excursion), a value of 5E-4 is assumed.

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Values of RF for noble gases are 1.0; all the airborne material can be transported downwind will affect the exposure of the population. For radioiodine, also use 1.0; it is assumed that the material is released as vapor. For salts in liquids evaporated during boildown of solution, use an RF of 1.0.

The LPF (LeakPath Factor) is assumed to be 1.0 for noble gases, 1.0 for radioiodine unless functional iodine removal devices are in the facility gaseous effluent exhaust system (use conservative estimate of removal efficiency). For particulate materials generated, if generated indoors and the airborne material from the excursion is released via the facility gaseous effluent exhaust system, use a LPF of 0.001 (filter efficiency of 99.9%) for the 1st stage of HEPA filtration and 0.002 (filter efficiency of 99.8%) for every stage thereafter or a conservative estimate of the transmission factor for other types of high efficiency particulate filtration (e.g., sand filters) in place.

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

This Summary Table is provided as a quick reference for the specific values derived for ARFs, ARRs, and RFs derived in the document. It is not intended to be used without a thorough understanding of the technical basis provided in the document. A cross-reference to the applicable subsections of the document covering the specific items is provided. Special attention should be given to an understanding of the suspension phenomenon, the range of relevant parameters covered in the experimental study upon which the values are based, any artifacts or limitations on the data that may be induced by the experimental apparatus, and the possible effects of relevant parameters that may not have been controlled or monitored.

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
NON-CONDENSIBLE GASES	Loss of containment: 1.0/NA. See Section 1.0.				
VAPORS	Evolution from chemical reaction or temperature: 1.0/NA. See Section 2.0.				
LIQUIDS					
Aqueous Solutions	Flowing air, no bubbles: 3E-5/1.0. See Section 3.2.1.1.	Shock effects: [1]. See Section 3.2.1.2.1.	Vented above liquid level, < bp, aqueous solutions density near 1 g/cm^3: 2E-3/0.3. See Section 3.2.1.3.1.	Solutions, fall distance <3 m: 2E-4/0.7. See Section 3.2.1.4.1.	Indoors, hard unyielding surface, nominal air velocities: 4E-7/hr;1.0. See Section 3.2.1.5.4.
	Flowing air, boiling: 2E-3/1.0. See Section 3.2.1.1.	Blast effects: 4E-3/hr x t;1.0 [2]. See Section 3.2.1.2.2.	Vented above liquid level, < bp, conc. solution heavy metal, density >1.3 g/cm^3: 1E-3/0.4. See Section 3.2.1.3.1.	Solutions, fall distance >3 m: [3]. See Section 3.2.1.4.1.	Indoors, cover debris or static conditions: 4E-8/hr;1.0. See Section 3.2.1.5.4.
			Vented below liquid level, 3.25-mm dia. orifice, <1.4MPa pressure: 1E-4/1.0. See Section 3.2.1.3.2.	Slurries, <3-m fall, <40% solids: 5E-5/0.8. See Section 3.2.1.4.2.	Outdoors, large pool, windspeed <13.4 m/s: 4E-6/hr;1.0. See Section 3.2.1.5.4.
			Superheated liquids (flashing spray), >50 C above solvent bp: 1E-1/0.7. See Section 3.2.1.3.3.	Viscous liquids, >8 cp, <3-m fall distance: 3E-5/0.7. See Section 3.2.1.4.3.	Outdoors, soil, windspeed <22.4 m/s: 9E-5/hr;1.0. See Section 3.2.1.5.3.

SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
Organic Combustible Liquids	Volatile radionuclides under all conditions: 1E+0/NA. See Section 3.2.2.1.1.	No experimental data on the response of organic, combustible liquids to other suspension mechanisms were found. Apply factors for the response aqueous solutions above for comparable stresses.			
	Non-volatiles, small pool fire, quiescent burning: 1E-2/1.0. See Section 3.2.2.1.1.				
	Non-volatiles, large pool, vigorous burning: 3E-2/1.0. See Section 3.2.2.1.2 & 3.2.2.1.4.				
	Non-volatiles, burned to dryness: 1E-1/1.0. See Section 3.2.2.1.4.				
	Non-volatiles, outdoors, aq. soln. or air-dried salts under burning fuel: 5E-3/0.4. See Section 3.2.2.1.3.				
	Non-volatiles, aq. soln. or air-dried salts under burning fuel, heat-conducting surface: 2E-1/0.3. See Section 3.2.2.1.3.				

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
SOLIDS					
Pyrophoric Metals (plutonium, uranium)	Plutonium, room temperature oxidation, unalloyed metal in dry air: 2 micrograms Pu/cm^2-hr; 0.7. See Section 4.2.1.1.1.	Shock effects: [1]. See Section 4.2.1.2.1.	See venting of pressurized powders and Section 4.2.1.3.	Spill of molten metal: see falling molten drop values at left and Section 4.2.1.4.	Use values for release from room temperature oxidation of Pu at left; see Section 4.2.1.5.
	Plutonium, room temperature oxidation, unalloyed metal in 100% RH: 7 mg Pu/cm^2-hr; 0.7. See Section 4.2.1.1.1.	Blast effects: no significant effects postulated. See Section 4.2.1.2.2.			
	Plutonium, room temperature oxidation, delta-phase metal in dry air: 0.072 micrograms Pu/cm^2-hr; 0.7. See Section 4.2.1.1.1.				
	Plutonium, room temperature oxidation, delta-phase metal in 100% RH: 0.6 mg Pu/cm2-hr; 0.7. See Section 4.2.1.1.1.				

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
Pyrophoric Metals (plutonium, uranium)	Plutonium, oxidation at elevated temperatures: 3E-5 x fraction oxidized; 0.04. See Section 4.2.1.1.1.				
	Plutonium, self-sustained oxidation: 5E-4/0.5. See Section 4.2.1.1.1.				
	Plutonium, disturbed surfaces, high turbulence, violent airborne reaction, falling molten metal drops: 1E-2/1.0. See Section 4.2.1.1.1.				
	Plutonium, explosive reaction molten metal, rapid vapor formation: 1E+0/0.5. See Section 4.2.1.1.1.				
	Uranium, complete oxidation of metal, 0 to 2 m/s gas flow, >500 C: 1E-3/1.0 [6],[a]. See Section 4.2.1.1.2.				
	Uranium, falling molten drops/disturbed surface: 1E-2/1.0 [6],[b]. See Section 4.2.1.1.2.				

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
Pyrophoric Metals (plutonium, uranium)	Uranium, explosive dispersal of molten metal: 1E+0/1.0 [6],[b]. See Section 4.2.1.1.2.				
Solids that Undergo Brittle Fracture	No data available. See Section 4.3.1.	No data available for shock or blast effects. See Section 4.2.2.2.	See aerodynamic entrainment (resuspension) of surface contamination below, and also Section 4.2.2.3.	[5]. See Section 4.2.2.4.	See aerodynamic entrainment (resuspension) of surface contamination below and Section 4.2.2.5.
Powders	Natural convection, <1000 C, non-reactive compounds: 6E-3/0.01 [6]. See Section 4.2.3.1.	Shock effects: no data available. See Section 4.2.3.2.1.	Venting pressurized powders, <3.4 MPa: 1E-1/0.5. See Section 4.2.3.3.	Airflow normal to fall direction, <1 m/s, fall distance <3 m: 2E-3/0.3. See Section 4.2.3.4.1.	Thick beds, homogeneous surface: 4E-5/hr;1.0. See Section 4.2.3.5.1.
	Natural convection, <1000 C, reactive compounds except PuF4: 1E-2/0.001. See Section 4.2.3.1.	Blast effects, accelerated airflow parallel to surface, <0.14 MPa: 5E-3/0.3. See Section 4.2.3.2.2.		Airflow normal to fall direction, <1 m/s, fall distance >3 m: [7]. See Section 4.2.3.4.1.	Thick beds, buried under debris or indoors static. volume: 4E-6/hr;1.0. See Section 4.2.3.5.1.
	Natural convection, <1000°C, PuF4: 1E-3/0.001. See Section 4.2.3.1.	Blast effects, deflagration above limited volume reactants (unconfined vapor cloud, 0.14 to 0.34 MPa: 1E-1/0.7 [6]. See Section 4.2.3.2.2.		Airflow normal to fall direction, >1 m/s, dispersed powder into flowing air where U = local windspeed in m/s: 0.0134 U + 0.00543. See Section 4.2.3.4.2.	Turbulence generated by falling debris: 1E-2;0.2. See Section 4.2.3.5.2.

SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
Powders		Blast effects, deflagration above large volume reactants, >0.34 MPa, strong flow directly impacts material/ severe turbulence: 1E+0/1.0. See Section 4.2.3.2.2.		Shock-vibration: 1E-3/0.1. See Section 4.2.3.4.3.	Vehicular traffic through or by freshly deposited powder: 1E-2/pass;1.0. See Section 4.2.3.5.3.
SURFACE CONTAMINATION					
Solid Combustible Substrate	Burning contained mixed waste: 5E-4/1.0 [6]. See Section 5.2.1.1.1.	Shock effects: no data available. See Section 5.2.1.2.1.	No data available. See Section 5.2.1.3.	Free fall spill: no data available. See Section 5.2.1.4.1.	Nominal flow conditions, <5 m/s: 4E-5/hr;1.0 [6]. See Section 5.2.1.5.
	Burning uncontained cellulosics: 1E-2/1.0 [6]. See Section 5.2.1.1.2.	Blast effects, accelerated airflow: 1E-3/1.0 [11,6]. See Section 5.2.1.2.2.		Shock-vibration: 1E-3/1.0 [6]. See Section 5.2.1.4.2.	Buried under debris, indoor static conditions: 4E-6/hr;1.0 [6]. See Section 5.2.1.5.
	Burning uncontained plastics except polystyrene: 5E-2/0.2 [6]. See Section 5.2.1.1.3.				
	Burning uncontained polystyrene (polyethylene, IX resin): 1E-2/0.9 [6]. See Section 5.2.1.1.3.				
	Airflow through burning mass >1 m/s: 4E-1/1.0 [6]. See Section 5.2.1.1.4.				

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
Non-Combustible Substrate (Hard, Unyielding Surfaces)	See Section 4.2.3.1.	Shock effects: [1]. See Section 5.2.2.2.1.	1E-1/1.0. See Section 5.2.2.3.	Free-fall spill: no data available. See Section 5.2.2.4.1.	Nominal flow conditions: 4E-5/hr;1.0. See Section 5.2.2.5.
		Blast effects: 5E-3/0.3. See Section 5.2.2.2.2.		Crush-impact/brittle fracture: [5]. See Section 5.2.2.4.2.	Buried under debris, indoor static conditions: 4E-6/hr;1.0. See Section 5.2.2.5.
				Shock-vibration: 1E-3/1.0. See Section 5.2.2.4.2.	
HEPA/Glovebox Exhaust Filters	Heating: 1E-4/1.0 [6]. See Section 5.2.3.1.	High pressure blowout, dynamic: 2E-6/1.0. See Section 5.2.3.2.1.	See Section 5.1.3.2.	Free-fall spill: no data available. See Section 5.4.4.	
		High pressure blowout, static: 1E-2/1.0. See Section 5.2.3.2.2.		Uncontained or unenclosed crush-impact (vibration): 1E-2/1.0 [6]. See Section 5.4.5.2.	
				Contained or enclosed crush-impact (vibration): 5E-4/1.0 [6]. See Section 5.4.5.1.	

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
INADVERTENT NUCLEAR CRITICALITIES (NUCLEAR EXCURSIONS)					
Solutions, large volume systems (>100 gallons in vented vessel)	$[(MAR_{c1} \times DR_{c1} \times ARF_{c1} \times RF_{c1}) + (MAR_{s1} \times DR_{s1} \times 5E\text{-}4 \times 1.0)]$ LPF where: MAR_{c1} = inventory radionuclides from criticality in a solution calculated by computer code such as ORIGEN2 based on 1E+19 total fissions; or, = [1E+19 fissions/1E+19 fissions] X table[8]. DR_{c1} = damage ratio for material involved in criticality, 1.0. ARF_{c1} = Airborne Release Fraction for solution criticality in NRC Reg Guides[9]: 1E+0 for noble gases, 2.5E-1 for radioiodines, 1E-3 for radioruthenium. RF_{c1} = Respirable Fraction[10] materials generated by criticality ... materials generated all in gaseous phase and RF = 1.0. MAR_{s1} = Inventory radionuclides in solution prior to the nuclear excursion evaporated, curies. DR_{s1} = Damage Ratio radionuclides in solution, 1.0. LPF = LeakPath Factor for airborne material[17] ... different LPFs are necessary for gaseous radionuclides and airborne particulate materials.				
Fully moderated/ reflected solids - (a coherent solid cannot be moderated and solids <100 micrometers in diameter must be intimately mixed with moderator to be fully moderated.)	$MAR_{c2} \times DR_{c2} \times ARF_{c2} \times RF_{c2} \times$ LPF where: MAR_{c2} = Inventory radionuclides from criticality in reflected/moderated solids calculated by computer codes such as ORIGEN2 based on 1E+18 total fissions, or, = [1E+18 fissions/1E+19 fissions] X table[8]. DR_{c2} = Damage Ratio for radionuclides generated by criticality, 1.0. ARF_{c1} = Airborne Release Fraction[9] in NRC Reg Guides. RF_{c1} = Respirable Fraction for airborne material in gaseous phase, 1.0[10]. LPF = LeakPath Factor for gaseous airborne material[12].				

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

Type of Material	Bounding Values for ARF or ARR/RF under Stress Situation				
	Thermal Stress	Explosive Release	Venting of Pressurized Liquid	Free-Fall Spill	Aerodynamic Entrainment (Resuspension)
Bare, Dry Solids	$[(MAR_{c3} \times DR_{c3} \times ARF_{c3} \times RF_{c3}) + (MARs3 \times DR_{s3} \times ARF_{s3} \times RF_{s3})]$ LPF where: MAR_{c3} = Inventory of radionuclides generated by bare, dry metal criticality based on total fission yield of 1E+17 fission by computer code such as ORIGEN2; or, = [1E+17 fissions/1E+19 fissions] X table[8]. DR_{c3} = Damage Ratio = A_s X 10-mm/Vol_f, where A_s = surface area of fissionable material exposed to the air, mm, and Vol_f = volume of fissionable material, mm^3. ARF_{c3} = Airborne Release Fractions in Table 6-4; or, = if using MAR values in NRC Reg Guide use ARFs[9] from that document. RF_{c3} = Respirable Fraction, assume 1.0 for all materials. MAR_{s3} = Inventory of fissionable material involved in criticality. ARF_{s3} = Airborne Release Fraction for ignited, oxidized metal - natural convection, 5E-4. RF_{s3} = Assume 1.0. LPF = Need LPF for both gases/vapors and airborne particulate material[12].				
Large Storage Arrays	$MAR_{c4} \times DR_{c4} \times ARF_{c4} \times RF_{c4} \times LPF$ where: MAR_{c4} = Inventory radionuclides generated in solid materials based on total fission yield of 1E+20 fissions by computer code such as ORIGEN2; or, = [1E+20 fissions/1E+19 fissions] X table[8]. DR_{c4} = Damage Ratio, assume all radionuclides generated at-risk. ARF_{c4} = Airborne Release Fraction, if using values in Reg Guide as MAR, use values for ARF[9]. Unless substantial clad/package failure is postulated, only gaseous/volatile materials are assumed to be made airborne. RF_{c4} = Respirable Fraction[10], assume 1.0 for all airborne materials LPF = LeakPath Factor for gaseous materials[12].				

[1] Assume mass inert material fragmented and made airborne as particles or droplets airborne as RF equal to TNT Eq.
[2] An ARR of 4E-3/hr is applied for the number of seconds estimated for the impulse to pass over the deposited material.
[3] See Ballinger et al. 1/88.
[4] Plutonium oxidation rate - use value in Table 4.2-2 (Stewart 1963) or 0.2 g PuO_2/cm^2 exposed metal surface per minute (Haschke July 1992).

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SUMMARY TABLE

RECOMMENDED AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs), AND RESPIRABLE FRACTIONS (RFs) FOR EVALUATION OF RADIOLOGICAL SOURCE TERMS UNDER ACCIDENT CONDITIONS

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[5] Fraction of brittle solids and aggregates fragmented into particles 10 micrometers AED and less (respirable fraction), PULF, is:

$$PULF = 2E\text{-}4 \times density \times g \times h \times [J/10^7\ g\text{-}cm/s^2]$$

where: 2E-4 = coefficient, cm^3/Joule
density = specimen density, g/cm^3
g = gravitational acceleration, ~960 cm/s^2 at sea level
h = fall distance, cm

[6] Limited to RF in source powder.
[7] PSPILL, see Section 4.4.4.4.3.
[8] Tables from Reg. Guide 3.33 (Spent Commercial Nuclear Fuel solution), 3.34 (uranium) & 3.35 (plutonium) "Radioactivity of Important Nuclides Released From the Criticality Accident ..." also attached to this document (Tables 6-1 through 6.4).
[9] ARF (Airborne Release Fraction) for:
fission product noble gases = 1.0
radioiodines and other radiohalogens that can be generated as vapors by accident conditions = 0.25
salts in liquid evaporated (assume 100 liter for large volume solution excursion) = 5E-4
non-volatile fission products (see Section 6.2.4.3)
[10] RF (Respirable Fraction) for:
noble gases = all the airborne material can be transported downwind and affects the exposure of the population, use 1.0
radioiodine = 1.0 (assume released as vapor)
salts in liquids evaporated during boildown of solution = 1.0
[11] Possible additional thermal stress (burning) from high temperatures generated by explosion.
[12] LPF (LeakPath Factor) is assumed to be 1.0 for noble gases, 1.0 for radioiodine unless functional iodine removal devices are in the facility gaseous effluent exhaust system (use conservative estimate of removal efficiency). For particulate materials generated, if generated indoors and the airborne material from the excursion is released via the facility gaseous effluent exhaust system, use a LPF of 0.001 (filter efficiency of 99.9%) for the 1st stage of HEPA filtration and 0.002 (filter efficiency of 99.8%) for every stage thereafter or a conservative estimate of the transmission factor for other types of high efficiency particulate filtration (e.g., sand filters) in place.
[a] >95% uranium in "Y" solubility class with remainder in "D" solubility class.
[b] 50% uranium in "Y" solubility class and 50% in "D" solubility class.

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FOREWORD

DOE Order 5480.23 (DOE 4-30-92) requires the performance of a safety analysis that develops and evaluates the adequacy of the safety basis for each facility within its scope. The method of analysis, and its presentation in the SAR, must therefore be sufficient to support the assessment that the facility can be operated in a safe manner. Additionally, in accordance with the graded approach, the level of analysis and documentation shall be commensurate with the magnitude of hazards being addressed, the complexity of the facility or systems being relied upon to maintain an acceptable level of risk, and the stage or stages of the facility life cycle for which DOE approval is sought.

Safety analysis revolves around five activities: Hazard Identification; Hazard Classification; Hazard Evaluation; Analysis of Normal Operations; and Quantitative Risk Analysis. Hazard Identification performs two functions:

1. Identification of the hazards and energy sources associated with a facility process.

2. Screening of insignificant hazards or hazards not amenable to analysis from further consideration.

Hazard classification is performed in accordance with DOE Standard 1027-92 (DOE December 1992) and is a function solely of the hazardous material inventory in the facility. It results in the classification of the facility or facility segments in terms of the following hazard categories:

1. Hazard Category 1 Facility - The hazard analysis shows the potential for significant offsite consequences from the airborne release estimated from the facility under postulated accident conditions.

2. Hazard Category 2 Facility - The hazard analysis shows the potential for significant onsite consequences from the airborne release estimated from the facility under postulated accident conditions.

3. Hazard Category 3 Facility - The hazard analysis show the potential for only significant localized consequences as a result of postulated accident conditions.

Hazard Evaluation performs the following functions:

1. Identification of preventative and mitigative features at a facility.

2. Analysis of various conjunctions of hazardous materials and energy sources to determine the potential accident initiators at a facility.

3. Analysis of accident initiators with respect to preventative and mitigative features to qualitatively develop accident scenarios describing what can go wrong at a facility.

4. Estimation of the consequences and frequencies of identified accidents, and a determination of the relative and absolute significance of the accident.

DOE Standard 1027-92 (DOE December 1992) specifies that the techniques and results of preliminary hazard analysis are sufficient for analyzing the accident risk of Hazard Category 3 facilities. For Hazard Category 1 and 2 facilities, however, the Standard allows additional analysis of processes and accidents using a range of analytical techniques that vary in sophistication and applicability to the process being studied. This grading of analysis, based on hazard classification and process type, is an application of the graded approach, which calls for a level of analysis commensurate with the magnitude of the hazard and the complexity of the facility and process.

The analysis of normal operations involves assessing the risks and consequences of routinely exposing workers, the public, and the environment to radioactive, chemical, and other hazards contained within a facility or discharges by the facility.

Quantitative risk analysis (QRA) is the systematic development of numerical estimates of expected consequences and frequencies associated with accident scenarios. QRA is based on mathematical techniques and engineering analysis to fully develop accident sequences in terms of the response of preventative and mitigative features to the initiating event. The decision to apply QRA is based upon the hazard category of the facility or facility segment being analyzed, and the relative and absolute significance of the scenario identified qualitatively during hazard evaluation. Category 3 facilities and segments are not expected to perform QRA. For Category 1 and 2 facilities and segments, scenarios posing a high concern may be analyzed as unique scenarios, while scenarios posing a moderate concern may be analyzed as representative scenarios.

In a QRA, the following items are addressed:

1. Sequence Selection - Accident sequences should be grouped in terms of internally initiated and externally initiated events, and further grouped by accident type (fires, explosions, spills, etc.).

2. Sequence Development - For each accident selected for quantitative analysis, the following activities are needed: Scenario Evolution; Consequence Quantification; and Determination of Likelihood.

Accident scenarios should be presented sequentially, from initiation to termination. Narrative descriptions, supported by analyses explicitly presented or referenced, are recommended. The initial conditions under which the accident occurs are specified and

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justified as being within the scope or normal operations for the facility or operation. The initiating event is identified as the cause of the accident, and represents the first deviation from normal operations in the evolution of the accident. Justification for the credibility and appropriateness of the event as an initiator is provided. Other failures that are a direct result of the initiating event are specified, and a step-by-step sequence of the course of the accident is provided and discussed. Identification is made of all protective and mitigative features, both passive and active, involved in the evolution of the accident. Those features designed or expected to prevent or mitigate the accident, but which are not involved in accident evolution, are identified, and their circumvention by or insignificance to the accident conditions is discussed. For operator actions required to mitigate the consequences of postulated accident, conservative time intervals should be assumed.

Consequence quantification specify the methods(s) of consequence determination. The physical and mathematical models employed in estimating consequences, describing any simplifications, approximations, or modeling assumptions introduced into the analysis are discussed. The facility source term resulting from the impact of the accident-generated conditions upon the materials, equipment and facility addressed are estimated using the five component linear equation discussed below.

DEFENSE PROGRAMS NON-REACTOR NUCLEAR FACILITIES SAFETY SURVEY RECOMMENDED VALUES AND TECHNICAL BASIS FOR AIRBORNE RELEASE FRACTION (ARF) AND RESPIRABLE FRACTION (RF) REVISION NO. 2

INTRODUCTION

As part of a task to estimate the potential downwind consequences for the worst case accidents postulated for nuclear facilities operated by the Department of Energy's Defense Programs, the literature on the airborne release of radioactive materials under accident-generated stresses was reviewed and evaluated and values for the airborne release selected that tended to bound the values that may be released by accident in these types of facilities. The emphasis of the program was on identification and evaluation of the maximum threat to the offsite population and, therefore, the concern was the single event that resulted in the release of the maximum quantity of respirable material. The purpose of this document is to provide reasonable, experimentally based factors of the bounding airborne release fractions (ARFs) and respirable fractions (RFs) that may be emitted from radioactive materials involved in these worst case events in DP fuel cycle facilities. High-energy insertion type events that are of concern for nuclear reactors are not covered by this document nor are some accident conditions peculiar to high-level waste tanks (e.g., response of salt or moist salts to accident-generated conditions). Some responses of materials found in high-level waste vitrification plants to accident stresses are covered (e.g., brittle fracture of glasses due to crush-impact, free-fall spill of liquids and slurries) but others (e.g., behavior of molten salts and glass) are not.

The amount of radionuclide released from a facility to the ambient atmosphere in the respirable fraction [assumed to be 10 micrometers, AED[1] and less], for the purposes of these analyses termed the Building Source Term, is estimated by a five-component linear equation:

$$\text{Building Source Term (BST)} = \text{MAR} \times \text{DR} \times \text{ARF/ARR} \times \text{LPF} \times \text{RF}$$

where: MAR = <u>Material-at-Risk</u> - the amount of radionuclides (in curies of activity for each radionuclide) present in a discrete physical location that is separated from other radionuclide-bearing areas by adequate distance or physical barriers so that the areas do not interact during postulated accident conditions.

DR = <u>Damage Ratio</u> - the fraction of MAR impacted by the accident-generated conditions.

[1] AED = Aerodynamic Equivalent Diameter.

ARF = Airborne Release Fraction - the coefficient used to estimate the amount of a radioactive material that can be suspended in air and available for transport under a specific set of accident conditions.

ARR = Airborne Release Rate - for mechanisms that are continuously acting to suspend radionuclides (e.g., aerodynamic entrainment/resuspension), a release rate is required to estimate the potential airborne release from postulated accident conditions. Generally, the rates are based upon measurements over some extended period to encompass most release situations for a particular mechanism. The rates are average rates for the broad spectrum of situations and, as such, the longest meaningful time unit (1 hour) used to reflect some average conditions. There is evidence (discussed later in the subsection on the aerodynamic entrainment of surface contamination) that in some situations (e.g., 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 rates are relatively uniform, the source is depleted by the removal of particles from the surface by aerodynamic forces and the amount of material airborne decreases with time unless the source is continuously replenished.

LPF = LeakPath Factor - the fraction of the radionuclides in the aerosol transported from the containment. There can be many LPFs for some accident conditions (e.g., the fraction transported from the package, such as a shipping container, to the cell or enclosure; the fraction leaked from the enclosure, cell or glovebox to the operating area around the enclosure or room; the fraction leaked from the room to the building-atmosphere interface).

RF = Respirable Fraction - the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system (commonly assumed to be particles 10 μm AED[2] and less). The definition for AED is given in the footnote below. Other definitions of "respirable particles" have been presented by various groups at different times (ACGIH 1985). The British Medical Research Council adopted a definition in 1952 classifying particles with a terminal velocity equal to that of a 5 micrometer diameter as "respirable dust." The USAEC defined "respirable dust" as insoluble particles that are part of inhaled dust which penetrates to the non-ciliated portions of the gas exchange region, and with a 50% respirable cut-size of 3.5 micrometers AED. The ACGIH is almost identical, differing only in the 2 micrometer fraction allowed. The USEPA defines "inhalable dust" (particles penetrating the upper respiratory airway and entering thorax) with a 50% cut-off at 15

[2] Aerodynamic Equivalent Diameter - the diameter of a sphere of density 1 g/cm^3 that exhibits the same terminal velocity as the particle in question.

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μm AED. The ISO (International Standards Organization - Europe) defines "inhalable dust" as particles entering the nasal or oral passages with a 50% cut-size of 10 micrometers AED. Use of a 10 micrometer AED cut-size for respirable particles is conservative (may be even overly conservative since the mass is a cube function of particle diameter).

Other response characteristics can be used to define particle size -- optical/projected diameter, geometric/linear diameter -- are dependent on the methods used to classify the particles. If the method used is optical/ electron microscopy or spectrometry, the particles are classified by the plane that intercepts the light/electron beam and represent the two-dimensional area intercepting the beam. If the method classifies the particle by physical size such as by sieve, the size classification is termed geometric/linear/least linear diameter (the measurement represents the small dimension of the particle that will pass through the openings in the sieve). If the method used to classify particles uses inertial impaction (cascade impactor) or sedimentation, the values are termed aerodynamic diameter or Stokes diameters. If the classification is performed assuming the particles have a density of 1 g/cm^3, the classification is by AED.

Although the principal emphasis in this document is directed towards the potential downwind hazard to the general population offsite, airborne particles larger than 10 micrometers AED released from the facility may constitute an onsite hazard (direct radiation) and may (if the larger particles are agglomerates that deagglomerate with time or can be subdivided by local conditions) be subject to re-dispersal.

For planned facilities and processes, the MAR is a value representing some reasonable maximum quantity of each radionuclide anticipated for the process or structure being analyzed. For operational facilities and processes, the value is usually derived from data on quantities that have been in the facility and listed in material control records; criticality limits for stations, areas or locations; periodic facility walkdowns; and previous estimates found in SARs or EISs.

The DR is estimated based upon engineering analysis of the response of structural materials and materials-of-construction for containment to the type and level of stress/force generated by the event.

The ARFs are based primarily upon experimentally measured values for the specific material (e.g., plutonium, uranium, mixed FPs) 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 stress represented by the measured ARFs and seek to define the accient conditions to show whether or not the stresses induced by the postulated events are bounded by the experimental parameters.

RFs for particles made airborne under accident-induced stresses are dependent upon a variety of factors such as the bulk density (how well the powder at rest compacts), the presence of moisture, how efficiently the type and level of stress deagglomerates the powder or fragments/subdivides the solid/liquid, how proximity of walls or surfaces on which airborne particles may impact/settle, the efficiency with which the stress suspends the powder/fragments of solid, etc. Data to evaluate these factors individually for all cases was not found in the literature. Measured RF data from the experimental studies are applied where available. Measured experimental data for the RFs are much more limited but are from the same general sources used for the ARFs. In order to keep the RFs at a reasonable rather than an ultra conservative value, the RF associated with the measured bounding ARF was selected rather than the highest value. In general, the highest RF values were found to be associated with the smallest ARFs (see data tables in text for experimental studies quoted) and, used in conjunction with the bounding ARF, resulted in ultraconservative estimates of the respirable fraction released.

The LPF is a calculated value based upon proven relationships between size of the particulate material and the transport by airflow and losses by deposition mechanisms (mainly gravitational settling). Values of LPFs have been recommended by Owczarski (ref?).

Radioactive materials are found in all physical forms - non-condensible gases, vapors (condensible gases), liquids (aqueous solutions, organic liquids, non-Newtonian fluids and slurries) and solids (monoliths, large pieces and powders). ARFs and ARRs for liquids and solids should be specified in terms of both a fraction (e.g., 0.01 = 1E-2 = 1%) or a fraction per time (e.g., 1E-2/hr) and a size distribution [e.g., 0.5 (50%) 10 micrometers Aerodynamic Equivalent Diameter (AED) or 0.5 respirable fraction (RF)]. With an estimate of the Material-at-Risk (MAR) and Damage Ratio (DR), the ARF/ARR is used to estimate the amount of radioactive material at the point of origin available for transport to the building-environment interface (e.g., stack, breach in structure, open doorway). The estimates of ARFs/ARRs applicable to various accident-generated mechanisms for the suspension of radioactive materials are based upon experimental data for specific types and levels of stresses/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 the powder is released into flowing gas in a dispersed fashion. In most cases, extrapolations of the values to encompass levels well beyond those covered in the experiments are not valid.

In most cases, the ARFs/ARRs for conditions bounded by the experimental parameters can be reasonably defined. The applicability of the experimental conditions to those postulated/calculated for various accident scenarios is uncertain. For these reasons, the

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ARF values quoted are only proposed as bounding for the conditions specified and are given with one significant digit.

Similarly, the values for RFs taken from experimental measurements are reasonably well defined. But the RFs are dependent upon the types and levels of stress imposed, the initial state (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 for the experiments were selected to bound the behavior of materials under accident conditions for a specific location or process. There is great uncertainty in applying the data to all materials. Thus, the RFs are an attempt to bound this parameter and are also given with only 1 significant digit.

The information is categorized by the physical form of the material-of-concern (e.g., non-condensible gas, vapor, liquid, solid) and suspension stresses (e.g., aerodynamic entrainment, free-fall spill, etc.). For the purposes of this study, it has been shown that four types of events (two operational, one natural phenomenon, and one operational/structural) may pose significant threats of offsite radiological impact. The types of events of concern are:

fire: generates heat and combustion gases that may destroy/stress the radioactive material and/or the substrate upon which radioactive materials may be deposited, compromise barriers and/or pressurize containers/enclosure that may lead to the airborne release of contained radioactive materials. Mass flux of vapors from the reacting surfaces and convective currents generated provide transport for particulate materials that may be generated.

explosion: generates shock and blast effects with potential for gas flow subsequent to the explosive event that may subdivide/deagglomerate and entrain material. Explosive reactions may result from chemical (e.g., oxidations involving branch-chain products, oxidations of gas-oxidant mixtures) or physical (overpressurization to failure of tanks or vessel, vapor explosions) reactions. Shock waves are supersonic pressure waves (pulses) that can transmit an impulse to materials and the surrounding sturctures resulting in shattering of solid items. Shock waves are a true wave phenomenon and involve little gross motion of propagating medium. The potential for damage from shock waves has been extensively characterized. Walls and other structures may reflect shock waves that may actually cause more damage than the primary shock. Blast effects are typically subsonic and involve material entrained in the gas flow. Blast effects are often more damaging. Blast effects are not subject to the same reflection/amplification phenomena as shock waves because they have significant momentum and inertia. The gas expanding from the explosion zone carries material from the explosion site. If the MAR explodes, the hazardous material will largely be carried by the blast. If the explosion is adjacent to the MARs then blast effects can cause damage above and beyond the initial impulse loading. Some explosive reactions may be followed by chemical reactions, material vaporization, or fires that lead to

substantial gas flows following the explosive event. These gas flows may also entrain material. Deflagrations do not involve shock but can simulate blast effects. Under proper conditions (e.g., confinement, structural features that enhance turbulence), deflagrations can transition to detonations and produce shock waves.

earthquake: generates severe lateral and vertical stresses upon the structure and equipment that may result in failure, breach, or collapse. The response of the materials of construction may dislodge materials-of-concern by vibration, impact of debris, and fragmentation. Seismic forces do not generate gas flow to transport particulate materials generated although flows are generated by falling debris and fires/explosion caused by the seismic event.

other specific facility/process related events: due to the particular characteristics of a given facility, process or facility-process combination, events that may not ordinarily result in the significant airborne release become important. The presence of opening in the exterior walls such as emergency exits that may be adversely impacted by some common events (impact by fork lifts or other transporters used), area of in exterior walls or enclosure more susceptible to damage, use of incompatible chemicals in the area, etc. Use of compressed gases (e.g., air, nitrogen) in some enclosures or vessels can result in the suspension of large fractions of exposed powder or liquids if the flow is directed on the surface and, if the gas cannot be adequately exhausted, can pressurize the enclosure or vessel.

The information presented here is directed toward evaluation of the radiological consequences of these events and the suspension phenomena that they generate.

Application of Data

Before the ARFs/ARRs 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 document. Many standard methods are applicable (e.g., the rupture pressure of tanks and piping based upon the material of construction, the thickness, the temperature and pressure). But in other cases (e.g., the blast energy for the fragmentation of solids and liquids as a result of the deflagration of flammable gas and oxidant mixtures in the free volume above the materials), standard engineering calculational methods are not available and interpretation of information and data (e.g., the heat of combustion from the reactants under the conditions specified and the fraction of the heat of combustion transferred by pressure impulse from the resulting deflagration) is required.

Once the forces and conditions imposed upon the material for dispersion/ fragmentation, suspension and transport are identified, the ARF/ARR and RF applicable can be selected. In most cases, precise correspondence between the event conditions and experimental conditions during the measurement of the ARFs/ARRs and RFs is not found.

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Interpretation of the information is required. For conservative, bounding analysis, the data are applicable if the measurement conditions exceed those calculated for the event (e.g., if the fall distances for spilled powders or liquids with characteristics like the materials used in the experiments are equal to or less than 3 m). If desired, the ARF/ARR can be reduced by interpolation (maintaining the slope of the experimental data) for conditions less than the maximum applied in the experimental studies providing the data on which the bounding ARF/ARR truly reflects the phenomena (e.g., the size of the drops formed by commercial spray nozzles for orifice diameters for pressure differentials greater than found in accidents is used to bound airborne materials from liquids sprays formed under accident conditions). If the conditions estimated for the event exceed the conditions imposed during the experimental study (e.g., smaller orifice diameters or greater pressure differential for sprays), extrapolation of the ARF or ARR/RF is not valid (data for the smaller orifice diameters or higher differential pressures should be obtained).

In most cases, extrapolation beyond the experimental data is valid for a limited range beyond the maximum (a factor of 2 to 5 dependent on the slope of the experimental data and the range of conditions covered in the experimental study) imposed in the experimental study. Models are available for the calculation of ARFs/ARRs and RFs for some phenomena (e.g., free fall spill of powders and liquids - Ballinger et. al., January 1988; PULF formula for fragmentation by brittle fracture, SAND September 1987).

LIST OF ACRONYMS

AED	Aerodynamic Equivalent Diameter: the diameter of a sphere of density 1 g/cm^3 that exhibits the same terminal velocity as the particle in question.
AMAD	Activity Median Aerodynamic Diameter: the diameter of the particle for which half the activity is associated with particle larger than and half the activity associated with particle smaller than this size particle.
AMMD	Aerodynamic Mass Median Diameter: the aerodynamic diameter of the particle for which half the mass is associated with particles is greater than and half the mass the mass is associated with particle less than the stated size.
ARF	Airborne Release Fraction: the coefficient used to estimate the amount of a radioactive material that can be suspended in air and made available for transport under a specific set of accident conditions.
ARR	Airborne Release Rate: the coefficient used to estimate the amount of material that can be suspended in air by the aerodynamic forces and made available for transport from material on the surface as a function of time. The rates are long-term averages representing materials suspended from a variety of conditions imposed upon the materials on the surfaces.
"D"	Class Uranium: uranium forms that have a dissolution halftime in simulated interstitial lung fluid of one day or less.
DR	Damage Ratio: the fraction of MAR impacted by the accident-generated conditions under evaluation.
FPs	Fission Products.
LLD	Least Linear Diameter: the size distributions determined by sieving. The fractions are categorized by the particles that can pass through the openings of a sieve and, if not spherical, represent the small dimension of that particle.
LPF	LeakPath Factor: the fraction of airborne materials transported from containment or confinement by the existing flow via the pathway configuration under evaluation.
"M"	Class Uranium: uranium forms that have a dissolution halftime in simulated interstitial lung fluid from 10 to 100 days.

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MAR	Material-at-Risk: the amount of radioactive materials (in curies of activity for each radionuclide present/being evaluated) present in a discrete physical location that is separated from other radionuclide-bearing areas by adequate distances or physical barriers so that the areas do not interact during postulated accident conditions.
MMD	Mass Median Diameter: the geometric diameter of the particle for which half the mass is associated with particles greater and half the mass associated with particles less than the stated size.
MR	Mass Ratio: the ratio of explosive energy (in terms of mass TNT Equivalent) to the mass of inert material impacted.
PSPILL	Powder Spill Computer Code: See Subsection 4.4.4.4.3.
PULF	Pulverization Fragments Calculation: See Subsection 4.3.4.
RF	Respirable Fraction: the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system (commonly assumed to be particles 10 μm AED and less).
"W"	Class Uranium: uranium forms that have a dissolution halftime in simulated interstitial lung fluid of between 1 and 10 days.
"Y"	Class Uranium: uranium forms that have a dissolution halftime in simulated interstitial lung fluid of greater than 100 days.

AIRBORNE RELEASE FRACTIONS (ARFs), AIRBORNE RELEASE RATES (ARRs) AND RESPIRABLE FRACTIONS (RFs)

1.0 NON-CONDENSIBLE GASES

1.1 SUMMARY

- Loss of Physical Containment. For non-condensible gases, the recommended ARF is 1.0. A value for RF is not applicable.

1.2 DISCUSSION

In DOE DP fuel cycle facilities, radionuclides in the form of non-condensible gases are only found under a few circumstances: as stored spent fuel, generated by physical or chemical reaction, and generated by inadevertent criticalities (see Chapter 6). The radiological impact of many of the non-condensible gases is limited by their lack of retention in the human body. Table 1-1 list the characteristics of some of the radionuclides commonly found in fuel cycle facilities. The information on Derived Concentrations Guides (DCGs) [values derived from the Annual Limit of Intake (ALI) that defines the amount of activity of that nuclide that a worker may be exposed to without significant damage] are taken from DOE Order 5400.5 (DOE 2-8-90). The last column shows the ratio between the DCG for the radionuclide compared to the DCG for ^{239}Pu (W class) and is an indication of the relative impact of the radionuclides. The noble gases (krypton, xenon) are not taken into the body and only expose the individual to a immersion dose during the passage of the cloud of gases. Their impact is from 5 to 10 orders of magnitude less than for the same level of activity of ^{239}Pu or other actinides as particles in the respirable size fraction. The impact of other non-condensible gases such as tritium (hydrogen) or carbon mon- or di-oxide is in the same range. Due to the limited exposure of most spent fuel at DP facilities and the long cooling times, the amount of non-condensible gases present in spent fuel is also very limited. The accident conditions ex-reactor also limit most scenarios to physical rupture of the clad that only affects the gaseous materials available on the surface of the fuel.

Table 1-1. Relative Offsite Impacts from Airborne Release of Various Radionuclides (DOE 5400.5, 2-8-90, Chapter III)

Radionuclide[1]	Halflife[2]	DCG, μCi/ml[3]	x:^{239}Pu[4]
H-3$_{water}$	12.2y	1.0E-7 (inhal, w)	5.0E+6
elemental		2.0E-2 (inhal, w)	1.0E+12
C-14$_{org}$	5730 y	6.0E-9 (inhal, w)	3.0E+5
CO		4.0E-6 (inhal, d)	2.0E+8
CO2		5.0E-7 (inhal, d)	2.5E+7

Table 1-1. Relative Offsite Impacts from Airborne Release of Various Radionuclides (DOE 5400.5, 2-8-90, Chapter III) [cont.]

Radionuclide[1]	Halflife[2]	DCG, μCi/ml[3]	x:^{239}Pu[4]
Kr-83m	1.8 h	2.0E-4 (immersion)	1.5E+8
-85m	4.5 h	1.0E-7 (immersion)	5.0E+6
-85	10.7 y	3.0E-6 (immersion)	1.5E+8
-87	76.3 m	2.0E-8 (immersion)	1.0E+6
-88	2.8 h	9.0E-9 (immersion)	4.5E+5
-89	3.2 m	1.0E-8 (immersion)	5.0E+5
Sr-89	52 d	2.0E-9 (inhal, d)	1.0E+5
-90	28.1 y	5.0E-11 (inhal, d)	2.5E+3
Y-90m	3.1 h	3.0E-8 (inhal, w)	1.5E+6
-90	64 h	2.0E-9 (inhal, w)	1.0E+5
-91m	50 m	6.0E-7 (inhal, w)	3.0E+7
-91	58.5 d	4.0E-10 (inhal, w)	2.0E+4
Zr-95	65 d	6.0E-10 (inhal, d)	3.0E+4
Nb-95	35.2 d	3.0E-9 (inhal, w)	2.0E+5
Tc-99	2.12E+5 y	1.0E-8 (inhal, d)	5.0E+5
Ru-103	39.6 d	4.0E-9 (inhal, d)	2.0E+5
-106	367 d	2.0E-10 (inhal, d)	1.0E+4
Rh-103m		3.0E-6 (inhal, d)	1.5E+8
-106m	130 m	6.0E-8 (inhal, d)	3.0E+6
I-129	1.7E+7 y	7.0E-11 (inhal, d)	3.5E+3
-131	8.0 d	4.0E-10 (inhal, d)	2.0E+4
-132	2.3 h	4.0E-8 (inhal, d)	2.0E+6
-133	20.8 h	2.0E-9 (inhal, d)	1.0E+5
-134	52.6 m	1.0E-7 (inhal, d)	5.0E+6
-135	6.6 m	1.0E-8 (inhal, d)	5.0E+5
Xe-131m	11.9 d	2.0E-6 (immersion)	1.0E+8
-133m	2.0 d	6.0E-7 (immersion)	3.0E+7
-133	5.2 d	5.0E-7 (immersion)	2.5E+7
-135m	15.6 m	5.0E-8 (immersion)	2.5E+6
-135	9.1 h	8.0E-8 (immersion)	4.0E+6
-137	3.8 m	9.0E-8 (immersion)	4.5E+5
-138	14.2 m	2.0E-8 (immersion)	1.0E+6
Ce-141	33 d	2.0E-9 (inhal, w)	1.0E+5
-144	284 d	6.0E-11 (inhal, w)	3.0E+3
Pr-144	13.3 m	3.0E-7 (inhal, w)	1.5E+7

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Table 1-1. Relative Offsite Impacts from Airborne Release of Various Radionuclides (DOE 5400.5, 2-8-90, Chapter III) [cont.]

Radionuclide[1]	Halflife[2]	DCG, μCi/ml[3]	x:^{239}Pu[4]
Cs-137	30.2 y	4.0E-10 (inhal, d)	2.0E+4
Pm-147	2.5 y	5.0E-10 (inhal, w)	2.5E+4
U-234	2.47E+5 y	4.0E-12 (inhal, d)	200
-235	7.1E+8 y	5.0E-12 (inhal, d)	250
-236	2.39E-7 y(?)	5.0E-12 (inhal, d)	250
-237	6.75 d	6.0E-9 (inhal, d)	3.0E+5
-238	4.51E+9 y	5.0E-12 (inhal, d)	250
-239	23.5 m	4.0E-7 (inhal, d)	2.0E+7
-natural		5.0E-12 (inhal, d)	250
Np-239	2.35 d	5.0E-9 (inhal, w)	2.5E+5
Pu-238	86 y	3.0E-14 (inhal, w)	1.5
-239	24400 y	2.0E-14 (inhal, w)	1
-240	6580 y	2.0E-14 (inhal, w)	1
-241	13.2 y	1.0E-12 (inhal, w)	50
-242	3.79E+5 y	2.0E-14 (inhal, w)	1
-243	4.98 h	8.0E-8 (inhal, w)	4.0E+6
-244	8E+7 y	2.0E-14 (inhal, w)	1
Am-241	458 y	2.0E-14 (inhal, w)	1

1 Radionuclide = specific radionuclide
2 Halflife = duration over which 1/2 of activity present will radioactively decay.
3 DCG = Derived Concentration Guide from DOE 5400.5 2-8-90 as μCi/ml (exposure pathway - inhal = inhalation; immersion). Clearance Class DCG based upon - d = day [clearance halftime < 1 day]; w = week [clearance halftime 1-10 days]; y = year [clearance halftime of > 100 d].
4 x:^{239}Pu = ratio of DCG for radionuclide compared to DCG for ^{239}Pu, curies ... an indication of the number of curies of the radionuclide that must be released to have the same offsite radiological impact of releasing 1 curie of ^{239}Pu.

In some cases, physical (e.g., metal-water) and chemical (e.g., acid-base) reactions may generate hydrogen gas containing traces of tritium or tritiated water vapor. Neither tritium nor tritiated water is a significant hazard (in many cases, the impact of tritium is considered to be considerably higher than indicated in Table 1-1) compared to the actinides. Hydrogen generation itself is of concern due to the potential explosion hazard from hydrogen-air mixtures.

Most radionuclides in the form of non-condensible gases are stored/held under pressure and physical constraints (e.g., tritium and noble gases in spent fuel held in the fuel matrix and cladding, cylinders of gases used in the laboratory). Non-condensible gases

generated during nuclear criticalities in solutions are the exception and their behavior under those circumstances is covered in Chapter 6. In either case, essentially all the gas is considered released upon the loss of gas-tight physical constraint. For very large containers (e.g., relatively gas-tight metal vessels) that are breached but maintain their physical integrity (e.g., compromised by loss of piping), the fraction of gas overpressure may be considered instantaneously released (e.g., for a gas initially at 2 atmospheres absolute/1 atmosphere gage, 5E-1 of the gas may be considered instantaneously released with the remainder lost with time due to diffusion, Bernoulli's effect, thermal expansion, etc.). In essence, in most cases, a value to 1E+0 is recommended.

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2.0 VAPORS (CONDENSIBLE GAS)

2.1 SUMMARY

- For generation of vapors plus release from physical containment, a recommended ARF is 1.0. A value for RF is not applicable.

2.2 DISCUSSION

Vapors (materials in gaseous form due to local conditions) may result from two phenomena: chemical reaction and temperature. Some vapors result from chemical reactions that generate a volatile compound (e.g., halogens in a reducing, acidic environment). Other vapors can be generated when the local temperature exceeds the boiling point of the element or compound (e.g., evaporation of water). Under most conditions, the ARF (the fraction of vapor formed initially airborne) assumed for vapors is 1.0. If the local conditions are not adequate for quantitative vaporization of all the material (e.g., inadequate chemical reactants, inadequate temperature), the ARF is the fraction of the material converted to vapor form. The release of vapors generated during inadvertent nuclear criticalities is covered in Chapter 6.

Loss for chemically reactive materials is difficult to quantify due to the uncertainty of the materials encountered along the pathway, the kinetics of these reactions, and the transport of the vapors to the surfaces. A conservative value is to assume all the material released is transported to the facility/environment interface without loss unless engineered emission control devices (e.g., for radioiodine - impregnated charcoal filters, silver substituted zeolite filters, silver nitrate coated ceramic saddles; HEPA or other filtration devices for condensed vapors or vapors adsorbed onto pre-exisitng particles) are present for removal of the specific material. In many cases, an assumption of complete transport of the airborne material without significant loss is very conservative but transport losses must be substantiated for the specific configuration under the worst case assumption for the event.

Many chemically volatile compounds are reactive and can be lost in transit by reaction with materials found along its path to the facility/environment interface or adsorption on pre-existing airborne particles. Temperature sensitive materials can condense homogeneously (particles formed directly from the vapor have been observed to be in the sub-micrometer diameter range) or on pre-existing particles. Aerosols form rapidly since entrainment of cooler air invariably accompanies the formation process. Various natural processes act to attenuate transport of particles (e.g., agglomeration, gravitational settling, turbulent diffusion) and filtration or other engineered devices such as water sprays have varying removal efficiencies for particles.

For temperature-sensitive vapors (e.g., metal vapors generated at high temperatures, tritiated water vapors), the amount of material volatilized can be estimated by the amount of

heat energy present and/or generated by the event. Similarly, condensation may also be calculated by heat transfer at the surfaces or by homo-or heterogenous condensation in air. Parenthetically, the mass flux of vapors to cool surface (diffusiophoresis) can be an effective mechanism to sweep small diameter (submicrometer) particles from the air.

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3.0 LIQUIDS

In order for a liquid to be made airborne, in most realistic situations, the bulk liquid must be subdivided into particles/droplets small enough to be entrained in the local airflow. In some cases, it may be possible for the activity coefficient for the solute to be adequately reduced that some material may be made airborne by vaporization.

This section describes mechanisms by which two types of liquids (aqueous solutions and organic, combustible solvents) become airborne; the descriptions are based on experiments. The mechanisms include thermal stress, explosive release, venting of pressurized liquids, free-fall spills, and aerodynamic entrainment (resuspension).

3.1 SUMMARY OF RECOMMENDED BOUNDING ARFS/ARRS AND RFS

Aqueous Solutions

Thermal Stress

- Heating of aqueous solution in flowing air without surface rupture of bubbles. For the airborne release of bulk liquid during heating of aqueous solutions in flowing air without noticeable bubbles breaking on the surface of the bulk liquid, conservative values are based upon the experimental data available

Median	ARF 3E-5/RF 1.0
Bounding	ARF 6E-7/RF 1.0.

- Boiling (continuous surface breaking of bubble of the bulk liquid with <30% of the volume of the liquid as bubbles) of aqueous solutions in flowing air. A bounding ARF for the airborne release from the bubble-burst at the surface for aqueous solutions exceeds all measured values. In the absence of a measured size distribution for the airborne droplets, a conservative value of is assumed for the RF bound. Median ARF values were measured from experiments with boiling aqueous solutions

Median	ARF 2E-3/RF 1.0
Bounding	ARF 1E-3/RF 1.0.

Explosive Release

- Shock Effects. For detonations or deflagrations in or contiguous to a pool of aqueous liquid, a bounding ARF of the mass of inert material airborne equal to the calculated TNT Equivalent with an RF of 1.0 is recommended.

- Blast Effects. For detonations and deflagration at a distance where the pressure impulse is essentially equal to a flow parallel to the surface of the

liquid, an ARF of 4E-3/hour (1E-6/second) for the time the pressure pulse is over the liquid and an RF of 1.0 are conservatively assumed.

Venting of Pressurized Liquids

- Depressurization of free volume above liquid surface, below boiling point of the liquid. Bounding ARF/RF for this situation are the same as for the release during the boiling of an aqueous solution because the droplet formation mechanism is the same. Lesser values may be applicable for a concentrated heavy metal nitrate solution such as uranium nitrate hexahydrate or UNH. The average values are 5E-4/0.9 for solutions and 3E-4/0.5 for concentrated heavy metal salt solutions.

Median (aqueous solution)	ARF 3E-4/RF 0.9
Median (conc. heavy metal solution)	ARF 2E-4/RF 0.3
Bounding (aqueous solution)	ARF 2E-3/RF 1.0
Bounding (conc. heavy metal solution)	ARF 1E-3/RF 0.4.

- Depressurization of liquid via a breach under the liquid surface level, below boiling point. Bounding ARF/RF are estimated using the mass fraction of droplets 10 micrometers and less in diameter formed by commercial spray nozzles (device designed to produce small drops) under conditions that will exceed those anticipated for most accident situation (3.25-mm diameter orifice at 200 psig upstream pressure).

Bounding	ARF 1E-4/RF 1.0

- Venting of superheated aqueous solutions, >30°C over bp solvent or liquid. For superheats less than 100°C above the boiling point of the liquid (<240 psig pressure), the bounding ARF/RF are 1E-1/0.7. The ARF appears to increase with decreasing source size and the volumes. The values used in the experiments for these parameters are much below those anticipated under most accident situation (100 ml). The average ARF/RF values are 4E-2/0.7.

Median	ARF 2E-2/RF 0.7
Bounding	ARF 1E-1/RF 0.7.

Free-Fall Spill

- Free-fall spill of aqueous solutions, 3-m fall distance. The recommended bounding values for free-fall spills of aqueous solutions equal to or less than 3 m are 2E-4/0.7 for aqueous solutions with values of 2E-5/0.3 for concentrated solutions of heavy metal salts. The median values for the two types of aqueous solution are 4E-5/0.7 and 1E-6/0.3, respectively.

Median (aqueous solutions)	ARF 4E-5/RF 0.7

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Median (conc. heavy metal solutions)	ARF 1E-6/RF 0.3
Bounding (aqueous solutions)	ARF 2E-4/RF 0.7
Bounding (conc. heavy metal solutions)	ARF 2E-5/RF 0.3.

- Free-fall spills of slurries, 3-m fall distance, <40% solids.

Median	ARF 2E-05/RF 0.7
Bounding	ARF 5E-5/RF 0.8.

- Free-fall spills of viscous solutions, viscosity >8 centipoise. The bounding ARF is consistent with the bounding ARF measured for heavy metal solutions airborne from free-fall spill of equal distance.

Median	ARF 6E-6/RF 0.8
Bounding	ARF 3E-5/RF 0.7.

- Free-fall spills of aqueous solutions, slurries and viscous solutions, fall distances >3 m. The empirical correlations for ARF and drop size distribution parameter presented by Ballinger et al. (January 1988) are recommended.

Aerodynamic Entrainment (Resuspension)

There appear to be very large differences in suspension rates under the experimental test condition as well as an order of magnitude uncertainty in measurements for individual conditions. On this basis, conservative values are applied.

- Indoors, on heterogeneous surface (stainless steel, concrete), low airspeeds
  Bounding — ARR 4E-7/hr; RF 1.0.

- Indoors, on heterogeneous surfaces, covered with debris or under static conditions
  Bounding — ARR 4E-8/hr; RF 1.0.

- Outdoors, from large pools/ponds, windspeeds to 30 mph
  Bounding — ARR 4E-6/hr; RF 1.0.

High wind

- Outdoors, on soil, windspeeds to 50 mph
  Bounding — ARR 9E-5/hr; RF 1.0.

High wind

Use of the factors for short time frames (<100 hours) would not introduce serious error due to the severe depletion of the source. For time period exceeding 100 hours, the reduction of the source must be accounted for from the entrainment of material.

$9E\text{-}5 * \frac{(70^2)}{(50^2)}$

Organic Combustible Liquids

Thermal Stress

- Volatiles under all conditions
  - Bounding 1.0, 1.0
- Indoors, quiescent burning small surface area pools
  - Median 6E-3, 1.0
  - Bounding 1E-2, 1.0
- Indoors, vigorous burning large pools
  - Bounding 3E-2, 1.0
- Indoors, burning solvent over aqueous phase
  - Median 1E-2, 1.0
  - Bounding 1E-1, 1.0
- Outdoors, aqueous solution or air-dried salts under gasoline fire
  - Bounding 5E-3, 0.4
- Outdoors, aqueous solution or air-dried salt under gasoline fire on heat conducting surface
  - Bounding 2E-1, 0.3.

No experimental data on the behavior of organic, combustible liquids in reponse to explosive release, venting of pressurized liquid, free-fall spills, or aerodynamic entrainment was found. Refer to the discussion preceding summary for aqueous solutions.

3.2 AQUEOUS SOLUTIONS

3.2.1 Thermal Stress: Evaporation and Boiling

Under most realistic scenarios involving the heating of aqueous solutions during postulated accidents in DP fuel cycle facilities, the relative vapor pressures of the solvent (water) and the solute (various compounds of radionuclides, generally acidic nitrate) preclude evaporation of the solute as a viable mechanism for the airborne release of the solute. Instead, the airborne release is postulated to result from the entrainment of minute drops of the bulk liquid formed by the mechanical disintegration of the surface of the bulk liquid. Mechanical disintegration mechanisms include bubble breakup during boiling, jet drops formed from the collapse of the crater remaining after bubble breakup, and secondary drops from the reentry of jet drops. Drops are carried to the bulk flow by convective and vapor

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flow away from the heated liquid. An increase in surface disruption would increase the airborne release, although capture of secondary drops by the large number of primary particles may place a limit on the release.

Kataoka and Ishii (April 1983) reviewed the literature and data on the entrainment of liquid droplets from the surface of a bubbling or boiling pool. Droplets are generated by bubble bursting, splashing or foaming. Some of the entrained droplets fall back into the pool and some are carried away by the streaming gas. Entrainment, E_{fg}, is defined as:

$$E_{fg} = \text{droplet upward mass flux } (\rho_f j_{fe}) / \text{ the gas mass flux } (\rho_g j_g)$$

where:
ρ_f = density of fluid;
j_{fe} = superficial velocity of liquid flowing upward as droplets;
ρ_g = density gas; and,
j_g = superficial gas velocity.

Two levels of the gas flow through the liquid upon the surface were noted:

1. bubbly flow (condition postulated for DP fuel cycle facility accidents): small gas flow (<0.1 m/s); droplets generated by discrete bubbles rising to surface of pool and collapsing; initial velocity of entrained droplets is a function of bubble burst time, bubble diameter, density of liquid and pressure around bubble; transition to next level at ~0.1 m/s and liquid void fraction 0.3.

2. churn turbulent flow: may be dominant mechanism (for post-LOCA LWR accident conditions); initial velocity of droplets determined by momentum exchange mechanism (during breakup of liquid ligaments formed from surface disruption); droplets generated by all three droplet generation mechanisms (i.e., bubble bursting, splashing, or foaming).

Three regions as a function of axial distance from the pool surface were identified:

1. near-surface region: immediate vicinity of surface; entrainment dependent on height and gas velocity; entrainment consists of all droplets entrained.

2. momentum-controlled region: intermediate axial distances above pool surface; entrainment consists partly of droplets with initial momentum to reach height and partly of droplets whose terminal velocity are equal to or less than the superificial gas velocity; three regimes as a function of superficial gas velocity in region:

- low gas flux: entrainment small and consists of very fine droplets; E_{fg} approximately proportional to gas flux.

- intermediate gas flux: larger drops ejected from pool; E_{fg} increases with the 3rd or 4th power of the superificial gas velocity.

- high gas flux: large gas slugs form and pool surface highly agitated; considerable droplets formed by splashing; E_{fg} increases with the 7th to 20th power of the superficial gas velocity.

3. deposition controlled region: entrained droplets of size whose terminal velocity is equal to or less than the superficial gas velocity.

A simple mechanistic model was developed based on the concepts presented above. Due to the enormous number of droplets generated, the motion of individual droplets could not be followed individually, and so droplet motion was handled statistically. Important physical parameters and distribution functions essential to the modeling and calculations were developed or assumed. Correlations for the height criteria and entrainment in each region were developed as a function of:

dimensionless gas velocity, $j_g^* = \sim j_g/[\sigma\ g\ \delta_g/\rho_g^2]^{1/4}$

dimensionless height above surface, $h^* = h/[\sigma/g\ \delta_\rho]^{1/2}$

gas viscosity number, $N_{mug} = mu_g/[\rho_g\ \sigma\ (\sigma/g\ \delta_\rho)^{1/2}]^{1/2}$

dimensionless vessel diameter, $D^*_H = D_H/\ [\sigma/g\ \delta_\rho]^{1/2}$

density ratio $= \rho_g/\delta_\rho$

σ = liquid surface tension.

All correlations agreed well with the published data and could be applied to estimate ARF for specific scenarios. The correlations are relatively straightforward although the values depend upon parameters that are not readily quantifiable for many practical situations and vary with temperature. Methods to determine the temperature to be used or the values for the parameters as a function of temperature were not presented. Use of the correlations for this study would require the definition of a range of accident scenarios (not done as of this time) to determine a bounding ARF/RF. The results indicate that large variations may be observed in measured data dependent upon the location and configuration of the sampling system.

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Some important observations, based upon the review of literature of entrainment of liquid droplets from bubbling or boiling pools performed by Borkowski, Bunz and Schoeck (May 1986), are:

1. the influence of surface effects on the amount and composition of the generated aerosols.

2. the possibility of chemical enrichment and depletion of substances in aerosols.

3. the existence of two groups of droplets with different mean sizes and amounts of airborne mass.

4. the limited range of ejected jet droplets due to initial velocity.

Droplet formation during boiling is dependent upon conditions of boiling and bubble characteristics. There appear to be at least two and possibly three boiling regimes that affect bubble and droplet formation. The first regime occurs at lower rates where the volume fraction of the bubbles is less than 30%, when discrete bubbles rise through the liquid and grow due to decreasing hydrostatic head. Bubbles may coalesce or divide during ascent. Droplets are formed from three mechanisms (bubble film disintegration, jet drops from crater collapse, and secondary droplets from jet drop reentry into bulk liquid). This regime is the predominant concern for fuel cycle accident situations. A second regime occurs at higher boiling rates; the liquid is turbulently mixed and progressively disintegrates at the surface forming drops from both mechanisms. A possible third regime occurs at very high boiling rates when splashing and foaming dominate the surface (Borkowski, Bunz and Sheock May 1986).

Gas flow conditions and material characteristics are important parameters in bubble-induced droplet formation. Bubble size determines the number and size of the droplets formed. Bubble size is determined by the volume of vapor, surface characteristics such as surface tension, and bubble contact angle. Contact angle changes due to local turbulence during bubble formation resulting in a distribution of bubble sizes. Many bubbles are unstable and coalesce and break up during ascent. Steam bubbles are in the range of 0.5 to 5 cm diameter at low pressure and nucleate boiling (presence of rough surface, suspended particles). The formation and detachment of macro-bubbles is a function of contact angle of the liquid and the degree of superheat. Bubble shape at the surface may range from spherical to hemispherical depending on size. The liquid in the dome of the bubble runs down the sides and thins the film. The bubble bursts when the internal pressure exceeds the external pressure and surface tension of the film. Droplets are formed by the film breakup. The crater remaining from the bubble rupture itself collapses forming an ascending liquid jet that decays into droplets after some critical length. Jets ascend up to 20 cm from the surface of the bulk liquid. Jet drops are only formed from bubbles <5 to 6 mm diameter. Droplets

from film breakup are only formed for bubbles >0.2 mm in diameter. Therefore, by inference, only jet drops are formed from bubbles <0.2 mm in diameter and only film breakup droplets are formed from bubbles >6 mm in diameter. The number and size distribution of droplets formed from film breakup correlates with the size of the bubble and may number into the hundreds for the upper limit of bubble diameter. Figure 3-1, taken from the reference document, shows a number distribution from the burst of two bubbles of 0.1% NaCl in water. Only one jet drop ejected from collapse of a bubble ~2-mm diameter with up to 6 ejected from very small diameter bubbles (high internal pressure). The diameter of the drop is ~20% of the bubble diameter (100 to 1000 micrometers for the conditions covered here) (Borkowski, Bunz and Shoeck May 1986).

3.2.1.1 Airborne Release During Heating of Shallow Pools of Liquid

The airborne release during heating of aqueous solution was measured and reported by Mishima, Schwendiman and Radasch (November 1968). This study involved the collection and measurement of airborne Pu during drying of shallow pools of concentrated acidic plutonium nitrate solution at three air velocities and the evaporation of 90% of the volume of a dilute acidic plutonium nitrate solution. Table 3-1 displays measurements extracted from the study reference document (see Table A.1 in Appendix A) and shows the ARFs from evaporation of concentrated plutonium nitrate solutions under three air velocities (0.1, 0.5, and 1.0 m/s). A schematic diagram of the apparatus is shown in Figure A.1 (Appendix A). Approximately 2.5 to 3 ml of a concentrated $Pu(NO_3)_4$ solution containing from 0.72 to 0.86 g Pu were placed in a shallow depression (~25.4-mm diameter x ~2.4-mm deep) in a 31.8-mm diameter x 6.35-mm deep stainless steel dish. The dish was placed in a teflon retainer that filled half of the diameter of a 38.1-mm diameter borosilicate glass tube. Filtered room air was drawn through the tube at three nominal velocities (0.1, 0.5, and 1.0 m/s) over the solution and through a water-cooled condenser to remove excess moisture; the airborne particles were then collected on an in-line glass fiber filter. The liquids were heated to various temperatures by heat lamps positioned over the liquid. The evaporation times ranged from 1.5 to 24 hours. None of the solutions were observed to boil during any of the experiments and the airborne release is most probably due to the aerodynamic breakup of the surface with the increase with temperature due to reduced surface tension. The airborne fractional releases measured are shown in Table 3-1; ARFs range from <1E-8 to 3E-5. The highest ARFs were measured at the highest temperature (1E-5 and 3E-5 at 100°C). The limited data also tend to indicate some increase in airborne release with increasing air velocity. The surfaces during the drying were relatively undisturbed (no visible surface disturbance). The upper bound release is 3E-5, and, in as much as the size distribution of the airborne materials was not measured, a conservative value for the RF of 1.0 is selected. The median value is 6E-7 (5.5E-7 rounded upward) with an average value of 7E-6.

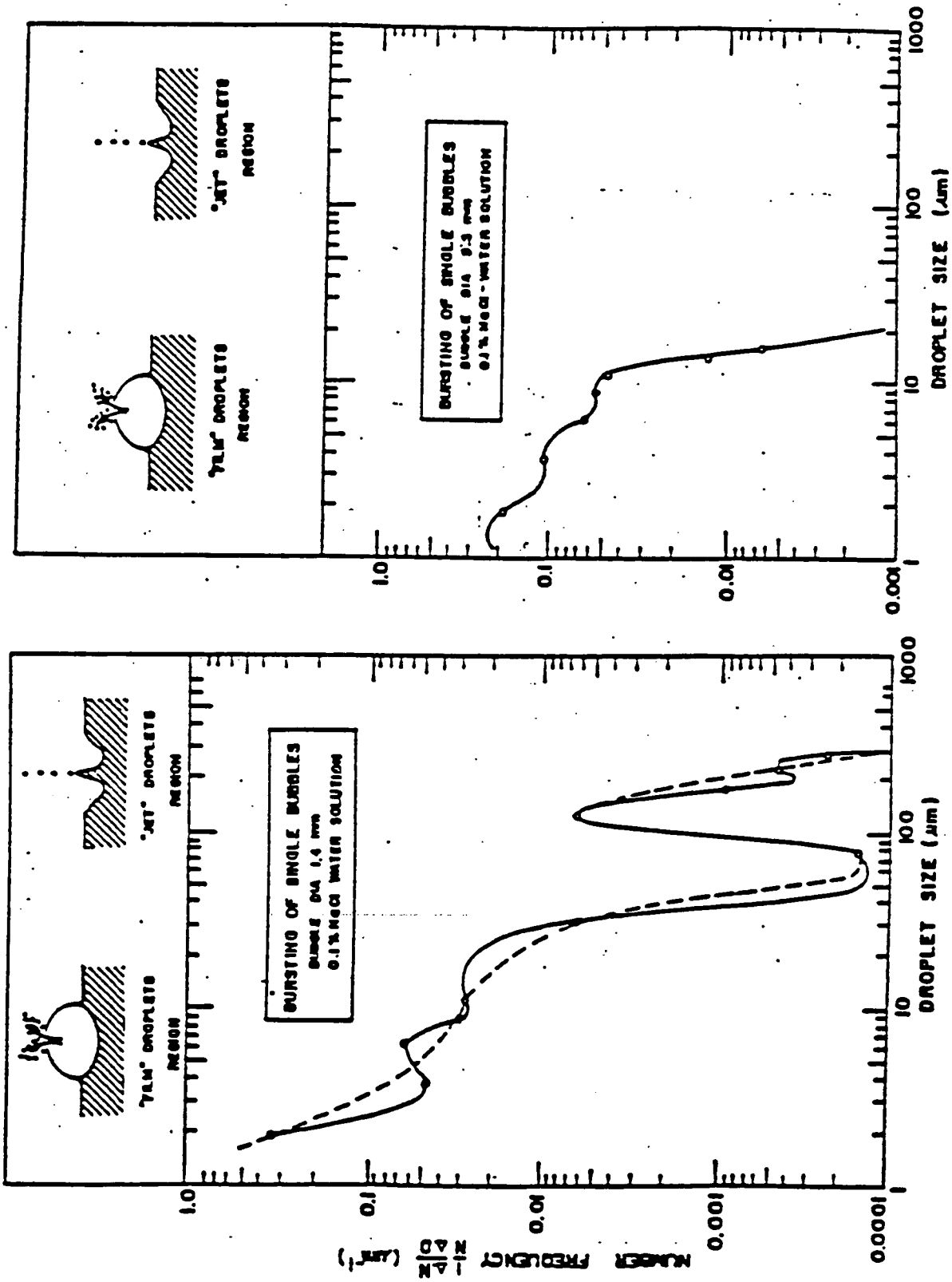

Figure 3-1. Size Distribution of Bubble Induced Droplets (Borkowski, Lunz, and Schock undated)

Table 3-1. Fractional Airborne Releases During the Heating with Flowing Air of Concentrated Plutonium Nitrate Solution (Table 1 from Mishima, Schwendiman, and Radasch, November 1968)

Temp, °C	Air Velocity, m/s	Sampling Time, hr	ARF
50	1.0	2	1.3E-7
75	0.5	5	<1.0E-8
90	0.5	2	5.3E-7
90	1.0	1.5	5.7E-7
100	0.1	2	1.0E-5
100	0.5	2	3.0E-5

The data are limited but do appear to consistently indicate a gradual increase in airborne release with temperature until boiling or near boiling temperatures. The air velocity range is very limited although the air velocity probably represents a much greater aerodynamic stress on the surface than the nominal velocity indicates (air velocity measurements are usually at much greater distances from the surface than in the experimental apparatus, and, air being a fluid, the velocity decreases with distance from the surface due to frictional forces). The concentrated plutonium nitrate solution used represents a very important class of liquids found in DOE facilities but its fluid characteristics (higher density, surface tension) may not make it bounding for other aqueous solutions.

3.2.1.2 Airborne Release During the Heating of Pools of Liquids

ARFs were also measured during the evaporation of 90% of the volume of aqueous solutions at three surface disturbance levels: simmering, disturbed surface, and boiling (Mishima, Schwendiman and Radasch November 1968). The results and experimental apparatus from the source document are shown in Table A.2 and Figure A.2, respectively, in Appendix A. In the experiments, 100 ml of a dilute $Pu(NO_3)_4$ solution (0.25 M HNO_3) containing 0.7 mg Pu was placed in a 180 ml borosilicate beaker. The surface area of the liquid was 11.5 cm^2. The beaker was held in the center of a transite support ring that positioned the beaker in a aluminum plate set upon a hot plate. A screen supporting a glass fiber filter filled the annular area between the support ring and beaker and allowed air to be drawn through the 4-liter borosilicate glass bell jar to entrain particulate material escaping from the beaker. The velocity through the annular filter was estimated to be 3 cm/s. The air was drawn out of the top of the bell jar via a water-cooled condenser to remove moisture. The condensate was collected. Airborne material was collected on an in-line glass fiber filter.

The pertinent results are shown in Table 3-2. The ARFs for the four runs at boiling ranged from 4.5E-7 to 1.8E-3. Three of the four values ranged from 3E-4 to 1.8E-3. The two highest values (1.1E-3 and 1.8E-3), because they include solution splattered from the vessel onto the glassware, were estimated by the sum of the filter acid leach and from acid washes of the equipment downstream of the filter position due to loss of the filter. The values are almost certainly high, but it is not known how high. Two of the runs (ARFs 4.5E-7 and 1.1E-3) used a 0.70 mg Pu source without an airflow. The two runs performed at simmering (no surface breaking) resulted in ARFs of 1.3E-6 and 4.5E-6 that are bounded by the evaporation value of 3E-5 quoted in Subsection 3.2.1.1. The four experiments with heating rates resulting in disturbed surfaces generated ARFs ranging from 5.8E-5 to 8.4E-4: an order of magnitude variation in estimates. A bounding value for heating of aqueous solutions of 2E-3 is selected, and, in the absence of a measured particle size distribution, a conservative value for an RF of 1.0 is selected. The median value is 6E-5 (6.4E-5 rounded off) with an average value of 7E-4.

Table 3-2. Fractional Airborne Release During Heating of Pools of Dilute Plutonium Nitrate Solution - 90% Volume Reduction (Table II, Mishima, Schwendiman, and Radasch, November 1968)

Average Hot Plate Temperature, °F	Average Boil-Off Rate, ml/min	Minutes Heated	Appearance Surface	ARF
150	0.6	151	Simmering	4.5E-6
150	0.5	150	Simmering	1.3E-6
164	0.66	121	Disturbed	5.8E-5
175	0.73	124	Disturbed	2.4E-4
188	1.2	64	Disturbed	8.0E-5
190	0.9	80	Disturbed	8.4E-4
200	1.4	66	Boiling	1.1E-3[a,b]
218	1.4	63	Boiling	1.8E-3[a]
218	1.4	59	Boiling	3.0E-4
220	2.1	42	Boiling	4.5E-7[b]

[a] Filter ruptured, estimate based on activity collected in acid washes of equipment downsteam of filter position.

[b] Only 0.07 mg Pu used as source. No air sweep used during these experiments. ARF estimate from activity collected in condensate.

The fraction of source material carried from the container and deposited nearby (fallout) ranged from ~3E-8 during simmering to 1.7E-2 during boiling and may be indicative of the liquid ejected from the container but not airborne during such event. As with the airborne materials, the fraction ejected will increase with the increase in surface disturbance.

The data are limited for each type of heated liquid. The loss of the filters coupled with not using air sweeps in two of the boiling experiments makes the data for that type of heating especially uncertain. The surface of the heated liquid is recessed from the airflow and may reduce the airborne material due to losses to the sides of the beaker prior to escape. The configuration may be indicative of airborne release from heated liquids from the tops of vessels. The liquids are very dilute aqueous solutions and should bound other more viscous liquids or those with greater surface tension.

3.2.1.3 Airborne Release of Dissolved Matter from Evaporation and Bubbling Aqueous Solution

Borkowski, Bunz, and Schoeck reviewed 12 experimental studies that examined the airborne release of dissolved matter from bubble-burst at the surface of aqueous solutions. The slope of the rate change for fraction entrained as a function of gas velocity changes at a gas velocity of 15 cm/s. The experimental data reported in this region are plotted in Figure 3-2.

The data by Mishima, Schwendiman, and Radasch (November 1968) covered in Subsection 3.2.1.2 are plotted along with data from six other studies under reasonably comparable conditions. Manowitz et al. (1955) measured the DF (decontamination factor, the ratio between the radioactivity retained in the liquid in the vessel to that boiled off) during evaporation of waste solution using a de-entrainment device (not specified). The DFs ranged from 1E-4 to 1E-5 depending upon the boiling rate and contents suspended in solution. Garner et al. (1959) performed experiments at reduced pressures and equilibrium condiditions to identify the main parameters for liquid entrainment during evaporation. Entrainment increased with evaporation rate and decreasing solute concentration. Entrainment rates ranged from 1E-5 to 1E-4. Garner et al. (1954) measured the drop size distribution and total entrainment during evaporation in vessels of various diameters (4-in. and 12-in. diameter tubes). Entrainment rates were in the 1E-5 range. Although ~95% of the drops were <20 micrometers diameter range, the total mass entrained was due to the drops >100 micrometers in diameter. Shor et al. (1957) measured the radioactivity carried over in boilers by continuous monitoring of the $^{137}CsCl$ at elevated pressures (0.93 to 1.0 MPa). Entrainment (1E-6 to 1E-4) correlated with boiling rate and had an initial high release. Heger et al. (1982, 1983) conducted bubbling experiments to simulate reprocessing plant components. Stirring air flow velocity was ~10 m/h (2.8 cm/s). Entrainment values ranged from 1E-7 to 1E-4. The prescence of TBP reduced the surface tension and increased entrainment by a factor of 5 to 10. The drops airborne were bimodally distributed with maxima at 0.3 and 0.8 micrometers diameter. Addition of the TBP increased the generation of larger diameters drops.

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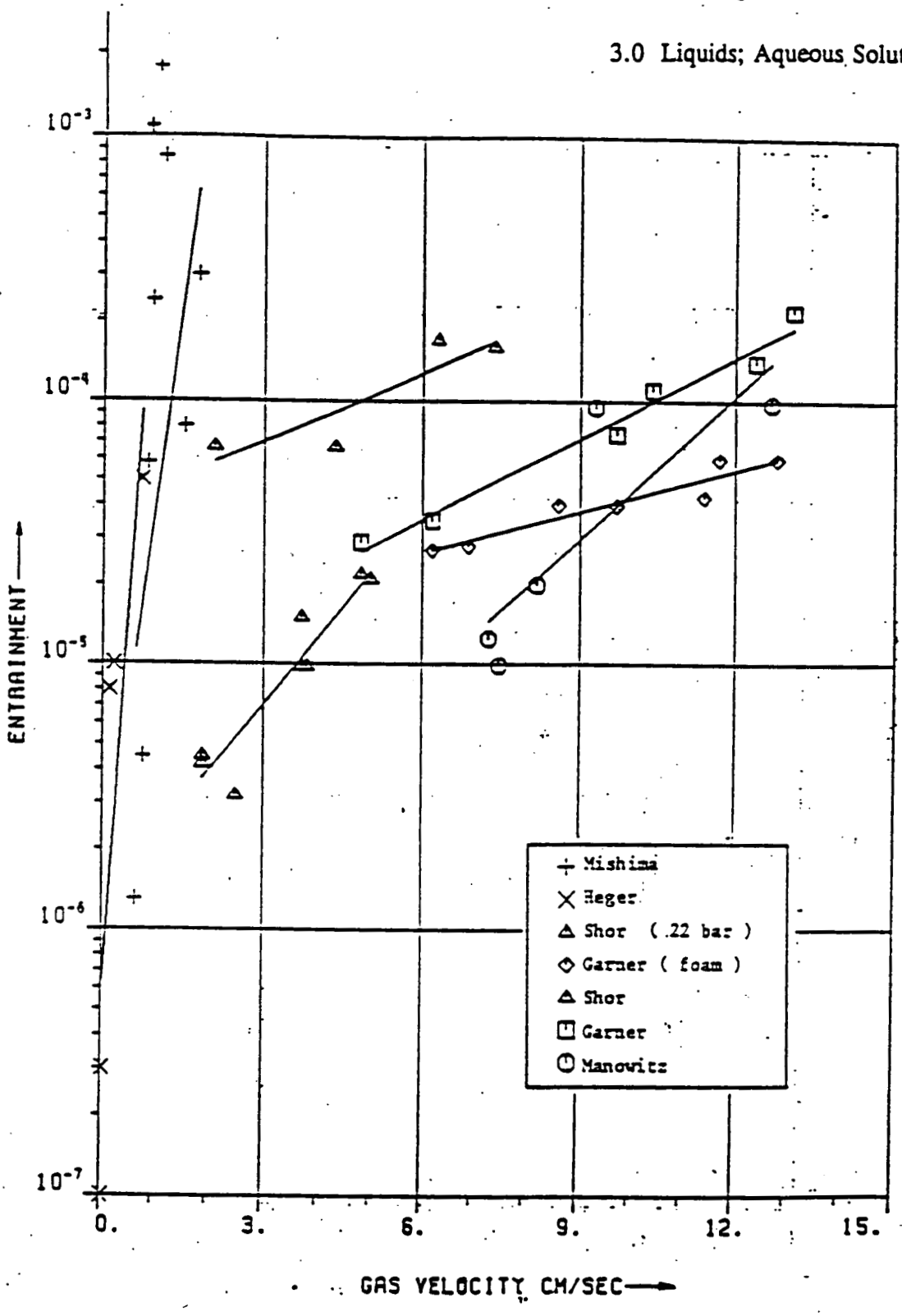

Figure 3-2. Entrainment Data Obtained at Small Gas Velocity (Borkowski, Lunz, and Schock undated)

It is evident that the ARF of 2E-3 measured by Mishima, Schwendiman and Radasch (November 1968) bounds the value measured by the other reported studies. Data generated by the venting of pressurized liquids shown in Figure 3-3 indicate that short of flashing spray conditions (superheating of the liquid by pressurization), a release value in the range of 1E-3 will bound the airborne release of liquids during boiling at normal atmospheric pressures. Thus, a bounding ARF of 2E-3 with an RF of 1.0 would conservatively bound the airborne release of respirable size drops during accident condition resulting in the boiling of aqueous solutions.

3.2.2 Explosive Release of Liquids

Liquids may be subdivided by the shock generated by detonation-like reactions or by shear stress at the surface generated by the accelerated airflow generated by the blast.

3.2.2.1 Shock Effects

Steindler and Seefeldt (1980) provide an empirical correlation to experimental data on the fragmentation of metals and aqueous solution by detonations [energy releases in microseconds with brisance (shattering effect)] (Ayer, et al. May 1988). The experiments covered the work performed by TNT related to the mass ratios (ratio mass of inert to TNT Eq.) of 1 to 10. The experiments were conducted with the condensed phase explosive embedded or contiguous to the material affected. Estimates of the ARF and size distribution for various mass ratios up to 1000 are provided in Appendix C of Ayer, et al. (May 1988) for a GSD (Geometric Standard Deviation, the slope of the line on log probability plot) of 8. The GSD is much greater than normally assumed (GSD 2) and provides greater fractions in the larger size ranges (an unconservative assumption for the assessment of radiological impacts). Due to the rapid change in size distribution, the maximum mass of inert material airborne in the respirable fraction is for an MR of 1. Therefore, a bounding ARF/RF of inert material equal in mass to the TNT Equivalent for the detonation is assumed.

3.2.2.2 Suspension of Liquid Due to Blast Effects (Accelerated Gas Velocities)

Mishima and Schwendiman (August 1973) reported the results of measurements of the airborne release of uranium from various surfaces (soil, vegetated soil, stainless steel, asphalt with UO_2 powder or UNH solution) before, during and after gasoline fires in a wind tunnel at air velocities of ~1 m/s and ~10 m/s. (The flame speed in flammable vapor mixtures is also on the order of 10 m/s, although flame speed may propagate to sonic velocities under turbulent conditions.) The results are listed in Table A.3 and the experimental apparatus is shown in Figure A.3 in Appendix A. The only experiments involving UNH solution were performed on a substrate of loose, sandy soil at air velocities of ~1 & 10 m/s. The ARF measured at 10 m/s from soil during a 28-hour sampling period was 3.9E-4 with an RF of

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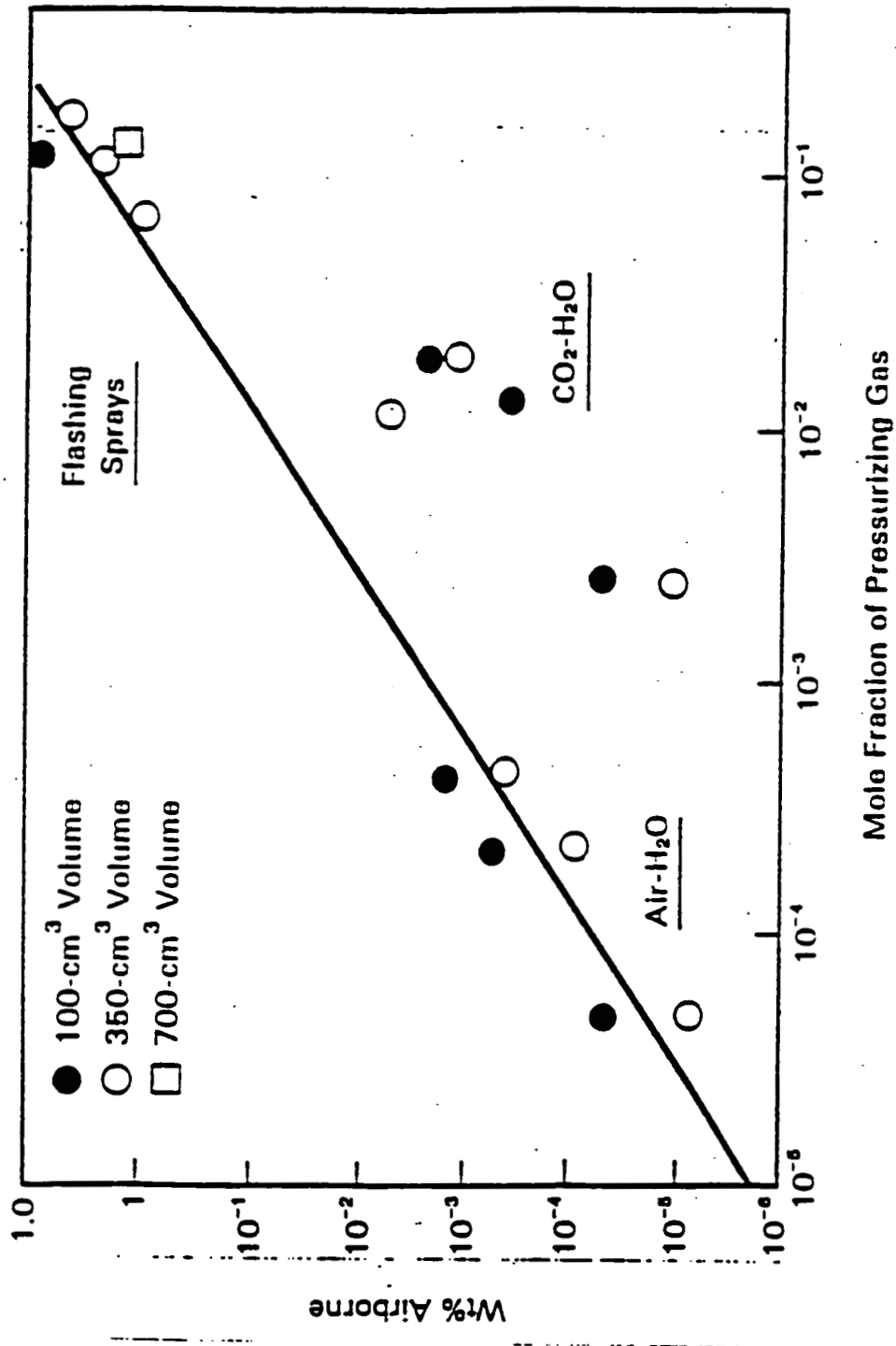

Figure 3-3. Weight Percent Airborne as a Function of Mole Fraction of Pressurizing Gas (Ballinger, Sutter, and Hodgson May 1987)

0.68. The value is comparable to other experiments involving UNH residues from the fire except one result from stainless steel at 10 m/s (ARF 2.6E-2 in 6 hours/RF 0.3; linear rate 4E-3/hr). Therefore, the rapid passage of air at an accelerated velocity from the deflagration of a flammable vapor mixture would not appear to have the potential to release large amounts of material from aqueous liquids. An ARF of 4E-3/hr for the time duration of the passage of the impulse over the liquid (generally on the order of 1 second) is recommended.

3.2.3 Venting of Pressurized Liquids

Droplets of an aqueous solution under pressure can be generated and suspended during the venting of the excess pressure as a results of three sets of conditions for accidents in fuel cycle facilities. Droplets can be generated by the bubbling action on the surface of the liquid resulting from the release of gases absorbed/trapped in the cold liquid, by spray generation if the pressure is relieved by venting a cold liquid through a small opening in the wall of the vessel, and by fragmentation of the liquid by the bulk vaporization of the solvent when the pressure over a superheated solution is relieved (flashing spray).

3.2.3.1 Depressurization of Free Volume Above Liquid Surface

Sudden depressurization of a liquid allows the release of dissolved/trapped gases. This sudden release of gases may result in the formation of bubbles that can form very small drops upon collapse and the drops formed can be carried with the venting gases. Figure 3-3 from Ballinger, Sutter, and Hodgson (May 1987) illustrates the relationship between the amount of gas/vapor released and the fraction airborne. Experiments were performed to measure the ARF as a result of venting pressurized volumes of aqueous solutions in quasi-equilibrium with their pressurizing gases (Sutter August 1983). Data from the referenced document (Table A.4 through A.7 in Appendix A) describing the airborne release of aqueous solutions are tabulated in Table 3-3. The experimental apparatus is shown in Figures A.4 and A.5 Appendix A.

The average ARF values as a function of pressure, solution density and source size are shown in Table 3-4 (tabulated as weight percent, 0.05 wt/o = 5E-4 fraction) from the reference and plotted in Figure 3-4. The ARF increases with pressure and decreases with density and source size. For the uranine solution (lower density liquid, ~1 g/cm^3), a bounding ARF of 2E-3 with an fraction of airborne material in the respirable size range of 1.0 appears conservative. For the UNH (higher density liquid, ~1.3 g/cm^3), a bounding ARF of 1E-3 (100 ml UNH at 500 psi) with a fraction of the airborne material in the respirable size fraction of 0.4 appears conservative. Since the suspension mechanisms (bulk liquid droplets formed by the surface rupture of bubbles) are the same, both bounding ARFs are at the same value as the bounding ARFs for boiling aqueous solutions. The median values for the uranine ARF/RF are 3E-4/0.9 and 2E-4/0.3 for UNH. The average values for uranine are ARF/RF 5E-4/0.9 and 3E-4/0.5 for UNH.

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Table 3-3. Measured ARFs from Venting Pressurized Aqueous Solutions (Tables A.4, A.5, B.4 and B.5 - Sutter, August 1983)

Volume Source, ml	Pressure, psig	Material	ARF	RF	ARF x RF
350	500	uranine	6.0E4	0.86	5.0E-4
	500	uranine	4.0E4	0.85	3.0E-4
	500	UNH	2.0E4	0.34	7.0E-4
	500	UNH	3.0E4	0.37	1.0E-4
	250	uranine	7.0E5	0.98	7.0E-5
	250	uranine	1.0E4	0.84	1.0E-4
	250	UNH	1.0E4	0.20	2.0E-5
	250	UNH	9.0E5	0.45	4.0E-5
	50	uranine	4.0E6	0.83	3.0E-6
	50	uranine	1.0E5	0.87	1.0E-5
	50	UNH	3.0E6	0.76	2.0E-6
	50	UNH	4.0E6	0.70	3.0E-6
100	500	uranine	2.0E3	0.90	2.0E-3
	500	uranine	1.0E3	0.70	8.0E-4
	500	UNH	7.0E4	0.46	3.0E-4
	500	UNH	1.0E3	0.38	4.0E-4
	250	uranine	4.0E4	0.78	3.0E-4
	250	uranine	7.0E4	0.77	5.0E-4
	250	UNH	4.0E4	0.36	2.0E-4
	250	UNH	6.0E4	0.45	3.0E-4
	50	uranine	4.0E5	NM	
	50	uranine	5.0E5	0.80	4.0E-5
	50	UNH	2.0E5	0.61	1.0E-5
	50	UNH	2.0E5	0.60	1.0E-5

Table 3-4. Average Weight Percent Airborne from Pressurized Liquid Release

Pressure, psig	350 cm^3 Source		100 cm^3 Source	
	Uranine	UNH	Uranine	UNH
500	0.05	0.025	0.15	0.08
250	0.01	0.01	0.06	0.05
50	0.0008	0.0004	0.005	0.002

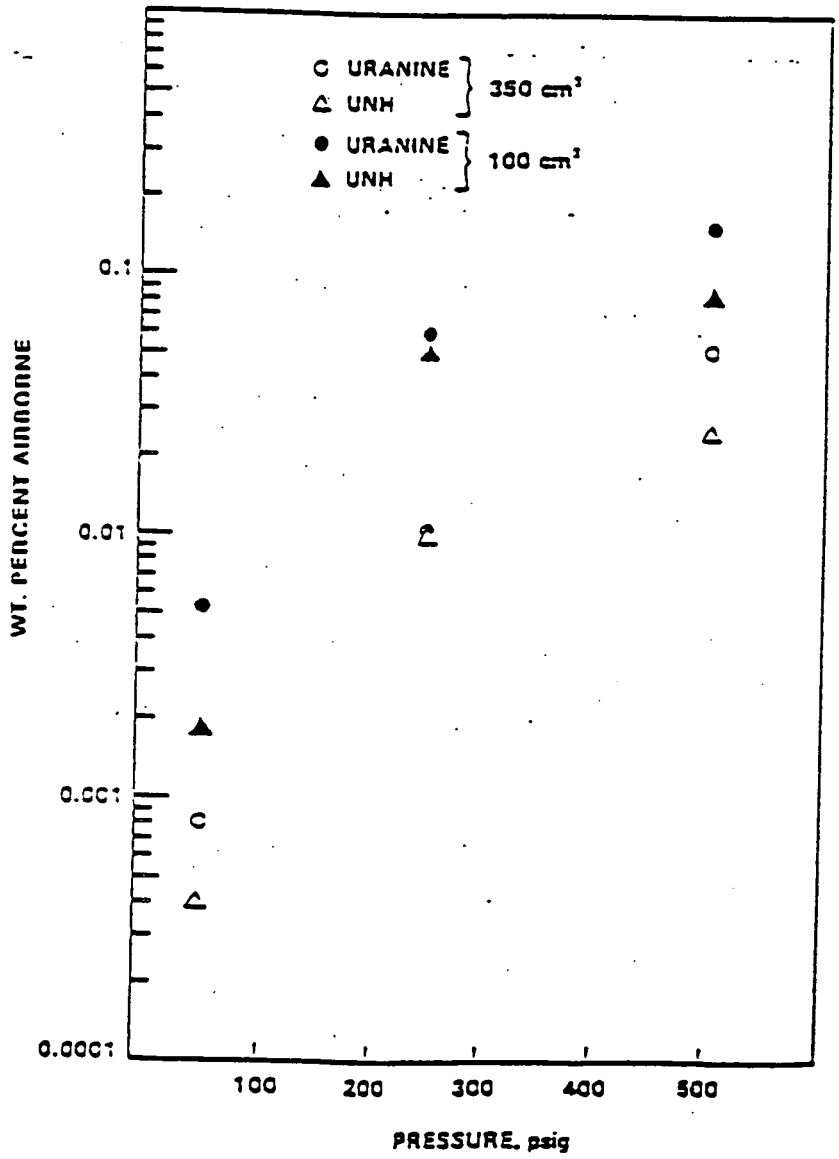

Figure 3-4. Average Weight Percent of Liquid Airborne as a Function of Pressure

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3.2.3.2 Depressurization via Breach Under the Liquid Surface (Spray)

If the container holding a pressurized liquid is breached, the liquid can escape in a variety of ways. For the purposes of airborne suspension, a conservative assumption would be the pressurized release of the liquid via a very fine hole as occurs in a commercial spray nozzle. The size distribution of some commercial spray nozzles as a function of orifice diameter and upstream pressure were shown in Figure 3-5 from Mishima, Schwendiman, and Ayer (October 1978). The size distribution of the liquid drops decreases with orifice diameter and increasing upstream pressure. It is not anticipated that drops formed from breaches, cracks, or leaks would generate finer drop size distributions than equipment specifically designed for that purpose. Therefore, the respirable fraction of the coarsest distribution generated by commecial spray nozzles shown in the figure is selected as the bounding ARF, 1E-4, with an RF of 1.0. For other size fractions, the values can be inferred from the 0.128-in. diameter spray nozzle values at 200 psig upsgream pressure. It is not anticipated that drops formed from breaches, cracks, or leaks would generate finer drop size distribution than equipment specifically designed for that purpose.

3.2.3.3 Venting of Super-Heated Solutions, "Flashing Spray"

Liquids heated above the boiling temperature of the liquid/solvent/diluent flash upon release--the excess heat above the boiling point of the liquid is expended in the bulk vaporization of the liquid and the remaining liquid is fragmented into fine droplets. The phenomenon has been investigated. Brockman (February 1985) reviewed the literature on the possible flashing of condensed moisture during the depressurization of a LWR post-accident containment vessel. Postulated vigorous boiling of water during depressurization with droplet entrained in vapor generated. Used simplified model to calculate amount of water entrained. Entrainment defined as the ratio between mass of liquid entrained/mass of vapor generated. Entrainment calculated by Rozen's et al. (1970) correlation. The correlation as shown by Kataoka and Ishii (April 1983) is limited to the deposition-controlled region with different correlations for the low and high superficial gas velocity regimes. The correlation used here is the general correlation for the entire region. The size distributions of droplets formed are based upon the suspension velocity and Weber breakup of liquid masses. Initial conditions for scoping calculations were:

- vessel volume: 50 000 m^3
- pool area: 500 m^2
- initial pressures: 0.3 MPa, 0.5 MPa & 0.7 MPa
- vent hole sizes: 1, 10, 100 & 1000 m^2
- total water inventory: 2.71×10^5 kg.

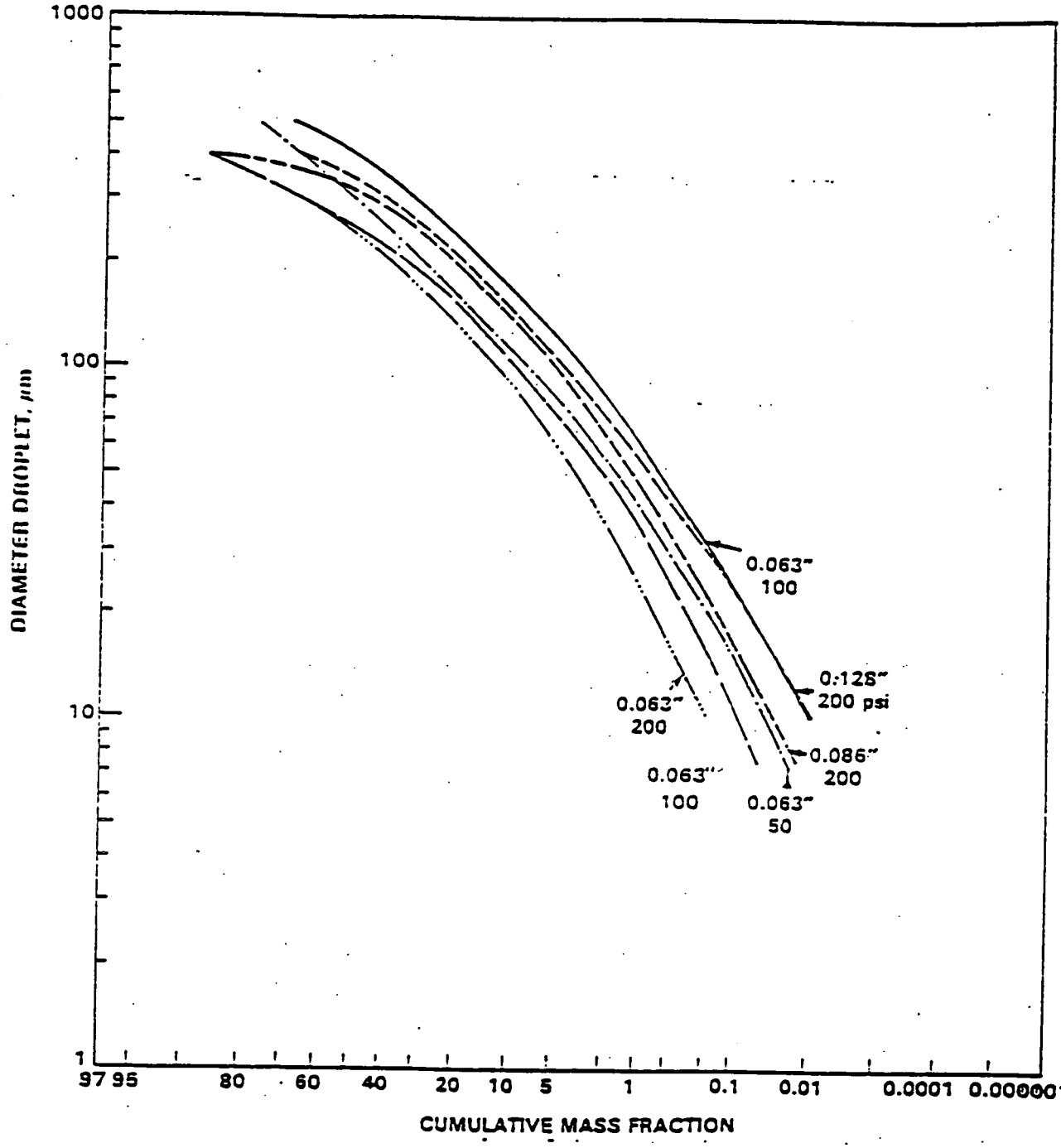

Figure 3-5. Mass Fraction vs. Droplet Diameters for Sprays as a Function of Orifice Diameter and Upstream Pressure (Mishima, Schwendiman, and Ayer October 1978)

Assumptions were:

- System comes to equilibrium instantly.
- Fluid temperature instantly comes to saturation temperature.
- Vapor generation in bulk liquid instantly poduces vapor flux at surface.
- Liquid vaporization does not contribute to the containment pressure. Blowdown is calculated without vapor source.
- Blowdown is calculated by choked flow through orifice while containment pressure is above 0.18 MPa. Below 0.18 MPa, blowdown is calculated by an orifice-pressure-drop/flow-rate relationship.
- Containment temperature at the time of failure is assumed to be at saturation temperature at the initial pressure and does not change throughout the calculation.
- Constant value of liquid specific heat and heat of vaporization are assumed.
- The liquid water at the start of the calculation is the total water inventory less the amout of water necessary to pressurize the containment to the initial pressure.
- The liquid water is depleted throughout the calculation by vaporization and entrainment. The removed water is not returned to the pool.
- The liquid water is assumed to reside in a pool of constant surface in a large single volume.

Table G-11, "Entrained Water and Droplet Size," in the referenced source tabulates the mass of water entrained, mass geometric mean diameter and GSD of the droplet size distribution as a function of initial pressure and vent hole area. The largest mass entrained at each pressure was associated with the largest vent hole area due to the rate of release. The ARF/RF values for the largest vent hole for each pressure listed are:

- 0.3 MPa: 2.4E-1/0.003 to 1.0E+0/0.0000006
- 0.5 MPa: 3.4E-1/0.002 to 1.0E+0/0.0000004
- 0.7 MPa: 3.9E-1/0.0000006 to 7.4E-1/0.0000004.

Not all the water was entrained at the highest pressure because the reduction of liquid in the pool by vaporization reduced the superficial gas velocity under these conditions. The possible effect of secondary flashing by the droplets was assessed and found not to be a serious concern but the possible reduction of the droplets due to evaporation of the solvent after release was not evaluated. Thus, although the author stated that the model tends to overestimate the entrainment, the possible increase in the fraction of dissolved fission products entrained due to the reduction of droplet size could result in significant underestimation. Nonetheless, the values for droplets in the respirable fraction from flashing sprays under these conditions do not appear to result in a significant fraction of the material as droplets in the respirable fraction - range of 7E-4 to 3E-7. The values for the many of the

variable parameters are temperature-dependent and methods for determining the temperature or change in temperature and the values for the parameters as a function of temperature were not provided.

Another reference for flashing spray values was experiments performed by Ballinger, Sutter and Hodgson (May 1987) to measure the airborne release and size distribution of aqueous solution over a limited range of conditions. Table 3-5 lists the experimental results obtained. Aqueous solutions were heated to pressures of 0.39 MPa (57 psig at ~134°C), 0.85 MPa (124 psig at ~161°C) and 1.65 MPa (240 psig at ~202°C) using source volumes of 700 cm^3, 350 cm^3 and 100 cm^3. Figure 3-6 taken from Ballinger, Sutter and Hodgson (May 1987) indicates the temperature of the aqueous solution at the stated pressures although the extrapolation to the lower temperature/pressure is questionable given datum point #5. The uncertainty at these lower values does not pose any significant concern. The liquid was released from the open top of the ~4-inch diameter apparatus via a double rupture disk arrangement. The experimental apparatus is shown schematically in Figures A.5 and A.6 in Appendix A. The fraction airborne increased with initial pressure and decreasing source size. The highest ARF, 9E-2, was measured at 0.85 MPa using a 100 cm^3 source. Approximately 69% of the airborne material was in the respirable size fraction. The ARF and RF depend upon the amount of heat (sensible heat in the liquid plus in the container) available and the heat needed to vaporize the solvent. The greater the fraction of solvent that can be flashed, the larger the ARF and RF. The ARFs and RFs measured are tabulated in Tables A.8 and A.9 in Appendix A.

Table 3-5. Measured ARFs and RFs During the Venting of Superheated Aqueous Solutions (Tables A.3 and A.4 - Ballinger, Sutter and Hodgson May 1987)

Source Volume, ml	Pressure, psig	ARF	RF	ARF x RF
700	125	1.0E-2	0.78	1.0E-2
350	240	5.0E-2	0.73	4.0E-2
	125	2.0E-2	0.66	1.0E-2
	60	9.0E-3	0.62	6.0E-3
100	125	9.0E-2	0.69	6.0E-2

Models exist for the size distribution of the droplets formed (Gido and Koestel November 1978, Brown and York 1962). Gido and Koestel (November 1978) base their model upon the fact that drops with center-to-surface temperatures of <5°K do not fragment. Their model requires evaluation of many parameters such as drop density, drop surface tension, vapor density, thermal diffusion, residence time, etc. Brown and York (1962) present a much simpler model:

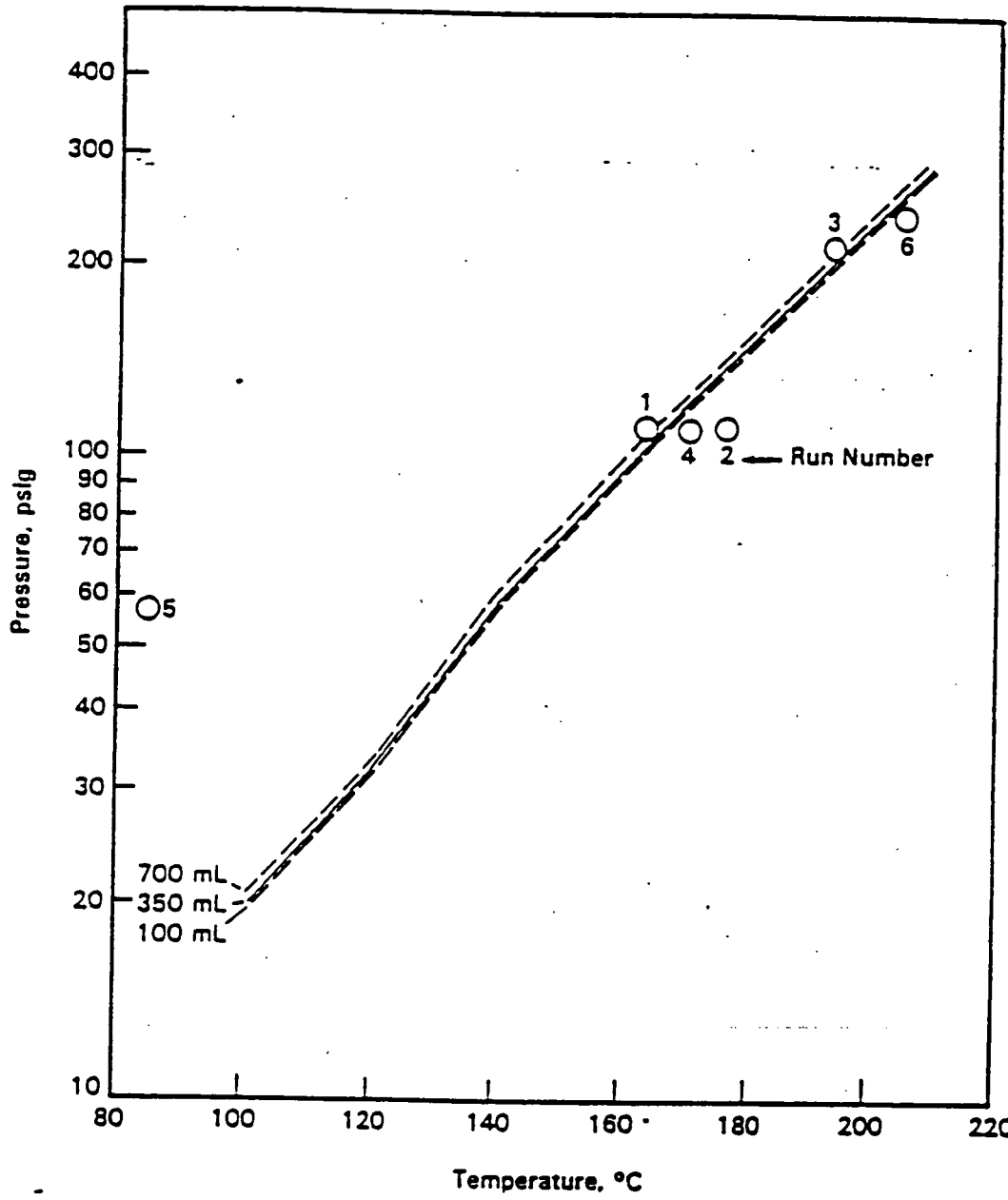

Figure 3-6. Measured and Predicted Temperatures for Flashing-Spray Releases (Ballinger, Sutter, and Hodgson May 1987)

$$D_{10} = (1840 - 5.18)\ T/N_{We}$$

where: D_{10} = linear mean diameter of the droplet, micrometers
T = temperature of the jet, °F
N_{We} = Weber number
= $density_{gas}$ x velocity of jet x diameter of jet/2 surface tension of liquid

A conservative assumption would be that all the excess heat is used to evaporate enough liquid to reduce the temperature below boiling. The non-volatile radionuclides are assumed to remain in the liquid and the fraction of droplets in the respirable fraction (droplets 10 micrometer AED) determined by Brown and York's (1962) formula are the ARF with a RF of 1.0. In as much as the liquid temperature is just at boiling, any additional heat could reduce the size of the liquid droplet (although it is more difficult to evaporate water from concentrated solutions) or even generate solid salt particles with the addition of sufficient heat. A bounding coupled value within the range of experimental conditions of ARF of 1E-1 with a RF of 0.7 is selected. The median values are 2E-2/0.7 with average values of 4E-2/0.70.

3.2.4 Free-Fall Spill of Liquids

Aqueous solution, slurries, and viscous liquids (non-Newtonian fluids) spilled onto a hard, unyielding surface can be subdivided into drops by the instability/shear stress at the surface of the liquid during the fall and by impact upon striking the surface (splashing). The passage of the falling material through the air space creates airflow patterns and turbulence that aids in suspension.

3.2.4.1 Aqueous Solutions

Experiments have been performed to determine the airborne fraction from the free-fall spill of aqueous solutions with a density near 1.0 (uranine) and 1.3 g/cc (UNH). Materials that may represent airborne material deposited on the walls were measured in some experiments. The fall distance was limited, less than 3 m, and the initial dispersion of the material was uncontrolled; material was released by inverting a glass beaker holding the liquid. The experimental apparatus is shown schematically in Figure A.7 and the measured results in Tables A.10 through A.13 in Appendix A. The measured ARFs/RFs are tabulated in Table 3-6.

The ARFs for the uranine solution under these conditions ranged from 4E-6 to 2E-4 and 1E-6 to 2E-5 for the UNH. The fraction of the source airborne as particles 10 μm AED and less ranged from 2E-6 to 8E-5 for the uranine solution and from 5E-7 to 1E-5 for UNH. Both the fraction airborne and the fraction in the respirable size range appear to vary with

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Table 3-6. Measured ARFs/RFs From the Free-Fall Spill of Aqueous Solutions (Tables A.2, A.4, B.2 and B.4 - Sutter, Johnston, and Mishima, December 1981)

Source Volume, ml	uranine or uranium, g	Spill Height, m	ARF	RF	ARF x RF
Uranine Solution					
1000	10	3	1.0E-4	0.45	6.0E-5
			8.0E-5	0.50	4.0E-5
500	5	3	4.0E-5	0.56	2.0E-5
			3.0E-5	0.44	1.0E-5
			3.0E-5	0.80	3.0E-5
			6.0E-6	0.82	5.0E-5
			5.0E-5	0.74	4.0E-5
			3.0E-5	0.70	2.0E-5
			4.0E-5	0.59	2.0E-5
			4.0E-5	0.64	2.0E-5
125	1.25	3	2.0E-4	0.52	8.0E-5
			3.0E-5	0.63	2.0E-5
1000	10	1	3.0E-5	0.53	2.0E-5
500	5	1	4.0E-6	0.62	2.0E-6
125	1.25	1	6.0E-6	0.72	4.0E-6
UNH Solution					
1000	208.7 U	3	1.0E-5	0.23	2.0E-6
			1.0E-5	0.19	3.0E-6
500	104.4 U	3	1.0E-5	0.994	1.0E-5
			2.0E-5	0.30	6.0E-6
			1.0E-5	0.16	2.0E-6
125	26.1 U	3	1.0E-5	0.36	5.0E-6
			2.0E-5	0.26	5.0E-6
1000	208.7 U	1	1.0E-6	0.51	5.0E-7
			1.0E-6	0.24	2.0E-6
500	104.U	1	1.0E-6	0.85	9.0E-7
125	26.1 U	1	4.0E-6	0.61	2.0E-6
			5.0E-6	0.62	3.0E-6

fall distance and source size. A conservative bounding value for the ARF for aqueous solution with a density near 1 would be 2E-4 with RF 0.6 in the respirable size range. For TRU solutions with greater densities, a bounding ARF of 2E-5 with 0.3 in the respirable size range appears to be conservative. The median ARFs/RFs for aqueous solutions are 4E-5/0.7 and 1E-6/0.3 for the concentrated heavy metal solutions.

An empirical model of ARF and droplet size distribution from free-fall spills of liquids beyond the fall distance range encompassed in the experiments has been developed by Ballinger, et al. (January 1988). The ARF is:

$$ARF = 8.9E\text{-}10\ Arch^{0.55}$$

where: Arch = Archimedes Number
= $(density_{air})^2 * (spill\ height)^3 * g/(solution\ viscosity)^2$
$density_{air}$, g/cc
spill height, cm
g = gravitational constant, 981 cm/s^2
solution viscosity, poise

No regression analysis produced a satisfactory correlation with AMMD (Aerodynamic Mass Median Diameter, micrometers) and a simple statistical correlation representation of lognormal drop size parameters is substituted. They are presented in Table 3-7.

Table 3-7. Statistical Summary of Drop Size Parameters for Lognormal Distributions (Table 3.4 - Ballinger, et. al., January 1988)

	AMMD, micrometers	GSD[a]
All data	21.5	7.3
UNH spill	27.2	6.0
Uranine Spill	27.1	3.0
Sucrose spill	12.5	12.3
Slurry spill	15.8	10.1

[a] GSD = Geometric Standard Deviation.

3.2.4.2 Slurries

Experiments have been performed to measure the ARF and RF from the free-fall spill of slurries (Ballinger and Hodgson, December 1986). The apparatus (see Figure A.5, Appendix A) and procedures as used in the free-fall spill experiments involving aqueous

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solutions. The pertinent data extracted from the reference document (Ballinger and Hodgson December 1986) are shown in Table 3-8 (see Tables A.14 and A.15 in Appendix A).

Table 3-8. Measured ARFs/RFs for Free-Fall Spill of Slurries (1 liter source, 3 meter fall distance) (Tables B.3 and B.4 - Ballinger and Hodgson, December 1986)

TiO_2, g/l	Glass Frit, g/l	Uranine, g/l	Sucrose, g/l	Viscosity, centipoise	Surface Tension, dyne/cm	SpG	ARF	RF	ARF x RF
10	0	20	250	3.2	58.2	1.12	9.0E-7	0.73	7.0E-6
100	0	20	200	NM	54.5	1.16	1.0E-5	0.64	7.0E-6
40	60	20	335	4.9	64.6	1.19	9.0E-6	0.77	7.0E-6
40	60	20	335	3.1	68.6	1.20	2.0E-5	0.76	1.0E-5
200	300	20	0	1.3	63.1	1.33	5.0E-5	0.78	4.0E-5
200	300	20	0	1.3	63.4	1.35	3.0E-5	0.81	2.0E-5
200	300	20	100	1.3	64.9	1.29	3.0E-5	0.78	2.0E-5
200	300	20	100	2.9	62.8	1.41	2.0E-5	0.72	1.0E-5

The bounding ARF/RF values are 5E-5/0.8 with median and average values of 2E-5/0.7 and 2E-5/0.8, respectively. The empirical model for calculation of ARFs and drop size characteristics was discussed in Subsection 3.2.4.1.

3.2.4.3 Viscous Solutions

Experiments were also performed to measure the ARFs/RFs from the free-fall spill of viscous solutions (Ballinger and Hodgson December 1986). The experimental apparatus is essentially the same as used for the free-fall spill experiments involving aqueous solution and slurries and is shown in Figure A.7 in Appendix A. Table 3-9 is a tabulation of pertinent data taken from the reference source (Tables A.16 and A.17 in Appendix A).

Figure 3-7 from that reference shows the ARF tends to decrease with viscosity. For solutions that have a viscosity >8 centipoise, the ARFs are less than 7E-6 with 0.9 of the airborne material in the respirable size fraction. For the range of experimental conditions (viscosity >1.3 centipoise, surface tension >65 dyne/cm, specific gravity >1.01) the ARF/RF are bounded by 3E-5/0.7 with median values of 6E-6/0.8. The average ARF/RF values were 1E-5/0.8.

3.2.5 Aerodynamic Entrainment (Resuspension) of Liquids

Liquid can be made airborne by the passage of air over its surfaces through either parallel airflow or airflow directed into the surface--"whitecaps," spume, and by film breakup due to capillary action of the liquid up the sides of its container. The latter effect

Table 3-9. Measured ARFs/RFs for Free-Fall Spill of Viscous Solutions (1 liter source volume, 3 meter fall height) (Tables B.1 and B.2 - Ballinger and Hodgson, December 1986)

Viscosity, centipoise	Surface Tension, dyne/cm	SpG	ARF	RF	ARF x RF
1.3	65.2	1.01	3.0E-5	0.59	2.0E-5
			3.0E-5	0.74	2.0E-5
2.6	68.9	1.10	7.0E-6	0.70	5.0E-6
			1.0E-5	0.76	8.0E-6
7.9	70.9	1.19	5.0E-6	0.80	3.0E-6
			7.0E-6	0.83	5.0E-6
17.5	77.4	1.23	3.0E-6	0.78	2.0E-6
			3.0E-6	0.90	2.0E-6
46.0	74.5	1.28	2.0E-6	0.84	1.0E-6
			3.0E-6	0.89	2.0E-6

may only be important for situations where the ratio of perimeter distance is a significant fraction of the surface area as in small pools used in experimental studies. Only a thin layer at the surface of the liquid can be involved in droplet formation since the droplets are formed by the film fragments that would not suspend if the film were too thick or the fragments too large. The airborne release fraction for this type of situation has been studied theoretically and measured under two sets of conditions. Calculations indicate that particles held to heterogeneous surface by a layer of water greater than 5 molecules thick cannot be resuspended at superficial gas velocities <5000 m/s (greater than sonic velocities) (Brockman February 1985). Other calculations performed in the paper indicate that the aerodynamic flow profile at the surface may not be properly estimated; particles 10 micrometers in diameter were entrained at the lowest superficial velocity, 1.8 m/s, although most calculations indicate that the minimum velocities are required for particles an order of magnitude larger. Nonetheless, the calculations indicate the force necessary to suspend shallow pools of liquid probably requires substantial superficial velocities for suspension and that release of liquid droplets under most ordinary conditions are very low.

3.2.5.1 Spray Release From Large Outdoor Pond

A model, SPRAYMASS, was developed from empirical formulas representing ocean sprays (Roblyer and Owczarski April 1992). Correlations between wind velocity and fetch (distance from the lee shore where turbulence begins) were developed from sea-salt aerosols (principally during surface breakup of bubbles formed in wave action) in the open sea, finite ponds and diffusion in atmosphere-surface boundary layers. The concentration of aerosol above ocean waves with finite fetch as a function of windspeed has been measured and is represented by:

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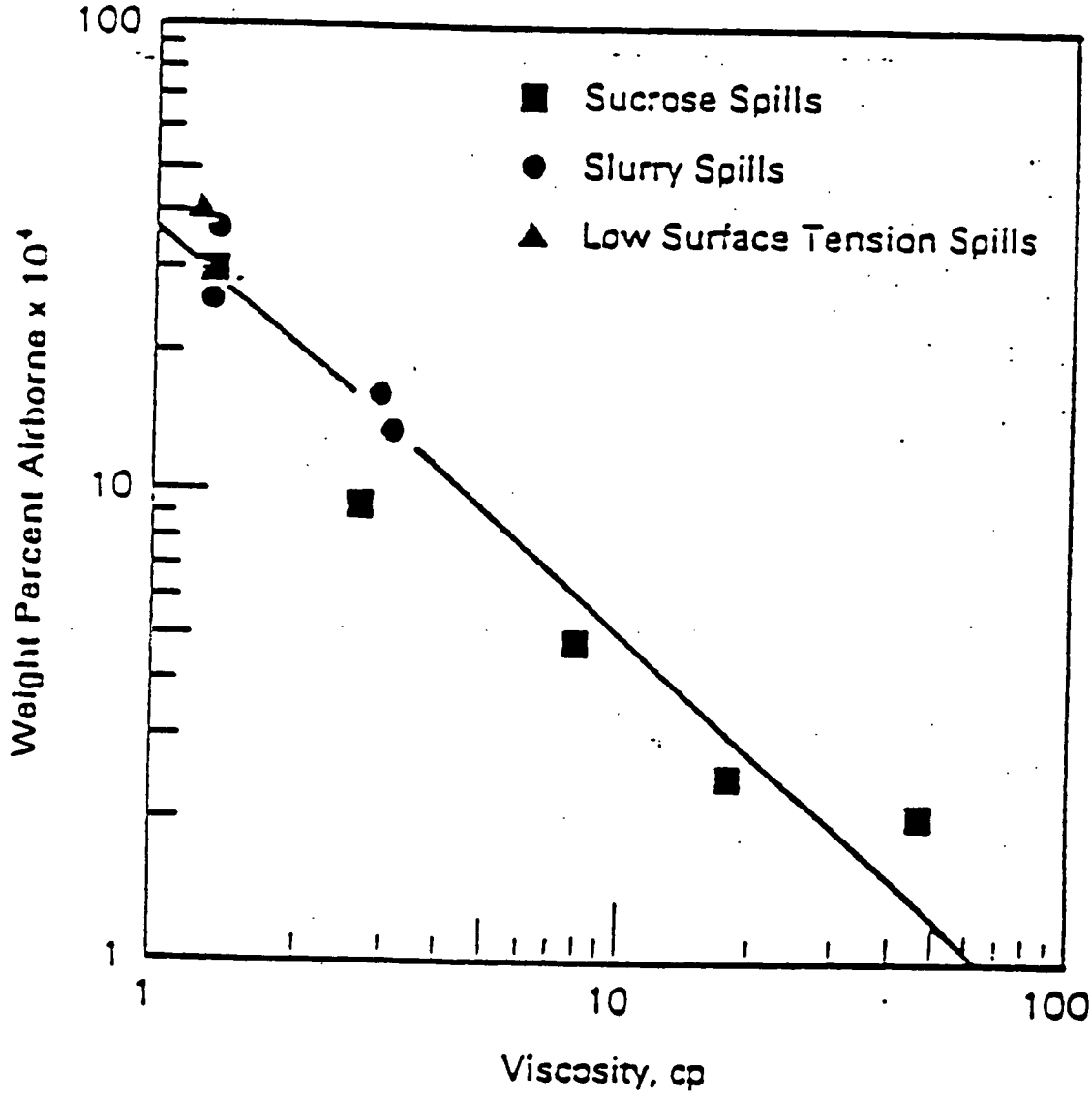

Figure 3-7. Weight Percent Airborne Versus Viscosity for Sucrose, Slurry, and Low Surface Tension Spills (Ballinger and Hodgson December 1986)

$$C_{air} = C_{water}(3.0E\text{-}11)(10^{0.098039v})$$

where v = windspeed, m/s.

With considerations of boundary layer meteorology, an upward escape velocity (mass release rate) for a 200-m x 200-m pond as a function of windspeed and fetch can be calculated and is shown in Figure 3-8 taken from Roblyer and Owczarski (Figure 4 - April 1992). With a fetch of 10 m (~33 ft), a windspeed of 15 m/s (~33.6 mph), and an effective active layer (depth of liquid actually involved in drop generation) under these conditions of 0.1 mm to 1 cm, the airborne suspension rate would range from 4E-8/h to 4E-5/h.

3.2.5.2 Suspension of Liquids From Shallow Pools of Concentrated Heavy Metal Salt Solutions on Stainless Steel

An indication of the ARF for this type of condition at very low velocities can be gained from the entrainment of plutonium solution in air at velocities from 10 to 100 cm/s passing over the surface (Mishima, Schwendiman and Radasch November 1968). The entrainment was from a very shallow pool (~2 to 4 mm) of limited diameter (~2.5 cm) using a dense solution. Evaporation periods lasted from 2 h to 24 h with temperatures from ambient (~21°C) to 100°C. For entrainment at ambient temperature with an evaporation period of 24 h at ambient temperatures, the ARF ranged from <2E-10 to 2.5E-9. The ARFs measured are listed in Table 3-10 taken from Table I in the reference document and found in Appendix A (Table A.1). The experimental apparatus is shown in Figure A.1 in Appendix A.

Although the nominal velocities used in these experiments appear to be much lower than those quoted in Subsection 3.2.5.1, the values represent velocities much closer to the surface (cms) than the usual height for meteorological windspeed measurements of 10 m. The measured ARFs overlap the values estimated in Subsection 3.2.5.1, and the ARRs range from 7E-12/hr to 1E-10/hr.

Table 3-10. Measured ARFs from Shallow Pools of Concentrated Heavy Metal Salt Solution (0.72 g to 0.82 g Pu, 24-hr sampling period) (Table I - Mishima, Schwendiman and Radasch November 1968)

Temperature, °C	Air Velocity, m/s	ARF	Rate fraction/hr
ambient	10	<1.0E-9	<1.0E-14/s
ambient	50	2.5E-9	3.0E-14/s
ambient	100	<2.0E-10	<2.0E-15/s

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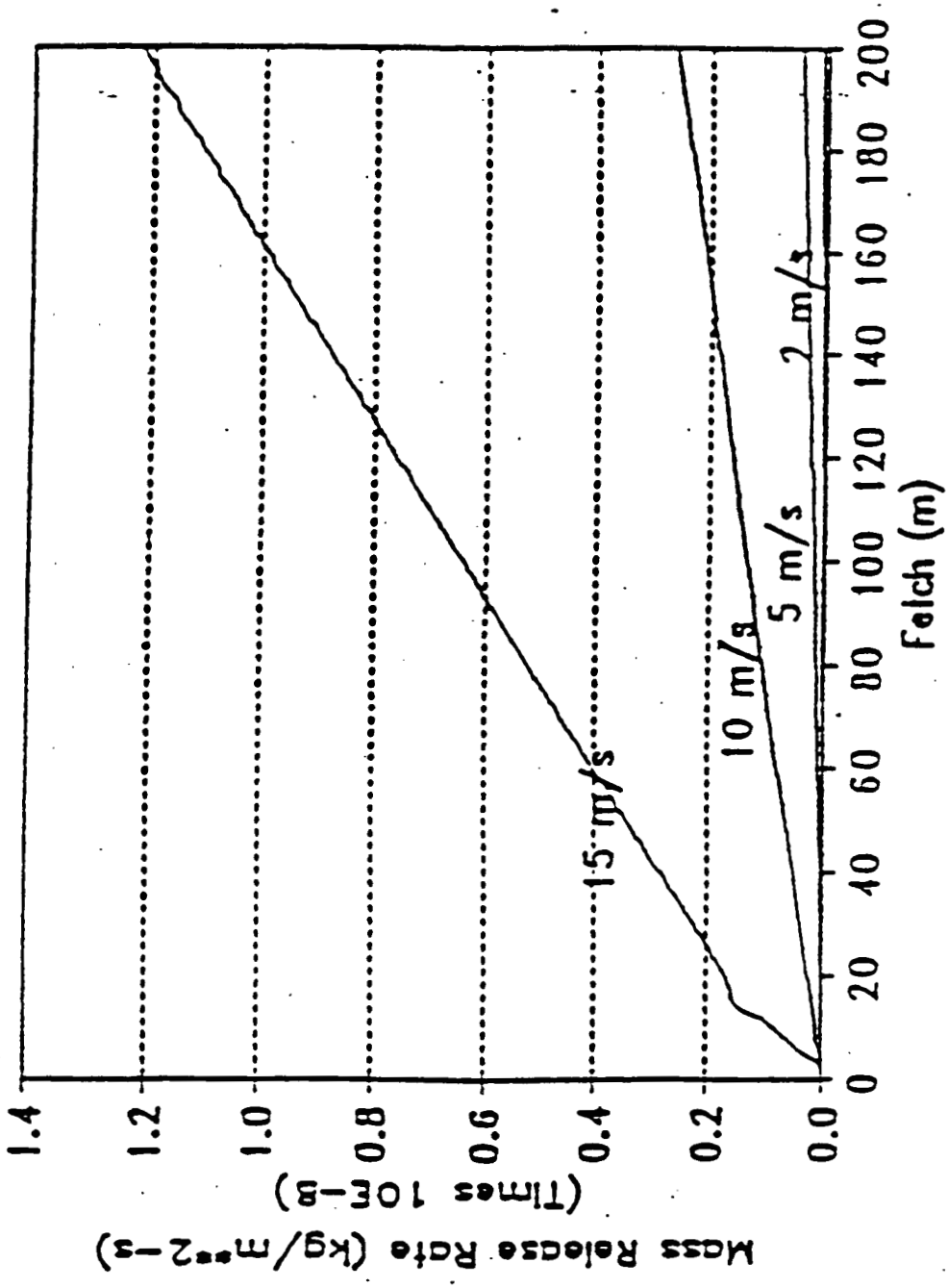

Figure 3-8. Mass Release Rate vs. Fetch, 200 by 200 Meter Pond (Roblyer and Owczarski 1992)

3.2.5.3 Suspension at Higher Windspeed From Various Surfaces

Aerodynamic entrainment (resuspension) at higher air velocities for UNH solution from various surfaces was measured in wind tunnel experiments (Mishima and Schwendiman August 1973). Measurements were made at velocities of 2.5 mph and 20 to 23 mph 1 ft above the surface of smooth, sandy soil. The experimental apparatus and measured values are shown in Figure A.3 and Table A.3 in Appendix A. The pertinent data are listed in Table 3-11.

Table 3-11. Measured ARFs/RFs of Uranium (UNH) From Soil at 2.5 mph and ~20 mph (Table III - Mishima and Schwendiman August 1973)

Substrate	Windspeed, mph	Sampling Time, hr	ARF	RF	Rate Fraction/hr
Soil	2.5	6	5.0E-4	0.76	9.0E-5
		24	1.0E-4	0.84	4.0E-6
	20	28	4.0E-4	0.63	1.0E-5

The ARF for 10 m/s (5E-4 in 6-hr, airborne suspension rate of 9E-5/hr) bounds the measured ARFs. The suspension rates from soil at both windspeeds appear to be approximately the same value (4E-6/hr to 9E-5/hr) with the two measurements at 1.0 m/s showing as much variation as between the measurements for the two windspeeds. The size of the airborne material is conservatively assumed to have an RF of 1.0.

3.2.5.4 Estimate of the Resuspension of Liquids From Soil

Sehmel and Lloyd (1976) measured resuspension rates of a powder deposited on a soil surface and deduced that a reasonable value for resuspension rate was 1E-8/s to 1E-10/s. Based upon these values and the fact that liquids absorb into the soil and are less susceptible to entrainment, a resuspension rate of 1E-10/s for the liquids on soil has been estimated for this study.

3.3 ORGANIC, COMBUSTIBLE LIQUIDS

3.3.1 Thermal Stress (Burning of Contaminated Combustible Liquids or Burning of Combustible Liquids Over Contaminated Aqueous Phase)

Radionuclides are present in combustible liquids during liquid-liquid extraction processes and during decontamination procedures. In some cases, the radionuclides can be in an aqueous solution under a burning organic layer (e.g., process liquids, solvents, fuels).

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The combustion of a liquid is a heterogenous reaction - heat from the flame radiates back to the liquid surface resulting in the evaporation of more fuel vapor that entrains air until a combustible mixture is attained and is ignited. The suspension of non-volatile materials appears to result from formation of drops of the bulk liquid. If the conditions are such that the surface film of the liquid is minimally disturbed, very little of the non-volatile components will be suspended from the bulk liquid. As the surface of the liquid is disturbed by turbulence of the vapor generation, the capillary action at the edge of the liquid, and the evolution of water vapors from the aqueous solution trapped beneath the organic layer, the suspension of non-volatile components increases. If the evolution of water vapors is very rapid, a large volume of the aqueous layer may be ejected and quench the fire. Flaming combustion (smoldering combustion is observed in some solid fuels such as cellulosics) may also be quenched when the oxygen concentration diminishes to 17.5% to 11% (generally flaming combustion ceases at oxygen concentrations of approximately 16%) (Malet et al. 1983, Jordan and Lindner 1982, 1983).

3.3.1.1 Burning of Small Volume/Surface Area 30% TBP (tri n-butyl phosphate)-Kerosine Solutions, No Vigorous Boiloff

For quiescent fire (relatively undisturbed liquid surfaces), the ARFs measured by Mishima and Schwendiman (June 1973) for the combustion of 30% TBP in a kerosine-type diluent traced with various radionuclides (U, Cs, Ce, Zr, I) are applicable. The measured values and experimental apparatus are found in Table A.18 and Figures A.8a and b in Appendix A. Twenty-five ml of 30% TBP-kerosine were placed in a 50-ml borosilicate beaker. Air (1- and 2-cfm) was drawn through a 2.7-in.-diameter stainless steel chimney around and over the beaker. Iodine (during the experiments using iodine tracer) was collected in a charcoal trap at the top of the chimney and airborne particulates in a glass fiber filter. The liquid was ignited and the liquid gently heated by a hand-held propane torch. Experiments were performed to self-extinguishment (no heating after initiation of flaming combustion) and supplemental heating to complete dryness. No aqueous phase in contact with the combustible organic was used in these experiments. The pertinent data are tabulated in Table 3-12.

Under the experimental conditions, the ARFs for all non-volatile materials appear to be less than 1E-2. Uranium ARFs range from 2E-4 to 3E-3, an uncertainty of approximately an order of magnitude. Cesium ARFs also show an order of magnitude uncertainty ranging from 2E-3 to 1E-2. ARFs for both cerium and zirconium are more consistent for the limited number of measurements made. The ARFs for iodine range from 7E-1 to 8E-1 and are assumed to be essentially 1E+0. In the absence of any measured airborne particle size distribution, all the airborne material is conservatively assumed to be in the respirable fraction. The volatile materials are considered to remain in the gaseous state although the volatile materials (generally iodine but may include other halogens and possibly some cesium

Table 3-12. Measured ARFs From Burning Small Volumes of 30% TBP-kerosine Traced with Selected Radionuclides (Table I - Mishima and Schwendiman June 1973)

	ARFs Self-Extinguishment		ARFs Complete Dryness	
	1-cfm	2-cfm	1-cfm	2-cfm
Uranium	2.7E-4	2.3E-4	—	3.0E-3
Cesium	2.2E-3	2.5E-3	1.9E-3	1.0E-2
Cerium	7.4E-3	5.6E-3	7.7E-3	7.1E-3
Zirconium	6.5E-3	ND	5.5E-3	2.4E-3
Iodine	6.57E-1	6.53E-1	8.17E-1	8.43E-1 8.28E-1 8.33E-1

compounds) may condense on various surfaces contacted or on pre-existing airborne particles and behave like the host particle thereafter. The effect cannot be readily characterized and the conservative assumption is that all the material is respirable.

3.3.1.2 Large Scale, Vigorous Burning, Pool Fires of 30% TBP-kerosine

The ARFs for strontium from a large-scale 30% TBP-kerosine burn were reported by Sutter, Mishima and Schwendiman (June 1974). One hundred and fifty liters (150-l) traced with 25 g of strontium nitrate were burned in 10-17-in. x 23-in. x 3-in. deep stainless steel pans placed on concrete block above an 8-in. pool of water on the floor of a 12-ft x 12-ft cell of insulating board held in a sheet steel silo. The combustible organic phase was not in contact with an aqueous phase. Kerosine was floated on the surface of the water pool to aid in the burning of the 30% TBP-kerosine PUREX-type solvent. The organic liquids were ignited and the airborne materials carried to the exhaust gas treatment/sampling train apparatus shown in Figure A.9 in Appendix A taken from the reference document (Figure 1 - Sutter, Mishima and Schwendiman June 1974). Two of the three burns generated useable data with ARFs of 2.2E-3 and 1.9E-3. The values are generally consistent with those generated in the small volume/surface area experiments in Subsection 3.3.1.1.

3.3.1.3 Airborne Release of UNH and Air-Dried UNH from Various Surfaces During a Gasoline Fire, Shallow Pools

Experiments were performed by Mishima and Schwendiman (1973) in a wind tunnel to measure the ARF/RF of uranium from various surfaces (sandy soil, sandy soil with vegetation cover, stainless steel and asphalt) at windspeeds of 1.0 m/s and 10 m/s.

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Windspeed measurements were made at the centerline of the 2-ft x 2-ft wind tunnel and therefore represent much higher windspeeds (50 mph to 60 mph) measured at 10-m height. UNH was placed upon the surface held in a 22-inch diameter flange in the floor of the wind tunnel. In some experiments with sandy soil, the UNH was allowed to air-dry for several days prior to testing. One gallon of gasoline was poured over the surface, ignited and the air drawn over the burning surface. In some cases, the airborne particles were only sampled during the actual burning; in other cases, the airborne particles were collected for much longer periods. The ARFs/RFs measured and the apparatus are shown in Table A.3 and Figure A.3 in Appendix A. The relevant data are listed in Table 3-13.

Table 3-13. Measured Transfer Coefficients and Decontamination Factors During the Burning of TBP-Kerosine Solvent (Table I - Malet et al. April 1983)

Trace Element	Transfer Coefficient	Decontamination Factor	Fraction Reaching Filter
(Small Scale Experiments)			
Cs	0.47	1310	3.6E-4
	0.32	>5270	<6.0E-5
	0.27	>4890	<5.5E-5
	0.49	>3760	<1.3E-4
Th	0.45	112	4.0E-3
	0.23	159	1.4E-3
	0.12	137	8.8E-4
(Large Scale Experiments)			
Ce	0.23	4260	5.4E-5
	0.42	1110	3.8E-4
	0.92	—	—
	0.89	—	—
	0.47	5620	5.4E-5

The ARFs range from 1.7E-5 (soil, 1.0 m/s) to 1.14E-1 (stainless steel, 10.0 m/s). The data are extremely limited with single values at some sets of conditions (surface, windspeed). The type of surface may have some effect in that the liquid can be absorbed into the substrate or the substrate conduct heat. If the substrate conducts heat well, the liquid could be boiled rapidly generating conditions much more favorable to generation of airborne liquid droplets (a possible mechanism for suspension of liquids and salts from all types of surface would be explosive release of moisture trapped under the salt during rapid heating of the material). The ARFs for soil and vegetation covered soil are lower than the ARFs for stainless steel under comparable conditions but are consistent with the ARFs for asphalt

(which does not conduct heat but the surface may have become plastic due to the heat and retained salts from the evaporation of solution). The conservative bounding values are ARF 2E-1/RF 0.3 (stainless steel, 10 m/s) for the actual combustion period for liquid solution on a heat-conducting surface, outdoors, for windspeeds to 22 m/s.

The bounding values for other outdoor surfaces at windspeeds up to 22 m/s are ARF 5E-3/RF 0.4 (liquid UNH on sandy soil, 10 m/s) for the actual combustion period. The median values are ARF 1E-3/RF 0.8 (liquid UNH on vegetation covered sandy soil at 1 m/s) with average values of ARF 1E-3/RF 0.5.

3.3.1.4 Combustion of TBP-kerosine Solutions Over Pools of Acid, Vigorous Boiloff

Halverson, Ballinger, and Dennis (February 1987) reported measurements of airborne uranium during the burning of combustible organic liquid over aqueous solutions. Small volumes of liquid were placed in metal beakers (except in one case where a borosilicate glass beaker was used to minimize the heat transfer through the beaker) on a load cell as shown in Figure A.10 Appendix A. The liquids were heated by heating tapes wrapped around the metal beaker except in the single case where a borosilicate glass beaker was used. In this case, radiant heat panels were used. The organic liquid ignited and air (27.5-cfm) was drawn up the 25.4-cm diameter chimney. Airborne particles were collected on glass fiber filters as a function of time. The pertinent data taken from Table A.6 in the reference document (see Table A.19 in Appendix A) are tabulated in Table 3-14.

The measured values for ARF appear to have two orders of magnitude variation. The conservative upper bound ARF is 1E-1. The RF was only measured for one experiment [50 ml 30% TBP-kerosine (U) + 150 ml acid (U + FP)] with a value of 0.99. In most cases, heat transferred through the metal solution holder resulted in a boilover that terminated the burning. Use of glass holders or no external heat addition after ignition delayed boilover. Only in experiments #52 and #53 (40% TBP in normal paraffin hydrocarbon) using heating tape to heat the liquid did the burning proceed to complete dryness. It appears that burning the liquids to dryness increase the ARF: the two highest measured ARFs are from this configuration (6.0E-2 and 7.1E-2). The variation found for the other experimental configurations may be partially due to the vigor in boiloff and composition of the aqueous phase. The presence of salts in the aqueous phase may result in a slightly greater heat capacity for the aqueous phase resulting in a more violent eruption upon boiling. Violent eruption of the aqueous phase could cause the generation and entrainment of organic droplets. The median ARF is 1E-2 with an average value of 2E-2. The ARF (1.5E-2) reported by Jordan and Lindner (September 1984) agrees with the median ARF for the other experimental conditions.

Table 3-14. Measured Uranium ARFs During the Burning of TBP-kerosine Over Aqueous Phase (Table A.6 - Halverson, Ballinger and Dennis February 1987)

Solutions Tested	Burn Duration, min	ARF	Remarks
100 ml 30% TBP-kerosine (U) + 100 ml acid	27.5 34.8 53.3	4.04E-3 5.57E-3 4.34E-3	Aqueous boiled over and quenched fire, 40% to 60% organic unburned
100 ml 30% TBP-kerosine (U) + 100 ml acid (FP)	24.8 34.0	2.52E-2 2.70E-2	Aqueous boiled over and quenched fire, 40% to 60% organic unburned
100 ml 40% TBP-kerosine + 100 ml acid (U + FP)	61.3 65.0	5.98E-2 7.09E-2	Burned to dry residue Burned to dry residue
50 ml 40% TBP-kerosine + 150 ml acid (U + FP)	40.0	1.7E-3	~40% organic unburned
50 ml 30% TBP-kerosine (U) + 150 ml acid (U + FP)	57.3	1.56E-2	Unburned organic residue
50 ml 30% TBP-kerosine (U) + 100 ml acid (U + FP)	51.0	8.09E-3	Unburned organic residue

3.3.1.5 Airborne Release During Combustion TBP-Kerosine

The airborne release of cesium, thorium and cerium was measured in tests using both small (78.5 cm^2) and large (0.4 to 5 m^2) surface areas for combustion of TBP-kerosine process solvent (Malet et al. April 1983). The experimental apparatus is shown in Figures A.11 and A.12 in Appendix A. In both cases, the solvent traced with materials to represent the behavior of heavy metal and fission product elements was held in metal trays and heated by electric heaters. Air was drawn through the test vessel to exhaust systems that collected the airborne materials. The transfer coefficient in air was determined by:

[initial mass element] - [final mass element]/initial mass element.

The decontamination factor was determined by:

[initial concentration element] x [volume]/mass collected on filter.

The pertinent results taken from the referenced documents (see Tables A.20 and A.21 in Appendix A) are presented in Table 3-15..

Table 3-15. Measured ARFs/RFs for Uranium Airborne During Gasoline Fires on Various Surfaces Involving UNH and Air-Dried UNH (Table III - Mishima and Schwendiman August 1973)

Substrate	Uranium Form	Air Velocity, m/s	ARF	Rate Fraction/hr	RF
Sandy soil	liq. UNH	1.0	1.7E-5	3.0E-6	0.75
		10	5.4E-3	4.0E-2*	0.40
Vegetation on sandy soil	air-dried UNH	1.0	9.6E-4	2.0E-4	0.78
		10	2.0E-3	4.0E-4	0.86
		1.0	7.4E-5	1.0E-5	0.64
			4.0E-4	6.0E-5	0.18
Asphalt		10	1.2E-3	2.0E-4	0.32
	liq. UNH	1.0	4.1E-4	1.0E-3*	0.70
Stainless steel		10	2.4E-3	6.0E-3	0.68
	liq. UNH	1.0	1.4E-2	6.0E-2	0.40
		10	1.14E-1	6.0E-1	0.34

* Calculated based on actual burn time for gasoline fire.

The transfer coefficient appears to be the fraction of the trace element not recovered from the test apparatus after the run. Others have experienced difficulties with recovering/detecting various elements in the residues from the combustion of TBP-kerosine solvents. The decontamination factor is the fraction of airborne material carried to the collection filters, although it appears that only the initial airborne concentration was used for the estimates (the concentration may have varied during the run). The ARFs reported from other studies are generally the fraction of the material used in the experiment that is carried to the collection filters that are within a few feet and the exhaust gases relatively contained from the point of origin to the collector. The fraction reaching filter is the transfer coefficient multiplied by the reciprocal of the decontamination factor. Thus, ARFs reported from other studies should be smaller than the transfer coefficient but greater than the fraction reaching filter. The values are within an order of magnitude or two for the cesium and cerium used for the small scale and large scale experiments and are considered to corroborate those values.

3.3.1.6 Airborne Release of Uranium During the Burning of Process Solvent

Jordan and Lindner (September 1983) performed small-scale burning experiments using TBP-kerosine mixtures without an aqueous phase. The experimental apparatus is shown in Figure A.13 and the uranium release as a function of the uranium concentration in the solvent is shown in Figure A.14 in Appendix A. The decomposition of nitric acid or

nitrates extracted into the solvent resulted in additional surface disturbance during burning. The ARF for uranium dissolved in the combustible liquid increased with uranium concentration and appears to range from 2E-3 to 2E-2. A bounding value of 1.5-2 was selected by the authors and is consistent with uranium release reported above in the absence of an aqueous phase.

4.0 SOLIDS

4.1 SUMMARY OF RECOMMENDED BOUNDING ARFS/ARRS AND RFS

Metal

Thermal Stress: Plutonium

- Airborne Release of particulates formed by room temperature oxidation (corrosion). Based upon the experimental measured values, the bounding ARRs, RFs recommended for the four situations covered are:

bounding (unalloyed Pu)	ARR (dry air) 2 μg Pu/cm^2-hr; RF 0.7
	ARR (100% RH) 7 mg Pu/cm^2-hr; RF 0.7
(delta-phase metal)	ARR (dry air) 0.07 μg Pu/cm^2-hr; RF 0.7
	ARR (100% RH) 0.6 mg Pu/cm^2-hr; RF 0.7

- Airborne release of particulates formed by oxidation at elevated temperature, greater than room temperature but less than self-sustained oxidation (ignition). The bounding values recommended apply to static oxidation at elevated temperatures less than ignition temperatures. The material-at-risk is the amount of oxide present under the specific accident conditions. If oxidation is not complete, Table 4.2-2 from Stewart (1963) showing plutonium oxidation rates or Haschke's (July 1992) value can provide a basis for such estimations.

  bounding — ARF 3E-5/RF 0.04.

- Airborne release of particulates formed by self-sustained oxidation (molten metal with oxide coat), self-induced convection. The bounding values recommended apply to situations involving the self-sustained oxidation in air of metal pieces under self-induced convection. Mishima's (1965, 1966) values exceed the combined value (ARF X RF) for all other measurements and are recommended for this situation.

  bounding — ARF 5E-4/RF 0.5.

- Airborne release of particulates from disturbed molten metal surfaces (flowing metal, actions resulting in continual surface renewal), high turbulence at surface, violent airborne reaction. The bounding values recommended apply to situations where ignited-molten plutonium is disturbed by direct impact of high air velocities such as during free-fall, sparking, energetic surface reaction as during the conversion of hydride to oxides. The 95% confidence limit ARF/RF values recommended by Carter and Stewart (September 1970) appear to bound the experimentally measured values reported.

formation, the solubility of the airborne oxides formed from plastic deformation and ignition of the thin film of metal generated by the impact of penetrators against hard targets is recommended to be of 50% "Y" class and 50% "D" class.

median	ARF 2E-3/RF 1.0
bounding	ARF 1E-2/RF 1.0.

- Airborne release from explosive dispersal of molten uranium. The airborne release values for the explosive release of molten uranium indicate that, if the uranium is molten and subdivided in very small drops (as by the exploding wire technique) and ejected into air at sonic velocities (as by the electrodynamic thruster technique described), all the uranium could be made airborne as a very fine particulate material (1.0 as particles/aggregates 10 μm AED and less) (Rader and Benson June 1988). The solubility class of the airborne material is anticipated to be like the airborne material formed during the impact of staballoy penetrators against hard targets such as armor (thin film formed by the plastic deformation of the metal in passage through the armor is ignited by frictional heat and rapidly cooled in the air). The maximum solubility values reported for the type of situation are 50% "D" class + 50% "Y" class.

bounding	ARF 1E+0/RF 1.0.

Explosive Release

- Shock Effects. For detonations in or contiguous to metal, a bounding ARF X RF of the mass of inert material equal to the mass of the TNT Equivalent estimated.

- Blast Effects. No significant airborne release is postulated for this configuration.

Venting of Pressurized Gases Over Metal

See the discussion of Venting of pressurized powders in this summary of Subsection 4.4.3.

Free-Fall Spill/Crush Impact

No significant airborne release is postulated for this accident configuration.

Aerodynamic Entrainment (Resuspension)

Based upon assumption that the airborne release during corrosion of plutonium metal is equal to the aerodynamic entrainment (resuspension) of the corrosion product from the metal surface, bounding ARF;RF values for this configuration are recommended for both unalloyed and delta phase metals:

bounding (unalloyed metal):	ARR (dry air) 2 μm metal/cm^2-hr;RF 0.7
	ARR (100% RH) 7 mg metal/cm^2-hr;RF 0.7
(delta-phase metal):	ARR (dry air) 0.07 μm metal/cm^2-hr;RF 0.7
	ARR (100% RH) 0.6 mg metal/cm^2-hr;RF 0.7.

Solids That Undergo Brittle Fracture (e.g. aggregates, glass)

No data are available to support recommended bounding values for thermal stress or blast or shock effects from explosive release.

Venting of Pressurized Gases over Solid

The entrainment of the material is a function of the characteristics of the flow over the particulate material that may be lying on the surface, the particles, and the surface. Some of the flow characteristics are dependent on the initial pressure and the size of the vent. No bounding ARF/RF can be recommended at this time.

Free-Fall Spill/Crush-Impact

The ARF X RF for the fragmentation of a solid that can undergo brittle fracture can be estimated by:

$$PULF = A\ P\ g\ h\ (J \text{ per } 10^7\ g\text{-}cm^2/s^2)$$

where: PULF = fraction pulverized into 10 μm and less size range
A = empirical correlation, 2E-4 cm^3/J (J = kg-m^2/s^2)
P = specimen density, g/cm^3
g = gravitational acceleration, ~960 cm/s^2 at sea level
h = height, cm.

Aerodynamic Entrainment (Resuspension)

For the aerodynamic entrainment of any particles of the solid material lying on the surface, see Aerodynamic Entrainment (Resuspension) of Powders.

000099

Powders

Thermal Stress

For the recommended bounding ARF/RF for various plutonium compounds subjected to thermal stress (temperature < 1000°C, natural convection, the total mass of size fraction can not exceed mass of this size fraction in source material.

Bounding (non-reactive compounds)	ARF 6E-3/RF 0.01
(reactive compounds except PuF_4)	ARF 1E-2/RF 0.001
(PuF_4)	ARF 1E-3/RF 0.001.

Explosive Release

No data are available for shock effects. For blast effects, the following bounding values were identified:

- Accelerated airflow parallel to surface. / Explosion ARF / RF

  bounding ARF 5E-3/RF 0.3.

- Deflagration of limited volume of flammable mixture above powder (volume mixture less than 10% free volume above powder). The RF is limited to the mass present in the source powder.

  bounding ARF 1E-1/RF 0.7.

- Deflagration of large volume of flammable mixture above powder.

  bounding ARF 1E+0/RF 1.0.

Venting of Pressurized Powders

Venting of pressurized powder or the venting of pressurized gases through a powder, <3.4 MPa:

median	ARF 5E-2/RF 0.4
bounding	ARF 1E-1/RF 0.5.

Free-Fall Spill of Powders/Shock-Impact

For the free fall spill of cohesionless powders:

- Fall distance <3 m, air velocity normal to powder flow <1 m/s

  median Earthquake ARF 3E-4/RF 0.5
  bounding ARF 2E-3/RF 0.3.

- Fall distance >3 m, air velocity normal to powder flow <1 m/s. Apply the calculations outlined in Subsection 4.4.4.3 provided ARF/RF values exceed 2E-2/0.3.

- Air velocities normal to direction powder flow >1 m/s (suspension of solid dispersed into flowing air. The mass airborne in the RF is limited by the total mass of material in this size fraction in the source material.

  ARF = 0.0134 U + 0.00543, RF 1.0

  where U = windspeed, m/s. High wind

- Suspension of powder due to vibration of substrate from shock-impact due to falling debris.

  bounding ARF 1E-3/RF 0.1.

Aerodynamic Entrainment (Resuspension)

Based upon the information on resuspension factors and rates found in the articles reviewed and the outdoor rates, the long-term ARR suggested by Sehmel and Lloyd (1976) appears to be reasonable bound, 4E-5/hr. Although ARRs appear to decrease with time, use of the initial ARR measured would be conservative. The ARR should also be applied to the residual material-at-risk that is being depleted by the entrainment. Not including this depletion of the source with time also tends to overestimate the release. The resuspension tends to fluctuate as the level of stress fluctuates and the surface conditions respond to the previous stresses. After an event, the powder released may be exposed to primarily aerodynamic stresses within the facility or remnants of the facility until remedial action can be taken. The time interval of exposure would be hours rather than seconds. Based on indications from a single experimental study, if the powder is shielded by remnants and debris of the structure or exposed to static conditions within the structure and the bounding ARR/RF for powder under the debris is small, the bounding ARFs/RFs for aerodynamic entrainment due to the passage of vehicular traffic and from the shock-impact of falling debris are the maximum measured experimental values. The total mass of material airborne in these size fractions is limited by the mass of material in the size fraction in the source material.

000101

- Homogeneous bed of powder exposed to ambient conditions (normal process facility ventilation flow or less, or atmospheric windspeeds <2 m/s) following an event

  bounding — ARF 4E-5/hr, RF 1.0.

- Homogeneous bed of powder buried under structural debris exposed to ambient conditions or under static conditions within the structure following an event

  bounding — ARF 4E-6/hr, RF 1.0.

- Entrainment of powders from road surface by passage of vehicular traffic.

  bounding — ARF 1E-2/passage, RF 1.0.

- Suspension of thick beds of powder by impact of/turbulence generated by falling objects, air velocity <1 m/s

  median — ARF 4E-4/RF 0.2
  bounding — ARF 1E-2/RF 0.2.

4.2 METALS (PYROPHORIC, SELF-SUSTAINING OXIDATION AT ELEVATED TEMPERATURES)

4.2.1 Thermal Stress

Most metals react with oxygen in some fashion beginning at room temperatures. At low temperatures, the reaction rates may be so slow that the oxidation is not readily recognized, or a protective oxide film may form that limits/reduces additional oxidation. Many metals generate heat from the oxidation reaction. Metals that attain a self-sustaining reaction at ambient temperature are called pyrophoric. Some nuclear metals (uranium, plutonium) can achieve a self-sustaining reaction at elevated temperature dependent upon surface-to-volume ratio and heat transfer conditions. Initially the oxidation rate is a function of the temperature; when heat is externally supplied and generated by the oxidation reaction, the kinetic controlled regime exists. At some temperature (a function of the balance between the heat available and the heat loss), the reaction becomes self-sustaining (plutonium ignition temperature ~500°C), and the reaction rate and the temperature become limited by the diffusion of the oxygen to the reaction interface. Under these conditions, known as the diffusion-controlled regime, temperatures range from 900° to 1100°C and plutonium (mp 641°C) is molten but uranium (mp 1132°C) is not. Both metals may form protective suboxide films at the interface that are adherent, but more stable oxides are formed as the

depth of the oxide layer increases. The matrix spacing for the some oxides is sufficiently different from the metal phase spacing that the oxide is non-adherent and can be made airborne by sluffing of the oxide from the oxidizing mass and entrainment in the convective currents generated by the heated metal. Other heat sources such as fires may also generate convective currents that may carry the airborne materials once ejected from the oxidizing mass. High temperatures (> 1000°C) may coarsen the size distribution of the residual powder or reduced suspension by sintering the powder oxide.

4.2.1.1 Plutonium

Haschke (July 1992) reviewed and evaluated the data on the oxidation of plutonium. "The oxidation is a 'paralinear' process involving three stages. ... has the functionality characteristic of a diffusion-controlled process. As the thickness of the adherent oxide layer increases on the metal surface, the rate of oxygen diffusion through the layer decreases according to a parabolic curve like observed for stage I ... formation of oxide particles begins during stage II ... characterized by linear rate ... at onset of stage II, the thickness of the inherent product layer attains a critical value determined by buildup of stress induced by forming of low-density oxide (molar volume = 23.67 cm^3) on the high-density metal (molar volume 12.10 cm^3/mol). This stress is relieved by cracking and spalling of oxide layer ... stage III is a similar linear process entered after a transition period, but origin of this change is unknown." "... observed increase in particle size with increasing reaction temperature interpreted as combination of two factors ... metal hardness and malleability with temperature ... hardness decreases with temperature ... increasing malleability reduces stress generated at metal-oxide interface and promotes formation of thicker product layer before spallation ....indicates formation of centimeter sized hydride particles if reaction temperature equal or exceeds half the melting temperature of metal in degree centigrade ... second factor that may alter particle size is kinetic in nature ... spallation involves nucleation of crack at surface and propagation of those cracks through the stresses material with ultimate coalescence and formation of free particles. Nucleation and propagation both time dependent ... growth rate of oxide layer large compared to spallation rate at high temperature and formation large particles are favored, at room temperature the oxide growth rate is extremely slow and the longer time available for spallation favors extensive crack formation and small particle size ... largest diameter observed for low-temperature oxide is ~5 μm in diameter ..."

Condit (October 1986) reviewed the airborne release of plutonium metal under fire and explosion conditions. The factors that have or have not a significant impact on the airborne release of plutonium are listed in Figure 4-1 from that document. Five configurations are covered below based upon the temperature of oxidation and the airflow (turbulence) around the oxidizing material or oxide. Other experimental data covering the airborne release of plutonium during more energetic accident situations (i.e., nuclear

Little effect:

- Mass of the sample
- Area to volume ratio
- Gas flow rates
- Gas chemistry by itself (complex alloy interactions)

Significant effect:

- Tumbling of reaction products through the gas stream
- Temperature
  - Fraction decreases up to around 1500°C (oxide sintering)
  - Fraction increases at higher temperatures (Pu vaporization)
- Alloying of the Pu
- Chemical state of the Pu

Unknowns:

- Processes at high temperature
- Broader experience with alloying
- Age of Pu
  - Helium
  - Americium
- Optimum firefighting and cleanup techniques

Figure 4-1. What Affects the Aerosolization Fraction in Plutonium Burning? (Condit October 1986)

weapons accidents) indicate larger release fractions for the plutonium metal under these circumstances (ARF 1E-2) and would correspond to the configuration covered here of disturbed molten metal surface (e.g., flowing molten metal where surface is renewed allowing greater surface turbulence), high surface turbulence, and violent reactions.

4.2.1.1.1 Airborne release from room temperature oxidation (corrosion). Stewart (1963) observed no detectible change in appearance of a plutonium metal surface in 7 days at room temperature and dry air. In moist air, a loose coating of powder was evident. Only 0.1 of the airborne particles formed in 100% RH air were in this size range. The oxide removal rate (μCi/cm^2-hr) as a function of metal phase and humidity is shown in Figure 4-2 taken from the reference document. The ordinate is expressed in terms of μCi of activity/cm^2-s. Assuming the specific activity (7.4 X 10^{-2} Ci/g) quoted for weapons grade plutonium by Raabe (November 1978) and Eidson and Kanapilly (February 1983), the author calculates the maximum rates for unalloyed and delta-stabilized metal in dry or moisture saturated air to be:

unalloyed	(dry air) 2 μg/cm2-hr
	(100% RH) 7 mg/cm^2-hr
delta stabilized	(dry air) 0.7 μg/cm^2-hr
	(100% RH) 0.6 mg/cm^2-hr.

Figure 4-3 also from Stewart (1963) shows the size distribution of the particles obtained at various temperatures (only the metal type is specified for one distribution). The diameter of the particles is given as equivalent spheres indicating that the dimensions are Geometric Diameter and must be multiplied by the square root of the density of PuO_2 (11.46 g/cm^3) to approximate the AED. Using distribution A from the figure (material airborne under static conditions at all temperatures in air), the RF is between 0.6 and 0.7.

Chatfield (1968) conducted a series of experiments to measure the airborne release in air flowing at velocities from 10 to 80 cm/s involving both delta-alloy and unalloyed plutonium. Experiments were performed using both horizontal and vertical glass tubes with exterior resistance heating. The experimental configuration was such that particles >20 μCi were lost prior to sampling. Size distributions of the airborne materials were by Casella cascade impactors that yield AED. Figures 4-4 and 4-5 plot the rate of release of activity (μCi/cm^2-s) as particle 10 μCi AED and less for both delta-alloy and unalloyed plutonium in dry and saturated air as a function of the reciprocal of the absolute temperature. The data are plotted in this fashion to ascertain if the release rate is linearly proportional to the oxidation rate. Assuming the specific activity for weapons grade plutonium given by Raabe (November 1978) and Eidson and Kanapilly (February 1983) of 7.4 X 10^{-2} Ci/g, the author calculates airborne releases to be:

000105

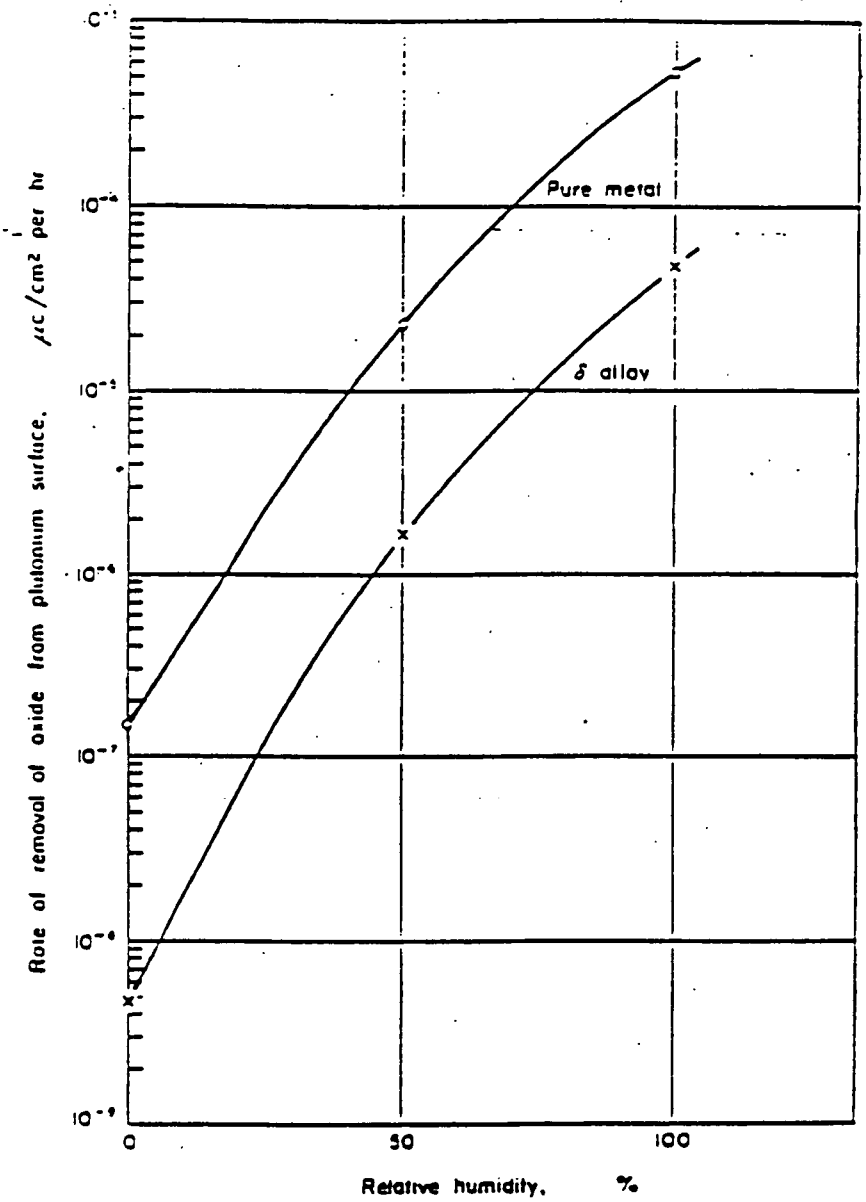

Figure 4-2. Dependence of Rate of Removal of Oxide Particulate from the Metal Surface on Humidity. Flow rates were:

Dry air	24 cm/s
Medium humidity	18 cm/s
Saturated air	14 cm/s

(Stewart 1963)

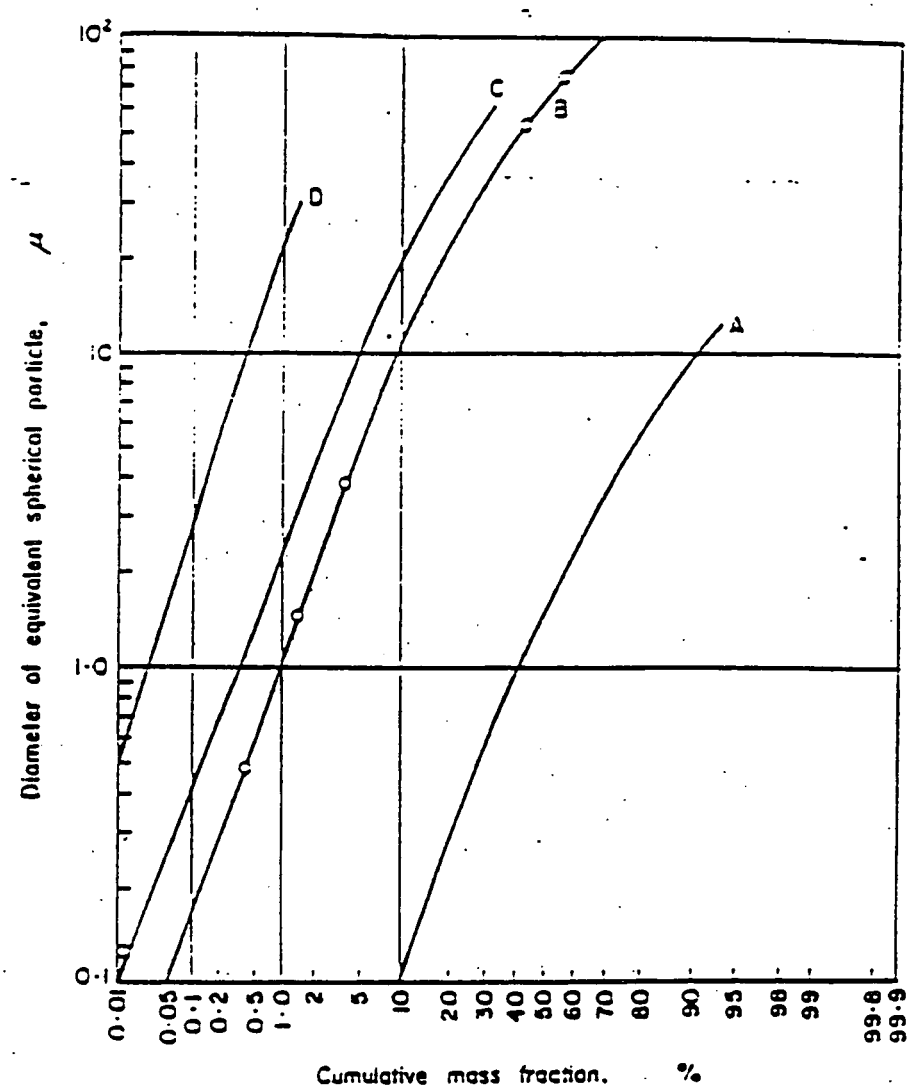

Figure 4-3. Particle Size Distributions Produced by the Oxidation of Plutonium Under a Variety of Conditions

Curve A	Material airborne under static conditions at all temperatures in air
Curve B	Oxide formed at 123°C from δ stabilized alloy
Curve C	Oxide formed at 400°C to 500°C
Curve D	Oxide formed above Ignition Point

(Stewart 1963)

000107

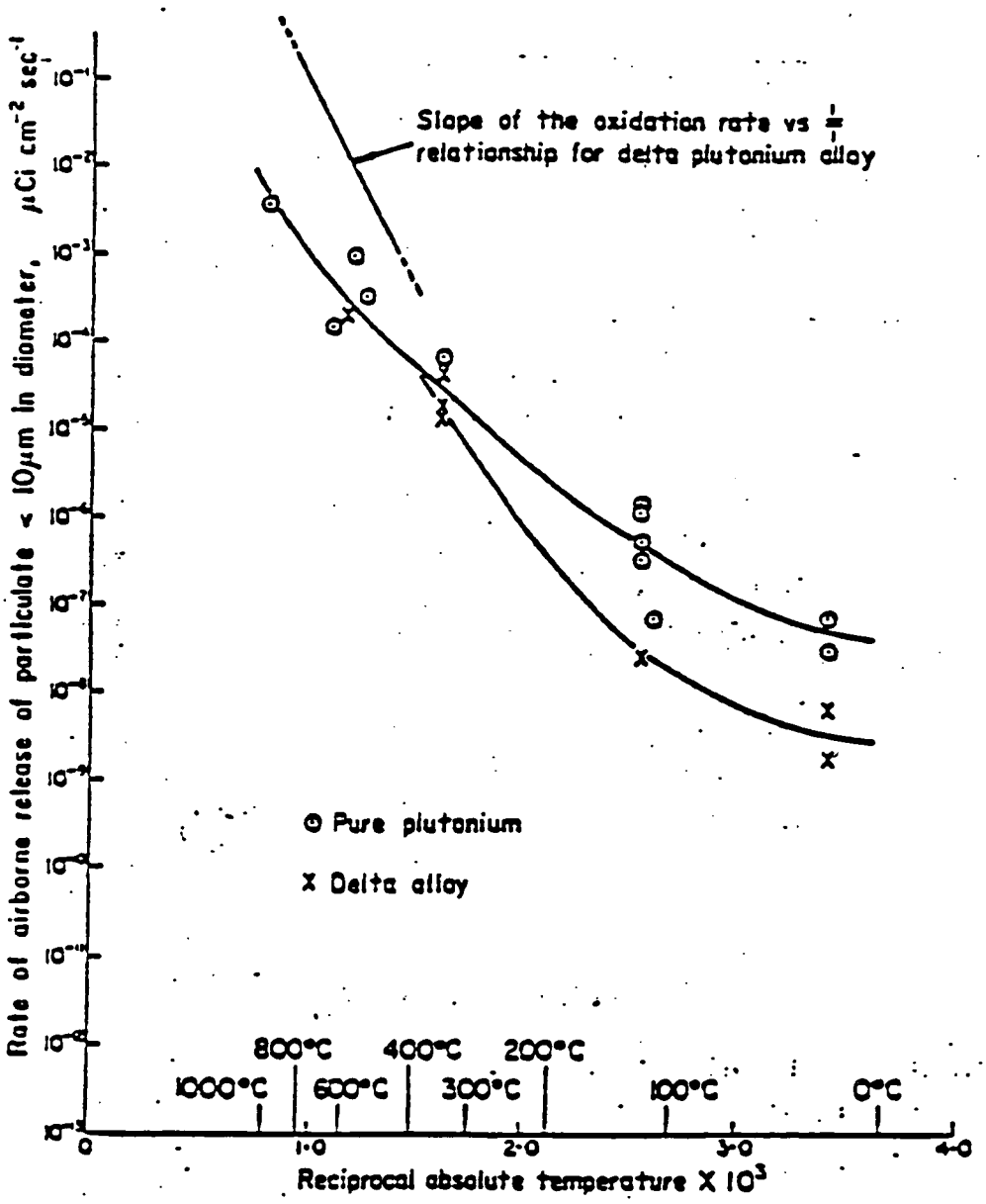

Figure 4-4. Release of Particulate Oxide Less Than 10 μm Diameter from Plutonium into Saturated Air

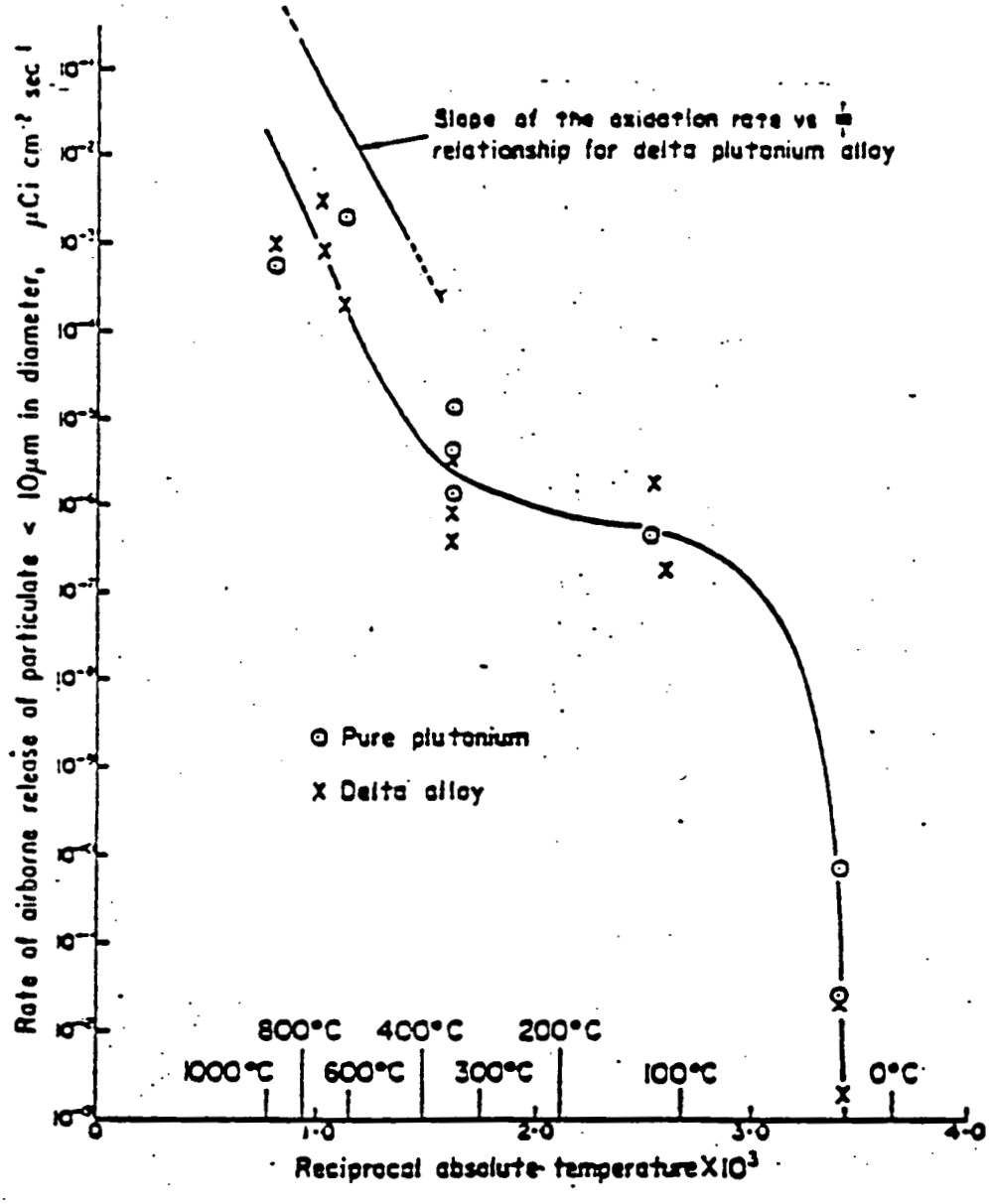

Figure 4-5. Release of Particulate Oxide Less Than 10 μm Diameter from Plutonium into Dry Air

000109

unalloyed	(dry air) 0.1 & 4μg Pu/cm^2-hr
	(100% RH) 2 & 4 mg Pu/cm^2-hr
delta-alloy	(dry air) 0.01 & 0.1 μg Pu/cm^2-hr
	(100% RH) 0.1 & 0.4 mg Pu/cm^2-hr.

The values are close to those from Stewart (1963) above.

On this basis, the recommended bounding ARRs/Rfs for the release from the room temperature oxidation (corrosion) of plutonium metal are:

unalloyed metal:	2 μg/cm^2-hr/0.7 (dry air)
	7 mg/cm^2-h/0.7 (100% RH)
delta-alloy	0.07 μg/cm^2-hr/0.7 (dry air)
	0.6 mg/cm^2-hr/0.7 (100% RH).

4.2.1.1.2 Airborne release of particulate formed by oxidation at elevated temperature (greater than room temperature but less than self-sustained oxidation). Stewart (1963) reported on the oxides formed by heating small pieces (less than 13 g) of unalloyed and delta-alloy plutonium metal to various temperatures in various atmospheres. Two shapes were used: billets (cylinder 0.7 cm diameter X 1.0 cm long) and swarf (turnings). Various experimental configuration were needed for different experimental conditions. The pertinent data are tabulated in Table 4-1 and the source data from the referenced document are found in Tables A.28, A.29a, and A.29b, and A.30 in Appendix A. The size distributions of the airborne materials are shown in Figures A.23 and A.24 in Appendix A.

At temperatures below the ignition temperature (experiments performed at 113° and 123°C), the unalloyed and alloyed metal behave differently. The oxidation rate for the delta-phase alloy was stepwise and two orders of magnitude less than for the unalloyed metal. The difference is attributed to the formation of a protective oxide film (the crystalline matrix spacing for delta-phase metal and the dioxide are very similar and the dioxide adheres to the metal surface). The film must crack and fall away before additional oxidation can occur. The particle size distribution of the bulk oxide is very wide (0.1 to 300 μm D_g). The oxidation and release rate were continuous during the oxidation of unalloyed metal. Except for a single high release value measured for delta-phase metal at 123°C in low humidity air with a very low fraction oxidized (1.5E-3), the ARFs for both types of metal phases are bounded by a release of 3E-5 (also very low fraction oxidized) and ranging to a value of 6E-7. The measured size distribution as Equivalent Sphere for oxidation at this temperature is shown as slope B in Figure 4-3 for the delta-phase and the mass fraction for the RF can be approximated by using the mass fraction for particles 3 μm. Under this assumption, an RF between 0.02 and 0.04 is indicated. If the metal is not completely oxidized in the event, the

Table 4-1. Measured ARFs During Oxidation of Unalloyed and Delta-Phase Plutonium at Elevated Temperatures in Air (Tables 3, 5 and 7 - Stewart 1963)

Metal Phase	Temperature	Mass Specimen (g)	Humidity mg H_2O/l air	ARF
delta	123°C	7.483	0.03	1.5E-3 (0.033 oxidized)
delta	113°C	7.344	1.50	3.2E-5 (0.054 oxidized)
delta	123°C	8.602	16.0	4.8E-6 (0.035 oxidized)
beta		11.021	0.03	1.4E-6 (0.57 oxidized)
beta		10.802	8.0	1.1E-6 (1.0 oxidized)
beta		7.191	8.0	3.3E-6 (0.76 oxidized)
alpha	113°C	9.397	16.0	1.3E-6 (0.21 oxidized)
beta	123°C	11.265	16.0	5.6E-7 (0.17 oxidized)
beta		8.154	16.0	1.0E-6 (0.65 oxidized)

* Mass Median Diameter in micrometers Aerodynamic Equivalent Diameter.

ARF/RF must be applied to the fraction of material oxidized. Some indication of the oxidation rate can be obtained from measured rates (as mg of PuO_2/cm^2-hr formed) shown in Table 4-2 from early data taken from the referenced source. Haschke (July 1992) reported "the observed (oxidation) rate of 0.2 g PuO_2/cm^2-min is independent of temperature."

The airborne release rates of respirable particles can also be estimated from Figure 4-4 and 4-5 taken from Chatfield (1968) by converting the rates expressed in activity/cm^2-hr to mass/cm^2-hr as shown Subsection 4.2.1.1.1.

On the basis that an ARF of 3E-5 bounds the experimentally measured ARFs at elevated temperatures less than ignition as well as most of the data for measured release during the self-sustained oxidation of plutonium under natural convection covered in Subsection 4.2.1.1.2 [the geometric mean of the ARFs for this condition determined by Carter and Stewart (1970) is 7E-6], a ARF/RF of 3E-5/0.04 is recommended.

4.2.1.1.3 Airborne release of particulates formed by self-sustained oxidation (molten metal with oxide coat), self-induced convection. Stewart (1963) reported on the oxides formed by heating to various temperatures small pieces (less than 13 g) of unalloyed and delta-alloy plutonium metal in various atmospheres. Two shapes were used: billets (cylinders 0.7 cm diameter X 1.0 cm long); and swarf (turnings). Various experimental configurations were needed for different experimental conditions. The data for higher temperature oxidation (in the region of temperatures found during self-sustained oxidation)

Table 4-2. Summary of Oxidation Rates for Plutonium at Temperatures Below 100°C[1] (Stewart 1963)

Metal Phase	Temperature °C	Relative Humidity %	Oxidation Rate mg PuO_2/cm^2hr	Source
α	30 90 90 100	95 55 95 0	0.01 15 during 10-60 hr period 200 after initially slower rate[2] 0.04	Sackman 1960
α	35 75 75	20 0 50	0.01 6×10^{-4} 0.4	Waber et al. 1960
α	50 50	0 100	0.025[3] 0.04	Dempsey and Kay 1958
γ	30 90 90 100	95 55 95 0	0.01 0.2 0.4 0.006	Sackman 1960

[1] The data have been extracted from graphs presented by the authors quoted and are intended to give a general trend only.

[2] The oxidation rates during the initial phase were much smaller; about 2 and 4 mg PuO_2cm^2hr at 55 and 95 per cent relative humidity, respectively. From the results of more recent studies it appears that the onset of such rapid corrosion is exceptional and may be due to impurities in the metal and its pretreatment (Sackman, private communication).

[3] This rate applied up to 20 hr and thereafter the weight of the sample remained constant.

are tabulated in Table 4-3, and the source data from the referenced document are found in Tables A.28, A.29a, A.29b, and A.30 in Appendix A. The size distributions of the airborne materials are shown in Figures A.23 and A.24 in Appendix A.

For oxidation of both delta-alloy and unalloyed metal at or above ignition temperature in air, the ARFs range from 1.5E-5 to 2.4E-3. The particle size distribution as a function of oxidation atmosphere conditions is shown in Figure 4-6 taken from the reference document. The highest ARF (2E-3 at 950°C in air) with the RF provided by the authors of 0.001 (in Figure A.22, Appendix A), the fraction of the source within offsite impact (ARF X RF = 2E-6) is less than that measured by Mishima (November 1966) of (ARF 5E-4 X 0.5 = 2.5E-4) ~3E-4.

Table 4-3. Measured ARFs During Self-Sustained Oxidation of Unalloyed and Delta-Phase Plutonium
(Tables 3, 5 and 7 - Stewart 1963)

Phase	Temperature	Mass Specimen (grams)	Atmosphere	Humidity mg H_2O/l air	ARF
delta	900°C	12.7	air	0.03	1.5E-5 (MMD 8 μm^1)
unalloyed	950°C	10.3		0.03	1.5E-5 (MMD 8 μm^1)
	630°C	15.06		0.03	2.4E-3 (MMD 11 μm^1)
delta	800°C	12.2		16.0	1.3E-4 (MMD 4.5 μm^1)
	895°C	1.95			6.0E-5 (MMD 2.1 μm^1)
delta	780°C	2.18			1.0E-4 (MMD 2.1 μm^1)
delta	820°C	1.15	carbon dioxide		(not self-sustaining)
delta		1.34	nitrogen		(no reaction)
delta	>1000°C	5.34	oxygen		2.1E-2 (violent reaction, MMD 0.3 μm^1)
delta	970°C	5.89	30% O_2: 70% N_2		1.8E-4 (0.25 oxidized MMD 29 μm^1)
delta	~1200°C	7.41	40% O_2: 60% N_2		1.9E-4 (MMD 16 μm^1)
delta	690°C	5.476	0 to 0.2 atm O_2		1.4E-4 (0.53 oxidized)
delta	625°C	5.476	0 to 0.099 atm O_2		5.4E-7 (0.17 oxidized)
unalloyed	620°C	7.216	0 to 0.167 atm O_2		1.2E-4 (0.12 oxidized)
	560°C	7.352	0 to 0.167 atm O_2		4.7E-5 (0.056 oxidized)

[1] Mass Median Diameter in micrometers Aerodynamic Equivalent Diameter.

Mishima (December 1965) measured the airborne release during the oxidation of unalloyed plutonium metal at elevated temperatures in flowing air and the size distribution of the residue. Right cylinders of unalloyed plutonium metal, 0.594 cm to 0.625 cm in diameter X 1.73 cm to 1.89 cm long, weighing 9.89 g to 11.34 g, were heated to temperatures exceeding the ignition temperature of the metal. Ignition temperatures ranged from 490°C to 500°C with temperatures (measured above the oxidizing specimen by thermocouple) during the complete oxidation of the specimens ranging from 410°C to 900°C. Air, at predetermined velocities ranging from 3.3 to 50 cm/s, was passed over the oxidizing specimen and particles entrained from the oxidizing mass were collected on a membrane filter. The size distribution of the powder residue was determined by a combination of sieving and air elutriation. The experimental apparatus is shown schematically in Figure A.15 and the measured results shown in Table A.24 in Appendix A. The pertinent data are shown in Table 4-4.

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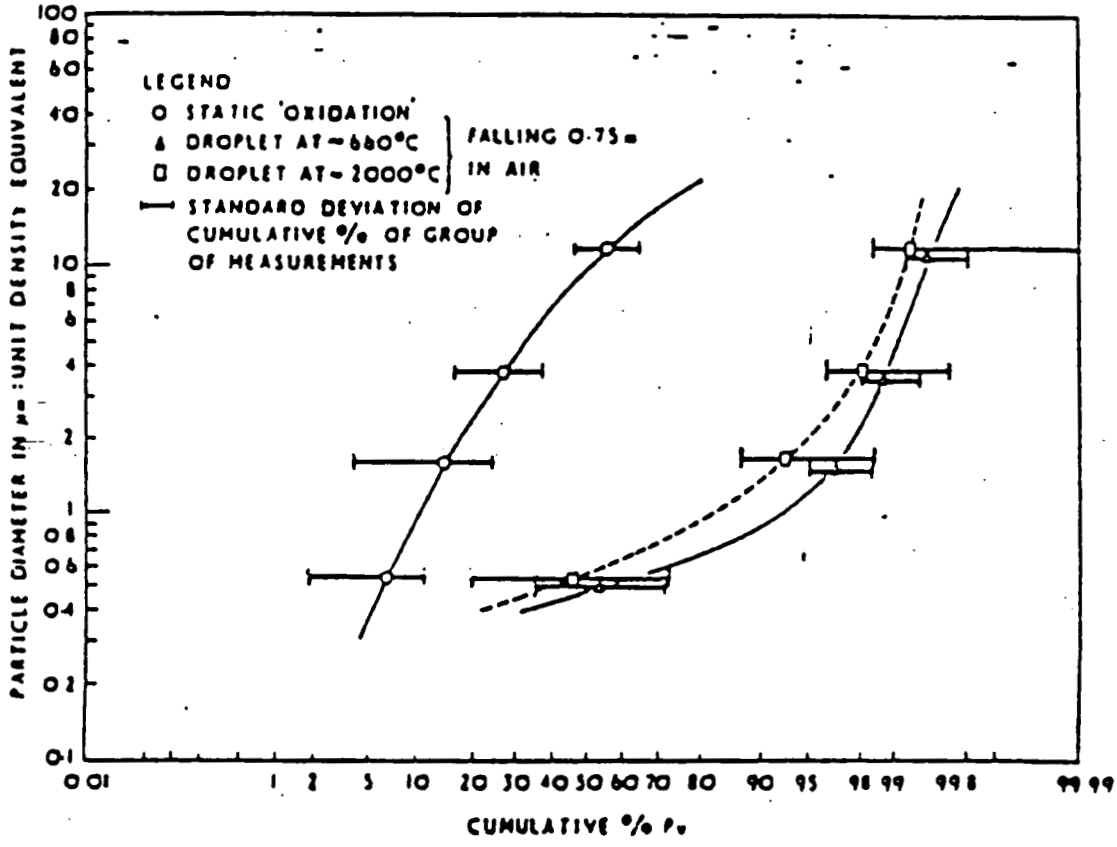

Figure 4-6. Representative Particle Size Distributions Obtained with Cascade Impactors for PuO_2 Aerosols Formed in Static and Dynamic Conditions

Table 4-4. Measured ARFs During Self-Sustained Oxidation of Unalloyed Plutonium Metal in Flowing Air (Table III - Mishima December 1965)

Sampling Duration (min)	Temperature Range °C	Air Velocity cm/s	ARF
155	Amb to 900°C	3.3	2.8E-8
74	Amb to 560°C	13.5	3.1E-7
75	Amb to 650°C	50.0	5.3E-7
146	Amb to 650°C	3.3	4.1E-8
153	Amb to 560°C	3.3	2.6E-7
117	Amb to 560°C	20.0	3.1E-8

The values appear to be lower than the ARFs reported by Carter and Stewart (1970) for the airborne release during the oxidation after ignition. The highest ARF is ~5E-7, an order of magnitude less than the geometric mean value specified by Carter and Stewart (1970). The measurements are limited and do not appear to be strongly influenced by any measured parameter (temperature, air velocity). A possible factor is the limited convective flow to entrain any particles ejected from the oxidizing mass due to the limited size of the specimen and the presence of a boat that may partially shield the oxide mass from the airflow. If the measurements represent almost comparable conditions, experimental variations for the measurements would be a factor of ~20. The fraction of the residual powder 20 μm AED and less was <3.1E-4. The material was friable and the value may represent some fraction of material fragmented during sieving.

Mishima (November 1966) reported the ARFs and RF from the self-sustained air oxidation of four large specimens of delta-phase and unalloyed plutonium metal. The three unalloyed pieces ranged in mass from 455.5 g to 1770 g. The single delta-stabilized specimen was 997 g. The metal specimen was placed within a ring made of insulating material set upon a sheet of insulating material (the metal would not self-sustain in the absence of the insulating material due to heat transfer to the metal enclosure). The top surface of the metal specimen was ignited with a heliarc torch. Air was drawn into a quartz chimney placed within one inch of the metal surface at a nominal velocity of 525 cm/s through the 2.685-in. (68-mm) i.d. chimney. Airborne material was collected on a glass fiber filter sealing the end of the chimney. Air was drawn through a side arm at 550 to 800 cm/s to collect airborne materials on a membrane filter for size distribution analysis by transmission electron microscopy. The experimental apparatus is shown in Figure A.16 and the results shown in Table A.25 in Appendix A. The size distribution measured for material airborne during the self-sustained oxidation of the largest metal specimen and considered representative of all measurements is shown in Figure A.17 in Appendix A. The pertinent data are listed in Table 4-5.

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Table 4-5. Measured ARFs During the Self-Sustained Air Oxidation Large Specimens of Unalloyed and Delta plutonium Metal (Table II - Mishima November 1966)

Total Sampling Time (min)	Weight Metal (g)	Form	ARF
90	569.8	Unalloyed	4.9E-4
45	1770	Unalloyed	1.4E-4
22	997	Delta	3.4E-5
60	455.5	Unalloyed	3.9E-6

With the limited data base, the ARFs do not appear to correlate with any measured parameter (mass, form) but Haschke (July 1992) reports that the airborne release is time-dependent. The largest ARF, ~5E-4, is in the range of but exceeds the 95% confidence level value (1E-4) specified by Carter and Stewart (1970). Although the masses are larger, the duration required for complete oxidation to self-extinguishment appear to be much less than required for much smaller specimens used by Mishima (December 1965) and the ARFs are two to four orders of magnitude larger. The principal differences between the conditions under which these measurements and the previous measurements were made are the specimen masses (larger) and air flow patterns (up and around at higher nominal velocities). The increase in ARFs are attributed to the higher convective flows and increased turbulence. The Mass Median Diameter shown in Figure A.17 is 4.2 μm Geometric Diameter and would approximate a 14 μm AED particle. Thus, an RF of 0.5 is a conservative assumption.

Carter and Stewart (1970) surveyed the data available primarily in the United Kingdom on the airborne release of plutonium during self-sustained oxidation. Based on the large body of data available, they recommended the following values for ignition and burning in air (melting), with air velocity less than 100 cm/s (static):

geometric mean	ARF 7E-6/RF 1.0
95% confidence limit	ARF 1E-4/RF 1.0.

Haschke (July 1992) reported in his conclusions "If the largest diameter of releasable is assumed to be 10 μm, the maximum releasable mass fraction for plutonium+O_2 is 0.0007 ...". Tables II through V that list the distributions state "Particle diameters are geometric, not aerodynamic." The fact that all estimates are geometric diameters, not AED was confirmed in conversations with the author. If the GSD is assumed to be 2.0, the mass fraction of particles 10 μm AED and less would be two or more orders of magnitude less. Thus, the ARF/RF 5E-4/0.5 from Mishima's data above that results in a mass fraction of 10 μm AED and less particles of 2.5E-4 certainly would bound Haschke's results.

Based on the results reported for this configuration, a bounding ARF/RF of 5E-4/0.5 is recommended.

4.2.1.1.4 Airborne release of particulates from disturbed molten metal surface (flowing metal, actions resulting in continual surface exposure of molten metal), high turbulence, and violent airborne reaction. Stewart (1963) reported on the oxides formed by heating small pieces (less than 13 g) of unalloyed and delta-alloy plutonium metal to various temperatures in various atmospheres. Two shapes were used: billets (cylinders 7 mm diameter X 10 mm long) and swarf (turnings). Various experimental configuration were needed for different experimental conditions. The data for higher temperature oxidation (in the region of temperatures found during self-sustained oxidation and other pertinent information are covered in Subsection 4.2.1.1.3. Results of one experiment in pure oxygen, which resulted in a violent reaction, are shown below:

> delta-phase plutonium, >1000°C, 5.34 g, atmosphere oxygen, ARF 2.1E-2, violent reaction, MMD 0.3 μm[3]) ...

Carter and Stewart (1970) reported the results of experiments to determine the ARF/RF for plutonium under fast reactor processing conditions. Two types of experiments to measure airborne release and particle characteristics were performed: free fall of ignited metal droplets and exploding wires. The ignited metal drop experiments were conducted in a 14-m diameter X 75-m tall vertical cylinder with a resistance furnace on top. The dimensions were limited by the size of the glovebox for delta-alloy Pu experiments. Taller tubes were used for the U experiments conducted. The metal was heated in the resistance furnace to the predetermined temperature. An upflow of air adequate to entrain particles <30 μm AED was passed through the cylinder. For static experiments (air velocities <1.0 m/s), the Pu was heated in air and the residue crumbled/disintegrated into the cylinder. For the 660°C experiments, the Pu was heated in argon to the desired temperature and fell through the upflow of air in the cylinder (ignited and attained temperature equivalent to ignited Pu below?). For the 2000°C (estimated from the temperature of ignited Pu in previous experiments) experiments, Pu metal was heated in air until ignited and allowed to fall through the upflow of air in the cylinder.

The morphology of the airborne particle from the free-fall drop of ignited metal appear to be very similar to that from the exploding wire experiments (see Table A.22 in Appendix A - Comparison Between Exploding Wire Aerosol and Droplet Fume in Liquid Suspension). Both show a wide size range of spherical particles with a significant number >1 μm AED. Sparking (incandescent airborne material) of the metal during the fall or on

[3] Mass Median Diameter in μm Aerodynamic Equivalent Diameter.

impact indicated the presence of large (0.1 to 1.0-mm) spherical particles in the residual powder and the presence of airborne vapor.

The total metal dispersed as particles or aggregates 10 μm unit density spheres (AED) or less was determined for each experiment. Figure 4-6 taken from Carter and Stewart (1970) shows representative distribution for the three major experimental regimes. The geometric mean value and, based on a graphic extrapolation of the values as a function of the probability of exceedance, the 95% confidence value. The geometric mean and 95% confidence total Pu airborne dispersion as a function of accident stress are shown in Table A.23 in Appendix A. The ARF/RF for the various conditions are:

geometric mean	ARF 3.5E-3/RF 1.0
95% confidence limit	ARF 1E-2/RF 1.0.

Both Mishima (August 1964) and Kanapilly (March 1982) reported on the measured ARF from Pu metal suspended over a gasoline fire. Two 100-gram Pu rods were suspended in a metal basket over a ignited pool of gasoline in a 4-ft square X 11-ft tall chimney. Estimates of the airborne released based on weight loss gave the highest values but difficulties in recovery of the residual materials creates substantial uncertainty in the estimates. The authors quote 5E-4 as a bounding ARF value. Stephens (July 24, 1992) reports that "Stewart, in his Vixen report, is clear about his interpretation of release fraction ... 'dispersed as oxide if combustion to loose oxide is complete.' Stephens estimates, based upon his discussions with Stewart, that the ARFs for the two tests are 0.74% (7.4E-3) and 0.84-0.94% (8.4E-3 - 9.4E-3). "The average ... is 0.84%, which Stewart quotes as about 1%."

Eidson and Kanapilly (February 1983) measured the airborne release from heating small specimens of delta-stabilized Pu metal in various gas mixtures. The atmospheres were air, inert (argon), reducing (hydrogen or hydrogen-nitrogen in argon) and gas mixture from the decomposition of fuel or Insensitive High Explosives. Pu metal pieces 0.5 g and 1.0 g are placed in tantalum crucible with a boat underneath to collect any powder residue that fell out of the crucible. A heated reaction atmosphere was introduced into the stainless steel foil-lined quartz tube surrounding the crucible-boat and passed into a foil-lined aerosol chamber. The particulate materials passing through the apparatus were collected on filters sealing the apparatus and exhaust. Airborne release was the summation of the activity collected on the filters and estimates of deposition based upon the activity collected on the foil samples extrapolated to the entire surface area of the tube and aerosol chamber. In later experiments, the entire tube and chamber were lined and provided estimates of deposition that appeared to be lower than estimates used in the earlier experiment. Size distribution and morphology of the airborne material are based upon transmission electron microscopy of material collected in the aerosol chamber. A schematic drawing of the system is shown in Figure A.18 and the

experimental results shown in Table A.26 in Appendix A. The pertinent experimental data and measured ARFs reported are shown in Table 4-6.

The ARFs appear to be in reasonable agreement (order of magnitude) with the ARFs specified by Carter and Stewart (1970) for Pu metal burning in air or melting. The maximum measured ARF is ~5E-3 exceeding Carter and Stewart's 95% confidence level value (1E-4), and that measured by Mishima (November 1966) (5E-4). The bounding ARF measured is from the values determined during the initial experiments and, according to the authors, may well be overestimated. The median ARF is 3E-5 with an average value of ~3E-4.

The size distribution of the residual powder were determined by a combination of 320 mesh sieve (~62 μm LLD, Least Linear Diameter - the sieves are vibrated during use to cause the particle to bounce on the sieve screen and the material passing through the screen indicates that the non-spherical particles have at least one dimension of the size of the opening) and sedimentation measurements. The range of residual powder in the less than 62 μm LLD was 18% to 41% with MMDs (Mass Median Diameter - half the mass of the powder is associated with particle less than and half the mass of powder is associated with particle greater than the stated size) from 5.7 to 7.5 μm D_g. The material was primarily PuO_2 (x-ray diffraction) with some unburned metal particles. The authors conclusions were that 1) atmosphere and temperature affected the formation of the powder residue but did not affect aerosol formation and, 2) mass-to-surface ratio did not have a discernible affect on aerosol formation under the experimental conditions.

The size distribution measured for the airborne particles under various conditions of atmosphere and temperature are shown in Figures A.19 and A.20 taken from the reference document. In all cases, the RF (particles 10 μm AED or less) range from 0.05 to 0.5.

Eidson, Yeh, and Kanapilly (1988) reported the airborne release and size distribution from heating 1-gram or 10-gram pellets or foil to 450°C in a reducing atmosphere followed in some cases by heating the powder produced in air. Gas velocities over the reacting materials ranged from 0.4- to 10-m/s in the 24-mm i.d. quartz reaction tube. The airborne materials were collected on a glass fiber filter or sized in a 7-stage cascade impactor. Point-to-plane electrostatic precipitator samples were taken for transmission electron microscopy to characterize the airborne materials. The pertinent data are shown in Table 4-7 with the data from the source document in Table A.27 in Appendix A.

The bounding ARF/RF is 5E-3/1.0 with a median value of 2E-4/1.0. There does appear to be a detectible effect by the atmosphere present or surface to mass ratio. The MMD of the residual powders ranged from 4 to 350 μm Stokes diameter (equivalent sphere).

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Table 4-6. Measured ARFs for Heating Small Specimens of Delta Phase Pu Metal in Various Atmospheres (Table A-2 - Eidson and Kanapilly February 1983)

Reaction Atmosphere	Mass of Specimen (g)	Temperature (°C)	ARF
argon (air)	0.1	1000	1.7E-4[1]
argon	0.5	1000	1.2E-5[1]
argon + IHE ash	1.0	1000	1.6E-5
air	0.5	23	2.4E-5[1]
	0.5	450	1.6E-4[1]
	0.5	450	2.0E-5[1]
	1.0	1000	9.0E-6
3% H_2 + argon	0.5	100	5.7E-6[1]
	0.5	200	1.5E-3[1]
	1.0	200	1.0E-5
	0.5	450	2.8E-5[1]
	0.5	450	4.1E-5[1]
	0.5	450	9.6E-5[1]
	1.0	450	3.7E-5
	0.5	650	1.4E-5[1]
	1.0	650	5.1E-5
	0.5	200 - 1000	8.8E-5
	1.0	100 - 450	1.3E-4
3% H_2 + 5% N_2 + argon	0.5	100	1.8E-5[1]
	0.5	450	1.5E-5[1]
	0.5	450	5.2E-3[1]
	1.0	450	2.3E-5
	0.5	650 - 750	5.2E-6[1]
Kel-F + argon	0.5	450 - 650	1.0E-5
Kel-F #800 + argon	0.5	450	2.5E-4
	1.0	450	3.2E-5
Kel-F #800 + air	1.0	650	2.6E-5
complex (1)[2]	0.5	450	7.6E-6[1]
complex (2)[2]	0.5	450	2.8E-5
	0.5	650	2.4E-4
complex (2)[2] + No + H_20	1.0	200	1.3E-5
	1.0	450	1.2E-5
	1.0	1000	1.3E-5

[1] Values determined during initial experiments. May be overestimated.
[2] Complex = IHE combustion product surrogate ... (1) + 100 ppm O_2 ... (2) < 5 ppm O_2

Table 4-7. ARFs From Heating Small Pieces Delta-Phase Plutonium Metal Under Specific Conditions (Table 1 - Eidson, Yeh and Kanapilly 1988)

Atmosphere	Linear Flow Velocity cm/s	Pu Mass grams	Specimen Shape	ARF[1]
3% H_2 + Ar then air	500	0.94	pellet	1.1E-4
	1000	1.05	pellet	1.1E-3
	1000	0.92	pellet	7.4E-4
3% H_2 + Ar	500	1.08	pellet	3.7E-3
	1000	1.12	pellet	4.6E-3
3% H_2 + 5% N_2 + Ar	500	1.05	pellet	3.0E-4
	1000	1.13	pellet	6.6E-5
	1000	1.05	pellet	4.5E-4
	40	1.39	foil	9.2E-5
	40	9.63	pellet	1.2E-5
	40	10.22	foil	8.5E-6
3% H_2 + Ar	40	1.40	foil	2.8E-4
	40	9.62	pellet	1.8E-5
	40	9.64	foil	4.2E-4

[1] All in the respirable fraction defined in this study as particles 5 μm AED and less.

The Activity Median Aerodynamic Diameter (AMAD), in which half the activity in the sample is associated with particles less than and half the activity is associated with particle greater than the stated size), for the airborne materials measured by cascade impactor ranged from 4 to 10 μm AED.

Chatfield (1969) measured the Pu airborne during the combustion (oxidation after ignition) or explosive release of unalloyed Pu foil encased in sodium. The oxidation experiments were performed in a horizontal glass tube externally heated by a resistance furnace. Air or gas, at a velocity of 0.8 m/s, was drawn through the tube over the Pu foil encased in a rectangular block of Na held in a nickel or tantalum boat to sampling equipment (Casella Mk 3 cascade impactor or membrane filter). The Pu-Na was heated in an argon flow to a temperature of 300°C and the flow switched to air. The results from these experiments are shown in Table A.31 (Tables #1 & #2 from the source document) in Appendix A. The ARF are presented as μCi of activity released but no specific activity for the source material was given. Under the assumption that the Pu is "weapons grade" material similar to that specified in Eidson and Kanapilly (February 1983) and Raabe et al. (November 1978) with a specific activity of 7.4 X 10^{-2} μ/g, the release fractions shown in Table 4-8 were estimated.

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Table 4-8. Airborne Release of Pu From Pu-Na Mixtures During Self-Sustained Oxidation (Table 1 - Chatfield 1969)

Weight Pu (grams)	Activity in Source (μCi)	Fraction Activity Airborne (μCi)	Mass Fraction Pu Airborne	RF[1]
0.0549	4.06E+3	1.7E-3	4.2E-7	0.88
0.0570	4.22E+3	1.5E-3	3.6E-7	0.80
0.0644	4.77E+3	1.8E-3	3.8E-7	0.72
0.0830	6.14E+3	1.5E-2	2.4E-6	0.40
0.1021	7.56E+3	5.0E-2	6.6E-6	
0.0899	6.65E+3	2.8E+0	4.2E-4	0.98
0.0946	7.00E+3	8.0E-2	1.1E-5	
0.1069	7.91E+3	5.6E-2	7.1E-6	
0.0732	5.42E+3	4.0E-3	7.4E-7	
0.0710	5.25E+3	5.0E-2	9.5E-5	
0.0981	7.26E+3	4.7E+1	6.5E-3	0.28
0.0900[2]	6.66E+3	1.8E-1	2.7E-5	0.11
0.0763[3]	5.65E+3	5.5E-2	9.7E-6	0.27
0.0651[3]	4.82E+3	2.1E-1	4.4E-5	0.41
0.0915[4]	6.79E+3	3.5E-2	5.3E-6	0.12

[1] Pu size data presented as particles 11 micrometers and less AED (unit density spheres). Conservative assumption to include all material in respirable fraction.
[2] Pu as dioxide powder dispersed on sodium wire.
[3] No sodium used in this experiment.
[4] No ignition, Pu heated in argon only.

The authors concluded that 1) total airborne release was unaffected by the presence of sodium (the ARFs measured for the two experiments in which only Pu was present were well within the range of ARFs for the remaining experiments), 2) the fraction of airborne particles in the <11 μm AED fraction was higher when Na was present (0.28 to 0.98 vs 0.27 and 0.40), and 3) the fraction <3.7 μm AED is also higher. The fact that the presence of Na did not result in greater total airborne release under the procedure used (Pu-Na heated in argon with air suddenly introduced at temperature) is surprising in that the reaction as described appears to be very energetic. Perhaps the fact that the Na surrounded the Pu and reacted first may have limited oxygen availability and the Pu oxidation rate. Thus, Pu oxide may not have been generated until the greater part of the turbulence from the sodium reaction was terminated. The ARF measured for the experiment in which Pu was only heated resulted in an ARF (5.3E-6) that was in the range for the other experiments but the RF was low (0.12). The wide variability in ARFs could not be attributed to any cause.

The ARFs measured range from 3.6E-7 to 6.5E-3. The maximum ARF measured was 6.5E-3 that is in the range reported by Eidson and Kanapilly (February 1983) and

Stewart (1963), 1E-2. The median ARF measured is 7E-6 with an average of 5E-4. The ARFs for the 2 experiment involving only Pu were 9.6E-6 & 4.4E-5; and average value of ~3E-5. The RFs are 0.27 & 0.41 (an average of 0.34). The average RF for the 5 experiment involving Pu with sodium were 0.76; twice as high as for Pu only. Since the value exceeds the measured values for 5 experiments, the reported ARFs may be an order of magnitude less.

The data from Eidson and Kanapilly (February 1983) and Eidson, Yeh and Kanapilly (1988) was included in this configuration primarily because the intent was to determine airborne release under more severe accident conditions and other atmospheres. With a few exceptions (5 ARFs ranging from 1.1E-3 to 5.2E-3) the results would be bounded by the ARF/RF recommended for airborne release during self-sustained oxidation. These results are for specimen weights ~1 gram or less and in some cases (heating in hydrogen and argon atmospheres) would appear to represent ARF for hydrides. The other data appear to support Carter and Stewart's recommended values for ARF/RF of 1E-2/1.0.

4.2.1.1.5 Airborne Release of Particulates from Oxidation of Small (Hundreds of Micrometers Diameter) Molten Metal Drops Passing Through Air or Explosive Reaction of Entire Metal Mass. Carter and Stewart (1970) reported the results of experiments to determine the ARF/RF for plutonium under fast reactor processing conditions. Two types of experiments to measure airborne release and particle characteristics were performed: free fall of ignited metal droplets and exploding wires. The ignited metal drops were conducted in a 14-cm diameter X 75-cm tall vertical cylinder with a resistance furnace on top. The dimensions were limited by the size of the glovebox for delta-alloy Pu experiments. Taller tubes were used for the U experiments conducted. The metal was heated in the resistance furnace to the predetermined temperature. An upflow of air adequate to entrain particles <30 μm AED was passed through the cylinder. For static experiments, the Pu was heated in air and the residue crumbled/disintegrated into the cylinder. For the 660°C experiments, the Pu was heated in argon to the desired temperature and fell through the upflow of air in the cylinder (ignited and attained temperature equivalent to ignited Pu below?). For the 2000°C (estimated from the temperature of ignited Pu in previous experiments) experiments, Pu metal was heated in air until ignited and allowed to fall through the upflow of air in the cylinder.

For the exploding wire experiments, 50 to 400 mg of metal were violently dispersed by the discharge of a large electrical charge (4000 J) through the metal in a 3.5-liter chamber. The aerosol within the chamber was discharged ~1 min after formation via a cascade impactor (size distribution of airborne particles) and a membrane filter (transmission electron microscopy for morphology).

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Vapor formation from droplets (exploding wire, violent ejection molten droplets)

95% confidence limit ARF 5E-1/RF 1.0.

Raabe, et al. (November 1978) reported the ARF and size distribution of the fume made airborne during the free-fall of ignited drops of delta-phase plutonium metal. Small discs were cut from 50-μm-thick foil in the size range believed representative of fragments that could result from explosive damage. The discs were positioned on a very thin film of combustible material on top of a 0.15-m wide X 0.18-m deep X 3-m tall stainless steel chamber with a glass viewing window down the front panel. The disc were ignited by a laser (500°C, adequate to ignite but not to vaporize metal) and formed drops 50 to 500 μm in diameter. The ignited material fell down the chamber. Air was drawn through a perforated plate down through the chamber. Large particles were collected in a aluminum foil lined cup at the bottom of the chamber with airborne materials carried to aerosol samplers (seven-stage cascade impactor, spiral centrifuge, point-to-plane precipitator + glass fiber filters). The experimental apparatus is shown in Figure A.21

Up to 4E-1 of the source was airborne from the free-fall. The airborne material was primarily a web-like chain of crystalline, cubic particles 0.004 to 0.1 μm on a side with a few discrete spherical particles up to 0.5 μm in diameter. The AMAD of the aggregates was 1 to 2 μm with geometric standard deviations of $\sim$1.5. The size distribution of the airborne material from the free-fall of a 400-μm drop as determined by the spiral centrifuge is shown in Figure A.22 (Appendix A).

Chatfield (1969) reported results of exploding wire experiments were primarily to determine the morphology and solubility of the particulate materials generated. Plutonium wire, 0.75-mm, or plutonium wire encased in 2-mm sodium metal tubing were placed in heavy current electrodes in the side of a 2.5-liter vessel. Energy was accumulated in a capacitor bank was discharged at 4000 J at 10 kV vaporing the wire at a very high temperature (peak temperature $\sim$50,000K). The fume formed by the condensation was collected directly on carbon-coated electron microscope grids with the remainder exhausted through a membrane filter. All the Pu or Pu-Na involved was made airborne. The Pu fume was composed of linear aggregates of generally spherical particles $<$0.2 μm in diameter. It was observed that in some cases only particles of similar size appeared to form aggregates. The MMD of the aggregate was 1.4 μm with a very narrow distribution. The size distribution of the aerosol is plotted in Figure 4-7 taken from the referenced source and, since the diameters plotted are Geometric Diameters, indicates that essentially all of the airborne material is in the respirable fraction.

On the basis of the experimental data presented, the airborne material is either 4E-1/1.0 or 1E+0/0.5. Since the latter combination bounds these experimental values, a bounding ARF/RF of 1E+0/0.5 is recommended.

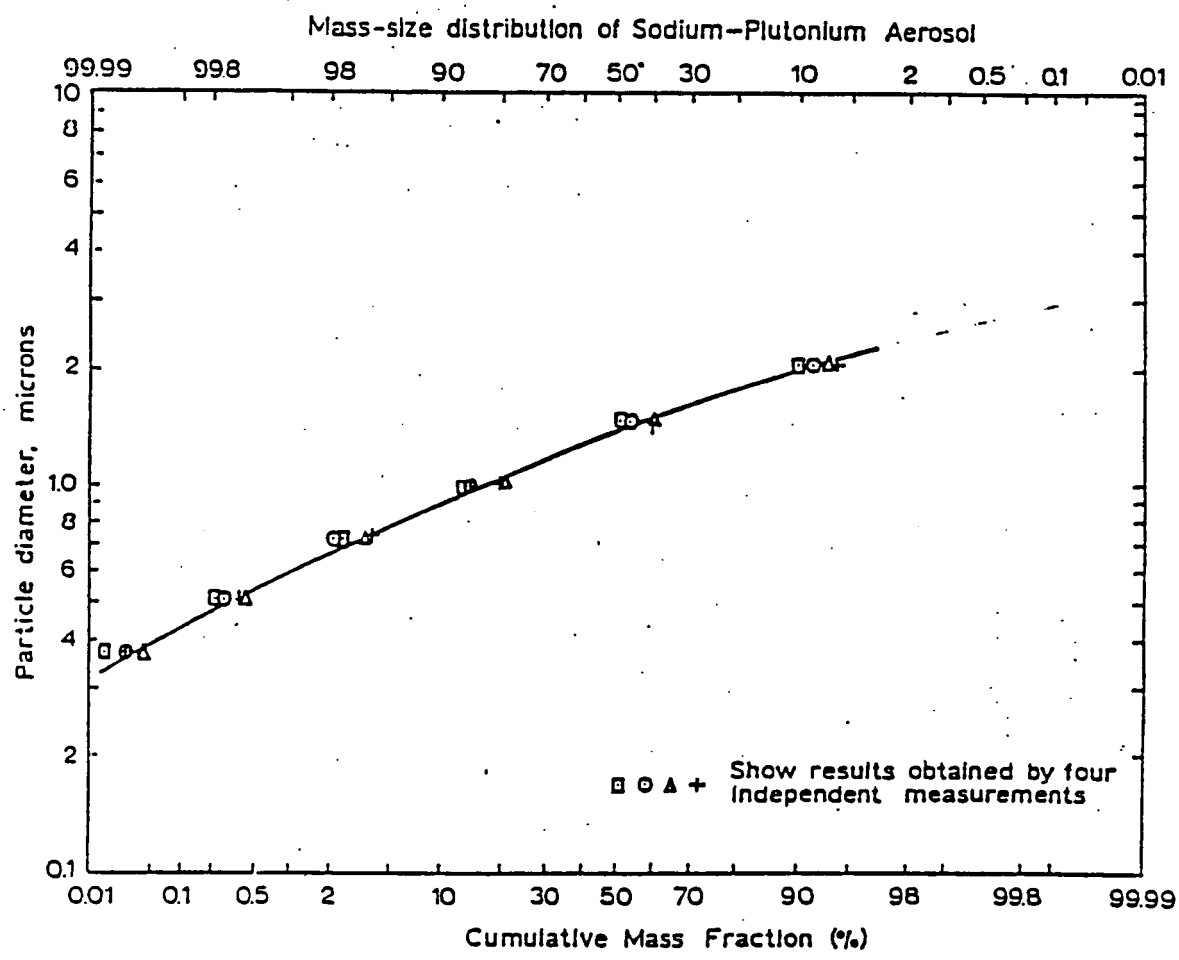

Figure 4-7. Mass-Size Distribution of Sodium-Plutonium Aerosol
(Figure 8 - Chatfield 1969)

4.2.1.2 Uranium

Mishima, et al. (March 1985) reviewed the published literature on uranium behavior under fire conditions. For natural or depleted uranium or uranium with ^{235}U enrichment <10%, the toxic hazard of uranium as a heavy metal is of greater concern than the radiological hazard. The radiological and toxicological hazard from uranium results from transport of inhaled, soluble uranium compounds to the kidneys. For non-volatile (soluble and non-soluble) materials to be an inhalation hazard, the size of the particles/aggregates must be 10 μm AED (more probably 3 μm AED) or less. For normal and depleted uranium, the materials must be soluble. For uranium with enrichments >10%, the radiological hazard is of concern and the solubility of the uranium in interstitial lung fluids determines the critical organ. Fire is a phenomenon that could subdivide uranium metal by conversion to the oxides.

Due to the similarity in matrix spacing, hyperstoichiometric uranium dioxide formed at the metal-atmosphere interface is adhering and limits oxygen availability. At temperatures <200°C, the hyperstoichiometric dioxide, UO_{2+x}, is the principal product. At slightly higher temperatures, a mixture of various suboxides (e.g. U_3O_7, U_3O_8, etc.) are found. At temperatures >275°C, UO_2 and predominantly U_3O_8 are produced. In the temperature range of 350° to 600°C, the UO_2 formed rapidly oxidizes to U_3O_8 that falls away as a black, fine powder. In the temperature range of 650° to 850°C, the UO_2 forms a protective layer that a some point breaks away. At temperature >900°C, the UO_2 is adherent and protective. The presence of water vapor accelerates oxidation in air at temperature <300°C and in carbon dioxide at temperatures <350° to 500°C. Uranium reacts with hydrogen, nitrogen and carbon at elevated temperatures and the presence of surface inclusions accelerates oxidation. The presence of some additive used to phase-stabilize uranium (e.g., aluminum, titanium, etc.) may change the first- or second-stage oxidation rates or the break weight (plateau) or prevent transition to protective oxide formation that may result in a single, accelerated oxidation rate. Some of the factors that affect oxidation rates are listed in Table 4-9 taken from the reference document. Measured oxidation rates in air, carbon dioxide and oxygen are available in the reference document, but the oxidation rate during a fire will be the sum of a variety of rates dependent upon local conditions at many sites on the metal surface and is difficult to predict.

Unlike plutonium, uranium is difficult to ignite. The presence of a adherent, protective layer of hyperstoichiometric dioxide at the interface limits oxygen availability. The heats of reaction are lower. Figure 4-8 taken from the reference document shows the ignition temperature for uranium as a function of surface area/mass ratio. At surface: mass ratios <1.0 cm^2/g, the ignition temperature exceed 500°C increasing rapidly indicating that large pieces of uranium are very difficult to ignite: large amounts of external heat must be supplied and serious heat loss prevented.

Table 4-9. Possible Factors Influencing Uranium Oxidation
(Table 4.1 - Mishima et al. March 1985)

Step	Possible Factors Influencing Rate
Metal surface of unit area oxidizing in air	1) Metal purity 2) Metallurgical condition (grain size, strains, etc.) 3) Temperature 4) Time 5) Gas composition 6) Type of oxide film formed (protective or not)
Loss of heat of reaction by conduction to the surroundings	1) Thermal conductivity of metal 2) Thermal conductivity of oxide coating 3) Cross-sectional area at right angles to direction of heat flow 4) Temperature gradient

The particle size distributions of the residual oxides produced under a variety of conditions have also been measured and are shown in the reference document (see Figures 4.8, 4.9 & 4.11). The distribution becomes coarser and the solubility in simulated lung fluid decreases as the temperature increases. Oxidation of the metal at <450°C generated a fine, black non-adherent powder. At temperatures around 535°C, the oxide was a fine, black powder sintered into lumps. At temperatures >700°C, the oxide appeared to be a hard, black scale.

The ARF and RF for three potential accident configurations for thermal stress (airborne release during the oxidation of uranium at elevated temperatures, airborne release during free-fall of molten uranium and airborne release during explosive release of fine molten metal drop) are covered below.

4.2.1.2.1 Airborne Release From Uranium at Elevated Temperatures. Mishima et al. (March 1985) characterized the oxide generated by the April 1983 burn test involving munitions containing depleted uranium (DU) penetrators and reviewed the literature on airborne release.

Tests subjecting munitions to rigorous fire conditions are performed prior to deployment to ascertain the thermal and blast hazards during transport and storage. Twelve 120-mm rounds containing 48 kg of DU as rods ~1 in. in diameter X 30" long were subjected to a wood and diesel fuel fire. The rounds cooked-off (i.e., the propellant used flared) and the DU rods were retained in the burning mass at temperatures from 800° to 1100°C range for ~3 hours. No detectible airborne DU was collected by air samplers surrounding the burn at distances <100 m. Samples of the oxides generated were collected and the particle size distribution, morphology and solubility in simulated interstitial lung fluid

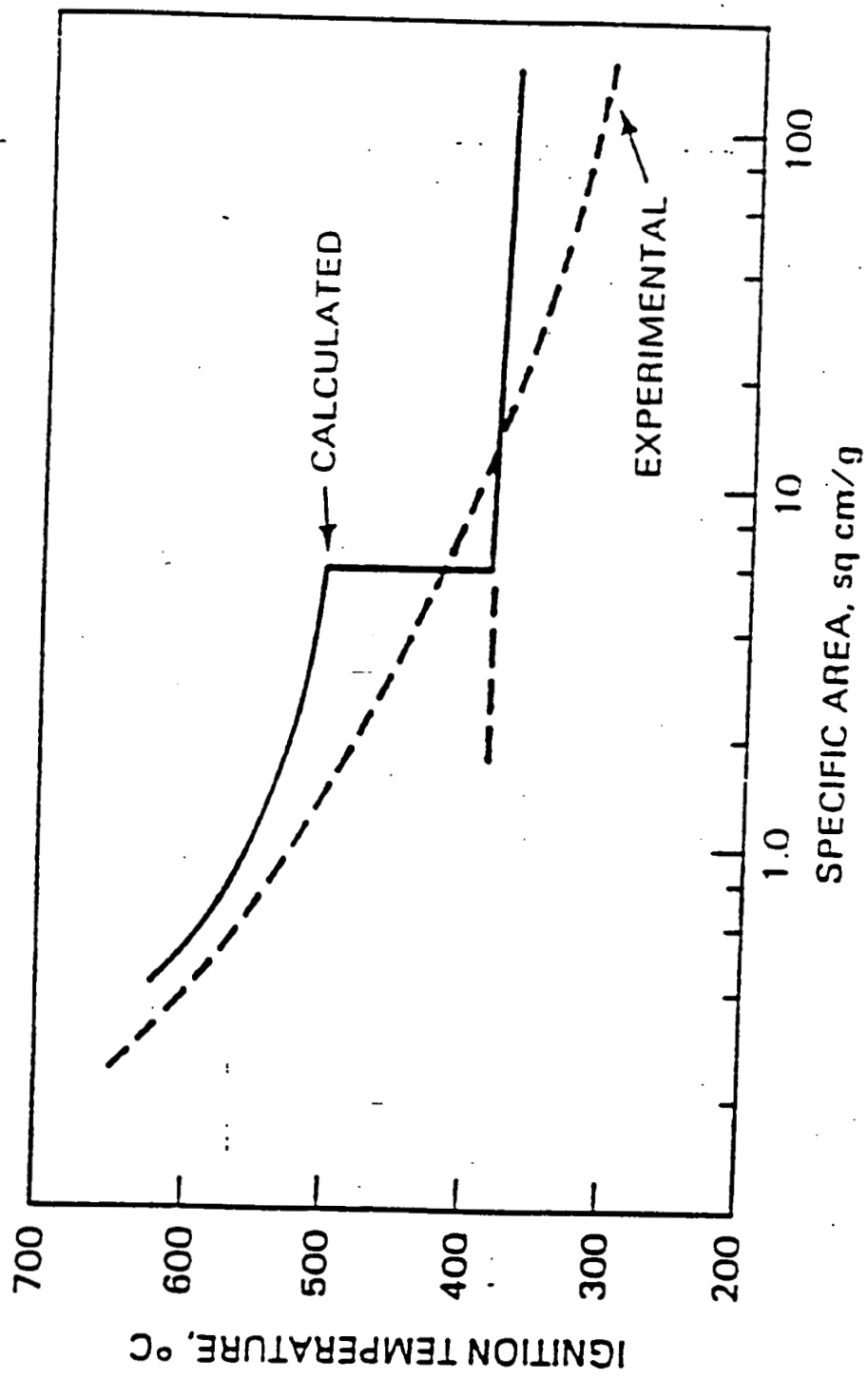

Figure 4-8. Dependence of Uranium Ignition on Specific Area
(Figure 4.1 - Mishima, et al. March 1985)

were measured. The fraction of the oxide generated by the burn < 10 μm AED ranged from 0.2 to 0.65 wt/o. The fraction of the residual oxide < 10 μm AED were predominantly U_3O_8 and all in the "Y" class (dissolution halftimes in simulated interstitial lung fluids of > 100 days).

The ARFs for uranium during oxidation at elevated temperatures found in the literature were:

Elder and Tinkle (December 1980):	
Air, up to 3.2 m/s, fire	5E-3[4]
Air/Air-CO_2, 3.2 m/s, 500°C	1E-7[4]
900°C	4E-6[4]
Carter and Stewart (September 1970)	
Air, static, molten metal	4E-4[4]
Free-fall molten drops	6E-3[4]

Carter and Stewart performed a series of experiments to measure the characteristics of airborne uranium from molten metal under static (no metal movement) and dynamic (free-fall drop) conditions. The experimental apparatus and procedures were covered in Subsection 4.2.1.1.1 "Airborne release of particulates from disturbed molten metal surface." The mean and 95% confidence level ARF X RFs from the oxidation of static molten metal with airflow around and over the metal was:

Static, Geometric mean	1.1E-4[5]
95% confidence level	3.6E-4[5]

Oxidation of Depleted Uranium (DU) Rods at Elevated Temperatures in a Fire

Elder and Tinkle (December 1980) performed a series of experiments on DU rods used as penetrators in armor-defeating weapons. The rods were made of staballoy (beta-stabilized uranium, 99.25% uranium + 0.75% titanium) with a nominal-diameter of 25.9-cm (~ 1-inch), a length of 0.345-m (13.6-inches), and weighing 3355 +/- 3 grams. The rods were subjected to oxidizing conditions (heat + air or air-carbon dioxide atmospheres) with a test configuration for each set of conditions. The various testing configurations are shown in Figure A.25 and A.26 in Appendix A. The rods were heated in a rack in an upflow of air. In the first three tests, the heat was generated from either ignited uranium turnings or munitions propellant. In the fourth test (Burn 4), heat was supplied by 10 batches of packing

[4] Particles 10 μm AED and less.

[5] Particles 10 μm AED and less (see Figure 4-9).

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materials (wood and paper). Measurements and observations indicated that the rods in the first three tests under went very little if any oxidation. From 42% to 47% of the three rods tested in Burn 4 were oxidized greatly exceeding the largest value for fraction oxidized in the laboratory study (30%) and was attributed to the spalling of the oxide coat from the temperature fluctuations resulting from introduction of the 10 batches of fuel. Individual 5-min air samples taken during portions of four fuel additions show the apparent airborne concentrations ranging from 4.2 to 783 mg U/m^3 with fractions <10 μm AED from 20% to 62%. The times during the oxidation process when the samples were extracted are not reported and the great variation in the mass airborne concentrations makes determining the ARF difficult.

The oxidation rate and airborne release were measured during thirteen laboratory experiments in air or 50% air - 50% carbon dioxide at temperatures from 500° to 1000°C. In twelve of the tests, a gas velocity of 2.23 m/s (5 mph) was passed around the oxidizing rod. In one experiment (air at 700°C), the test was performed under static conditions (no gas flow). No self-sustained reaction was observed under any of the test conditions. The fractions oxidized under these conditions ranged from 6.0% to 30.2% (see Table A.32 in Appendix A). The total aerosol mass (summation of the high volume filter sample, precutter and cascade impactor stages + back-up filter) are shown in Figure 4-10 from the reference document. It is difficult to ascertain if the presence of carbon dioxide has any discernible effect upon the airborne release due to the experimental scatter and different oxidation periods used. The mass of particles 10 μm AED and less as a function of temperature is shown in Figure 4-11 taken from the reference document. The values range from ~1E-7 at 500°C to 8E-6 at 700° and 900°C for the fraction of the total mass oxidized. Adjusted for the time to completely oxidize the metal would increase the apparent ARFs to 1E-4 to 4E-2 with RFs from 0.006 to 0.17. The ARF X RF ranges from 5E-5 to 4E-3 that are comparable to the values reported by Carter and Stewart (1970).

The authors listed the following conclusions:

1. Uranium particles in the respirable size range (10 μm AED and less) were made airborne when the rods were exposed to temperature exceeding 500°C for time greater than ~0.5 hours.

2. Production of oxide and airborne materials were enhanced by forced-draft and temperature cycling during oxidation.

3. Metal rods with the test configuration did not exhibit any tendency towards self-sustained oxidation, although complete oxidation would no doubt be achieved if adequate fuel and time (longer than 4 hours) were provided.

Review of Experimental Studies on Airborne Release From Depleted Uranium Munitions

Jette et al. (August 1989) reviewed the published information available on the characteristics of the DU particles suspended during testing (firing of kinetic energy rounds against hard targets, burn tests during hazard classification of rounds prior to deployment) of the munitions and one study on the characteristics of the aerosols from the explosive ejection of molten metal droplets. Many studies have been performed on the DU particles formed by the impact of penetrators against hard targets (Gilchrist and Nicola January 1979; Glissmeyer and Mishima November 1979; Chambers et al. October 1982; Sutter et al. January 1985; Wilsey and Bloore May 1989; Parkhurst et al. April 1990; Jette, Mishima and Hadlock August 1990). Generally, a substantial portion of the mass of DU in the penetrator becomes airborne by the impact against hard targets (armor) of sufficient thickness to expend most of the energy of the kinetic round (up to 80%). The size of the airborne material is very fine with fractions in the 10 μm AED and less range of 0.34 to 1.0. The airborne materials are predominantly U_3O_8. Up to 50% of the particles in the respirable fraction may be "D" class (dissolution halftime < 10 days).

The other large group of studies providing information on the potential behavior of uranium under accident conditions are the hazard classification test conducted on munitions prior to deployment (Gilchrist, Parker and Mishima March 1978; Hooker et al. March 1985; Haggard et al. July 1986; Parkhurst et al. March 1990). A pre-determined number of boxes of munitions are subjected to an intense wood-fuel oil fire. The distance large fragments (pieces of munitions components and cases; packing) are ejected, the thermal and blast levels are determined to establish the exclusion area requirements in the event of accidents in transport and storage. In all cases, no airborne DU was collected in the air samplers set downwind at various distances downwind of the fire. Size distributions of the residual oxide powders (predominantly U_3O_8) were determined and estimates of the respirable fraction are based on the presence of particles of 10 μm and less AED in the residual oxide. The size distributions measured show less than 0.01 of the residual oxides are in the respirable size range. The material in the respirable fraction is much less soluble than the airborne oxide from impact tests ranging from 96% to 100% in the "Y" class.

From the data presented in Figure 4-9 from Carter and Stewart (1970), the geometric mean ARF X RF of 1E-4 was reported. The 95% confidence level ARF X RF of 4E-4 reported by Carter and Stewart (1970) is exceeded by ARF/RF estimated for tests performed by Elder and Tinle (December 1980). The gas flow and temperatures used exceeded those used by Carter and Stewart (1970). Six of nine ARF X RF values obtained are less than 1E-3 and with the greater values at the higher temperatures 900°C). The ARF/RF values of 1E-3/1.0 is recommended as the bounding values for this thermal stress configuration. The value, >95% "Y" class with remainder "D" class uranium, for the lung solubility class is

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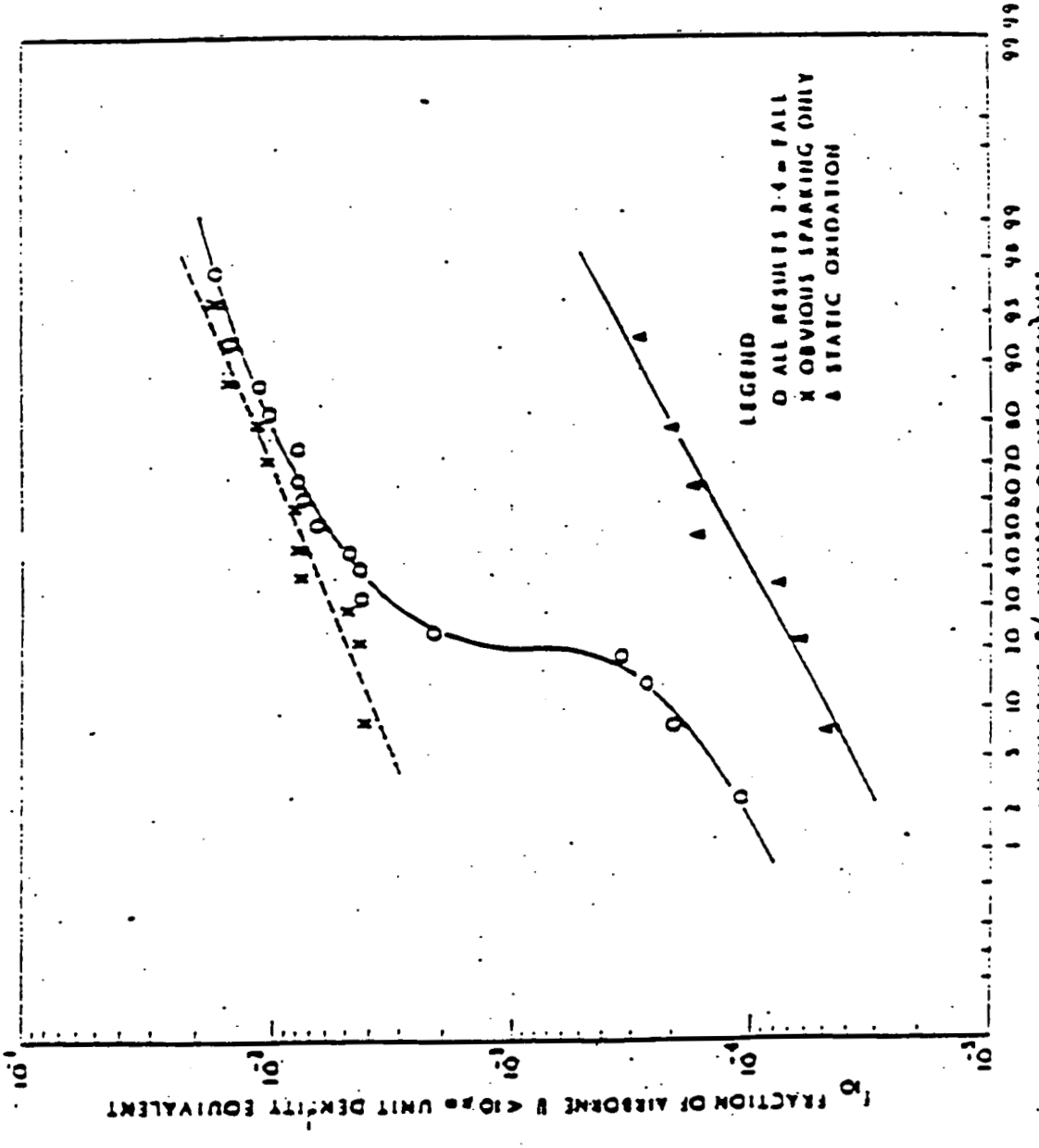

Figure 4-9. Uranium Metal Burning in Air; The Distributions of the Measurements of the Respirable Aerosol Fractions in the Static and Dynamic Experiments (Carter and Stewart September 1970)

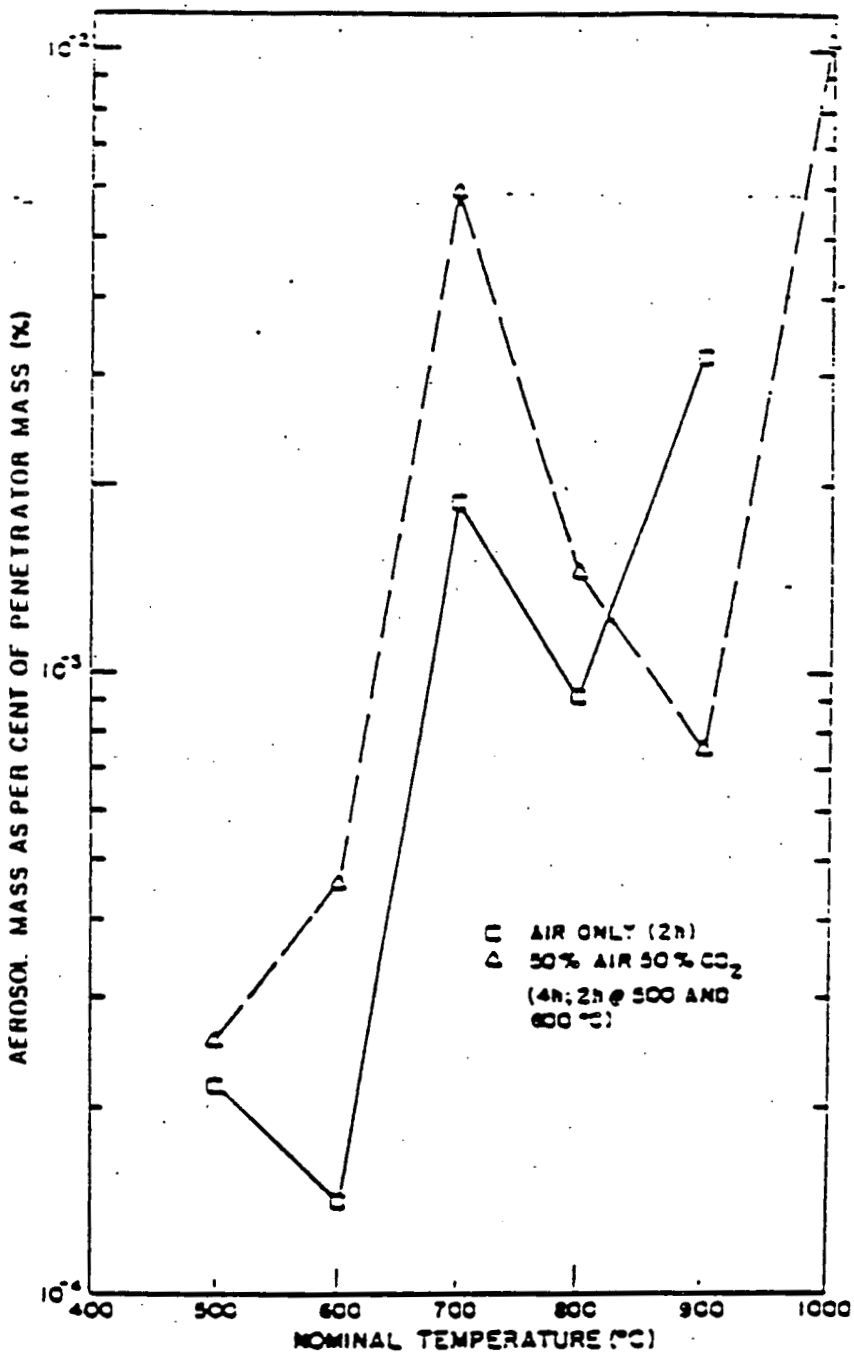

Figure 4-10. Aerosol Mass as a Function of Temperature
(Figure 22 - Elder and Tinkle December 1980)

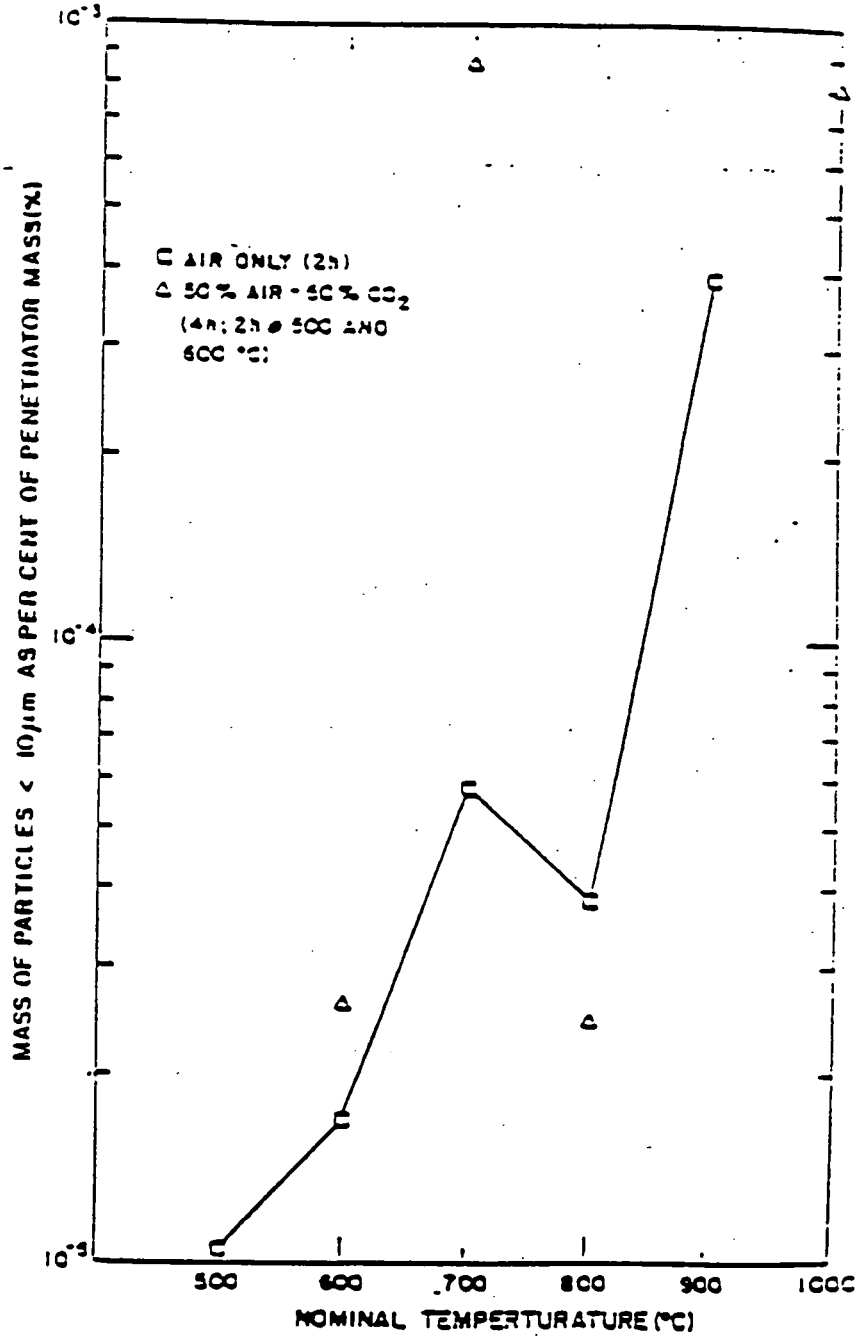

Figure 4-11. Respirable Mass as a Function of Temperature
(Figure 23 - Elder and Tinkle December 1980)

assumed to be that determined for the sintered oxides collected from wood-oil fires involving DU rods in munitions and is recommended as the bound for the lung solubility class.

4.2.1.2.2 Airborne Release From Molten Metal. Carter and Stewart performed a series of experiments to measure the characteristics of airborne uranium from molten metal under static (no metal movement) and dynamic (free-fall drop) conditions. The experimental apparatus and procedures were covered in Subsection 4.2.1.1.1. The size distributions of the airborne materials are shown in Figure 4-9 taken from that document (the velocity of the updraft through the vertical tube was set at a velocity to carry particles <30 μm AED). The distribution of the airborne material from the experiments under static conditions appears to be a single mode. The airborne material from experiments under dynamic conditions (2 to 4 m free-fall) are bimodal. The distribution from the experiments in which "obvious sparking" was observed appears to fit the coarser (upper) curve with the finer (lower) curve represented by the airborne material under static conditions.

Fractional airborne release values for these conditions are found in Table A.23 in Appendix A and are:

Airborne release from molten uranium metal:	
Dynamic, Geometric mean	1.9E-3[6]
95% confidence level	6E-3[6]

On the basis of the available experimental data, the "median" ARF X RF value is assumed to be the geometric mean value, 2E-3, reported by Carter and Stewart (1970). The bounding value is assumed to be the 95% confidence ARF X RF value, 6E-3, reported by Carter and Stewart rounded upwards to be the same as the comparable value for Pu, 1E-2. Since the airborne material cooled rapidly after formation and would be comparable to the fine particulate material from the plastic deformation and rapid oxidation of a thin film of metal generated during the impact of DU rods against hard targets (armor), the measured value for this situation, 50% "Y" class + 50% "D" class is recommended.

4.2.1.2.3 Airborne Release from Explosive Dispersal of Molten Uranium. Rader and Benson (June 1988) generated molten uranium by the exploding wire technique and accelerated the molten drops downrange by an electrostatic device. Approximately 36% of the molten material had been aerosolized by the time the drops had traveled 6-ft and would probably all aerosolize within the next 10 to 12-ft. The size of the airborne particles was <1 μm AED with a geometric standard deviation of ~2. The majority of the airborne material was in the form of web-like aggregates. Experiments performed in inert gas (argon) aerosolized orders of magnitude less material although the size distribution/geometric

[6] Particles 10 μm AED and less.

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standard deviation of the airborne material remained unchanged demonstrating the importance of oxidation to the airborne release phenomena.

On the basis of the available experimentally measured value, the recommended bounding ARF/RF for this accident configuration is 1E+0/ 1.0. As in the previous subsection, the recommended solubility class for this type of airborne material (rapid cooling of fine particulate material/fume) is 50% "Y" class and 50% "D" class.

4.2.2 Explosive Release

Materials can react explosively from internally generated stress (e.g. rapid heating, chemical reactions in composite/aggregate materials) or from external stresses. Only shock effects appear to have the characteristics to result in a significant airborne release from metals. (See Introduction for additional information on explosions.)

4.2.2.1 Shock Effects

Steindler and Seefeldt (1980) provided an empirical correlation to experimental data for the fragmentation of metals surrounding a detonation. The ratio of the mass of the explosive material, as Equivalent (mass) of TNT, to the mass of the inert materials absorbing energy is the Mass Ratio (MR) and the fragmentation as a function of the MR is shown in Appendix B. The correlation covers a MR of 1-10. The mass of inert material fragmented into particles 10 μm AED and less equal is at a maximum for a MR of 1.0. Assuming that the mass of material airborne as particle in the RF is equal the estimated TNT Eq. would be a conservative upper bound for the ARF for this phenomenon and is recommended.

The explosive dispersal of molten Pu and U was covered in previous subsections.

4.2.2.2 Blast Effects

No experimentally measured values for ARF/RF available. No significant airborne release is postulated.

4.2.3 Venting of Pressurized Gases Over Metal

Release of pressurized gases lying over the metal could suspend material if the surface of the metal were covered with loose oxide (corroded) and the aerodynamic profile over the surface possessed the characteristic to entrain the oxide. Venting of powders is covered in a subsequent section and the values determined to bound the entrainment of powders would certainly bound material in this configuration (see Subsection 4.2.3.3, Venting of Pressurized Powders).

4.2.4 Free-Fall Spill/Crush-Impact

Free-fall spill of the metal nor the resulting impact do not appear to provide mechanisms to aerosolize significant quantities metals. The metal tends to deform plastically upon impact and, if an oxide layer exists on the surface, impact may dislodge the powder. Plutonium metal is generally a product and, as such, is stored under conditions that minimize corrosion. No relevant data have been found for this mechanism.

Airborne release from free-fall of molten metal covered in Subsections 4.2.1.1.1 and 4.2.1.1.2.

4.2.5 Aerodynamic Entrainment (Resuspension)

Aerodynamic entrainment from a coherent, bulk solid would be limited to the surface dust unless the solid is eroded by the airflow. The phenomena would be similar to suspension of a powder from a hard, unyielding surface. For large pieces that project beyond the boundary layer, entrainment due to "wake effect" may be a significant process. The only experimental data for the resuspension/aerodynamic entrainment from a coherent monolith of material that have been reported are found in Stewart (1963). It is assumed that the airborne release of Pu during oxidation at room temperature is the aerodynamic entrainment (resuspension) of the corrosion products (oxides) from the metal surface and that the bounding values measured for that configuration would bound the aerodynamic entrainment from the metal (see Subsection 4.2.1.1.1). It would be conservative in that it is assumed that sufficient corrosion product exists for material that is normal stored under conditions to minimize corrosion and is contained. The ARF/RF values previously quoted for this configuration are recommended:

unalloyed metal	ARF (dry air) 2 μg Pu/cm^2-hr; RF 0.7
	ARF (100% RH) 7 mg Pu/cm^2-hr; RF 0.7
delta-phase metal	ARF (dry air) 0.07 μg Pu/cm^2-hr; RF 0.7
	ARF (100% RH) 0.6 mg Pu/cm^2-hr; RF 0.7.

No experimental data for the aerodynamic entrainment of uranium metal were uncovered. The data reported for the oxidation of uranium in air (Mishima March 1985) did not shown rates for temperatures less than $-400°C$. Since the oxidation of uranium is inhibited by the formation of a adherent oxide layer at the metal-atmosphere interface, the values reported above for plutonium should also be conservative for uranium.

4.3 SOLIDS THAT UNDERGO BRITTLE FRACTURE (E.G. AGGREGATES SUCH AS CONCRETE/CEMENT, LIMESTONE/SANDSTONE, ETC., AND GLASSES SUCH AS VITRIFIED HL WASTE)

4.3.1 Thermal Stress

Data from the experimentally measured airborne release from heating either form was not uncovered. If heated for an adequate period of time, aggregate such as cement/concrete will undergo chemical change to carbon dioxide, water and calcium oxide that may carry any non-volatile radionuclides as contamination on the particles generated. Borosilicate glasses incorporating HL waste do not appear to have the potential to release any significant amount of non-volatile radionuclides - the materials were heated to temperature exceeding those anticipated for most fire situation during formation and are not anticipated to undergo any chemical change under fire condition. Borosilicate glasses are more resistant to thermal shock when cool but could be affected by very rapid cooling rates (molten glass poured into large bodies of cool water). Molten glass does not appear to possess the characteristics to generated a physical (vapor) explosion - it does not remain plastic over the required temperature range to generate fine (100 μm AED) drops of molten glass adequate to result in the rapid heat transfer necessary for vapor explosions. Molten glass poured in pools of water would lead to vigorous boiling that could suspended solid particles carried in the liquid (see Borkowski, Bunz and Shoeck May 1986). A possible method to estimate the fragmentation of glass by rapid cooling is to calculate the energy from cooling the glass and using that value in the crush-impact correlation outlined in Subsection 4.2.2.4. Not withstanding, a bounding ARF/RF can not be recommended at this time due to the lack of applicable data.

4.3.2 Explosive Fragmentation

4.3.2.1 Shock Effects

The response of materials that undergo brittle fracture such as aggregates and glass may not be adequately described by the Steindler and Seefeldt empirical correlation based on materials that undergo plastic deformation such as metals and aqueous solutions. Although the elastic response of materials can play an important part for the instantaneous stress generated by detonations, the presence of solids of varying strengths (e.g. concrete) would indicate some subdivision that is a function of the initial particle size of the solids. Therefore, this correlation can not be recommended for application to the response of aggregate materials. At the current time, no experimental data is available to estimate the fragmentation and suspension from the effects of shock upon material that undergo brittle fracture.

4.3.2.2 Blast Effects

For the pressure impulses generated by explosive events that may entrain and hurl aggregate materials, the crush-impact correlation presented below may be used to characterize the response provided an impact velocity can be estimated.

4.3.3 Venting of Pressurized Gases Over Solid

A fraction of any product from corrosion, abrasion, wear on the surface of a solid could be carried by the gases vented from over the solid (see Brockman February 1985). The entrainment would be a function of the characteristics of the flow, surface, and powder lying on the surface (see Section 4.3.5). Whether the entrainment would resemble the aerodynamic entrainment from a thick bed of homogeneous powder or of sparse surface contamination from a heterogeneous surface depends upon the amount of material. The aerodynamic profile of the gases impacting the loose material on the surface would depend upon the overpressure and the size of the vent. No experimentally measured value for either situation are available. No bounding ARF/RF can be recommended at this time.

4.3.4 Free-Fall Spill/Crush-Impact

Brittle materials (e.g. glass, aggregate such as mechanically-compacted UO_2, concrete, limestone) can be fragmented when impacted or crushed. Jardine et al. (1982) performed experiments to measure the fraction and size distribution generated by the impact of various materials resting on a unyielding surface. Figure 4-12 taken from the reference documents illustrates that the size distribution of UO_2 pellets to an impact energy density of 1.2 J/cm^3 is linear. Note that both the sieve and Coulter Counter data shown are physical diameters and must be corrected by the square of the material density (10.96 g/cm^3). Thus the average grain size shown corresponds to a particle ~29 μm AED. The degree of fragmentation and the size distribution are a function of the material, the strength/age of the material, and the energy input per volume (Mecham et al. October 1981). The fraction in the size range 10 μm AED and less is relatively uniform as shown in Figure 4-13 from the reference document and was empirically correlated with the energy input (J/cu-cm) in Subsection 5.1.3, Appendix F in Vol. 4 of SAND (September 1987) as:

$$PULF = A\ P\ g\ h \text{ (J per } 10^7 \text{ g-cm}^2/\text{s}^2)$$

where: PULF = fraction pulverized into 10 μm and less size range
A = empirical correlation, 2E-4 cm^3/J (J = kg-m^2/s^2)
P = specimen density, g/cm^3
g = gravitational acceleration, ~960 cm/s^2 at sea level
h = height, cm.

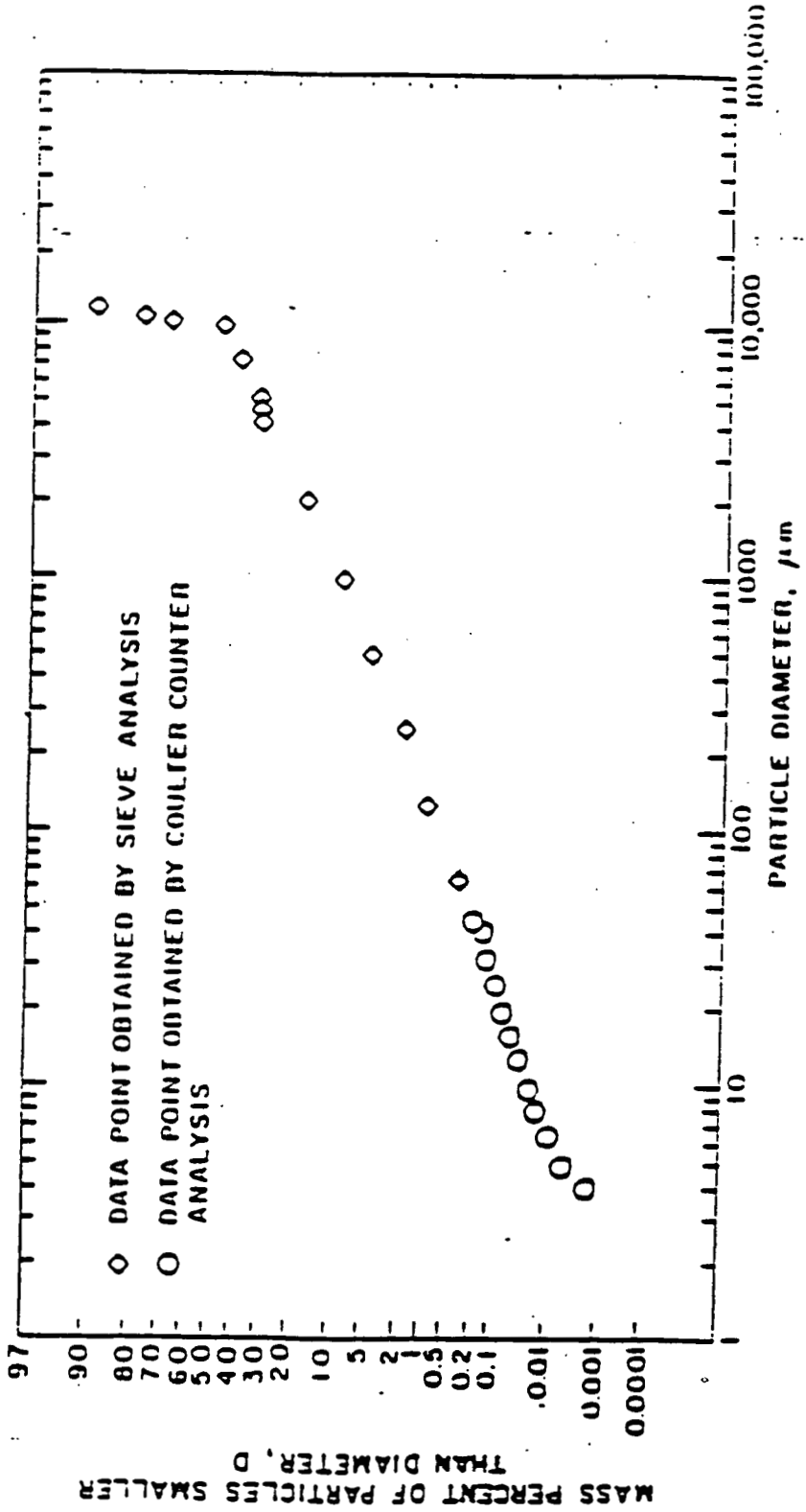

Figure 4-12. Particle Size Distribution Resulting from UO_2-2 Pellet Impact Test Data for UO_2 Specimen #2 Including Mean Grain Size of Original Crystalline UO_2 Particles. (Size Distribution 3 pellets 13.7-mm diameter x 13.6-mm long; drop-weight 1.2 J/cm^3.) (Jardine, et al. 1982)

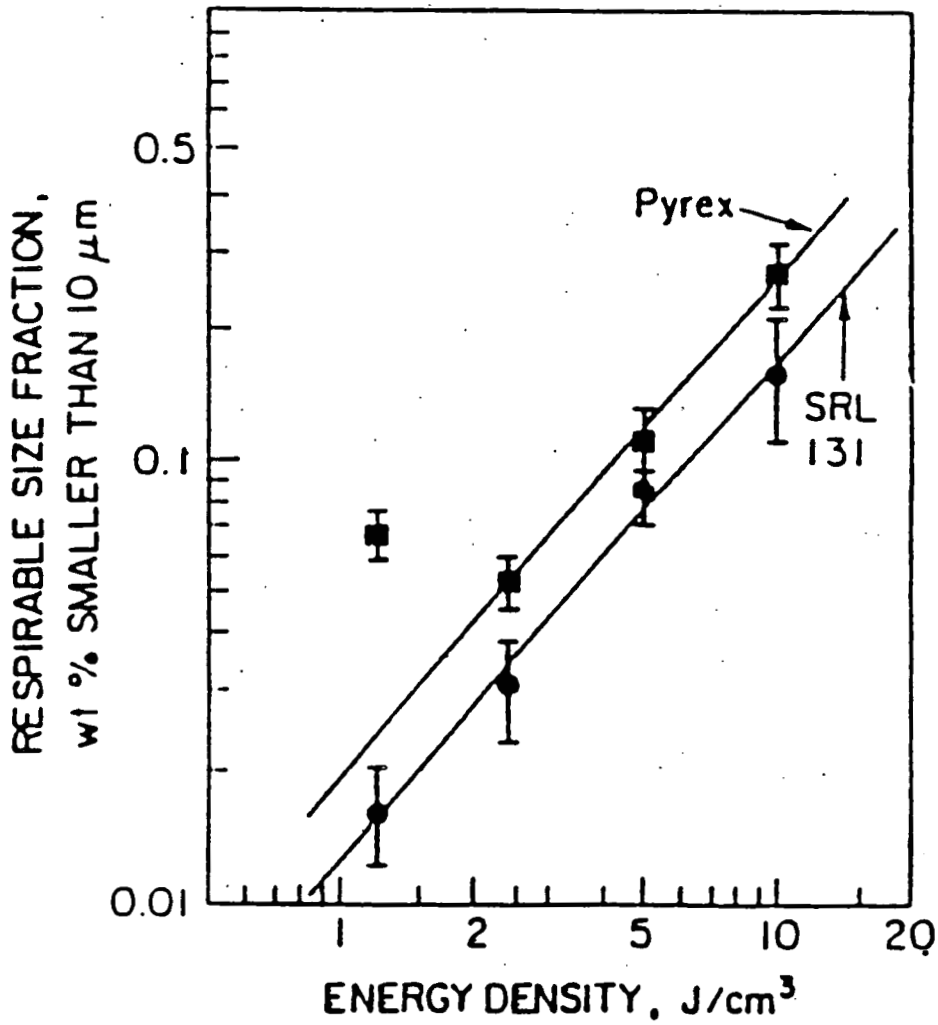

Figure 4-13. Variation of Respirable Size for Impact Tests of Pyrex and SRL-131 Glass Specimens as a Function of Impact Test Energy Density (Jardine, et al. 1982)

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Use of this correlation to estimate the RF and the very conservative assumption that all the RF is made airborne by the impact is recommended.

4.3.5 Aerodynamic Entrainment (Resuspension)

Only the materials that have been converted to particles are at risk from aerodynamic entrainment from the surface of the solid or surfaces upon which the particles reside. The materials are expected to behave as a thick bed or sparse surface contamination dependent upon the amount of material present as particles. See the appropriate portion of Subsection 4.2.3.5 covering the individual suspension configuration.

4.4 POWDERS

4.4.1 Thermal Stress (Oxidation and/or Suspension by Convective Currents)

Experiments are reported by Mishima, Schwendiman and Radasch (July 1968, November 1968) covering the airborne suspension of particulate materials during the heating of various compounds. Two types of situations are covered - the suspension of non-reactive powders during heating in a flowing airstream and the suspension during oxidation of reactive compounds in a flowing airstream.

Plutonium fluoride, oxalate, and air-dried oxalate powders withdrawn from production, air-dried Pu nitrate from the low temperature drying of concentrated Pu nitrate solutions, or the 15 to ~150 μm AED fraction from the air oxidation of Pu metal were placed in the shallow depression of a stainless steel planchet on top of a graphite core used for induction heating. A thermocouple in a 3.2-mm diameter well drilled into the side of the planchet measured the temperature during the experiment. A 75-mm quartz bell that formed the bottom of a 42.2-mm ID quartz chimney surrounded the planchet. Air at a pre-determine flow was drawn up and around the planchet, through the apparatus, and the entrained material was collected on a glass fiber filter sealing the upper end of the chimney. At the flows used, the nominal velocities through the chimney were adequate to carry particles from up to 17 μm in diameter at 0.1 m/s to ~300 μm in diameter at a nominal velocity of 1.0 m/s. A 0.076-mm thick mild steel liner covering the interior surface of the chimney was used to collect any material lost to the wall during heating but analysis indicated no significant loss in any experiment (Results from these analyses were not reported due to the uncertainty in results created by the difficulty in the analytical separation from the high iron contents of sample solutions). The experimental apparatus is shown in Figures A.27a and A.27b in Appendix A. The measured suspension rates during the heating of the plutonium solid compounds are found in Tables A.33, A.34, A.35, A.36 and A.37 also in Appendix A.

All sampling periods were one hour for all tests and, therefore, the ARF are same as the suspension rates converted to fraction of source. The measured ARFs are the fraction of

the initial activity collected on the glass fiber filter during the experiment. In some experiments, portions of the material passing through-the chimney were collected on a membrane filter and sized by optical microscopy using a graticule to determine the size distribution of the airborne materials. Particle were grouped into seven categories - <5, 5-8, 8-12.5, 12.5-20, 20-32, 32-50 and >50 μm equivalent spheres. The size quoted in the text must be multiplied by the square root of the density of Pu oxide (11.46 g/cm^3) to approximate the AED. These measurement are the basis for the RFs quoted in the tables. In the case of compounds that were oxidized, the time required to convert all the powder to oxide is not known. This introduce an additional source of uncertainty into the use of these measurement as the ARF during the heating and oxidation of the powders. In most cases, microscopic examination of the residual materials after the heating indicate that for the conditions under which the higher releases were measures (higher temperatures conditions and air velocities), the oxidation was relatively complete. Furthermore, the airborne materials were entrained in an induced flow that probably exceeds that anticipated for convective flow and should bound the entrainment for convective flow. The pertinent data from these tables for the two situations are listed in Tables 4-10 and 4-11.

4.4.1.1 Non-Reactive (Chemically Under Test Conditions) Compounds

The measured ARFs from heating of non-reactive plutonium dioxide particles are tabulated in Table 4-10.

Table 4-10. Airborne Release from Non-Reactive Powder During Heating in Flowing Air (Table V - Mishima, Schwendiman and Radasch July 1968)

Temperature, °C	Airflow, m/s	ARF
Ambient	0.1	6.1E-6
	1.17	5.6E-3
800-900	0.1	5.3E-6
	1.17	2.5E-4

The source material for these experiments was the oxide in the size range of 15 to 150 μm AED (the upper value is given as 44 μm but is the fraction passing through a 325 mesh screen and is LLD rather than AED for the lower value). Thus, all the material is greater than 10 μm AED (RF). The two values at each separate air velocity appear to be relatively consistent with the ARF for the higher temperature lower than that at ambient temperature. Since the lower air velocity (0.1 m/s) is calculated to carry particles as large as 17 μm that is barely above the lower size of the powder used (although it was noted during the oxidation experiments that the oxide formed was friable), the low ARF value would be anticipated. Particle as large as 300 μm could be carried by the higher velocity (1.17 m/s)

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and the ARF values here probably represents the material that could be entrained. It would appear that for non-reactive powders, temperature has little effect on entrainment. Therefore, a bound based on entrainment at high velocities compared to convective flow, for the material of 6E-3 is recommended.

The size distribution of the airborne material was not measured during these experiments. The entrainment appears to be entirely due to the airflow with temperature playing a minor or negligible role. In our experimental studies, special efforts were required to obtained powder with RF of 0.1 and powders at rest are difficult to deagglomerate (see Figure A.41). The RF for reactive powders discussed below generated very small RFs (<0.00001). Since entrainment for non-reactive powders depends solely on airflow and the same airflow was applied in the experiments with reactive powders, there is no compelling reason that the RFs should be orders-of-magnitude apart. The oxides formed from these reactive compounds can be very fine under the proper circumstances although, under the experimental conditions, large amounts of fine oxide were not generated. Under fuel cycle facility accident conditions, much of the oxides present would be from the oxidation of reactive compounds and metal that would have characteristics similar to those generated by heating reactive compounds used in these experiments. In these bases, an RF value of 0.01 was selected as a reasonable, conservative value consistent with other measured RFs discussed below.

4.4.1.2 Chemical Reactive (Under Test Conditions) Compounds

The measured ARFs during heating of reactive plutonium compounds in flowing air a listed in Table 4-11.

The median and bounding ARFs for the four reactive compounds tested are:

	median	bound
partially oxidized Pu oxalate	4.4E-3	8.8E-3
Pu oxalate	1.0E-4	9.5E-3
Pu fluoride	<8.0E-5	7.0E-4
a.d. Pu nitrate	1.5E-4	1.5E-3

The ARFs for reactive plutonium compounds appear to fall into 2 groups. The ARFs measured for the two oxalate forms have maximum values near 1E-2. The value for nitrate is much lower but the median value for this compound is similar to the value for oxalate. Due to the uncertainty of the completeness of the oxidation, it is assumed that the nitrates behave as oxalates and an ARF of 1E-2 is recommended for these compounds.

Table 4-11. ARFs/RFs During the Heating of Reactive Compounds in Flowing Air (Tables VI, VIII & X - Mishima, Schwendiman and Radasch July 1968 and Table IV - Mishima, Schwendiman and Radasch November 1968)

Air Velocity, cm/s	Temperature, °C	ARF[1]
Partially Oxidized Plutonium Oxalate		
10	ambient	5.6E-4
	1000	2.7E-3
50	ambient	<8.0E-5
	1000	6.2E-3
100	ambient	6.6E-3
	400	6.5E-4
	700	7.8E-3[2]
	1000	8.8E-3
Plutonium Oxalate		
10	ambient	<8.03-5
		<8.0E-5
	700	9.0E-5
	1000	8.0E-5
50	ambient	<8.0E-5
		1.4E-4
	700	<8.0E-5
	1000	1.2E-4
100	ambient	1.0E-4
		4.0E-4
		9.8E-4
		5.8E-3
	400	4.9E-3
	700	9.5E-3
	1000	3.3E-3
Plutonium Fluoride		
10	ambient	<8.0E-5
	1000	<8.0E-5
50	ambient	<8.0E-5
	1000	<8.0E-5
100	ambient	<8.0E-5
		<8.0E-5[2]
	400	1.1E-4
	700	7.0E-4[2]
	1000	7.0E-4[2]
		2.0E-4

Table 4-11. ARFs/RFs During the Heating of Reactive Compounds in Flowing Air (cont.)
(Tables VI, VIII & X - Mishima, Schwendiman and Radasch July 1968
and Table IV - Mishima, Schwendiman and Radasch November 1968)

Air Velocity, cm/s	Temperature, °C	ARF[1]
Air-Dried Plutonium Nitrate		
10	1000	6.2E-5
50	400	1.9E-5
	700	2.3E-4
	1000	1.5E-3[2]
100	400	1.7E-4
	700	1.3E-4
	1000	1.9E-4
		1.3E-4

[1] Sum of material collected on foil chimney liner and filter sealing chimney.
[2] Size distributions determined by optical microscopy indicates a RF < 1E-5 to < 1E-8. May indicate that oxides formed at high temperatures sinter together during oxidation forming aggregates that are larger in size.

The maximum and median ARFs for fluoride appears to be an order of magnitude less with less variability for individual measurements. Therefore, a bounding ARF of 1E-3 is recommended for this compound.

The upsweep air velocities used during the tests appears to be adequate to entrain all significant particle sizes as shown in Figure 4-14 (Figure 9 from Mishima, Schwendiman and Radasch November 1968). The size distributions of the airborne materials during the heating of some compounds are shown in Figures A.28, A.29a, A.29b, A.29c and A.30 in Appendix A. The sizes designated on the graphs are equivalent spheres (the linear diameter of the particle) and, since the theoretic density of PuO_2 is 11.46 g/cm^3, the sizes must be multiplied by ~3.4 (the square root of the density) to arrive at the diameters in AED. The RF estimated from the size distribution plots indicate a value ~1E-5 to 1E-8 associated with ARFs ranging from <7E-4 to 8E-3. Although the RFs measured appear relatively consistent associated with ARFs spanning the range of ARFs found for all materials, the values are very small and a RF of 0.001 (10^{-3}) is recommended for all these materials under these conditions to provide a high degree of conservatism.

Thus, the recommended bounding ARFs for the response of powders to thermal stress are:

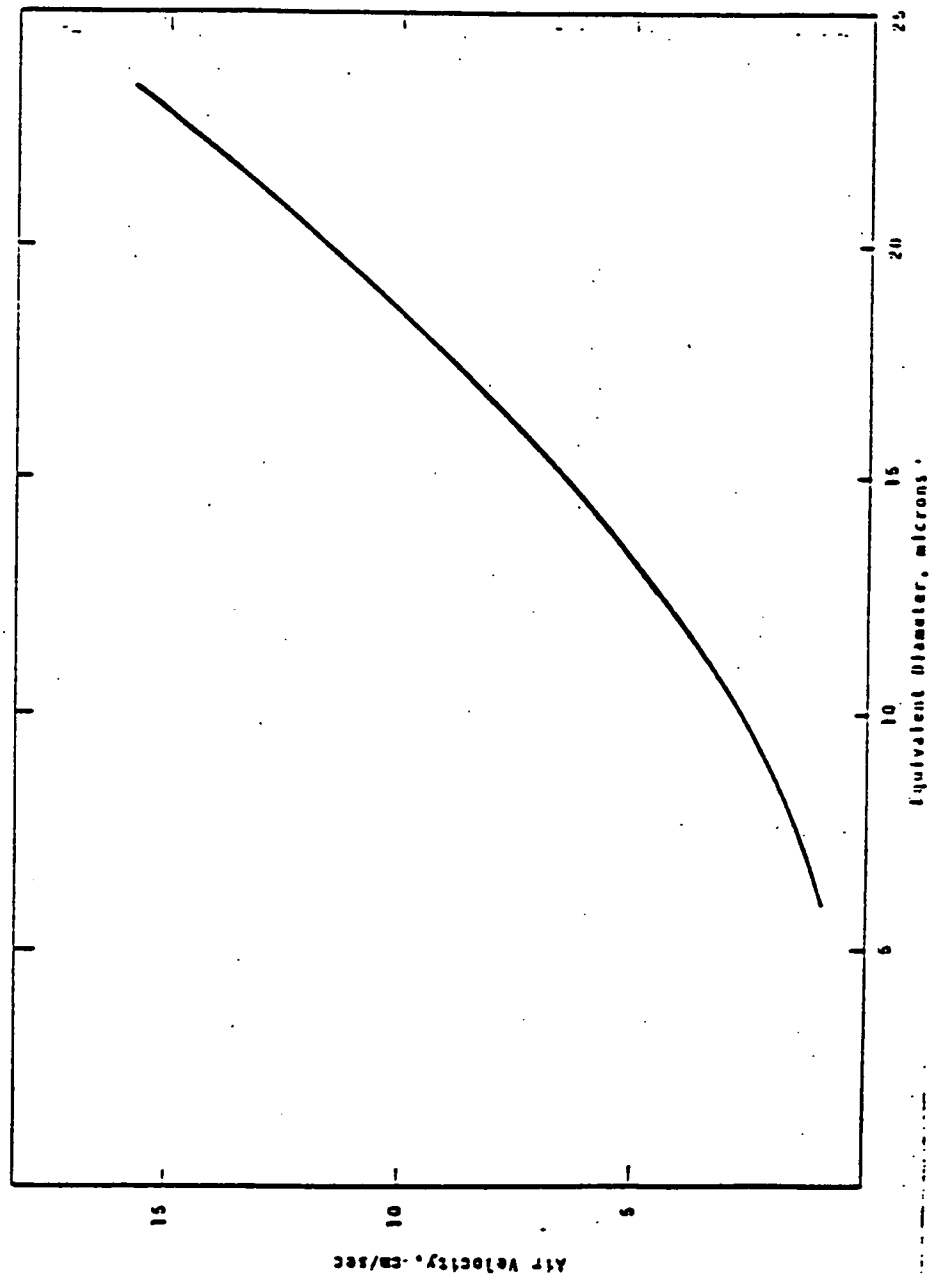

Figure 4-14. Equivalent Diameter PuO_2 Particle Lifted by Various Air Velocities (Figure 9 - Mishima, Schwendiman and Radasch November 1968)

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non-reactive compound	6E-3/0.01[7]
reactive compounds (except fluorides)	1E-2/0.001
plutonium fluoride	1E-3/0.001.

4.4.2 Explosive Dispersion

The effects of shock upon powder is unknown. Blast effects from both detonations and deflagrations are assumed to result in the entrainment of powders without substantial subdivision of the finer fractions (the relaxation time of a particle 10 μm in diameter is 3 X 10^{-4} second and would most probably be entrained rather than fragment) that are the primary concern for inhalation. Fragmentation of the coarser fraction that have adequate momentum upon impact or chemical reactions for reactive compounds are possible. The primary entrainment mechanism is assumed to be the accelerated gas velocity resulting from the blast effects; that is the suspension of powders by the impact of air at velocities greater than those normally associated with aerodynamic entrainment under non-accident conditions (i.e. suspension by air velocities used for ventilation and exhaust and by ambient outdoor winds). Two types of aerodynamic entrainment of powders are found, aerodynamic entrainment from homogenous beds (beds of powder greater than two particle diameters deep) and aerodynamic entrainment of sparse particles contamination from a heterogeneous surface (i.e. hard, unyielding surface). The former is covered here and in Subsection 4.2.3.5 and the latter is discussed in Subsection 5.2.x.x.

4.4.2.1 Shock Effects

No data are available. Gerrard (1963) reported the detection of a velocity component towards the surface from detonation that appeared to pass through powder on the surface and was reflected by the surface. If such is the case, it would be anticipated that powder could be suspended by the reflected wave.

4.4.2.2 Blast Effects (Aerodynamic Entrainment from a Homogeneous Bed of Powder)

The impact of the gas flow upon powder deposited upon a surface is dependent upon the characteristics of the gas flow, powder and surface. The experiments performed by Royster and Fish (1967) illustrates the importance of the angle the air flow impacts the surface on the efficiency of suspension. Experiments were performed where air was drawn into an apparatus at a 30° angle and directed upon sparse populations of particles deposited on various surfaces. The apparatus is shown in Figure A.32 in Appendix A. The material entrained was collected on a filter sealing the inlet to the air blower. The fraction of activity

[7] Cannot exceed the mass of material in this size fraction in the source material.

removed by the apparatus compared to other estimation techniques is shown in Table A.38 in Appendix A and illustrates the fact that, under ordinary circumstances of parallel flow to surface, aerodynamic forces are not very effective for removal particles deposited upon surfaces. Figure 4-15 taken from the referenced article shown the effect of velocity impacting at an angle to surface upon the fraction of 5 and 0.5 μm diameter particles entrained from a stainless steel surface. Removal is relatively complete at fairly low velocities impacting the surface.

Entrainment from blast effects is divided into three categories:

1. Accelerated flow parallel to surface.

2. Deflagration of a Limited Volume of Flammable Mixture Above Powder (air may impact the surface deposit from various angles but blast effects are limited).

3. Deflagration of a Large Volume of Flammable Mixture Above Powder (air impact surface from many angles and full impact of blast effect may impinge on powder deposited upon surface).

4.4.2.2.1 Accelerated Flow Parallel to Surface. In a survey of published literature on accident generated particulate material (Sutter May 1982), no experimental study was found that followed the release history of the aerosol or dust cloud immediately after the event. Many of the experimental studies centered around the suspension of coal dust following explosions but the models developed are for large piles of coal or ore that are not applicable here (the amount of powder involved in accident in fuel cycles under most circumstances is orders of magnitude less and parameters used in the analysis that are not meaningful such as velocity at half height) although the materials are adhesionless powders similar to the ceramic oxide powders found in many fuel cycle facility accident situations. Two types of powders were addressed: cohesive (6 to 80 μm diameters) and free-flowing (100 to 150 μm diameter). Different entrainment mechanisms govern the types of materials. A variety of observations on the sequences or phenomena governing entrainment are reported.

For velocities following weak or marginal explosions, Singer, Cook and Grumer (1972) reported entrainment resulted from the erratic rupture and removal of large clumps from the surface of cohesive dust ridges and their dispersal in the midstream. They attributed the entrainment to a five step process: 1) detachment of single particles from the loose material on the surface; 2) detachment of small clumps and particles; 3) partial fracturing and subsequent entrainment of large clumps; 4) ridge breakup and complete breakup of large clumps; and, 5) continued breakup and dispersal of clumps in midstream. Steps #1 through #4 required from 0.1 to 0.5 seconds to entrain 2 grams of material from

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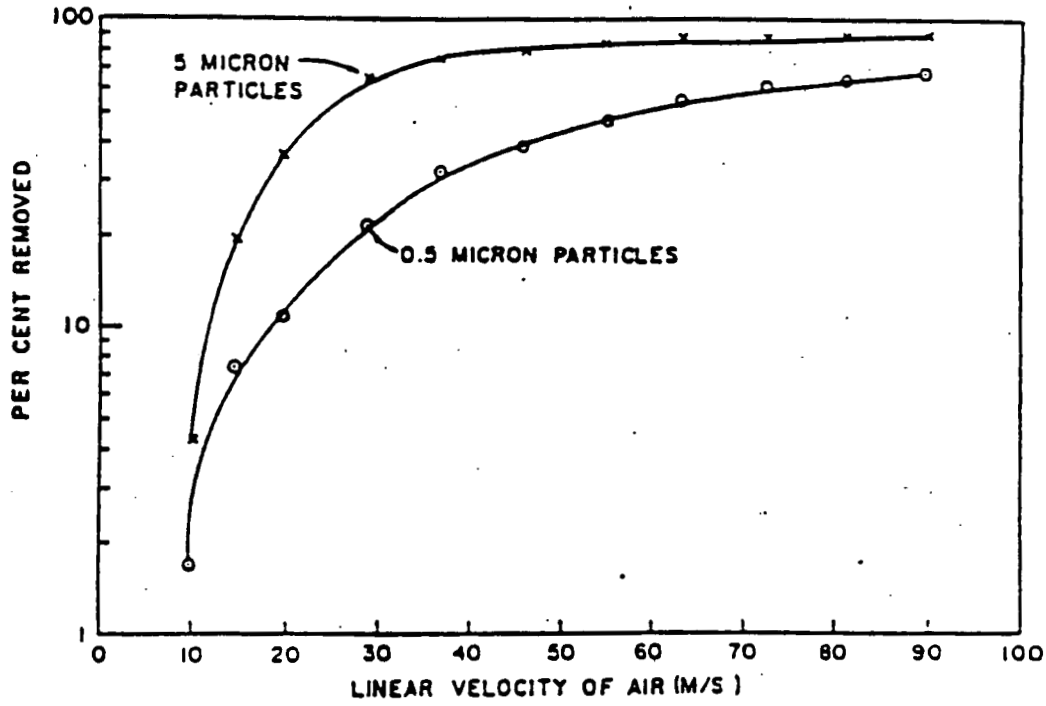

Figure 4-15. Smair Removal of ThO_2 from Stainless Steel
(Figure 7 - Royster and Fish 1967)

cohesive dust ridges. Fresh deposits were more readily dispersed and deposits became cohesive when slightly compacted (such as after spill of material).

Singer, Harris and Grumer (1976) observed that explosions generated oscillatory flow (increased flow followed by flow reversal) in wind tunnel experiments. Entrainment appeared to be a weak function of the instantaneous air speed over the bed. Wetted or wetted-dried layers of coal and rock dust dispersed faster due to the selective lifting of relatively large briquetted fragments. Entrainment proceeded simultaneously by longitudinal regression of the leading edge of a cohesive bed and the lifting of material from the surface layer. The threshold instantaneous air velocity to entrain bulk quantities from cohesive beds ranged from 5 to 30 m/s (11 to 67 mph). If the threshold velocity is exceeded for one component of a mixed layer but not the other, the components can be entrained individually.

Chepil (1945) observed that the entrainment process begins with a rolling or sliding particle motion as drag forces exceed friction forces. Punjrath and Heldman (1937) attributed entrainment to the sudden increase in aerodynamic shear stress from the transition from laminar to turbulent flow. Einstein (1942) observed that entrainment depended on the fluctuation of the air velocity at the surface rather than of critical fluid properties (e.g., mean velocity of bulk flow). Kalinske (1947) and Graf and Acaroglu (1968) reported entrainment was due to fluctuating pressure and velocity components. Parthenaides and Passwell (1970) presented the entrainment rate equations for the erosion of cohesive beds based on the fluctuating flow components inducing instantaneous tensile stresses within the bed that exceed the weakest bond holding particles in the bed.

No theory for entrainment due to the pressure waves generated by explosion appears to be generally accepted. Various equations were uncovered that estimated the entrainment rate under these conditions but all required either experimentally derived/empirical factors or parameters not readily determined for accident conditions. Estimates of entrainment rates still require estimates of the duration of the pressure wave/accelerated flow over the deposit to arrive at estimates for ARFs. Singer, Cook and Grumer (1972) reported entrainment rates of ~ 10 g/m^3 at 5 m/s to ~ 90 g/m^3 at 40 m/s (89 mph) for velocities at the mid-height of the deposit. Freeman (1972) reported concentrations of 700 to 1100 g/m^3 in 1 second at a explosion equivalent to 1E+8 g TNT (not indicated if entrainment or due to blast effects).

In the absence of any directly applicable predictive models or release data, other related experimental values are applied. From the information quoted above, it appears the entrainment process results from the creation of surface flaws by the detachment of particles or clumps. Once created, the surface flaws allow more general lifting of the surface until the entire surface is disrupted. The process requires some period to initiate as shown by the 0.1 to 0.5 seconds necessary to entrain 2 grams from a cohesive surface (Singer, Cook and Grumer 1972).

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Mishima and Schwendiman (August 1973) reported the entrainment of UO_2 powder and air-dried UNH from various surfaces at two air velocities (~1.1 and 8.9 m/s 1-ft above the surface) at ambient temperatures. The experimental apparatus is shown in Figure A.3 and the experimental results listed in Table A.3 in Appendix A. An ARF and RF of 7.6E-2 and 0.14 were measured for the higher of two values for the suspension of UO_2 powder from a stainless steel surface for a wind velocity of 8.9 m/s 1-ft above the surface (comparable to a 22 m/s under normal wind speed measurements) in a 24-hour period. The velocity of the bulk fluid at distances above the surface may not be a meaningful measurement and the velocity profile near the surface may be more relevant. In the case of explosion-generated air velocities, the duration of the peak velocity is in terms of milliseconds. Approximately 60% of the resuspended powder (4.56E-2) was made airborne during the first hour of the wind as shown in Figure 4-16 taken from the referenced document. If resuspension is assumed to be linear over the initial hour (recent studies indicate that the resuspension of sparse particle contamination is not linear especially at the beginning and end of the suspension period and that the suspension from the bed of a cohesive material appear to be initiated at surface imperfections), the ARF would be 7.6E-4 per minute. For the flow to be parallel over the surface, the center of the explosion must be some distance from the deposited material. The entrainment due to the pressure wave over the surface will only be over the deposit for a short period of time and needs some duration (0.1 to 0.5 seconds?) to initiate. On this basis, reasonably conservative values for the ARF and RF for the suspension of a powder from a smooth, unyielding surface by the pressure impulse generated (gas flow parallel to surface) by an explosion appear to be 5E-3 and 0.3 respectively.

4.4.2.2.2 Deflagration of a Limited Volume (unconfined vapor or <0.25 of free-volume above powder) of Flammable Mixture Above Powder. For the entrainment due to the rapid burning of a limited volume of combustible mixture (equal to an unconfined vapor explosion - cloud volume, <0.25 volume of container) over the deposited material, the value will exceed the entrainment from accelerated parallel flow but be less than a value of 1E+0.

If the expansion wave from the deflagration incident on the surface is essential planar, gases may be pushed through the powder and be reflected from the surface resulting in suspension of the powder under pressure. In order to generate a pressure wave that will have an essentially planar impact upon the surface, it would be necessary to have an ignition source that is far from the surface or that is distributed parallel to the surface or that is confined in a direction perpendicular to surface (this also requires that the radial distance to reach the radial constraint is less than the distance to the surface). Even with these restrictive geometry considerations, this may not be equivalent to the passage of a wave front since the wave can travel in the absence of bulk flow. Timing of the wave reflection, and its speed through the powder, are relevant to the extent the powder will pressurize. The maximu pressure in the powder would be inside the expanding wave front at a distance from the ignition point equal to that at the bottom of the powder bed (surface). The total volume of gas pushed into the bed and then expelled is probably a relevant parameter. Use of

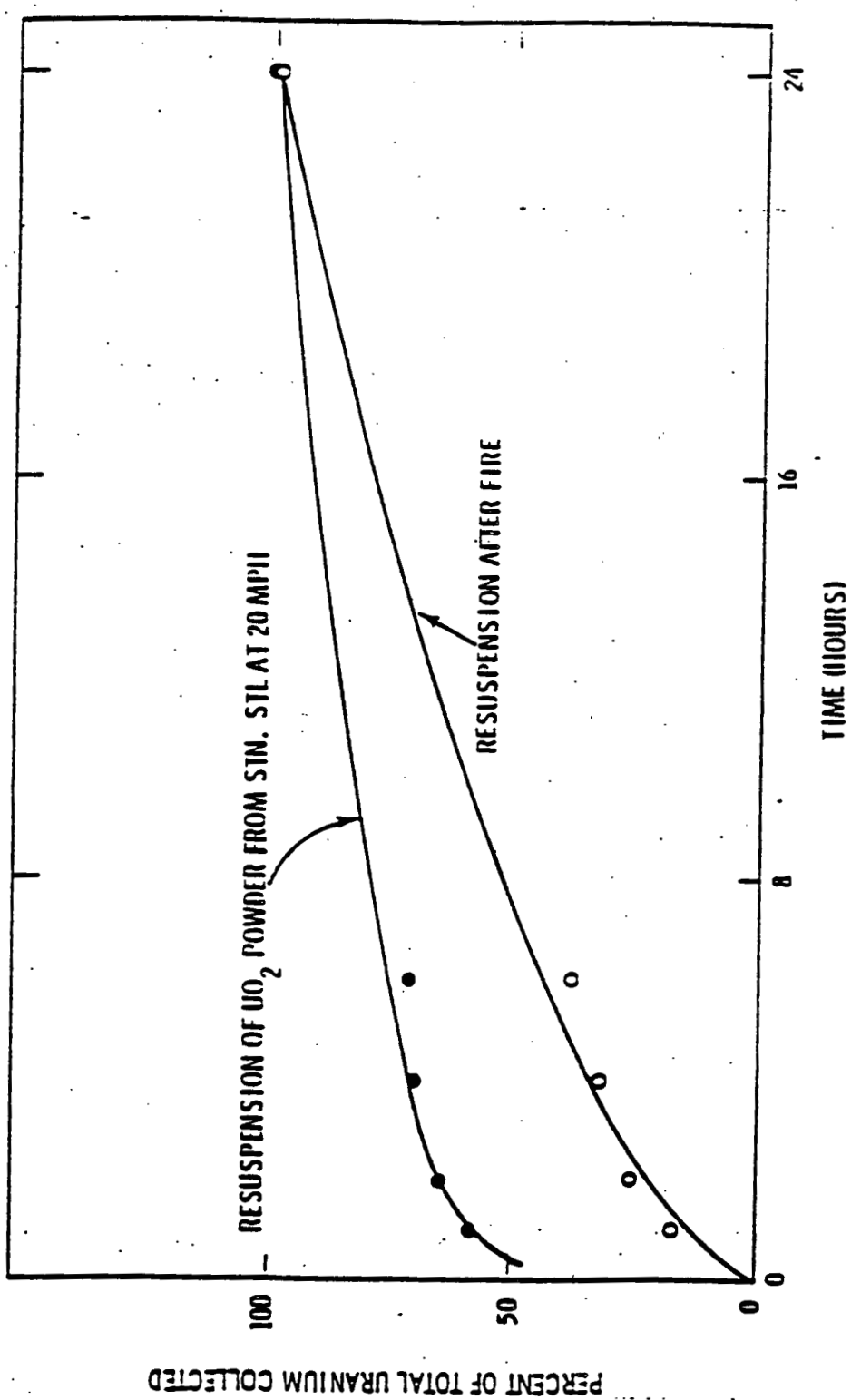

Figure 4-16. Aerodynamic Entrainment of Uranium Dioxide Powder from a Stainless Steel Surface at an Air Velocity of 20 mph
(Figure 16 - Mishima and Schwendiman August 1973)

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experimental data from the venting of pressurized gases through a powder bed is probably conservative since the experiments released from 2.7 to 27.2 liter of air through 100 g and 300 g of powder.

Sutter (August 1983) reported the results of venting gases at 50 to 500 psig through a bed of TiO_2. Two source masses were tested (100-g and 350-g). The experimental apparatus is shown in Figure A.32 in Appendix A with the relevant data listed in Tables A.39a and A.39b. The releases from the smaller masses were twice that for the 350-g source. For most process situations, powder masses are much larger than 100-g and these were not considered. The ARFs and RFs are shown in Table 4-12.

Table 4-12. ARFs/RFs from Venting Pressurized Gas Through Powder Beds (Tables A.3 and B.3 - Sutter August 1983, 350-g source only)

Gas Pressure, psig	ARF	RF
500	1.09E-1	0.54
		0.40
250	1.05E-1	0.48
		0.73
50	4.5E-2	0.46
		0.88

The highest measured value is 1E-1 for both 500 and 250 psig. It is difficult to determine uncertainty with only a single measurement at each pressure level. Based on measurements for dispersion during venting of pressurized powders, the uncertainty varies with the level of release. At the higher levels, the measurements appear to vary by a factor of 2 to 4. There did not appear to be any extraordinary deposit on the ceiling of the vessel after these experiments. For experiments conducted outdoors, estimated plume heights for the venting of powders at 0.34 MPa was 4.5-meters and 10.7-meters at a pressure of 6.9 MPa. Therefore, an ARF/RF of 1E-1/0.7 is recommended for the entrainment of powder from a bed by the deflagration of a limited volume of flammable mixture provided the quantity does not exceed the amount of particles in the respirable size range in the source powder (deflagrations are not assumed to result in additional fragmentation of the powder).

4.4.2.2.3 Deflagration of a Large Volume of Flammable Mixture Above Powder. If a flammable gas mixture with a reactive component cloud volume exceeding the one-fourth the volume of the container/vessel/enclosure deflagrates over powder lying on hard, unyielding surfaces, the gas currents generate act upon the powder as gas flow directed act the surface from various angles of attack (an efficient mechanism to suspend particles from surfaces). Braaten, Shaw and Paw U (1986) did not observe any substantial entrainment during the velocity increase to 20 m/s in a wind tunnel. John, Fritter and Winklmayr (1991)

observed some suspension of deposited powder during the increase to 40 m/s in a wind tunnel. Wright (1984) reported the suspension of ~95% of the deposited powder from the floor of a wind tunnel during the few seconds necessary to raise the velocity to 60 m/s (~135 mph). Thus, for the reaction of larger volumes of flammable gas mixtures above the powder, an ARF of 1E+0 is assumed with the RF equal to the RF of the source powder.

4.4.3 Venting of Pressurized Powder

If the gases around and in a powder are compressed during pressurization, the gases expand rapidly during venting and result in the airborne dispersal of the powder. Sutter (May 1982) reported estimates for the ARFs for two reported accidental overpressurization in nuclear fuel cycle facilities. A release of 1 mCi of 604 Ci of activity from the catastrophic rupture of an ion exchange column at 0.69 MPa (the estimated pressure at column failure) and estimated an ARF of 2E-6. An estimated 1.2 to 1.3 mCi of Pu was reported released during the depressurization at 60 psi of a slip-fit container (may also have been wrapped in multiple layers of plastic) holding 12,168 Ci as PuO_2 powder. The ARF estimated for this incident is 1E-7.

Experimental data for the airborne release of 2 powders with varying densities (TiO_2 with a material density of 4.2 g/cm^3 and UO_2 with a material density of 10.96 g/cm^3) for two masses-at-risk (100-g and 350-g) have been reported by Sutter (August 1983), and Ballinger, Sutter, & Hodgson (May 1987). Both airborne releases from the venting of pressurized powders and from venting pressurized gases through powder were measured. The apparatus for venting pressurized powders is shown in Figures A.33a and A.33b. The details of the venting of a pressurized powder through a powder bed has been discussed in Subsection 4.2.3.2.2, "Deflagration of a Limited Volume of Flammable Mixture Above Powder". The arrangement to collect the airborne materials in the 10-ft diameter stainless steel tank used for confinement is the same as used for liquid releases and is shown in Figure A.4 in Appendix A.

Initially, tests for the venting of pressurized powders were performed using pressure to 6.9 MPa but significant masses of powder were impacted and adhered to the ceiling of the 10-ft tall containment vessel compromising the measurement of the fraction airborne. Although powder may indeed be lost by adhesion to structural features in actual accident situations, the ARFs measured by such test would not bound the ARFs from unimpeded aerosolization. Figure 4-17 taken from the referenced document shows the weight percent airborne as a function of pressure. Although some powder may have been lost by impaction/adherence to the ceiling in tests performed at 3.5 MPa, the losses at this and lower pressure did not appear to be affected significantly. Either some material is loss by adhesion to the ceiling or entrainment is not a linear function of pressure and the reduction is due to some characteristic of the tests or release mechanism. All subsequent test for venting of

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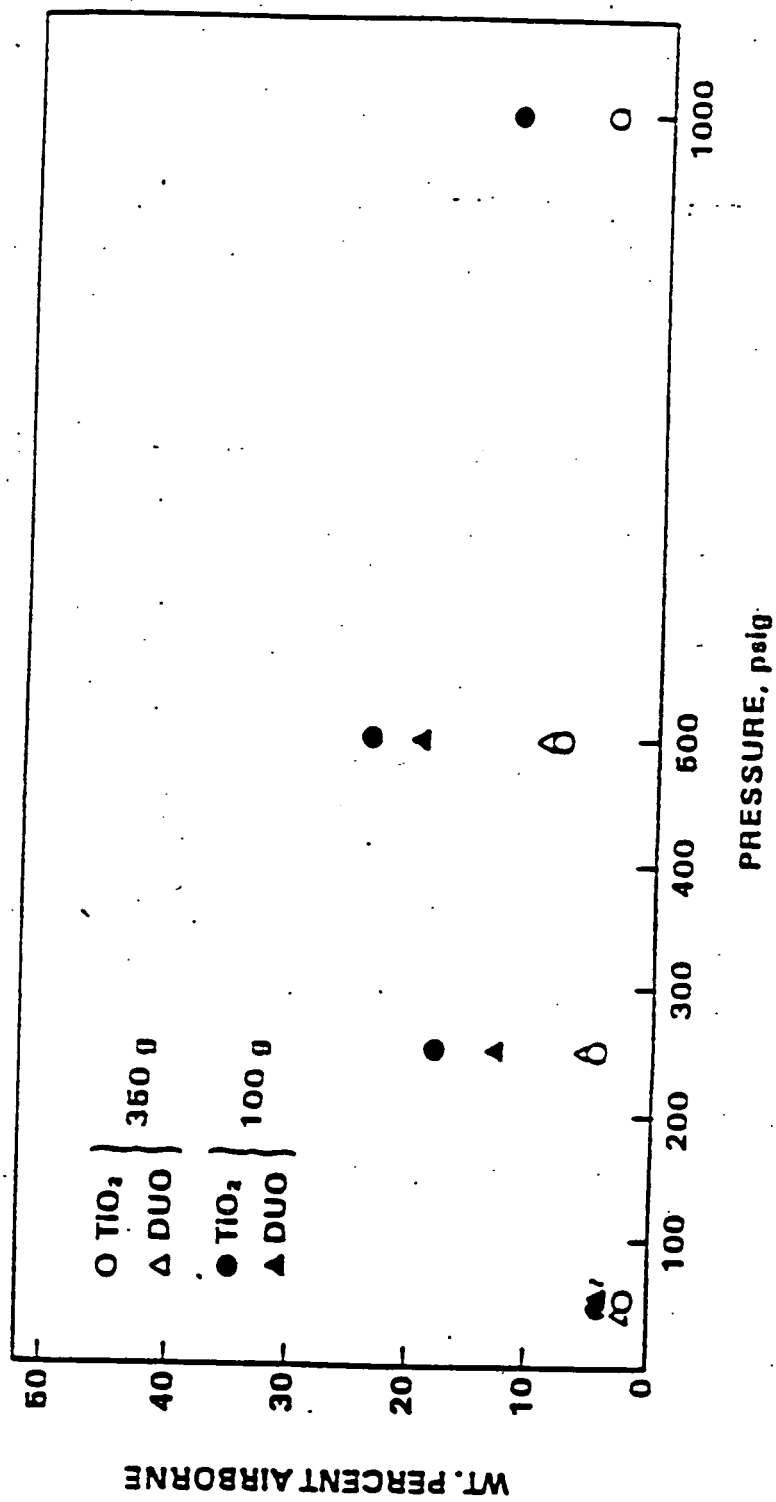

Figure 4-17. Average Weight Percent of Powder Airborne as a Function of Pressure (Figure 7 - Sugger August 1983)

pressurized powders or the venting of pressurized gases through powders were limited to pressures of 3.4 MPa or less.

An additional factor that may have affected the airborne release during the venting of pressurized gas through a powder was the potential increased dispersal action by the remnants of the rupture disks (thin metal foils) used to initiate the venting at the correct pressures. In as much as the effect would enhance the airborne release, the results were considered conservative and no attempt made to ascertain the potential increased suspension.

For the same pressures, the airborne releases measured for both venting configuration using the small mass-at-risk (100 g) were approximately twice those measured for the larger mass-at-risk (350 g) and may indicate that the depth of material may influence the release fraction. The masses used in the experiment are not representative of the powder masses normally associated with processes and are much less. On this basis, only the ARFs/RFs from experiments using the larger powder masses are considered. The data are shown in Tables A.39a, A.39b, A.40a, A.40b, A.40c, A.40d (Sutter August 1983) and A.40e and A.40f (Ballinger, Sutter and Hodgson May 1987) in Appendix A. The pertinent data is tabulated in Table 4-13.

The ARFs for the larger source mass only ranged from 5E-5 to 1E-1. The three greatest measured ARF values are for the venting of pressurized gas (3.4 and 1.7 MPa) through powder beds and the venting of pressurized TiO_2 at 3.4 MPa. The two values for the venting of pressurized UO_2 at 3.4 MPa are at essentially the same value. As mentioned above, the values for the venting of pressurized gas through a powder bed may be enhanced by the dispersal of powder resulting from the passage of the rupture disk remnants through the powder. The median value is 5E-2 with an average of 5E-2. The RFs ranged from 0.29 to 0.88 with a median value of 0.44 and an average of 0.47. The RFs associated with the bounding ARF values range from 0.31 to 0.72 with all but a single value at 0.54. An RF value of 0.5 rounded downward from 0.54 to be consistent with the single digit protocol. On these bases, a bounding ARF/RF of 1E-1/0.5 are recommended.

4.4.4 Free-Fall Spills/Crush-Impact

The following subsections discuss the spill of powder accelerated by gravity upon impact with hard, unyielding surface and the impact of spills of objects upon powder lying at rest.

4.4.4.1 Free-Fall Spill of Powder in Air Velocities <1 m/s Normal to the Direction of Fall

4.4.4.1.1 Factors that Affect Dust Generation. Plinke et al. (1991) surveyed the literature on dust generation and performed test to ascertain the factors that may affect dust

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Table 4-13. ARFs/RFs from the Venting of Pressurized Powders (Tables A.1, A.2, A.3, B.1, B.2 and B.3 - Sutter August 1983 and Tables A.5 and A.6 - Ballinger, Sutter and Hodgson May 1987)

Material	Pressure, MPa	ARF	RF
TiO_2	6.9	4.5E-2	0.64, Material adhered to ceiling
	3.4	6.1E-2	No RF, cascade impactor overloaded
		9.8E-2	0.40/0.44
		1.09E-1	0.54/0.40, Pressurized gas release
UO_2		9.0E-2	0.34
		9.0E-2	0.31
TiO_2	1.7	2.89E-2	No RF, cascade impactor overloaded
		7.6E-2	0.44
		1.05E-1	0.48/0.72, Pressurized gas release
UO_2		6.0E-2	0.42
		6.0E-2	0.29
TiO_2	0.69	9.4E-3	No RF, cascade impactor overloaded
	0.34	6.2E-3	No RF, cascade impactor overloaded
		3.6E-2	0.38/0.48
		4.5E-2	0.46/0.88, Pressurized gas release
UO_2		2.0E-2	0.33
		2.0E-2	0.31
	0.17	1.73E-3	0.35
	0.12	1.11E-3	0.60
	0.06	5.0E-5	0.61

generation to determine methods to evaluate the extent of potential hazards to workers health and safety. Background literature attributed dust generation rates to some function of the ratio between the separation forces generated by the operation/event versus the binding forces present in the powder. Some parameters that affect the separation forces are bulk density, fall height and sample mass. Factors affecting binding forces identified were particle size distribution and moisture content. (Bulk density is an indication of initial dispersion. Fall distance and sample mass along with bulk density are indices of the speed and momentum of the falling material and an indices of turbulence upon impact. The amount of air that can be entrained in the particle mass increases dispersion and would enhance aerosolization. Confinement of the falling material such a in these experiments would increase turbulence at impact enhancing aerosolization of the powder.) Particle shape was also identified as a possible critical parameter in some materials. The dustiness of powders [the authors define "dustiness" as the ability of a material (powder or solid) to generate particles by mechanical

or aerodynamic stresses normally encountered in routine use] was found to be independent of test methods. An early model indicated that:

$$L = 16.6\,(W)^{-0.75}(S_g)^{3.9}(D)^{-1.2}(M_g)^{-0.45}$$

where:
- L = fractional mass loss, mg of dust/kg of material dropped
- W = moisture content, %
- S_g = geometric standard deviation of the size distribution for the dropped material
- D = material bulk density, g/cm^3
- M_g = mass median diameter of the size distribution for the dropped material, μm.

The experimental apparatus used is shown in Figure A.34 in Appendix A. The individual data points were not reported but the results of the tests are shown graphically in Figures A.35a, A.35b, A.35c, A.35d, and A.35e in Appendix A.

Four readily available materials in powder form were allowed to free-fall spill known distances and the material airborne was collected as a function of aerodynamic particle diameter in a cascade impactor. Two powders were non-porous and non-reactive to water, inorganic, crystalline materials (sand and limestone). One porous, reactive, inorganic material (cement) and one porous, reactive, organic material (flour) were also tested. Sand and limestone are similar to some process generated wastes (e.g., slag and crucible) and coarse fractions of process materials (e.g., heavy metal oxides). The finer cohesive heavy metal oxides are similar in characteristics to cement but a non-reactive with water. The solid salts of other heavy metal compounds (e.g., fluoride, chloride, oxalate, hydride) are not represented here.

The powder fell in the test apparatus from a funnel with an interchangeable tube through a hole in the center of the lid of the receiving hopper. The interchangeable diameter tubes (24-, 37- and 49-mm) adjusted the material flow rates. The total mass dropped ranged from 2 to 10 kg and the flow rates (ranging from 0.1 to 10 kg/s) determined by the time required to release a known mass of material. The fall distance was measured from the bottom of the tube to the top of the pile of material. The stream of falling powder impacted a natural pile of powder formed of the same material under the same conditions. Air was entrained in the falling powder stream.

The dusty air generated was drawn into the second section (the aerosol collection section) of the apparatus by a fan that was turned off after all the powder had been released. A second fan circulates the air through the elutriation column (flow velocity designed to prevent particles >25 μm AED from being carried to the cascade impactor) and air return channel. The mass collected per impactor stage or filter was used to determine the size

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specific dust generation rate, G_i (fraction of dust particles generated with an aerodynamic diameter i). The summation of all fraction collected was the total dust generation rate, G. (The total dust generation rate, G, is expressed as mg airborne/mg source and is equivalent to the ARF.)

The size distribution and moisture content for the source powders were determined.

At low F (material flow rates), the falling stream of material stops abruptly on top the pile and slides down the sides. At higher Fs, the individual material exhibit different behavior:

- sand: the falling stream penetrates the pile and displaces material radially.
- limestone: the pile is compressed by the falling stream and forms a crater, 70- to 150-mm in diameter. The diameter of the crater increases with fall distance. The falling powder stream strikes the center of the crater and bounces back in all directions.
- cement: behavior is between the responses of the previous two materials. The penetration of the pile by the falling stream of powder is not as deep as with sand and does not compress the pile as much as limestone. The impact does not result in bouncing of the powder. Most of the material slides down the sides of the pile.
- flour: the only material tested that formed piles with a peaked top. Material slid down sides of pile without penetrating.

Dust appears to be generated by two mechanisms: impact of the falling stream creates separation forces; and, the change in flow direction of the entrained air in the impaction area due to its inability to enter in the solid powder results in radial flow that transport airborne particles away. The total dust generation rate are substantially different for the four materials tested and

- increased with increased fall distance. Greater fall distance appears to increase the normalized entrained air, V, increasing total dust generation. The slopes of dust generation rates for sand, cement and flour are almost identical indicating similar responses to energy input.
- decreased as F (material flow rate) increases. The material in the center of a falling stream of powder is less exposed to the surrounding air and the material in the center of the falling stream increases with F. As a result, less air is entrained, V, in the falling powder stream and reduces the radial flow

that is a factor in the transport of suspended powder from the impact area. For sand and cement, the decrease in G may also be due to the reduced impact forces imposed on these materials by their penetration into the pile. The decrease in G for flour appears to be due to the reduction in entrained air. The increase in G with F observed for limestone is attributed to the proportionately greater increase in separation forces resulting from the formation of a crater by the material in the impact area with the reduced shock absorption from the reduced layer of powder.

- the G decreased with increased W (moisture content) for all materials tested. Cement formed agglomerates with the addition of moisture altering the particle size distribution of the source material and was not tested. The rates varied substantially for the other 3 materials. For the crystalline, non-reactive to water materials (also appear to be non-cohesive), additions of small amounts of water increased the liquid film of the surface of the individual particles and appear to increase the capillary interparticle binding forces. For the non-porous, reactive to water materials (flour), the effect was less pronounced due to the absorption of the water.

The coefficients derived from an analysis of variants on the data from the tests performed on the various materials were compiled in the equation:

$$G_i = \text{const}(H)^A(F)^B(W)^C(\text{Frac}_i)^E[D_i \ln(D_i/25)]$$

where:
- H = fall distance, cm
- F = material flow, kg/s
- W = moisture content, %
- Frac_i = fraction of particles in i size range in source material
- Di = average diameter of particles collected on cascade impactor stages

A, B, C, D & E are coefficients calculated by analysis of variants and varied with material.

The formulae accounted for 72% to 93% of the experimental variation for the four materials and indicates that the parameters chosen are appropriate for the purpose. The correlation between measured and predicted size specific dust generation rates is shown in Figure 4-18.

In all cases, for drop heights ranging from 0.25- to 1.5-m, values for G were less than 2E-4 or 3E-4.

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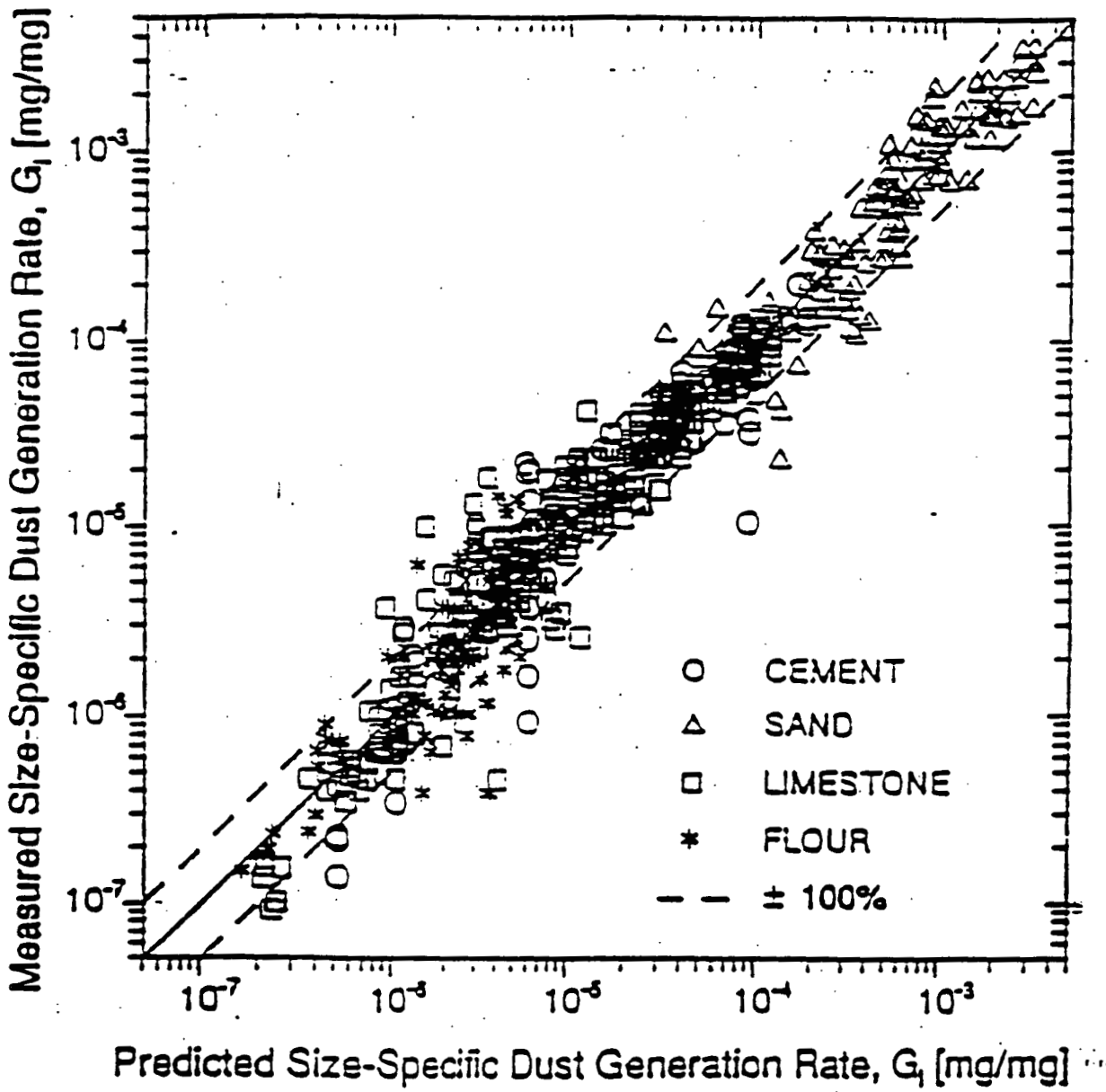

Figure 4-18. Measured Size-Specific Dust Generation Rate Versus Predicted Size-Specific Generation Rate from Equations 8-11 (Figure 7 - Plinke, et al. 1991)

4.4.4.4.2 Free-Fall Spill of Powder Experiments. Sutter, Johnston and Mishima (December 1981) reported on experiments performed to measure the fractional airborne release of powders [TiO_2, density 4.2 g/cm^3; DUO (depleted uranium dioxide), density 10.96 g/cm^3] during the free-fall spills of powders. The size distribution of the two source powders measured by a liquid sedimentation technique using suspensions of ultrasonically dispersed powder in water containing a surfactant is shown in Figure 4-19 taken from the referenced document. Various masses ranging from 1000- to 25-g were spilled from a beaker suspended from the ceiling of a 3.05-m (10-ft) diameter X 3.05-m (10-ft) tall stainless steel vessel. The powder airborne was collected by high volume total particulate and cascade impactor samplers. The material deposited on the walls at various heights on the walls of the vessel were estimated by aluminum foil strips stuck to the walls at various locations. The experimental apparatus is shown in Figure A.5 in Appendix A. The pertinent data are tabulated in Table 4-14 and the measured data are found in Tables A.41a, A.41b, A.41c and A.41d in Appendix A.

The bounding ARF/RF for both types of powder is 2E-3/0.3. The median ARF/RF are 3E-4/0.5.

The bounding ARF/RF for the greater spill height is 2E-3/0.3. The median ARF/RF is 9E-4/0.4 with average values of 9E-4/0.5. The maximum RF measured for spill from the greater height is 0.9 associated with the smallest ARF measured for these conditions.

The bounding ARF/RF for the lesser spill height are 5E-4/0.5. The median ARF/RF are 8E-5/0.5 with average values of 1E-4/0.6. The largest RF measured was 0.9 for the next to smallest ARF measured under these conditions. The measured ARFs are consistent with the values measured in Plinke et al. (1991) at approximately the same fall height.

The variation in the measured ARF values appears to be somewhat dependent on the level of the values. For ARFs at 1E-3 to 1E-4, the values appear to reflect variability of a factor of 5 to 10. At ARF level of 1E-4 to 1E-5, the variability appears to in the range of an order of magnitude or greater.

Figure 4-19 indicates that the RF of the source material is 0.95+ for both powders. The measured RFs indicate that the airborne particles have not been completely deagglomerated by the stresses imposed by the event.

4.4.4.4.3 Free-Fall Spill of Powder Model. Ballinger et al. (January 1988) proposes a model using the assumption that the powder disperses at a constant angle during falling and the diameter and velocity of the powder front can be calculated from the angle of dispersion and properties of the powder. Particles are sheared off during the descent and remained suspended. The model does not account for the suspension of particles upon

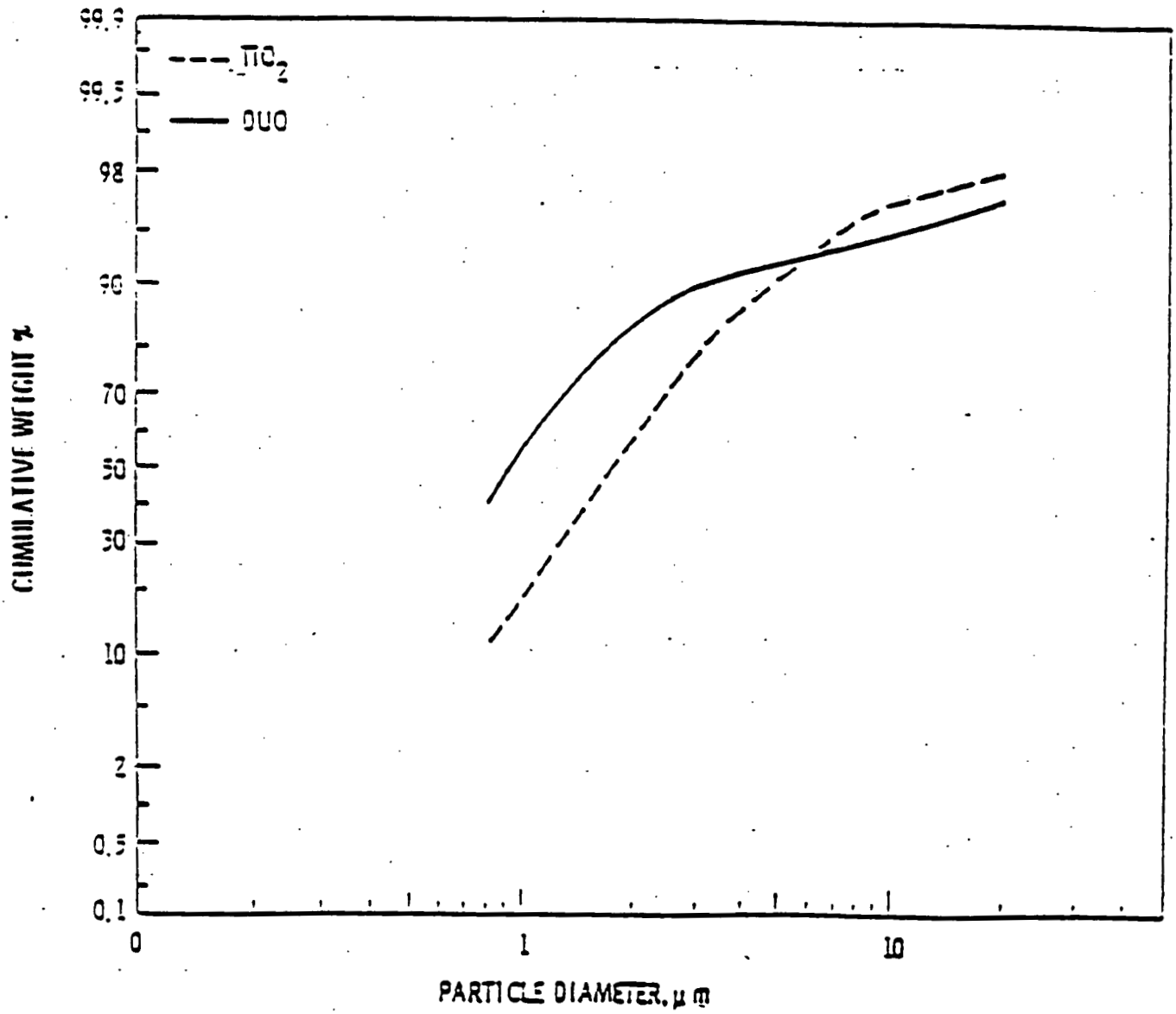

Figure 4-19. Titanium Dioxide and Uranium Dioxide Particle-Size Distribution (Figure C.1 - Sutter, Johnston and Mishima December 1981)

Table 4-14. Measured ARFs/RFs from the Free-Fall Spill of Powders
(Tables A.1, A.3, B.1 and B.3 - Sutter, Johnston and Mishima December 1981)

Fall Height, m	Material	Source Mass, g	ARF	RF
3	TiO_2	1000	1.5E-3	0.25
			9.6E-4	0.40
	UO_2		2.3E-4	0.25
			1.2E-3	0.49
		500	4.0E-4	0.70
			1.1E-3	0.38
	TiO_2	471.9	1.9E-3	0.34
		460.0	9.0E-4	0.40
		450.4	3.3E-3	0.62
		431.1	2.0E-4	0.40
		100	1.2E-3	0.31
			9.9E-4	0.46
	UO_2		4.0E-5	0.91
			4.0E-4	0.44
	TiO_2	25	7.0E-4	0.50
			8.0E-5	0.50
1	TiO_2	1000	5.0E-4	0.53
			1.7E-5	0.40
	UO_2		6.0E-5	0.46
			8.0E-5	0.50
		500	4.0E-5	0.83
			8.0E-5	0.52
	TiO_2	451	8.0E-5	0.42
		441.1	8.0E-5	0.41
	UO_2	100	2.0E-5	0.93
			7.0E-5	0.51
	TiO_2	25	1.0E-4	0.62
			2.0E-4	0.58

impact. The powder spill model is based upon the following assumptions that appear to be somewhat inconsistent with observations in Subsection 4.4.4.4.2:

- the growth rate of the powder front is constant and can be characterized by an angle of dispersion.
- the amount of powder airborne is proportional to the drag force on the powder.
- the diameter of the powder front at the start of the spill is equal to the diameter of the container from which it was spilled.

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A computer code, PSPILL, was developed to model powder spills. The model was run for varying values of M_o (mass of powder spilled, kg). An algorithm was developed based upon the statistical analysis of the results of the computer runs. The algorithm may be used to predict the ARF if the air density and viscosity are 1.18 kg/m^3 and 1.85E-5, respectively. The fraction airborne release is:

$$ARF = 0.1064\ (M_o^{0.125})(H^{2.37})/\text{bulk density powder}^{1.02}$$

where:
ARF = airborne release fraction
M_o = mass of powder spilled, kg
H = spill height, m
bulk density of powder, kg/m^3

The correlation coefficient for the algorithm is 99.4%.

The best available correlation for particle size of the airborne material is:

$$AMMD = 12.1 - 3.29(\text{bulk density powder}) + 7540(F)$$

where:
AMMD = aerodynamic equivalent mass median diameter, μm
F = fraction airborne
bulk density powder, kg/m^3

The equation only has a 46% correlation coefficient due to the variability in the data. The geometric standard deviation (rate change of the size distribution with mass) of the size distribution for all powders (based on the powders used in the experiments), TiO_2 and UO_2 are 4.82, 3.73 and 5.60, respectively.

The recommended median and bounding ARF/RFs are based on the experimental measurements uncovered. For fall distances less than 3-meters, the measured combination of ARF/RF that yield the highest fraction of material in the respirable fraction, 2E-3/0.3, is recommended as the bounding value. The median value recommended are the median values determined considering both powders, 3E-4/0.5. For fall distance greater than 3-meters, the bounding value can be estimated using the model discussed in Subsection 4.2.3.4.3 if the value calculated exceeds the ARF/RF combination of 2E-3/0.3.

4.4.4.2 Free-Fall Spill of Powder in Air Velocities >1 m/s Normal to Direction of Fall (Entrainment of Dispersed Soil Spilled into Flowing Air)

Sutter (August 1980) reported the results of experiments to measure the entrainment of dispersed soil spilled into flowing air. Contaminated soil was collected, mixed and dried

and pumped into a 0.61-m X 0.61-m wind tunnel. The experimental setup is shown schematically in Figure A.39 in Appendix A. The size distribution of the soil is shown in Figure A.40 and tabulated in Table A.44. The soil was deagglomerated and pumped into the wind tunnel at speeds of 1.4-, 4.6-, 6.8- and 8.9-m/s (3.1, 11, 15 and 20 mph). The results are listed in Table 4-15 and are plotted on Figure 4-20 taken from the referenced source. The fraction airborne, ARF, is:

$$ARF = 0.0134\ U + 0.00543$$

where U = windspeed, m/s.

Table 4-15. Airborne Soil Particle Size Distribution (Table 6 - Sutter August 1980)

Wind Speed, mph	Aerodynamic Mass Median Diameter, μm	%10 μm and less
3.2	>10	44
10.4	6.7	63
15.2	9.8	50
20.0	5.3	90

The RF measured at various windspeeds, shown in Table 4-15, ranges from 0.44 at 1.4 m/s to 0.90 at 8.9 m/s. The ARF at 8.9 m/s is 0.125 and, using the measured RF, 0.90, the fraction of soil less than 10 μm diameter is −0.113. The fraction of the soil <10 μm diameter listed in Table A.43 is 0.00088. It would appear that a large mass of smaller particles was shed by the larger soil particles or some fragmentation has occurred.

The equation would only apply to soil or powder with a similar size distribution and characteristics. Process powders tend to be finer and more coherent and the observation here may not be applicable. On the basis of the experimental measurements, bounding ARF/RF of 0.0134 U + 0.00543/1.0 (limited by the total mass of material in this size fraction in the source material) are recommended.

Bounding ARF - Entrainment of dispersed soil spilled into flowing air:

ARF 0.0134 U + 0.00543
RF 1.0 (limited by mass of material in RF of source material)

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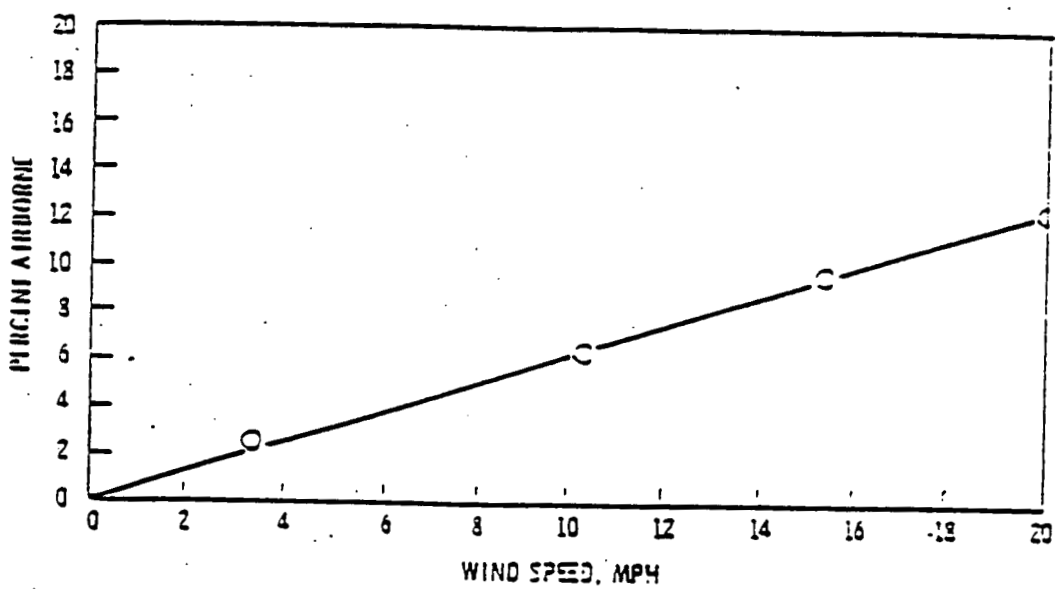

Figure 4-20. Percent of Soil Airborne as a Function of Wind Speed
(Figure 6 - Sutter August 1980)

4.4.4.3 Shock-Vibration

Under some circumstances, powder at rest could be ejected into the air by the response of the solid substrate on which the powder rests by the vibration/jolting induce by the impact of falling debris. The effect could be minor for very solid substrates such as structural members. The flexing of thin, metal sheets could be substantial especially if the flexing is repetitive. Also the cohesiveness of the powder could inhibit suspension. Powders at rest are difficult to deagglomerate and disperse often requiring substantial mixing in suspensions to attain their original size distribution.

No study applicable to this phenomenon was found. It would appear that the value for ARF should exceed that for resuspension alone (see Subsection 4.2.3.5 below) but be less than for a free-fall spill of the powder (2E-3/0.3 above). The powder undergoing shock-impact is bounced into the air while subject to the same airspeeds as would impact the material for aerodynamic entrainment. It would be less than for free-fall of the same powder since it is not subject to the same intensity at a level close to the surface nor for as long. A arbitrarily selected bounding ARF/RF of 1E-3/1.0, estimated by Mishima, Schwendiman and Ayer (October 1978) was quoted for the suspension of powder-like surface contamination by shock-vibration. Particles comprising surface contamination are assumed to be more widely dispersed and not as agglomerated as "thick" layers of particles that represent powders. Figure A.41 indicates the forces necessary to deagglomerate/disperse powders. The experiments performed by Langer (1987) discussed in Subsection 4.2.3.5.2 involving the suspension into flowing air of powders on plywood by impact of large pieces of debris indicated a maximum value of 1E-3. Therefore, for powders, the same value for the ARF, 1E-3, is recommended but the RF is reduced to 0.1 due to the difficulty of deagglomeration of powders.

4.4.5 Aerodynamic Entrainment (Resuspension)

Particle can be entrained from surface in two configurations: 1) entrainment of particles from the surface of a homogeneous bed (e.g., relatively flat pile of powder, soil), and 2) entrainment of particles from sparse deposits on a heterogeneous surface (hard, unyielidng). Since the entrainment of particles is a function of the characteristics of the flow, particles and surface, the entrainment of particles from the surfaces can be substantially different. Entrainment from homogeneous beds is discussed in this subsection covering powders exposed to normal air flow characteristics. The entrainment from sparse deposits on hard, unyielding surface will be covered in the subsection discussing aerodynamic entrainment of surface contamination (Subsection 5.2.1.5).

The suspension of particles from the surface of a homogeneous bed (includes powders and contamination on soil) under routine process (stable ventilation flow velocities and patterns indoors) and meteorological (windspeeds less than 5 m/s) conditions appears to be

dependent upon the interaction of various factors such as source, surface, upwind topographical and flow characteristics. The suspension of material from the surface of a homogeneous bed at higher air velocities was covered in Subsection 4.4.2.2.1.

4.4.5.1 Entrainment From the Surface of a Homogeneous Bed at Gas Velocities Found in Process Facilities and Normal Atmospheric Conditions

4.4.5.1.1 Review of Literature on Resuspension Phenomenon, Resuspension Factors, and Resuspension Rates. Sutter (May 1982) reviewed much of the known information and data for resuspension factors and rates and fractional releases. Both suspension by aerodynamic and mechanical stresses are covered.

Resuspension factors are defined as the ratio between the airborne concentration of a pollutant per cubic meter directly over a contaminated surface and the areal pollutant surface contamination. The units are meter^{-1}. In concept, the factor represents the uniform concentration above a contaminated surface at whatever height. As measured, the factor represents the airborne concentration of a pollutant measured at some height above the surface collected over some period of time versus the surface contamination without knowledge of what is the true inventory-at-risk. The relationship may have some relevance for indoor (static volumes and relatively reproducible conditions) but does not appear to reflect the physics of the situations outdoors.

For outdoors situation where the contaminated surface is predominantly soil (although contamination can be resuspended from vegetation, asphalt roadways, rocks, buildings surfaces, etc.) and the aerodynamic or mechanical stress can be imposed from many directions and levels, the situation is much more complex. Particulate contamination is assumed to agglomerate (become attached) with the soil particles. The removal and displacement of material from soil surfaces as a function of surface stress show three types of behavior termed - saltation, surface creep and suspension.

Saltation is defined as a mode of soil/sand particle movement where particles have alternate contact with air and ground in a layer close to the surface and affects particles in the size range of approximately 100 to 500 μm in diameter. The size range of particles suspended is shown in Figure 4-21 taken from Martin et al. (October 1983) indicating that particles in this size range are the most readily suspended (depends upon local wind conditions and particle morphology). (Note that the graph plots the square root of particle diameter vs friction velocity and is not a direct indication of the air speeds nor particle diameters.) This is the approximate size range for saltating particles. Saltating particles can initiate surface creep and suspension upon impact and/or continue saltation.

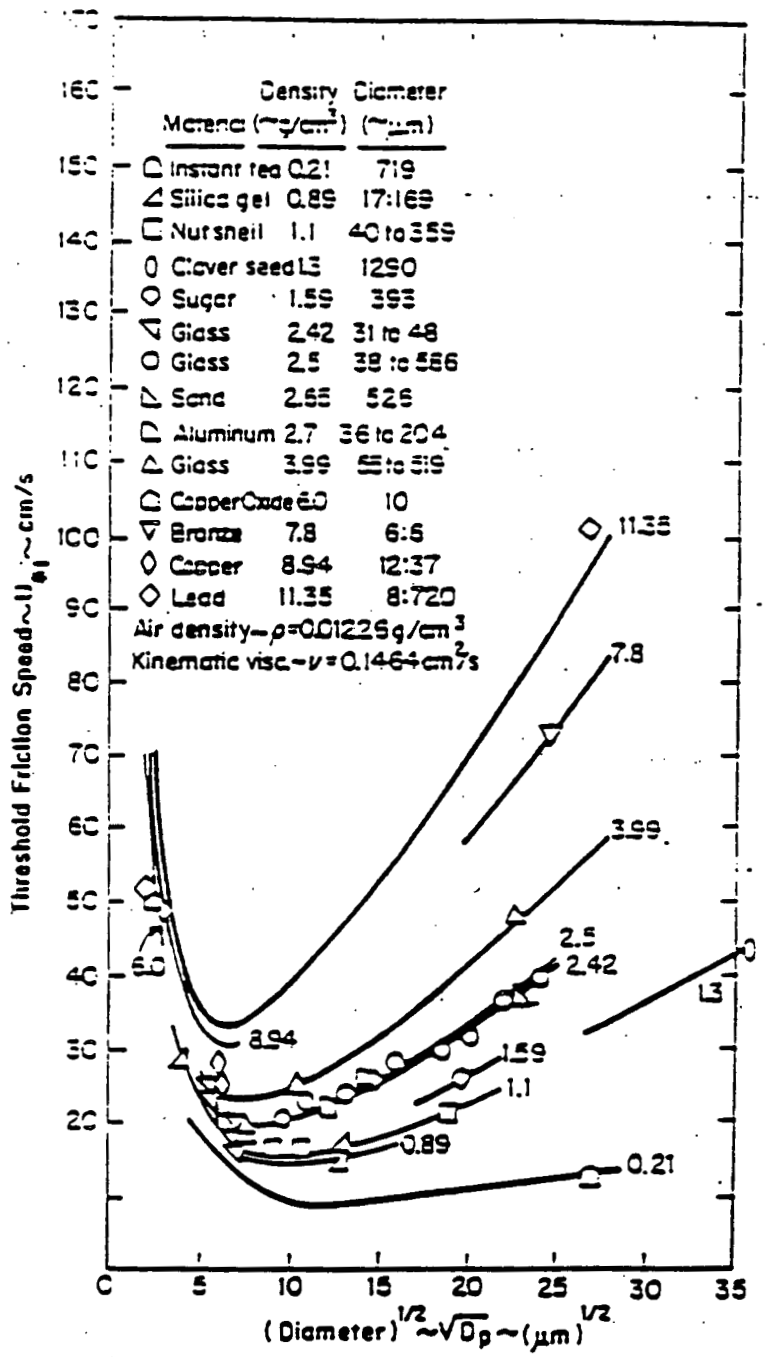

Figure 4-21. Particulate Threshold Friction Speed
(Figure 2 - Martin, et al. October 1983)

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Larger particles move by surface creep where particles always maintains contact with the surface. Surface creep affects particles in the size range of 500 to 1000 μm (0.5 to 1.0 mm) in diameter and cover the behavior of particles that slide or roll across the surface pushed by wind stresses and momentum exchange resulting from the impact of saltating particles.

Suspension is the mode of movement where particles do not come in contact with the surface locally. Suspension affects particles in the size range less than 100 μm in diameters and cover the behavior of particles that tend to follow the air motions.

The fraction of soil eroded by the three modes varies greatly - 50 to 75 wt/o by saltation, 5 to 25 wt/o by surface creep, and 3 to 40 wt/o by suspension.

Three tables (Tables 4-16, -17, & -18) taken from the referenced source are included. Table 4-16 tabulates resuspension factors (mostly from soil or vegetated soil but unspecified city surfaces are included) from wind stresses. The values range from ~1E-10/m to 5E-5/m. Table 4-17 tabulates the resuspension factors measured for mechanical stresses and are almost completely for indoors situations. The values range from 1E-10/m to 2E-2/m. Table 4-18 shows the resuspension rates from the published literature and all represent outdoors conditions (a mix of soil erosion and experimental data). The values ranges from 4E-9/hr to 4E-1/hr. Not all the relevant factors (e.g., windspeeds, particle size distribution of soil or pollutant, local surface conditions) are given nor is it always clear whether the relevant factors are known.

Sehmel (1980) provided a comprehensive review of literature on the resuspension/suspension (erosion) of soil. Resuspension is defined as re-entrainment of material deposited on the surface from the atmosphere. Suspension is defined as the entrainment of particles on the surface from non-atmospheric processes. The term resuspension is used to cover both processes since, once the material is entrained, it is not possible to distinguish the behavior of material generated by either process. For soil, the pollutant particles are attached to the host particles. The data are insufficient and inadequate to validate deposition, resuspension, diffusion and transport deposition and airborne plume models.

Soil transport was extensively covered. Various equations are available to estimate soil loss predominantly for agricultural purposes and are not particularly relevant here. Models based upon wind stresses on individual soil particles are subject to formidable uncertainties when required to integrate over the entire surface area. Due to the uncertainty as to the applicability of these models, direct measurements of resuspension are preferred.

Table 4-19 taken from the referenced source lists some of the factors that may influence outdoors resuspension from the soil. Not all these factors are operative in any

Table 4-16. Resuspension Factors from Wind Resuspension Stresses
(Table 2.2-1 - Sutter, May 1982)

Location	Source Material	Wind Speed Dependency	Resuspension Factor Range, m^{-1}	Reference
Nevada Test Site, Schooner	^{131}I		10^{-7} to 6×10^{-5}	Anspaugh et al. 1970
Nevada Test Site, GMX near center GMX near edge	Pu		 3×10^{-10} 3×10^{-9}	Anspaugh, Shinn, and Phelps 1975
New York–average air concentrations and surface depositions	Fallout		5×10^{-9} to 2×10^{-6}	Calculated from Bennett 1976
New York	^{238}Pu		5×10^{-8}	Bennett 1976
United Kingdom	^{238}Pu		5×10^{-9}	Bennett 1976
Palmares, Spain	Pu 10 day samples	U <9.7 m/sec	1.4×10^{-9} to 7.8×10^{-6}	Calculated from Icanzo and Salvador 1970
Nevada Test Site, dusty rural air	Pu		7×10^{-6}	Langham 1971
Hanford, Washington	Inert tracer, 1 m	Increases	1.7×10^{-10} to 2.7×10^{-7}	Schmel and Lloyd 1975
Rocky Flats, Kentucky	Pu		10^{-9} to 10^{-5}	Schmel and Orgill 1973
Maralinga trials	U 0.3 m ht 0.6 m ht	U <5 m/sec	3×10^{-4}	Stewart 1967
Paving stones	U_3O_8, 2 m^2 source	U <5 m/sec	8×10^{-9} to 6×10^{-6}	Stewart 1967
Sandy desert grass	U_3O_8, 9 m^2 source		1×10^{-9} to 5×10^{-5}	
Sandy soil with charred debris	^{210}Po, 1 m^2 source ^{210}Po, 1300 m^2 source	U <5 m/sec U <5 m/sec	2×10^{-9} to 9×10^{-6} 7×10^{-8} to 1×10^{-5}	Stewart 1967
Monte Bello Islands, hurricane trials	Fallout: 16 m source, lightly vegetated sand and rock near tower. Shot near road, no disturbance.	U <5 m/sec	1×10^{-6} to 1×10^{-5} 1×10^{-8} to 2×10^{-7} 1×10^{-8} to 1.5×10^{-6}	Stewart 1967

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Table 4-16. Resuspension Factors from Wind Resuspension Stresses (cont.)
(Table 2.2-1 - Sutter, May 1982)

Location	Source Material	Wind Speed Dependency	Resuspension Factor Range, m^{-1}	Reference
Cleared sandy soil	YCl_3, aqueous, 1 m^2 source YCl_3, aqueous, 9 m^2 source	U < 5 m/sec	9×10^{-11} to 5×10^{-8} 5×10^{-10} to 6.2×10^{-7}	Stewart 1967

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Table 4-17. Resuspension Factors from Mechanical Resuspension Stresses (Table 2.2-2 - Sutter, May 1982)

Location	Source Material	Wind Speed Dependency	Resuspension Factor Range, m^{-1}	Reference
Unventilated room	Be	Vigorous sweeping	1×10^{-2} to 4×10^{-2}	Mitchell and Sutsler 1967
Small unventilated room	Alpha floor contamination	People walking	3×10^{-4} to 2×10^{-2}	Calculated from Brunskill 1967
Change room with no ventilation	Alpha on coveralls	2 to 4 people changing coveralls	2×10^{-4} to 1.7×10^{-2}	Calculated from Brunskill 1967
Change room, concrete floor, 9 air changes/hr	"Loose" alpha floor contamination	4 to 6 people moving in room	2×10^{-4} to 3×10^{-3}	Brunskill 1967
Simulated work	Asbestos contaminated coat	Machining operations Stacking sheets	1.2×10^{-3} to 5.3×10^{-3} 2.0×10^{-3} to 4.2×10^{-3}	Carter 1970
Room--concrete floor	Pu facility	No circulation Fan air stress Fan and dolly movement No circulation after tests	1×10^{-3} to 2×10^{-4} 3×10^{-4} to 3×10^{-3} 4×10^{-3} to 1.5×10^{-2} 5×10^{-4} to 1×10^{-3}	Glauberman, Bootmann, and Breslin 1967
Room--concrete floor	U facility	No circulation Fan air stress Dolly movement Fan and dolly movement	7×10^{-5} to 4×10^{-4} 3×10^{-5} to 2×10^{-4} 1×10^{-4} to 2×10^{-4} 2×10^{-4} to 1×10^{-3}	
Maralinga trials	Fallout U Pu	Road survey, at 1-2 days Cab Land Rover, 5th hr 8th hr Dust stirred, 0.3 m ht Vehicle dust, 0.3 m ht Pedestrian dust, 0.3 m ht	1×10^{-8} to 2×10^{-6} 6.4×10^{-5} 2.5×10^{-5} 1×10^{-3} 3×10^{-7} to 7×10^{-4} 1.5×10^{-6} to 3×10^{-4}	Stewart 1967 Stewart 1967

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Table 4-17. Resuspension Factors from Mechanical Resuspension Stresses (cont.)
(Table 2.2-2 - Sutter, May 1982)

Location	Source Material	Wind Speed Dependency	Resuspension Factor Range, m^{-1}	Reference
Particles settled in room	ZnS MMD = 3.1 μm σg = 1.9 CuO MMD = 2.0 μm, σg = 2.3, alpha particulate	Vigorous work-sweeping Walking Light work Light sweeping Pedestrian and equipment	1.9×10^{-4} 3.9×10^{-5} 9.4×10^{-6} 7.1×10^{-4} 4.6×10^{-3} to 5×10^{-5}	Fish et al. 1967 Walker 1978
Civil defense trial	^{131}I	Bomb recovery operation with brick/plaster dust Enclosed space Open area	4.6×10^{-3} to 5×10^{-5} 4×10^{-5} to 2×10^{-4} 2×10^{-6}	Stewart 1976
Nevada Test Site	Pu	Extensive vehicular traffic	7×10^{-5}	Langham 1971
Laboratory room	PuO_2	No movement 14 steps/min 36 steps/min	2×10^{-8} 2×10^{-6} 5×10^{-6}	Jones and Pond 1967
Monte Bello Islands, hurricane trails	Fallout	Road survey from back Land Rover, 4th day 7th day At tailboard, 7th day	 8×10^{-7} to 3×10^{-5} 7×10^{-7} to 4×10^{-6} 1.6×10^{-5} to 3.1×10^{-5}	Stewart 1967
Australian desert "Totem" 1953	Fallout gamma	Walking survey Vehicle survey at tailboard Inside vehicle	3×10^{-7} 2×10^{-6} 2×10^{-5}	Stewart 1967

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Table 4-17. Resuspension Factors from Mechanical Resuspension Stresses (cont.)
(Table 2.2-2 - Sutter, May 1982)

Location	Source Material	Wind Speed Dependency	Resuspension Factor Range, m^{-1}	Reference
Contaminated field	Pu	Downwind tractor in tractor cab Fertilizing Subsoiling Planting, light discing Subsoiling Planting, light discing Mowing	5×10^{-8} to 1.0×10^{-6} 2.4×10^{-7} 7.9×10^{-9} 5×10^{-6} 1.8×10^{-8} to 7.9×10^{-6} 5×10^{-6} 1.8×10^{-8} to 7.9 to 10^{-6} 1.8×10^{-5}	Calculated from Milham et al. 1976
Tractor cab in contaminated field	Pu	Tractor operations	4×10^{-9} to 2×10^{-6}	Milham et al. 1976
New York	Fallout Pu	Average air concentration/ surface concentration	5×10^{-9} to 2×10^{-6}	Calculated from Bennett 1976
Palmares, Spain	Pu	Yearly average farming —	1.2×10^{-10} to 8.8×10^{-7}	Calculated from Iranzo and Salvador 1970
Contaminated sludge	Pu	Rototilling	5.6×10^{-8}	Calculated from Myers et al. 1976

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Table 4-18. Resuspension Rates
(Table 2.2-3 - Sutter, May 1982)

Location	Resuspension, sec^{-1}, Determined from:			Reference
	Source Material	Calculated Using Transport Mode and Concentration at Only One Height	Integration of Measured Concentrations	
Corn leaves	Pollen		10^{-6} to 10^{-4}	Calculated from Aylor 1976
Nevada test site	Pu	2.7×10^{-12} to 4.8 to 10^{-10}		Anspaugh, Shinn, and Phelps 1975
Nevada test site, GMX	Pu	10^{-12} to 10^{-10}		Healy 1974
Nevada test site	Pu	1×10^{-10} to 5×10^{-8}		Healy 1974, calculated from Wilson, Thomas, and Stannard 1960
Hanford site	ZnS			Healy 1974, recalculated from Healy 1955 and Healy and Fuquay 1958
Eroding field 0.5 tons/acre/mo 40 tons/acre/mo 310 tons/acre/mo	Soil	 2×10^{-9} 2×10^{-7} 1×10^{-6}		Calculated from Skidmore and Woodruff 1968
Prairie terrain	Calcium molybdate	10^{-8} to 10^{-10}		Schmel and Lloyd 1975
Hanford site	Respirable particulates	10^{-11} to 10^{-7}		Schmel 1979

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Table 4-19. Variables Which Influence Resuspension
(Table 1 - Sehmel 1980)

Pollutant Particle Properties	Soil Properties	Particle-Soil Interaction	Surface Properties	Topography	Meteorological Variables
Chemical Reactivity	Moisture content	Attraction forces	Areas of erodible surface	Agricultural	Air density, affected by:
Density	Radio of erodible to non-erodible fractions	• Molecular forces: Van-der-Waals forces	Cohesiveness of particles	Broken	• Humidity
Hydrophobic		• Chemical binding forces (Valence forces)	• Binding action of materials	Desert	• Pressure
Hydrophilic Particle Diameter	Soil size frequency distribution	• Electrostatic forces	• Surface moisture	Diurnal	• Temperature
• Respirable • Nonrespirable	Specific gravity structure	• Magnetic forces Capillary forces at the surface of aggregates filled with liquid	Cover Obstructions	Flat Forested	Soil burden carried • Influence on air velocity
• Frequency Distribution	• Organic matter	Chemical reaction	Roughness, large scale	Hills	• Avalanching
Shape	• Lime content	Contact area effect on adhesion	• Mechanical turbulence	Humidity	• Saltation
Surface Roughness	Texture Temperature	• Particle shape • Particle size • Nature of particle and surface • Surface roughness • Adhesion of agglomerates vs. individual particles	• Overall sheltering Roughness, small scale • Orientation of obstacles • Percent of area covered by non-erodible aggregates or obstacles	Seasonal Temperature Undulating Uniform Urban	Surface moisture content • Dew • Frost upheaval Relative humidity Temperature

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Table 4-19. Variables Which Influence Resuspension (cont.)
(Table 1 - Sehmel 1980)

Pollutant Particle Properties	Soil Properties	Particle-Soil Interaction	Surface Properties	Topography	Meteorological Variables
Chemical Reactivity	Moisture content	Attraction forces	Areas of erodible surface	Agricultural	Air density, affected by:
		Crystallization of dissolved substances	• Sheltering of individual particles	Valley	• Surface dry
		Deposition of suspended colloidal particle	• Stability of aggregates against abrasion and disintegration by moisture and watering	Water	• Surface drying • Surface frozen
		Hardening binders			• Wind speed Wind removal forces
		Liquid bridges Mineral bridges Relative humidity	Temperature Topographic features • Broken		• Mean wind speed • Frequency, period, and intensity of gusts penetrating to the surface
		Temperature	• Uniform		• Transient and steady drag
		Time of contact	Vegetative cover		• Vertical wind profile
		Viscous surface coating	• Live vegetation • Plant residue		• Stability • Vertical turbulent exchange • Surface roughness • Temperature stratification • Wind direction

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given situation and some factors may dominate in certain regimes. The range of published resuspension factors for various aerodynamic and mechanical stresses are shown in Figure 4-22 from Sehmel (1980) and are the same as shown in Tables 4-16 and 4-17. Although shown together, it is difficult to compare the listed values due to the differences in conditions and measurement techniques.

4.4.5.1.2 Experimentally Measured Resuspension Rates. Sehmel and Lloyd (1976) reported the results of a 4-month study of the resuspension of a submicrometer diameter tracer from a lightly vegetated soil surface due to ambient wind stresses. An aqueous slurry of submicron sized calcium molybdate stabilized with a surfactant was sprayed on the surface of a lightly vegetated area in a circle with a 22.9-m radius on the Hanford site. The surface roughness height was 34 mm. The average concentration over the area was 0.63 g molybdenum/m^2. Material resuspended were sampled by the arrangement shown schematically in Figure A.35 using sampler as shown in Figure A.36 that aligned the sampler inlet with flow. During the first two test periods (10/2/73 to 11/4/73 and 11/16/73 to 12/16/73) only one sampler was used at each height and all samplers operated continuously. During the third test period (1/16/74 to 2/8/74), the sampling arrangement was as shown in Figure A.34 and a single sampler at each height turned on automatically for three velocity ranges (1.3 to 3.6 m/s, 3.6 to 5.8 m/s, and >5.8 m/s). The maximum recorded gust during these periods was 20.1 m/s (45 mph). Samples were not taken during periods of precipitation. The sampler inlet were isokinetic for a windspeed of 0.52 m/s. Corrections for anisokinetic sampling are difficult to estimate for the continuous sampling and are at least an order of magnitude less than the measured levels.

Resuspension rates for the test conditions were of the order of 4E-5/hr to 4E-7/hr. The proper application required an equation that continuously depletes the source since there are 8760 hr/yr and from 0.35% to 35% of the source is depleted per year. The error would not be significant for short periods of time (e.g., 4E-5 of the source is depleted in one hour at a resuspension rate of 4E-5/hr). An uncertainty is the possible loss of resuspended materials if the plume height exceeded the sampling height. Furthermore, it is uncertain which surface areas are being sampled by the samplers. The material plume spreads as it rises and travels downwind. The material sample is some cumulative fraction of some unknown upwind area.

Most recently, several researchers have investigated the long-term effects of the radionuclides deposited from the Chernobyl Nuclear Power Generating Station incident. Garland and Pigford (1992) investigated the resuspension of the material under a variety of circumstances. Resuspension factors varied inversely with the amount deposited. Some seasonal variation was observed and some increase due to traffic. Generally, results support the use of the lowest resuspension factors. Typical and mean resuspension factors from site with highest deposition during the initial periods were 5E-9 and 2E-8 and decreased for next periods. The sampling configurations nor periods were given but they most certainly exceed

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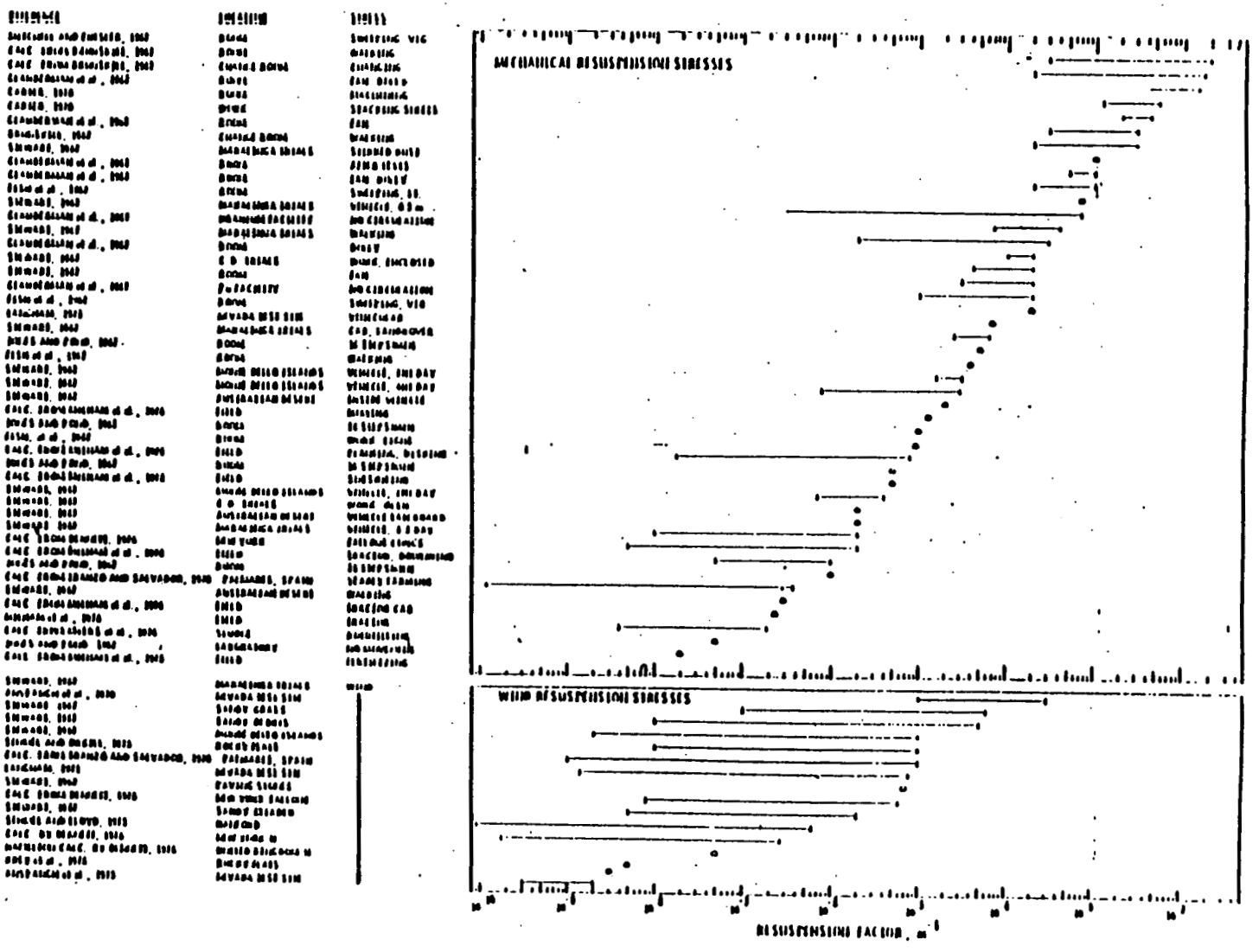

Figure 4-22. Resuspension Factor Ranges from Mechanical and Wind Resuspension Stresses (Figure 2 - Sehmel 1980)

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a second and are more likely in days. Therefore, even the initial resuspension factors would be less than the rates measured by Sehmel and Lloyd (1976).

Garger, Gavrilov and Zhukov (1992) modeled the transfer and fallout of radionuclides deposited from the Chernobyl accident. The airborne concentration and deposition rate of radionuclides due to resuspension and activities were modeled for normal and unfavorable steady-state meteorological conditions. Resuspension rates of 1E-9/s at 5 m/s and 2E-7/s at 15 m/s were calculated based on air sampling.

Based upon the information on resuspension factors and rates found in the two reviews, the experimentally measured rates tend to indicate that the long-term resuspension rate bound determined by Sehmel and Lloyd (1976), 4E-5/hr, is reasonable and not overly conservative. Although the rates appear to decrease with time (and even higher rates are probably possible for short periods of time during the initial phases of the aerodynamic entrainment), using the initial, higher rates would be conservative. The fraction released with time is for the material-at-risk that is difficult to define and decreases with depletion of the material-at-risk by the entrainment and other phenomena such as burial, cover by debris deposited on the surface. etc. The resuspension tends to fluctuate as the level of stress fluctuates and the surface conditions respond to the previous stresses. After an event, the powder released may be exposed to primarily aerodynamic stresses within the facility or remnants of the facility until remedial action can be taken. The time interval of exposure would be hours rather than seconds. Thus, a bounding ARR of 4E-5/hr with a RF of 1.0 is recommended.

No experimental data on the effects of large debris over the deposited powder on aerodynamic entrainment were found. Schmitt (May 1975) reported an approximate order of magnitude reduction in particulate emissions from carbon microsphere used to extinguish a fire. Due to the decrease in aerodynamic stress if the powder is shielded by remnants and debris of the structure or exposed to static conditions within the structure, a bounding ARR/RF for powder under debris of 4E-6/hr with an RF of 1.0 is recommended.

- Bounding ARR/RF, homogeneous bed of powder exposed to ambient conditions (normal process facility ventilation flow or atmospheric conditions, <2 m/s) following an event: 4E-5/hr, 1.0[8]

- Bounding ARF/RF, thin layer of powder buried under structural debris exposed to ambient conditions or under static conditions within the structure following an event: 4E-6/hr, 1.0[8]

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[8] Mass of material airborne in RF is limited by the total mass of that size fraction in the source material.

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4.4.5.2 Entrainment by Airflow/Turbulence Induced by Large Falling Objects

Under some circumstances substantial portions of structural features and equipment may fall into radionuclide-bearing-powders released from containment. If the fall of the objects generates a substantial air movement, the powder impacted may be suspended by the aerodynamic stress imposed.

Langer (1987) dropped three rocks (1.29 kg, 1.17 kg, and 1.82 kg) 3.7-m onto powder on a plywood sheet (called the "impact area") or held in a can in a vented metal box placed on the impact area. The experimental apparatus is shown schematically in Figure A.36 and the results in Table A.42 in Appendix A. Air (430 cfm) was drawn into the box via a filter that removed particles >5 μm in diameter and passed through the impact area at a velocity of 0.8 mph (0.36 m/s). Most of the air (91%, 390 cfm) was drawn through a 8-in. diameter cyclone with a 10 μm AED cutoff. The particles penetrating the cyclone were collected on a special high volume filter paper. The remainder of the air (~9%, 40 cfm) was passed through a cyclone with a 5 μm AED cutoff, a one-stage impactor that removed all particles >0.5 μm AED, and the particles penetrating the system were collected on a glass fiber filter. Two optical spectrometers (1 lpm instrument that classified particles 5 to 100 μm into 4 classes and a 3 lpm instrument that divided particles 0.2 to 12 μm into 16 classes) provided real-time aerosol particle size distributions and number concentrations.

Four powders were tested - sand (<2000 μm and <500 μm), sand plus Al_2O_3, Al_2O_3, and nickel metal. An indication of the size of the powders is found in Table A.42. The intent of the experiments was to determine the release of plutonium powders impacted by building debris. For typical plutonium dioxide powder formed in the foundry, ~0.01% is in the respirable size range (defined by the author as particle <3 μm AED), 0.3% in the inhalable range (defined by the author as particles <10 μm AED) and ~2.2% was <25 μm AED (based on data from optical sizing of the powder). All three materials used as surrogates were free-flowing (non-cohesive) powders unlike fine PuO_2. The size distribution of both Al_2O_3 (gritty, free-flowing, large proportions of fines) and nickel (hard, nearly spherical metal, free-flowing) were finer than that for foundry PuO_2. Airborne releases for non-cohesive powders should be greater than for cohesive powders with Al_2O_3 characteristics most closely paralleling the PuO_2. The density of Al_2O_3 is 3.965 g/cm^3, approximately one-third that of PuO_2, and 11.5 g/cm^3 for nickel. The relevant data from the experiments are tabulated in Table 4-20.

The highest measured ARF for all materials is 1E-3 for the Al_2O_3 uncontained on the pad. The RF associated with this configuration is 0.3, a value near the middle of the RFs measured. The median ARF/RF for all materials under these test conditions was 4E-4/0.2 with an average value of 6E-4/0.2. The range of ARFs is a factor of 5, 2E-4 to 1E-3.

Table 4-20. Measured ARFs/RFs from the Impact of Structural Debris on Powders (Table 1 - Langer November 1987)

Material	Configuration	<10 μm AED	>10 μm AED	ARF	RF
Sand, <2000 μm	qt. can	2.5E-6	2.6E-4	2.6E-4	0.01
Sand, <500 μm 1.8% <25 μm	qt. can	2.0E-5	2.8E-4	3.0E-4	0.07
Sand, <500 μm 1.8% <25 μm	on pad	3.1E-4	5.6E-4	8.7E-4	0.36
Sand, <500 μm plus 2.6% Al_2O_3	on pad	7.2E-5	4.3E-4	5.0E-4	0.14
Al_2O_3 <300 μm 24% <25 μm	on pad	3.3E-4	8.9E-4	1.2E-3	0.27
Nickel 0.2% <25 μm	on pad	1.0E-4	7.5E-5	1.8E-4	0.57

Without multiple measurements under the same test conditions, it is difficult to estimate a level of uncertainty. The limited range of test conditions and the difficulty in reproducing the test conditions described introduce considerable uncertainty. The analytical measurementconsiderable uncertainty. The analytical measurement instruments used should not result in a high level of uncertainty. Other measurements under similar circumstances at this level of ARF resulted in an order of magnitude uncertainty in the values. This level or greater of uncertainty appears appropriate for these values.

There are only single experiments on each material and configuration. It is assuring that the ARF for nickel metal powder with approximately the same density and a finer distribution of particles as PuO_2 is less than the ARFs measured for sand and, as expected, the ARF for Al_2O_3, a low density fine powder, is high. The size and weight of the debris used and the fall heights appear to be very unrealistically low for potential conditions in most nuclear facilities where large-sized debris from multiple levels may impact the released materials. In as much as the release mechanism appears to be air turbulence and shock-vibration of the released powder both potentially increasing with mass and size of debris and fall height, the values measured in these experiments may not be bounding. The "median" value for all experimental configurations tested were ARF/RF of 4E-4/0.2. Due to the uncertainty in the measured values and the test conditions, it is recommended that a conservative value for the bounding ARF of 1E-2 with a RF of 0.2 be applied.

4.4.5.3 Suspension of Material by Vehicular Traffic

In the event that radioactive materials in powder form are spilled onto a roadway during transport or deposited by airborne transport during the accident, the deposited material may be impacted by vehicular traffic unaware of the presence of the material or by

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evacuation of personnel. Sehmel reported the results of experiments performed to measure the suspension of material on an roadway from the passage of a vehicle (passenger car and 3/4-ton truck) through the deposited material and in an adjacent lane. Particles of ZnS <25 μm in diameter (MMD <5 μm in diameter) were deposited on the asphalt surface of a 3-m X 30-m section of roadway (one lane of a two-lane road). The ZnS particle size distribution during deposition is shown in Figure A.38a in Appendix A. Sampling towers were located at three distances (3, 6, and 9 m) from the road with filter samplers at 0.3-m, 1-m, 2-m and 2.4-m heights. Realtime ZnS monitors were located at the 0.6-m level of each tower. Deposition samplers were located between the towers on each row and at 1-m, 18-m and 30-m. The arrangement is shown schematically in Figure A.38b in Appendix A.

The experimental results are tabulated in Table A.43a (resuspension by a passenger car) and Table A.43b (resuspension by a 3/4-ton truck). The integrated average resuspension per passage by or through the deposited material was calculated by mass balance using an average source of 0.5 g ZnS/ft^2. The resuspension rate for a passenger car driven past the unaged deposited materials ranged from 4.8E-5/passage to 1.1E-3/passage and increased with vehicles speed. The resuspension rates for a passenger car and 3/4-ton truck driven through unaged deposited material ranged from 1.9E-4/passage to 1.09E-2/passage and 2.5E-3/passage and 6.7E-3/passage, respectively. The measured rates are plotted against vehicle speed on Figure 4-23 taken from the referenced source.

The resuspension rate decreased rapidly with time. The resuspension rates after four days of aging are shown in Figure 4-24 taken from the referenced source and show an order of magnitude decrease. The calculated effects of ageing are shown in Figure 4-25 from the referenced source. The highest resuspension rate for unaged deposited material is 1E-2/passage for a passenger car driven through the material and is recommended as the bounding value. In the absence of any measured RF values, a conservative value of 1.0 is recommended as the bounding RF.

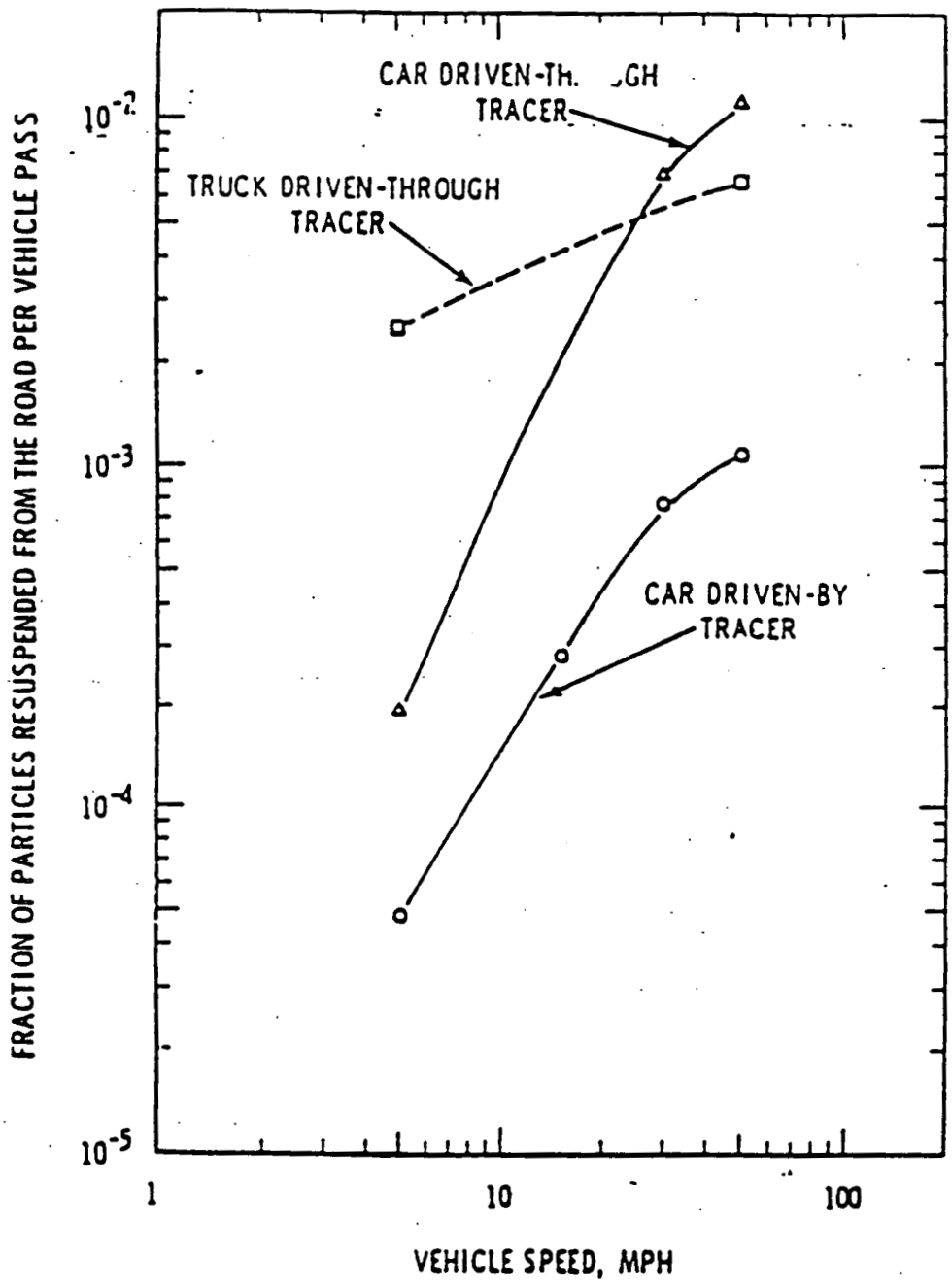

Figure 4-23. Particle Resuspension Rates from an Asphalt Road Caused by Vehicle Passage (Figure 3 - Sehmel 1976)

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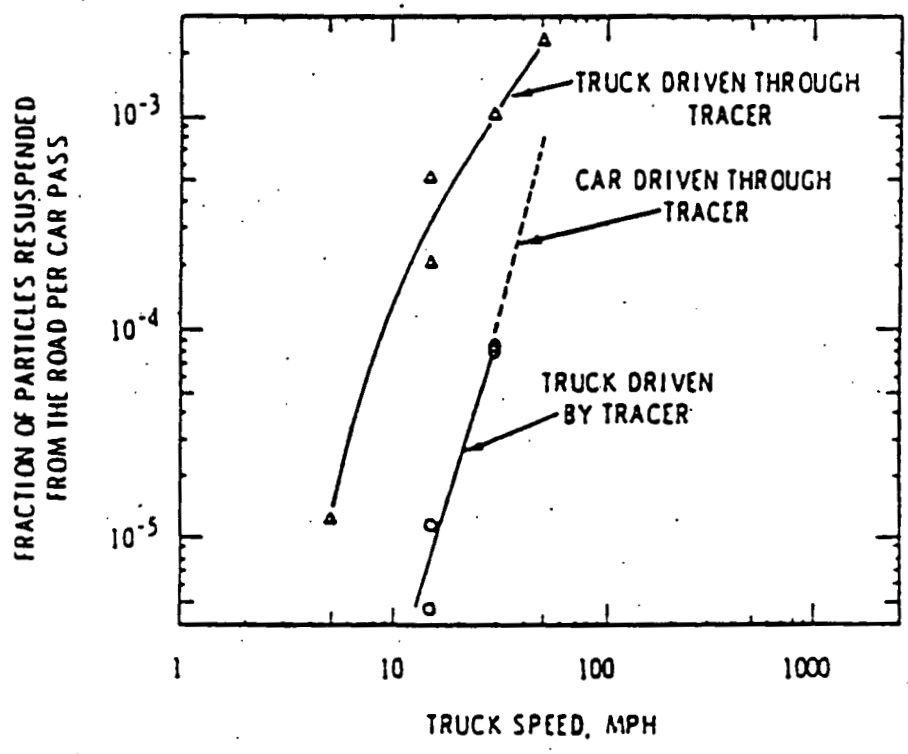

Figure 4-24. Particle Resuspension Rates from an Asphalt Road Caused by Vehicular Traffic Passage Four Days After Particle Deposition
(Figure 5 - Sehmel 1986)

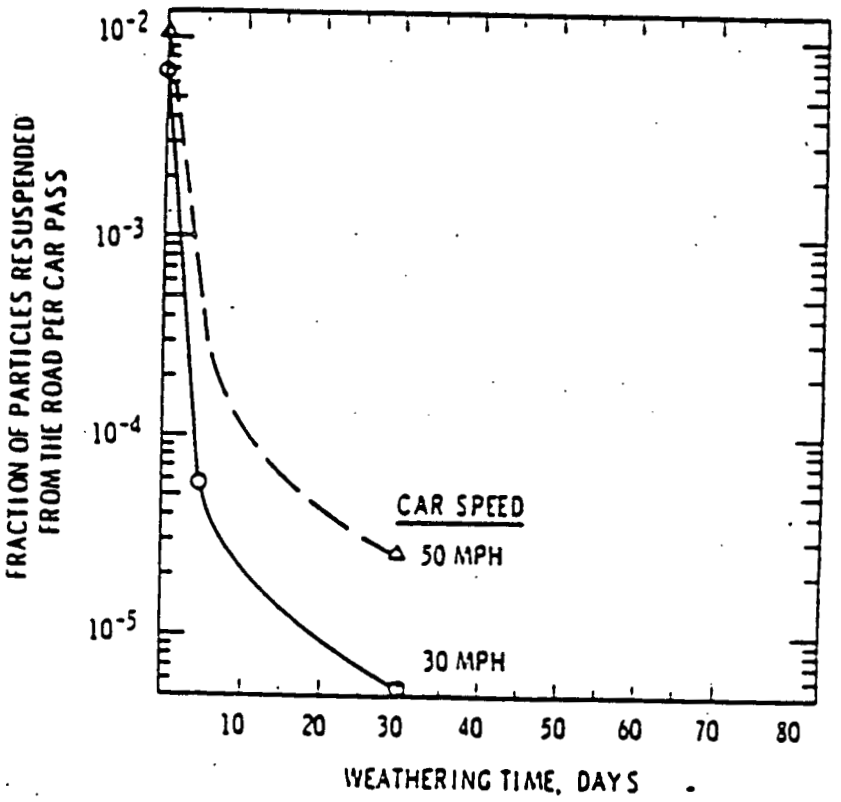

Figure 4-25. Particle Resuspension Rates from an Asphalt Road as a Function of Weathering Time (Car Driven Through Tracer) (Figure 4 - Sehmel 1976)

5.0 SURFACE CONTAMINATION

Release fractions are recommended for materials on which surface contamination may be found. These materials include combustible solids, such as trash, wood, and wall board; trash may be made up of paper, rags, cardboard, and plastic (wrapping sheets, bags, containers, glovebox windows, tools, casings, and ion exchange resins). Information is also reported for non-combustible materials, generally large pieces associated with the facility structure, enclosure, or containers and sometimes glass or plastic equipment. Surface contamination on solid, non-combustible, hard, unyielding surfaces, including exhaust ducts, is also examined.

5.1 SUMMARY OF RECOMMENDED ARFS/ARRS AND RFS

Contaminated, Combustible Solids

Thermal Stress

- Packaged Mixed Waste. For contaminated combustible materials heated/burned in packages with non-contaminated exterior surfaces, the following values are recommended. These values are based on maximum experimentally determined ARF and conservative assumption of RF.

median	ARF 8E-5/RF 1.0[9]
bounding	ARF 5E-4/RF 1.0[9]

- Uncontained Cellulosics. For burning of unpackaged cellulosic materials, such as paper, cardboard, rags, and wood, the following values are recommended; these values are based upon maximum experimentally determined ARF/RF for variety of cellulosic materials.

median	ARF 5E-4/RF 1.0[9]
bounding	ARF 1E-2/RF 1.0[9]

- Uncontained Plastics. The following values apply to contaminated combustible materials burning in uncontained atmosphere (no packages).

  - all plastic materials except polystyrene: Based upon maximum experimentally determined ARF and RF for polychloroprene and polymethylmethacrylate:

[9] Mass airborne in RF cannot exceed the total mass in RF of the source contaminant material.

5.0 Surface Contamination; Su

bounding

- polystyrene: Based upon
  and RF for very limited s
  polystyrene contaminated
  range of ARF 2E-3 to 8E

bounding

- Entrainment during Passage of A
  experimentally determined ARF
  burning of very small specimen :
  air-dried solution contaminants u
  following values are recommend

bounding, powder
bounding, solution or air-

Explosive Releases

There are no applicable data for the shc
contaminated combustible solids. The values r
judgment.

- Shock Effects. Materials can be
  material is extremely flexible. F
  porous surfaces. The bounding
  due to vibration-shock of substra
  significant response.

bounding

- Blast Effects. Reasoned judgme
  mechanism is bounded by susper
  vibration.

bounding

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[9] Mass airborne in RF cannot exceed th
material.

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Venting of Pressurized Gases Over Contaminated, Combustible Waste

No applicable data.

Free-Fall Spill, Crush-Impact

There are no applicable data for free-fall spill of combustible solids. For the situation where the material impacts with a surface (shock-vibration induced by impact), the bounding ARF/RF is based on reasoned judgment that suspension under these circumstances are bounded by suspension postulated for powders from surfaces by shock-vibration (see Subsection 5.2.1.2.1):

bounding ARF 1E-3/RF 1.0

Aerodynamic Entrainment (Resuspension)

No applicable data were found. The bounding ARRs/RFs quoted are based on reasoned judgement that entrainment under these conditions are bounded by suspension of powder under similar circumstances.

bounding - for nominal flow conditions indoors (normal process facility flows) and outdoors (<5m/s) ARR 4E-5/hr; RF 1.0

- for static conditions indoors (essentially no flow) or surface contamination buried under debris, ARR 4E-6/hr; RF 1.0

Contaminated, Non-Combustible Solids

Thermal Stress

Bounding values were selected based on reasoned judgement that the suspension of surface contamination (most probably in the form of a sparse population of particles attached to the surface) under thermal stress is bounded by the suspension of reactive powders under thermal stress in a flowing airstream (see Subsection 4.4.2.2.1).

bounding ARF/ 1E-2/RF 0.001

Explosive Releases

- Shock Effects. The bounding values are based upon the maximum mass of respirable particles predicted by the Steindler and Seefeldt (1980) correlation.

bounding - mass respirable particle released equal to mass TNT Eq estimated; mass of substrate carrying surface contamination; assumption depth of layer fragmented by detonation.

- Blast Effects. The bounding ARF/RF are based on reasoned judgment that suspension under these conditions would not exceed comparable values for loose powders under similar circumstances (see Subsection 4.4.3.2).

  bounding ARF 5E-3/RF 0.3

Venting of Pressurized Gases Over Contaminated, Non-Combustible Solid

No applicable data. Based on assumption that any release conservatively bounded by bounding ARF/RF postulated for powders in Subsection 4.4.3.3.

bounding ARF 1E-1/RF 0.5[9]

Free-Fall Spill, Crush-Impact

No applicable data. Based upon assumptions that release for various mechanisms bounded by airborne release of powder under similar circumstances.

- Free-Fall Spill, materials that undergo and do not undergo brittle fracture. No significant airborne releases postulated during free-fall.

- Impact, shock-vibration.

  - Materials that undergo brittle fracture: airborne release by brittle fracture bounded by ARF/RF postulated for brittle fracture in Subsection 4.3.3.

    bounding - PULF = A P g h ($J/10^7$ $g\text{-}cm^2/s^2$)

  - Materials that do not undergo brittle fracture: airborne release by shock-vibration bounded by release postulated for powder by shock-vibration in Subsection 5.2.2.2.1.

    bounding ARF 1E-3/RF 1.0

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[9] Mass airborne in RF cannot exceed the total mass in RF of the source contaminant material.

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Aerodynamic Entrainment (Resuspension)

Assumed bounded by ARR/RF postulated for aerodynamic entrainment of powders (Subsection 4.2.3.5).

- bounding - for nominal conditions indoors (process facility ventilation flows) and outdoors (<5 m/s) ARR 4E-5/hr; RF 1.0[9]
  - for static conditions (1 m/s and less) or from surface contamination covered by debris ARR 4E-6/hr; RF 1.0[9]

HEPA Filters

Thermal Stress

Based upon conservative extrapolation of the maximum experimental measurement of release of particles accumulated by the passage heated air through HEPA filters.

bounding ARF 1E-4/RF 1.0

Explosive Releases

- Shock Effects. Based on experimentally measured releases of accumulated particles from HEPA filters subjected to shock waves.

  bounding ARF 2E-6/RF 1.0

- Blast Effects. Based on maximum measured release of accumulated particles by passage of high velocity air through filters.

  bounding ARF 9E-3/RF 1.0

Release of Pressurized Gases Through Filters

Releases bounded by ARF/RF for blast effects in Subsection 5.2.3.2.2.

bounding ARF 1E-2/RF 1.0[9]

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[9] Mass airborne in RF cannot exceed the total mass in RF of the source contaminant material.

Free-Fall Spill, Shock-Impact

No applicable experimental data for airborne release of particles during free-fall of HEPA filters uncovered. No significant release postulated during free-fall. Releases on impact bounded by conservative extrapolation of maximum releases measured for contained (in packages) and uncontained HEPA filters.

bounding - enclosed (e.g packages, housing) HEPA with accumulated particles upon impact with hard unyielding surface ARF 5E-4/RF 1.0
- unenclosed HEPA filters with accumulated particles upon impact with hard, unyielding surfaces ARF 1E-2/RF 1.0[9]

Aerodynamic Entrainment (Resuspension)

Since the filters are designed and manufactured to collect and retain particles in flowing air, no significant release of accumulated particles is postulated by passage of air across face of filter. Even if the filter medium is exposed, no significant release of accumulated particles by nominal air velocities is postulated.

5.2 CONTAMINATED, COMBUSTIBLE SOLIDS

There are a wide variety of contaminated, solid, combustible materials found in nuclear facilities. These materials are generally trash, such as paper; rags; cardboard; plastic from wrapping, sheeting, bags, containers, windows, tools, casings. and ion exchange resins. There could also be contaminated structural material such as wood and wall board. The nature of the contaminant also shows great variation, ranging from solid particles adhering to the surfaces (resulting from wiping smearable contamination) to materials absorbed in the surface or matrices of the substrate (e.g., dilute aqueous solutions that have evaporated, solutions that have been absorbed in the material). Trash is generally held in a plastic bag in a container that is sealed after filling. Other forms of contaminated solid combustibles (e.g., windows, tools, casings) are uncontained until retired from use. Because each combination of substrate and contaminant may react differently to the various stresses imposed and suspend materials on their surfaces or absorbed into their matrices by different mechanisms, ARFs for these situations needed experimental definition.

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[9] Mass airborne in RF cannot exceed the total mass in RF of the source contaminant material.

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5.2.1 Thermal Stress

Contaminants on solid, combustible materials can be suspended by the destruction of the substrate during the formation of pyrolyzates or smoldering combustion and entrained in the vapor flow/convective currents generated. Various factors may affect either the burning rate (such as the availability of oxygen or the surface area of the combustible material exposed) or the entrainment (such as whether air passes through a burning mass). For example, individual thin layers of cellulose such as sheets of paper or tissue will burn rapidly and release the mineral content as ash. Burning of solid materials is a heterogeneous process; volatile vapors are released and mix with the air to form a flammable mixture. This action forms the commonly observed diffusion flame. Strands of cellulose also burn by smoldering combustion (the glowing portion observed in wood fires). If the thin layers of paper rest on other loosely packed combustible materials, the vapor generation provides a lifting force that can suspend small particles and inject them into the convective flow induced by the flame. But if the thin layers are tightly packed, the layers cannot burn efficiently due to the lack of oxygen and the burning may only be a surface phenomenon or only smoldering combustion can occur. In such cases, the suspension of contaminants and ash may be significantly reduced. Other possible scenarios include enhanced suspension via explosive burning of carbon monoxide when exposed to a large influx of oxygen, or limited oxygen accessibility owing to fire conditions.

Because of the range of potential burning conditions, experimental measurements of the airborne release of surface contamination were used to provide the basis for the release fractions cited below. Various experimental studies have been performed to measure the ARF during the burning of contaminated solid materials (Mishima and Schwendiman October 1970, April 1973; Halverson, Ballinger and Dennis March 1987). The range of ARF values for the various materials is shown in Figure 5-1. The experimental data for each form are limited and only span a limited range of parameters. Inspection of the results for burning of contaminated, combustible wastes shows that for the range of uncertainty in the data, the ARFs/RFs could be categorized into several categories - packaged mixed waste, uncontained cellulosics, uncontained plastics (excluding polystyrene), polystyrene, and situations where airflow is passed through the burning mass or the ashes from the burning mass falls into an induced airflow.

5.2.1.1 Packaged Waste

Current requirements have led to the packaging of contaminated, combustible waste in relatively substantial packages such as metal containers and drums. Although the packaging is not as substantial, the only data on packaged waste was reported by Mishima and Schwendiman (April 1973) for the ARF from burning mixed waste (paper, rags, tape, plastic, cardboard, oil) contaminated with uranium dioxide powder (size distribution is shown in Figure A.41 in Appendix A), uranyl nitrate liquid, and air dried uranyl nitrate and should

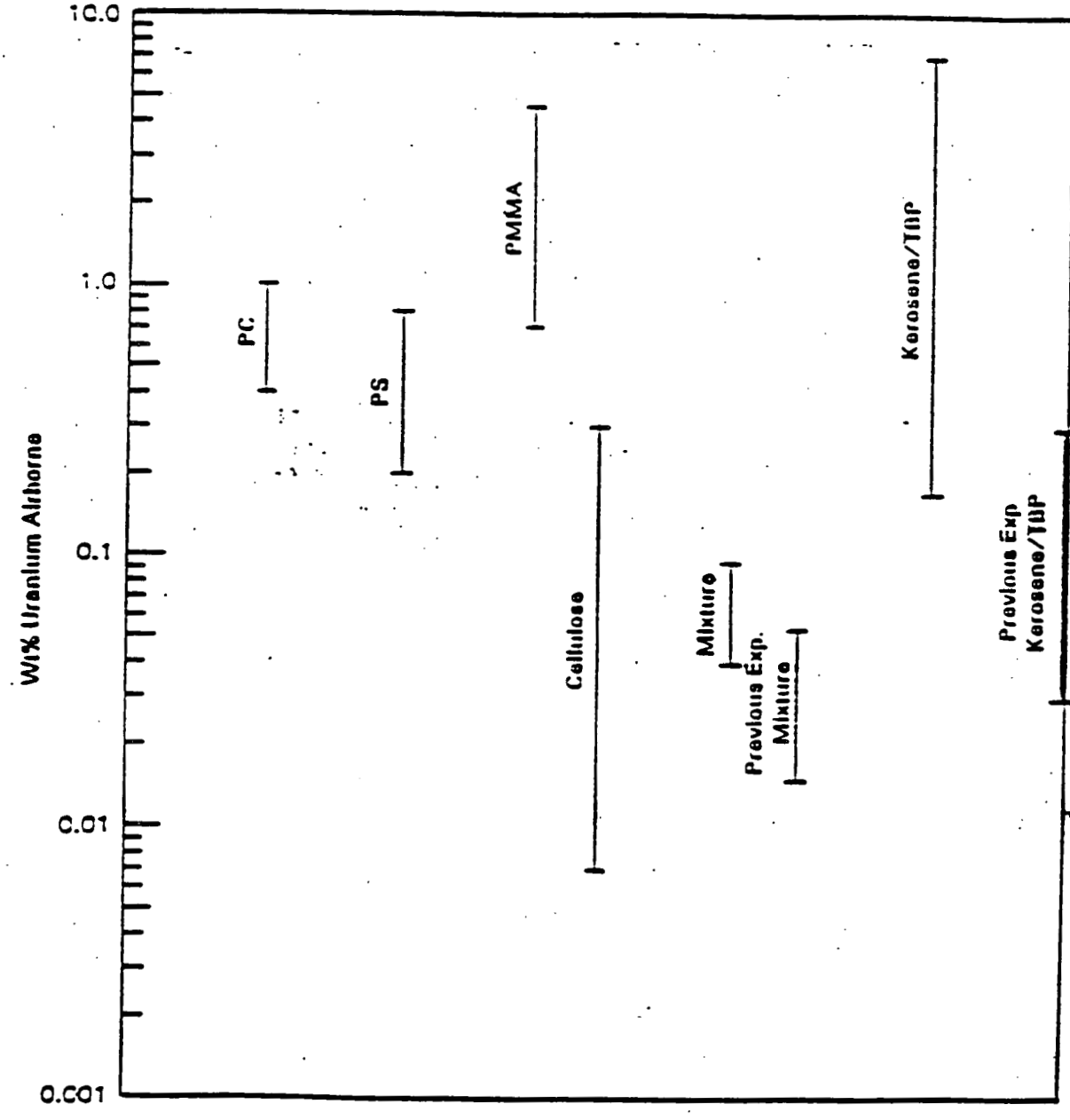

Figure 5-1. Results from Burning Contaminated Combustibles
(Figure 2 - Halverson, Ballinger, and Dennis March 1987)

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bound the airborne release from more substantial packages. The presence of more substantial material surrounding the contaminated, combustible waste would limit the availability of oxygen and force particles generated in the interior of the mass to pass through the ash/residue formed prior to release. The pre-contaminated wastes were packaged in a plastic bags and sealed in an 18-in. x 18-in. x 24-in.-high cardboard carton. The carton was placed on a grille-like holder shown in Figure A.42 in Appendix A in a 10-ft diameter x 10-ft tall stainless steel vessel system shown in Figure A.3. The carton was ignited and allowed to burn to self extinguishment under natural convection. Fractional airborne release was determined by collecting airborne material at the vessel outlet on the ceiling. The results are tabulated in Table A.46 in Appendix A and the relevant data shown in Table 5-1.

Table 5-1. ARFs from Burning of Packaged, Contaminated, Mixed, Combustible Wastes
(Table II - Mishima and Schwendiman April 1973)

Mass U, g	U Cpd.	ARF
9.1	UO_2	5.3E-4
25.2	a.d. UNH[1]	3.0E-5
25.5	UNH[2]	8.3E-5
25.5	UNH	4.7E-5
64.1	UO_2	1.7E-4
51	UO_2/UNH	4.1E-5
25.5	UNH	3.0E-5
50.2	UO_2	5.2E-5
25.5	a.d. UNH	1.5E-4
51	UNH	1.5E-4
51.6	UO_2	1.5E-4

[1] a.d. UNH = air dried uranyl nitrate hexahydrate
[2] UNH = uranyl nitrate hexahydrate

The ARFs range from 3E-5 to 5E-4, roughly an order of magnitude. No differences for compound are discernible from the limited data set. The recovery of uranium from the residue varied greatly and, eliminating the high value, indicates a possible substantial loss that places even greater uncertainty on the results. The maximum ARF measured was 5E-4. The median value is 8E-5 with an average ARF of 1E-4.

Contamination was also measured on the floor and walls following the runs and is listed in Table A.46. Some of the contamination detected on the walls may have been airborne material that deposited during the experiments. The contamination may also have been materials directly ejected from the fire. Wall deposition was not included in the ARF reported in as much as many more deposition surfaces exist around waste under most fire

situations and the airborne material lost by this mechanism, if any, would be less than under normal accident conditions.

Two explanations for the ARFs compared to the ARFs for uncontained materials (covered below) are possible. One is that the presence of an uncontaminated ash/residues imposes a barrier that attentuates the generation of particle of contaminant and, in a sense, acts as a filter. The second is that the packaging limits the oxygen availability leading to smoldering combustion rather than flaming combustion (considerable ash and unburned residue was found after each run) resulting in less entrainable ash. In this latter case, the ARF for cellulosics determined below would be multiplied by combustion efficiency. Since there is not a readily available method to define combustion efficiency (i.e., efficiency in producing an entrainable ash), the maximum ARF values measured are recommended as a bound for this configuration.

Based upon the above data, a bounding ARF of 5E-4 is recommended for packaged waste. In lieu of any measured size distribution for the airborne materials, a conservative, bounding RF of 1.0 is recommended. As in all cases, the mass of material airborne in the RF cannot exceed the total mass of RF in the source material.

5.2.1.2 Uncontained, Combustible Materials

The ARFs from the burning of contaminated cellulosic materials have been measured in three sets of experiments by Mishima and Schwendiman (1970): in an upflow of air during combustion, very small specimens in a stainless steel shallow dish in an upflow of −60 mm/s, and in a shallow aluminum pan centered in a 0.18-m i.d. quartz tube. The results of these experiments are found in Tables A.47, A.48 and A.54 in Appendix A. The relevant data from the three sets are summarized in Table 5-2.

The experimentally measured ARFs during the burning of contaminated cellulosic material are bounded by a value of 1E-2 with a median value of 5E-4 and an average value of 2E-3. The measured RFs are for the release from cellulosics contaminated by a fine, non-reactive powder. Nonetheless, the conservative measured RF value of 1.0 and an ARF of 1E-2 are recommended. The mass of material airborne in the RF cannot exceed the total mass of the RF in the source material.

5.2.1.3 Uncontained Plastics/Elastomers

Experimental ARFs are available for three materials - polychloroprene, polystyrene and polymethylmethacrylate. The results for the individual materials is presented below but, due to the similarity of the ARF and the uncertainty in the measurements, the ARF/RF for polychloroprene and polymethylmehtcrylate are combined.

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Table 5-2. Measured ARFs and RFs from the Burning of Contaminated Cellulosic Materials

Composition	Burn Time, min	Velocity, m/s	ARF	RF
liquid Pu nitrate contaminant (Table II - Mishima and Schwendiman October 1970)				
10-g corrugated cardboard	12.0	0.06	1.0E-2	—
10-g corrugated cardboard	6.2	0.06	5.0E-4	—
5-g cheesecloth	6.2	0.06	4.3E-3	—
5-g cheesecloth	6.7	0.06	5.2E-3	—
paper towels (Halverson, Ballinger, and Dennis March 1987)				
0.1 g DUO/g	14.0		1.88E-4	—
0.03 g DUO/g	17.0		2.39E-4	0.97
0.09 g DUO/g	33.5		3.03E-4	—
0.09 g DUO/g	11.0		4.78E-4	—
0.08 G DUO/g	10.4		5.46E-4	
0.09 G DUO/g	12.7		4.78E-4	
0.095 g DUO/g	11.4		9.03E-4	0.47
0.1 g DUO/g	7+		3.01E-3	—
0.1 g DUO/g	10.3		1.53E-3	—
0.2 g DUO/g, aero entrainment	15.8+		1.08E-4	—
a.d. UNH	9.8		2.9E-4	—
a.d. UNH	8.3		1.0E-4	—
UNH liquid	44.5		7.5E-5	—
UNH liquid	15.3		7.0E-5	—
air passes up through burning material (Mishima and Schwendiman October 1970)				
10 g tissue paper + DUO	3.7	1.04	3.4E-1	—
10 g tissue paper + DUO	6.0	0.46	3.3E-1	—
10 g tissue paper + DUO	3.5	1.04	3.8E-1	—
10 g cheesecloth + DUO	2.0	1.04	2.0E-1	—
10 g cheesecloth + DUO	2.1	1.04	3.5E-1	—
10 g cheesecloth + DUO	1.7	1.04	3.3E-1	—
10 g cheesecloth + DUO	3.2	0.46	7.0E-1	—
10 g corrugated cardboard + DUO	2.6	0.46	1.2E-1	—
	3.5	1.04	8.0E-2	—
	2.8	0.46	1.6E-2	—
	1.7	1.04	1.2E-1	—
10 g tissue paper + UNH	2.5	1.04	8.0E-3	—
10 g cheesecloth + UNH	7.7	1.04	2.0E-3	—
10 g cheesecloth + UNH	2.5	0.46	3.4E-6	—
10 g cheesecloth + UNH	3.1	1.04	5.0E-4	—
10 g cor. cardboard + UNH	13.0	1.04	1.3E-2	—
10 g cor. cardboard + a.d. UNH	7.0	1.04	2.0E-3	—
	7.0	1.04	1.0E-3	—

5.2.1.3.1 Polychloroprene (PC) (elastomer, rubber). Five experiments were conducted using plutonium nitrate and rubber from surgeon's gloves (Mishima and Schwendiman October 1970) and five experiments were performed using PC contaminated with DUO powder, UNH liquid and a.d. UNH (Halverson, Ballinger and Dennis March 1987). The experimental results are listed in Tables A.48 and A.50 in Appendix A and the relevant data summarized in Table 5-3.

Table 5-3. Measured ARFs from Burning Contaminated PC (Table A.1 - Halverson, Ballinger and Dennis March 1987)

Burn Time, min	Composition	ARF	RF
7	5 g rubber, Pu nitrate	7.0E-4	—
9	5 g rubber, Pu nitrate	1.9E-3	—
5	5 g rubber, Pu nitrate	2.0E-4	—
7.2	5 g rubber, Pu nitrate	8.0E-4	—
6.2	5 g rubber, Pu nitrate	6.2E-3	—
7.5	DUO powder	1.0E-2	—
10.0	DUO powder	8.0E-3	—
15.7	DUO powder	3.7E-3	0.16
9.0	UNH liquid	3.5E-2	—
7.5	a.d. UNH	4.2E-3	—

The bounding ARF for the very limited data set (only single results for UNH liquid and a.d. UNH contaminants) is 4E-2 (3.5E-2 rounded upwards). The single RF value, 0.16, was determined for another set of conditions and the ARF is the lowest measured (based on previous experience, the lowest ARFs generated the highest RFs). The median value is 4E-3 with an average of 7E-3.

5.2.1.3.2 Polystyrene (PS) (molded plastic, containers, IX resin). Only three experiments were performed to measure the ARF during the burning of contaminated PS. Only liquid UNH was used as a contaminant. The results are listed in Table A.52 in Appendix A and the relevant data summarized in Table 5-4.

Table 5-4. Measured ARFs and RF from Burning of Contaminated PS (Table A.2 - Halverson, Ballinger and Dennis March 1987)

Burn Time, min	Composition	ARF	RF
18.5	0.17 ml UNH/g PS	1.6E-3	—
12.8	0.4 ml UNH/g PS	1.8E-3	—
12.8	0.5 ml UNH/g PS	7.8E-3	0.90

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The highest measured ARF is 7.8E-3 with an RF of 0.9. The median value (if such a value has any meaning with the very restricted data set) is 1.8E-3 with an averaged value of 3.7E-3.

5.2.1.3.3 Polymethylmethacrylate (PMMA) (lucite/perspex, windows). Thirteen experiments were performed to measure the ARF from burning contaminated PMMA. All three forms of uranium compounds were tested using granular PMMA. One experiment measured the aerodynamic entrainment from DUO powder mixed with PMMA. Tests were performed with the location of the contaminant (powder mixed with the PMMA, a thick layer on the surface, a pile of powder on the surface, and the powder under the PMMA). The results are tabulated in Table A.53 in Appendix A with the relevant data summarized in Table 5-5.

Table 5-5. Measured ARFs and RFs from Burning of Contaminated PMMA (Table A.3 - Halverson, Ballinger and Dennis March 1987)

Burn Time, min	Composition	ARF	RF
20.2	DUO powder, no combustion (aerodynamic entrainment)	2.5E-3	—
31.5	DUO powder	3.2E-2	—
34.6	DUO powder	3.0E-2	—
18.4	Thick layer DUO powder	3.5E-2	—
17.0	Thick layer DUO powder	3.6E-2	0.84
19.5	Pile DUO powder	4.4E-2	—
19.3	Pile DUO powder	4.5E-2	—
21.0	DUO powder under PMMA	1.3E-2	—
18.6	DUO powder	3.7E-2	—
30.3	DUO powder	1.5E-2	0.95
26.0	0.12 ml UNH liquid/g PMMA	1.9E-2	0.84
15.5	0.05 ml UNH liquid/g PMMA	2.0E-3	—
16.7	0.12 ml UNH liquid/g PMMA	2.0E-2	—
16.6	a.d. UNH	6.0E-3	0.63

The highest measured ARF is 5E-2 (4.5E-2 rounded upward). Neither of the two RFs measured (0.84 and 0.95) were for the same conditions as those in which the highest ARF was measured. The highest measured ARF using UNH was 2E-2. The RF measured (0.84) was associated with an ARF (1.9E-2) very near the maximum value. The single ARF measured using air dried UNH is within the range of values for UNH liquid. The median value for all ARFs is 3E-2 with an average value of 3E-2 (2.5E-2 rounded upward). The median values for DUO and UNH are 4E-2 and 1E-2, respectively. In keeping with the selection of conservative values, a bounding ARF of 5E-2 and an RF of 1.0 are recommended. As in previous cases, the RF cannot exceed the RF of a source powder.

Therefore, if the RF of a source powder is less than 5E-2 (5%), the RF must be adjusted accordingly.

The bounding ARFs/RFs for this class of materials under thermal stress are divided into two groups - polychloroprene and polymethylmethacrylate, and polystyrene - by the measured values. Based upon the experimental data, the similarity in measured values, and the limited data available, bounding ARF/RF recommended for the PC + PMMA group are 5E-2/1.0 with the mass airborne in the RF limited by the total mass of RF in the source material. If the RF airborne exceeds that value, the RF airborne must be reduced accordingly. The bounding ARF/RF recommended for polystyrene are 1E-2/1.0.

5.2.2 Explosive Releases

Experimental data on the behavior of combustible solids, such as trash, during explosive events have not been uncovered. Based upon some general observations, the behavior of the substrate can be somewhat defined and the behavior of the surface contamination inferred. An attempt will be made to provide some train of logic for certain situations that appear to be amenable to definition.

5.2.2.1 Shock Effects

Combustible solids will undergo fragmentation by the shattering effect of detonation like other materials. Due to the extreme flexibility of some materials (thin sheets of paper, rubber, plastic), these materials may be more subject to dislodgement by shock-vibration at very short distances from the blast interface. No experimental data on the airborne release of contaminants from this phenomenon were uncovered.

If the solid is fragmented by the shock wave, the Steindler-Seefeldt correlation for fragmentation by detonation indicates that 100% of the material impacted would be fragmented to 10 μm AED and less at an MR of 1.0. The fraction is reduced to 9.2% at an MR of 2. Therefore, the most material fragmented into the respirable size particles at an MR of 1.

The particulate contamination on the surface of the combustible material may be dislodged by the vibration of the substrate in response to the shock wave. The small mass of the particulate contamination would probably require many cycles before dislodging and the airborne release would be small. The particle attached to porous surface such as wood or paper would probably not be dislodged by fragmentation of the substrate.

Due to the flexibility of the materials generally comprising combustible wastes, it is assumed that the principal response of the substrate material to vibration and shock is flexing. Materials adhering to the surface are ejected by the movement depending on how

the contaminant is attached to the surface. The only experimental data that may have any relevance is for aerodynamic entrainment from surfaces and the dislodgement mechanisms are different. The recommended bounding ARF for suspension from a pile of powder from a hard, unyielding surface due to accelerated flow generated by an explosion parallel to the surface is 5E-3 with an RF of 0.3 (see Subsection 4.C.2.a). The stresses upon the surface contaminant, much of which is embedded in the surface, appear to be fewer than those described for powders on unyielding surfaces. The stresses are certainly greater than those assumed for the resuspension of materials from nominal airflow in facilities or outdoors, 4E-5/hr. An ARF of 1E-3 with a RF of 1.0 was arbitrarily selected for this phenomenon by Mishima, Schwendiman and Ayer (October 1978) in the analysis of the consequences of severe natural phenomena on mixed oxide fuel fabrication facilities. The value is 20% of the value assigned for the suspension of loose powders by explosion generated accelerated flows parallel to the surface and orders of magnitude greater than values assigned for resuspension. On these bases, an ARF of 1E-3 with a RF of 1.0 is recommended as a bound for the suspension of surface contamination from combustible solid waste from the accelerated airflow generated by an explosion.

Due to the high temperatures that may be generated and the dispersive action of the pressure impulse from the explosion, burning of the combustible material may also be a concern.

5.2.2.2 Blast Effects

Due to the extreme flexibility of most of the materials that comprise combustible wastes (e.g., sheets of tissue paper, toweling, paper, plastic, rags), the principal impact of accelerated velocity would appear to be dispersal of the material with loss by dislodgement of the contaminant by shock-vibration. It is assumed that the ARF is bounded by the ARF/RF, 1E-3/1.0, developed below for the airborne release of powders due to shock-vibration. Ignition and burning of the combustible material and the suspension of the contamination should also be considered if applicable.

5.2.3 Venting of Pressurized Gases over Solid

No applicable data were uncovered.

5.2.4 Free-Fall Spill

Loss/dislodgement of surface contamination during the free-fall spill of contaminated, combustible materials would not appear to generate any significant stress upon the surface and will be bounded by the ARF/RF developed for shock-vibration below. In many cases the combustible materials would have high surface to mass ratios (e.g. paper, cardboard, plastic sheets and wrapping) and would generated little force during impact with surfaces. In

the case of material with appreciable mass, the dislodgement of surface contamination upon impact would appear unlikely but would be bounded by the bounding ARF/RF described in Subsection 4.4.4.3 for the suspension of powder by vibration-shock.

5.2.4.1 Free-Fall Spill

No applicable data were uncovered. For materials with high surface to mass ratios, no significant suspension of surface contamination is postulated.

5.2.4.2 Vibration-Shock on Impact After Free-Fall

For materials with appreciable mass that generate significant forces upon impact with a surface (forces adequate to result in dislodgement of the surface contamination), the bounding ARF/RF for the suspension of powder, 1E-3/1.0, described in Subsection 5.2.1.2.1, is recommended.

5.2.5 Aerodynamic Entrainment/Resuspension

The value for the aerodynamic entrainment (resuspension) of powder lying on a heterogeneous surface under nominal flow condition indoors or outdoors has been assigned a value of 4E-5/hr with a RF of 1.0 (Subsection 4.4.5). For thin layers of powders lying on the surface of a heterogeneous surface under debris or for static conditions within facilities, the ARR is degraded to 4E-6/hr with a RF of 1.0. It is not anticipated that the resuspension of contaminants for solid, combustible wastes would exceed these values under the same conditions. On these bases, these values are also recommended as bounds for the ARF/RF for the resuspension of surface contamination from combustible solids.

5.3 SOLID, NON-COMBUSTIBLE (HARD, UNYIELDING) SURFACES (INCLUDES EXHAUST DUCTS)

The surface contamination on solid, non-combustible surfaces is assumed to be a sparse population of loose (not combined with the surface matrix) particles lying on the heterogeneous surface. In actual cases, surface contamination can range from contamination mixed with a worn, abraded surface (e.g., rust, concrete) to materials chemically attached to the surface. For contamination mixed with a powdery surface, responses for powders are more appropriate.

5.3.1 Thermal Stress

The flexing (expansion and contractions) of metal and other non-combustible surfaces may eject some particles contaminating their surfaces. The experimental data that most closely represent such situations would be the suspension of powders during heating and

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oxidation (see Subsection 4.3.1). An ARF of 1E-2 with a RF of 0.001 were recommended for powders under thermal stress (Mishima, Schwendiman and Radasch July 1968) and appear to bound any anticipated release for this situation.

5.3.2 Explosive Releases

5.3.2.1 Shock Effects

The Steindler and Seefeldt (1980) correlation estimates that 100% of the non-explosive material with a density of 1.0 g/cm^3 impacted is fragmented into particles in the respirable size range at an MR (mass of non-explosive material/TNT Equivalency of explosion in same mass units) of 1.0. Only 10% of the non-explosive material is fragmented into particles in the respirable size range at an MR of 2. Therefore, assuming activity in surface contamination in twice the mass of the TNT Eq. of non-explosive surface material would be conservative. An assumption of how much inert substrate is associated with the surface contamination and is involved in the fragmentation is necessary to determine the fraction of the surface contamination made airborne.

5.3.2.2 Blast Effects

The ARF/RF assumed for the suspension of surface contamination by shock-vibration postulated for airborne release of surface contamination from solid, combustible substrates (Subsection 5.2.2.1), ARF/RF 1E-3/1.0, is assumed to bound any releases under these circumstances.

5.3.3 Venting of Pressurized Gases Over Solid

No applicable experimental data were uncovered. Any airborne release of surface contamination under these circumstances is assumed to be bound by the release during the venting of pressurized powders, ARF/RF 1E-1/0.5, in Subsection 4.4.3.

5.3.4 Free-Fall Spill/Crush-Impact

No applicable measured data were uncovered. No significant impacts are anticipated for material that will undergo plastic deformation (e.g., metal, plastics, wood) during free-fall or upon impact with a hard, unyielding surface. Any suspension of surface contamination should be bounded by the bounding values postulated for suspension by shock-vibration. For materials that undergo brittle fracture (e.g., aggregate, glass), no suspension is anticipated during free-fall but suspension can occur at impact.

5.3.4.1 Free-Fall Spill

No significant suspension is anticipated; no data were available.

5.3.4.2 Crush-Impact/Brittle Fracture

5.3.4.2.1 Solids That Undergo Brittle Fracture. If the solid can brittle fracture (e.g., aggregate, glass) due to crush-impact forces, the activity present on the surface may be carried by the fragments. The fragmentation of solids into particles in the respirable size range was discussed in Subsection 4.4.3. The fraction is calculated by:

$$PULF = A\ P\ gh$$

where: PULF = fraction pulverized into particles 10 μm diameter or less
A = empirical correlation, 2E-4 cm^3/J (J = g-cm/s);
P = specimen density, g/cm^3;
g = gravitational acceleration, ~960 cm/s^2 at sea level; and,
h = height, cm.

5.3.4.2.2 Solids That Do Not Brittle Fracture. If the solid is plastic and does not undergo brittle fracture (e.g., metal, plastics), the shock-vibration value developed for powders on hard, unyielding surface in Subsection 5.3.2.1, ARF/RF 1E-3/1.0, although probably highly conservative, will bound releases of surface contamination by shock-vibration.

5.3.5 Aerodynamic Entrainment/Resuspension

The parameters governing the suspension of particles from a heterogenous surface (e.g., metal, some plastic, concrete, glass) are the same as for suspension from a homogeneous bed; the parameters are the characteristics of the flow, particles and surface. The effects of the various factors that contribute to the parameters (e.g., aerodynamic lift forces, drag forces, adhesive forces) vary greatly. Figure 5-2 taken from Brockman (February 1985) shows the effect of particle size on various adhesive forces. Figure 5-3 taken from Fromentin (January 1987) illustrates the effect of surface roughness on the suspendability of small particles. Adhesion decreases with substrate surface roughness until the macroroughness becomes the same size as the particles when in increases rapidly (Hubbe, 1984). The surface roughness of the particles, the presence of moisture, the plasticity of the surface (Johnson, Kendall and Roberts 1971), and other factors all appear to affect the adhesion of particles to substrates or to each other.

Current consensus assumes that flow must be turbulent before significant suspension occurs (Fromentin January 1987). This is not necessarily the case for the aerodynamic

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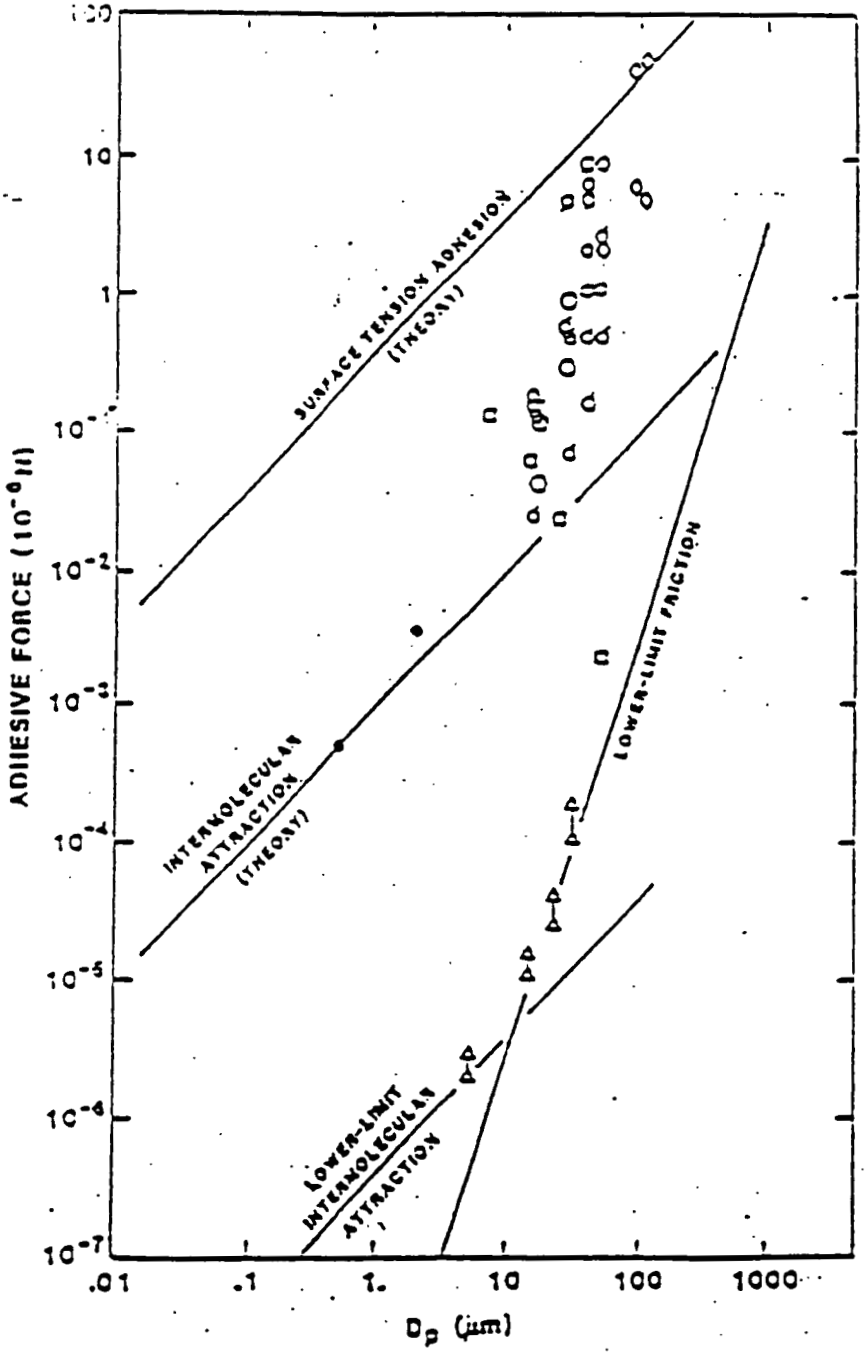

Figure 5-2. Variation in Adhesive Forces Observed for Various Size Particles (Brockman February 1985)

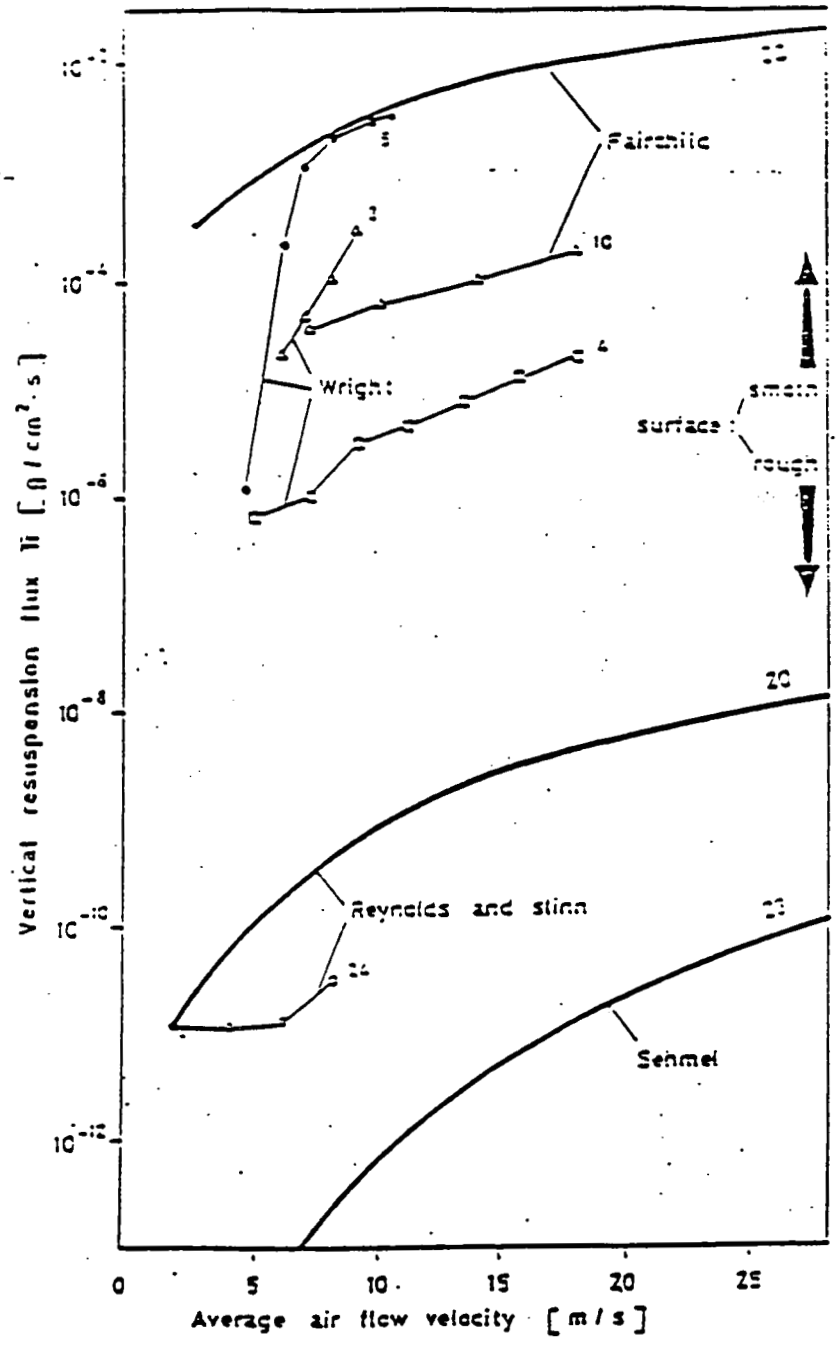

Figure 5-3. Resuspension Flux F_r Air Flow Velocity for Particles Smaller Than 10 Micrometer Diameter
(Fromentin January 1987)

entrainment under process facility ventilation flow or outdoors at windspeeds less than 5 m/s. The turbulent flow is divided into three regions: 1) core; 2) transition; and 3) viscous sublayer with regions two and three comprising the wall region (Alonso, Bolado and Hontanon July 1991). Current consensus also agrees that turbulent bursts (intermittent ejections of discrete fluid elements from the wall region towards the core) play some role in suspension (Cleaver and Yates 1973). The burst process is composed of three steps: 1) deceleration of axial fluid velocity within local region near wall, 2) progressive acceleration from approach of fluid with mean velocity, and 3) before affected region totally accelerated, ejection of fluid from region of unaccelerated fluid (Alsonso, Bolado and Hontanon July 1991). The process is shown schematically in Figure 5-4.

Currently, there are two general concepts for aerodynamic entrainment - force balance and energy balance. The force balance concept states that when the aerodynamic lift/drag forces exceed the adhesive forces, particles on the surface of the substrate are suspended. Most authors have subscribed to the force balance concept. Recently, Reeks et al. (May 1985a, May 1985b, June 1985a, June 1985b, 1988) have proposed an energy balance concept that postulates the resuspension of small (< 100 μm diameter) particles by energy transfer from the turbulent flow. The concept is similar to the removal of molecules from surface by Brownian motion. The energy maintains the particle in motion at the surface within the surface potential well. Particles are suspended when they accumulated sufficient vibrational energy to escape the potential well.

Authors (Reeks et al. May 1985a, Wright 1984) have reported suspension of large fractions of deposited particles during the buildup to test velocities. Wright (1984) reports that the initial suspension of 95% of the deposited particles on the floor of a wind tunnel during increase to 60 m/s ($\sim$135 mph). Braaten, Shaw and Paw U (1986) reported negligible loss during an increase to 20 m/s in a wind tunnel. John, Fritter and Winklmayr (1991) found some suspension of 8.6 μm sodium fluorescein particles when filtered air at 40 m/s from a nozzle was impinged upon the Tedlar surface. The point may be moot for the conditions covered here since the material is continually subjected to some if not the actual air flow during deposition and any initial suspension occurring in the initial seconds would be lost with the release from the occurrence.

Garland (1982), Corn and Stein (July 1965), Cleaver and Yates (1973) and Wright (1984) found resuspension fluxes inversely proportional to time (decayed with time) while Sehmel and Lloyd (1976) did not find any apparent decay over a 21-month test period.

A vast array of literature exists on various aspects of the resuspension of sparse particles from the surface of substrates (Corino and Brodkey 1969; Corn 1966; Dahneke January 1975; Ettinger 1974; Fairchild 1982; Fish 1967; Hall 1988; Hubbe 1984; Jordan 1954; Larsen August 1958; Nelson 1973; Punjrath 1972; Spenser 1976). Zimon's (1969) text book provides a good theoretical background of the topic. More recently several

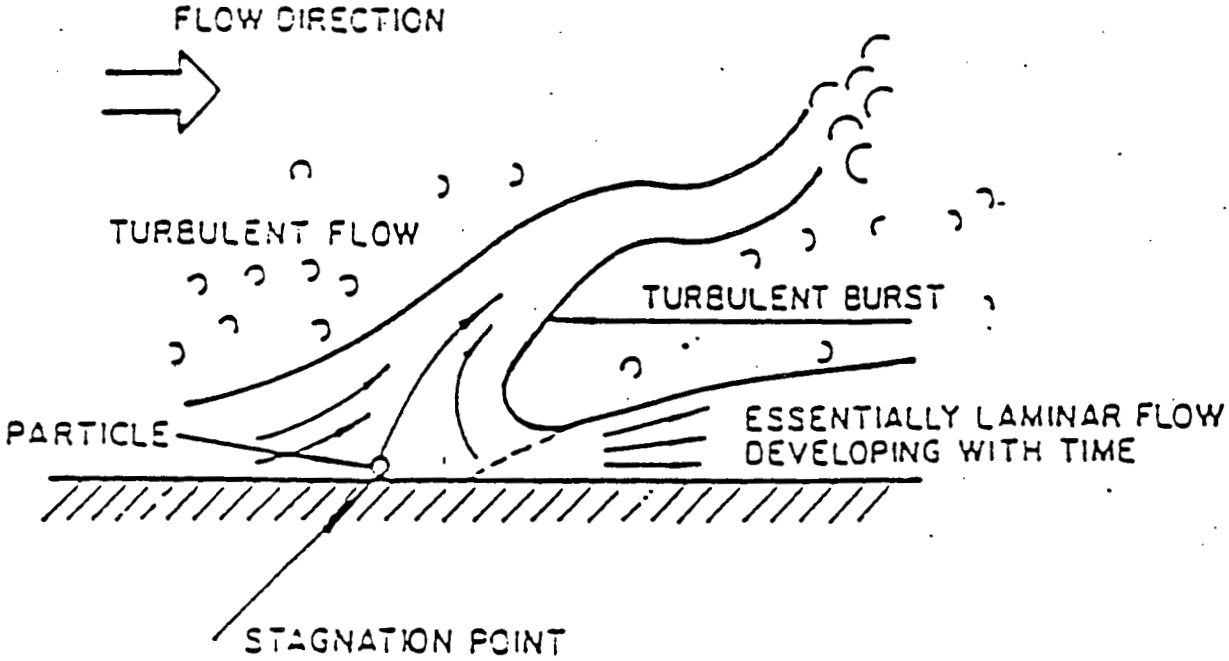

Figure 5-4. Schematic Diagram of Turbulent Burst in the Wall Region
(Fromentin January 1987)

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reviews (Brockman February 1985; Fromentin January 1987, September 1989; Alonso, Bolado and Hontanon July 1991) directed towards the dry resuspension of particles in light water reactor coolant systems during the depressurization of the containment following a severe core disruptive events have been published. In general, most of the experimental data has been obtained on sparse particle suspension from heterogeneous substrates with few field studies that is the converse of the situations for suspension from homogeneous beds covered in Subsection 4.4.5. Fromentin (January 1987) concluded from his review that:

- Both theoretic and experimental studies of the suspension of solid particles from solid surfaces are still in an elementary state.

- There is still controversy over which basic resuspension concept to apply - force balance or energy balance.

- Due to an incomplete understanding of the turbulent boundary layer, and more precisely of the bursting phenomenon, uncertainty exist as to the removal forces acting on particles.

- Some very important effects such as particle agglomeration on the surface (alters the size of the particles to be suspended and raise questions as the deagglomeration in flow), saltation (role of energy transfer from impacting particles on suspension), initial suspension, have not been well studied.

- The wide range of values for adhesive forces and the lack of models to explain influence of roughness (both substrate and particle surface) results in great uncertainty.

A few field studies have reported the suspension of particles from heterogeneous substrates. Garland and Pigford (1992) reported a resuspension factor (K) of 1E-6 for fallout from Chernobyl from the Harwell parking lot. If a sampling period of 24 to 72 hours is assumed, the resuspension flux would be 1 to 4 E-8/hr. Sutter (1982) lists Ks reported for Bennett (1976) of 2E-6 to 5E-9 for New York City and the United Kingdom and 6E-6 to 8E-9 for paving stones. These are in the same range or less than reported by Garland and Pigford (1992). Sutter reported K values for the study of resuspension of plutonium as oxide powder or dried nitrate solution from various floor covering (Jones and Pond 1967) ranging from 1E-10/hr to 1E-8/hr assuming an 16-hr sampling period for air movement only. The values appear to be consistent with the bounding value recommended for homogeneous beds of powder of 4E-5/hr under process facility ventilation flow conditions and outdoor at < 5m/s. Under the same assumptions, particle deposits shielded from the ambient flow by debris or in a static (no induced flow) facility, a resuspension flux and order of magnitude less, 4E-6/hr, is recommended.

Therefore, the bounding ARFs/RFs for aerodynamic entrainment (resuspension) of surface contamination (sparse population) from a heterogeneous (hard, unyielding) surfaces recommended are:

- for nominal flow conditions
  indoors and outdoors (<5m/s) — ARF 4E-5/hr; RF 1.0
- for static conditions indoors or surface
  contamination buried under debris — ARF 4E-6/hr; RF 1.0

5.4 HEPA FILTERS

5.4.1 Thermal Stress

The ARF from the heat-induced damage to a HEPA filter is estimated to be very small. HEPA filters resisted temperature as high as 825°C for period of tens of minutes before loss of efficiency and 500°C for in access of 45 min (Hackney 1983). The filter medium is very fine diameter glass fiber that softens and melts when heated and thus, tends to retain materials adhering to the fibers. The release rate for several types of HEPA filter in flowing air at elevated temperatures less than required to induce failure (up to 400°C) are very low (Ammerich et al. 1989).

HEPA filters, both unused and removed from service due to high differential pressures (clogged), were tested using solid particles at a range of temperatures less than required for failure. The efficiencies of the filters prior to testing for 1.8 μm particles ranged from 99.97% to 99.9999989%. Two high flow (2000 cfm) and one 1000 cfm HEPA filters with glass fiber media and various sealant and gasket materials were tested. No releases were found at temperatures below 150°C (175°C for one of the high flow filters). For the 1000 cfm type filter, the release rates for temperatures from 175°C and 190°C started at 1E-6/min and reduced to 5E-8/min within 1 hour (the lower limit of detection was 2E-8/min). The high flow HEPAs were tested to temperatures of 200°C and 250°C with release rates starting at 2E-4/min and 2E-5/min and reducing to 3E-7 in 60 min and 2E-8/min in 30 min. There was no release of contamination from a oven-fired, mineral sealant, high flow type filter at temperatures up to 350°C and the release in other types of HEPA filters is associated with the emission of smoke (binder, degradation of inert dust on filter, pyrolysis of sealant and gaskets). Thus, it appears that the heat-induced release from 1000 cfm HEPA filter prior to failure may be as high as 1E-5. It is assumed that HEPA filters destroyed by flame intrusion or by the impacted of air at a temperature sufficiently high to melt the glass fiber are subjected to high temperature air to result in the release given above for heat-induced release. The RF is assumed to be 1.0 without an experimental basis. ARFs for high-flowrate HEPA filter may be an order of magnitude higher (1E-4). On these bases, ARF/RF values for the impact of heat upon loaded HEPA filters of 1E-4/1.0 are recommended.

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5.4.2 Explosive Releases (High Pressure Filter Blowout)

5.4.2.1 Shock Effects: Dynamic Pressure Impact - Release of Collected Contamination from Blowout of HEPA Filter by Pressure Pulse

Very limited experimental data has been reported on the release of collected contamination as a result of the failure of glass fiber media HEPA filters from a dynamic pressure pulse. Gregory et al. (February 1983) reported the release of 0.341, 1E-6 and 2 E-6 of the collected solid particles for high-flow HEPA filter during explosive transient. The large release from the first filter was attributed to a medium that was slightly creased prior to the test and appears to be an artifact of the test equipment. All the filters appeared to have vented by blowout of the filter media at selected locations along the rear folds of the pleated filter mat. The areas for the other two filters vented were very small. Thus, it would be anticipated that the amount of the deposited material subjected to the mechanical stress of the filter rupture is a minute fraction of the nearly 200 ft^2 filter mat. Only during the initial stages of use would a large fraction of deposited material be located in the rear fold. Thus, if the high value is discounted, ARF/RF value of 2E-6/1.0 would bound the data and are recommended.

5.4.2.2 Blast Effects: Static Pressure Impact - Release of Collected Contamination from Blowout of HEPA Filter by Static Pressure

Gregory et al. (October 1983) also performed tests on from standard (1000 cfm) glass fiber media HEPA filters. The break pressure for standard HEPA filters ranged from 9.1 to 20.0 kPa with a mean value of 16.3 kPa. High flowrate HEPA filter demonstrated lower structural capacity with break pressures ranging from 9.0 to 15.9 kPa with a mean value of 11.0 kPa. Removal efficiency of the standard HEPA filters for 0.46 μm diameter polystyrene latex beads upon tornado condition degraded from the 99.97% for a clean filter under normal conditions to 98.9%. The release of the approximately 1 kg of 0.46 μm diameter PSL collected for one type of standard HEPA filters was 1.46% and 0.71 with a mean value of 0.935%. Bounding ARF/RF values of 9E-3/1.0 are recommended.

5.4.3 Venting of Pressurized Gases Through Filter

See Subsection 5.4.2.

5.4.4 Free-Fall Spill, Crush-Impact (Vibration)

Material accumulated on the filter media could be dislodged by the jarring of the media/filter by a single severe shock (e.g., earthquake, impact of heavy object such as aircraft engines, forklift) or by mechanical vibration. In the case of a severe shock, it is assumed that the housing holding the filter banks would also be compromised and material

made airborne within (contained) and out of the housing (uncontained) are of concern. The media is a relatively fragile material with considerable flexibility and dislodging only the accumulated particles does not appear to be consistent with experience. Rather, the fragmentation of the media by the vibration/shock appears to be principal mode for particle generation as shown in Table A.55 from Arnold (1986) where filters without accumulated Pu (although other inert, airborne materials may be collected) release the same fraction of particles as loaded filters within each filter set.

Arnold (1986) reported on a series of studies conducted at the Rocky Flats Plant on the particles generated by HEPA filters (large plenum sized filters, 2-ft x 2-ft x 1-ft), and filters used to seal the exhaust outlets on gloveboxes (8-in x 8-in x 6-in and 12-in x 12-in x 6-in) subjected to repetitive slamming on a hard, unyielding surface and mechanical crushing. In one study, 30 plenum-sized filters, wrapped in two layers of plastic, were mechanically crushed and approximately 0.75 lb of material in an outer box holding the filter during transport were collected. Less than 5 wt/o of the collected material was in the size range of <200 μm (LLD, sieves used) and <0.5 wt/o was <25 μm. All the filter media disintegrated under test conditions for filter from plenum FU2B (from a recovery facility where strong acid vapors are present in the effluents) and the particulate weight listed is that for all the media. The Matrix Weight listed in that table for filters from other plena is the total weight of the filters and ranges from 13,190 g to 24,380 g. On that basis, the media represents from 5.3% to 12.2% of the total filter rate. The average weight of a plenum sized filter in this study was given as 17.613 kg (the average weight of plenum sized filters was 18.18 kg and 18.1 kg in other studies) and the total weight of 30 plenum sized filters would be 528.39 kg. The total mass of particles collected, 0.75 lb (255 g), represents 0.0483 % of the total filter weight. If it is conservatively assumed that the total media mass is 5% of the total filter weight, the particles collected represent 0.97% of the filter media mass and the fraction <25 μm LLD is 0.005% of the filter media mass.

Thirty plenum-sized filters were crushed in a hydraulic press and a total of 34.1 g of particles collected. The total filter weight was 528.29 kg with a media mass of 26.42 kg under the assumption that the media mass is 5 wt/o of the total filter mass. Thus, the particles represent 0.13 wt/o of the total media mass. The size distribution of particles generated was found to be 8.525% <200 μm with no measurement of the 10 μm fraction. In the other portions of this study, the 10 μm fraction was no greater than 10% of the <200 μm fraction and on this basis, the fraction 10 μm and less would represent 0.0013 wt/o of the media mass.

In another study, five plenum-sized filters were tapped and crushed and a total of 349 g of particulate materials collected. The total weight of the filters was 90,900 g and the material generated represents 0.384%. Under the assumption that the media mass is 5% of the filter weight, the particles collected represent 7.68% of the media mass. The fraction 10 μm and less was 9.261 wt/o of the total collected and 0.71 wt/o of the filter media mass.

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Two different glovebox-sized filters were also studied in this effort and the same test conditions. A total of 9 g was collected with a total filter weight of 41.4 kg. The particles collected represent 0.022 wt/o of the total filter mass and, under the assumptions used previously, 0.43 wt/o of the filter media mass. The size distribution of the particles generated was not characterized but in all other studies reported was <10% (in most cases much less). Under the assumption the 10 μm fraction is 10%, the particles generated represent 0.043 wt/o of the media mass.

The data shown in Table A.55 are from a study where plenum-sized filters from a variety of plena were wrapped and plastic and projected 3-ft onto a hard, unyielding surface (concrete floor). Table 5-6 presents the relevant data from Table A.55 taken from the referenced document.

For the fraction 10 μm in diameter and less generated based upon the assumed total media mass, the bound is 5E-3 with a median of 2E-3 and an average of 2E-3. This is consistent with the results above that indicate releases of particles 10 μm in diameter and less ranging from 1E-5 to 7E-3.

5.4.5.1 Release of Collected Contamination During Failure by Crush-Impact, Enclosed

It is assumed that the fraction of particles 10 μm diameter and less released from the double-wrapped HEPA filters that were crushed, 5E-5, based upon the fraction of filter media fragmented by the mechanical stress bounds the release from enclosed HEPA filter subjected to crush-impact stresses that compromise the enclosure. The enclosures for HEPA filters are substantially more robust than plastic wrap and the shock-impact would be no worse than mechanical crushing. Due to the great uncertainties associated with the test results, an additional order of magnitude increase is imposed resulting in a ARF/RF of 5E-4/1.0 for this stress.

5.4.5.2 Release of Contamination by Failure of HEPA Filter by Crush-Impact, Unenclosed

The fractions of particles 10 μm in diameter and smaller generated by crushing or repetitive jarring of spent, plenum-sized HEPA filter ranged from 1E-5 to 7E-3. From the data in Table A.40, it would appear that the response of the filter is dependent on previous service that appear to somewhat correlate to Pu loading. Under the assumption that the particles generated represent the fragmentation of the filter media and that the surface contamination remains associated with the filter media during this process, the bound value under the study conditions was 7E-3 (particles generated by tapping and crushing plenum sized filters). Conservative ARF/RF values for the phenomenon are 1E-2/1.0 and include glovebox sized filters.

Table 5-6. Fractions of Media Mass as Particles 10 micrometers and Less Generated by HEPA Filters Under Shock/Vibration Stresses

Wt. Pu, g	Wt. Particles 10 μm and less[3], g	ARF[1]	ARF[2]
FU2B Plenum, Pu Recovery Facility, all filter media disintegrated upon being subjected to mechanical stress, ARF[2] based upon Wt. Particles 10 μm and less divided by Wt. Particulate (g) that is the media weight.			
43	<6.0	<1.0E-1	<5.0E-3
38	<6.6	<2.0E-1	<4.0E-3
41	<6.3	<2.0E-1	<4.0E-3
39	<5.6	<1.0E-1	<4.0E-3
45	<6.2	<1.0E-1	<4.0E-3
35	<6.0	<2.0E-1	<4.0E-3
42	<5.9	<1.0E-1	<4.0E-3
46	<5.2	<1.0E-1	<4.0E-3
FU2B-2, second stage HEPA filter from FU2B Plenum			
6	<0.9	<2.0E-1	<1.0E-3
7	<0.3	<4.0E-2	<3.0E-4
13	<0.3	<2.0E-2	<3.0E-4
12	0.4	2.0E-2	4.0E-4
Incinerator			
1	1.3	1.3E+0	1.0E-4
0	0	inf	2.0E-3
2	1.5	7.0E-1	2.0E-3
1	1.6	1.6E+03.1E+0	2.0E-3
1	3.1	0	3.0E-3
0	0	<7.0E-1	0
2	<1.4	2.4E+0	<1.0E-3
1	2.4		2.0E-3
202 Plenum			
0	<1.1	inf	<1.0E-3
1	<2.4	<2.4E-0	<3.0E-3
1	<1.4	<1.4E+0	<2.0E-3
0	<0.9	inf	<1.0E-3
0	<1.4	inf	<2.0E-3
1	0.3	3.0E-1	3.0E-4
1	<2.3	<2.0E-1	<3.0E-3
0	<0.2	inf	<2.0E-4

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Wt. Pu, g	Wt. Particles 10 μm and less[3], g	ARF[1]	ARF[2]
141 Plenum			
1	0	0	0
1	0	0	0
0	0.8	8.0E-2	9.0E-5
0	0	0	0
0	0	0	0
0	<0.04	inf	<5.0E-5
0	0.02	inf	2.0E-5
0	0	0	0
321 Plenum			
0	<0.1	inf	<2.0E-4
0	1.0	inf	1.0E-3
0	0	0	0
0	0	0	0
0	0	0	0
0.02	0	inf	<2.0E-5
0	0	0	0
0	0.1	inf	1.0E-4

[1] Airborne Release Fraction estimated on Pu loading
[2] Airborne Release Fraction estimated on basis of media mass = to 0.05 of total filter wt.
[3] Back calculated from stated fraction 10 μm and less on Table A.55.

6.0 INADVERTENT NUCLEAR CRITICALITY (NUCLEAR EXCURSION)

6.1 SUMMARY

Under appropriate accident conditions, fissile and fissionable radionuclides may undergo a self-sustaining nuclear reaction (chain reaction) called an inadvertent nuclear criticality or a nuclear excursion. The airborne release from a nuclear excursion is estimated by use of the five-component linear equation used to estimate the airborne release from other events covered in the previous chapters. However, because the evaluation of nuclear excursions is a complex process, some additional topics used in the equation are discussed below.

For nuclear excursions, the material-at-risk (MAR) is determined by the fraction of fission products generated by the criticality and the fraction of the fissile/fissionable material that may be suspended by the event generated conditions (primarily heat). (Since fissile materials (^{233}U, ^{235}U, ^{239}Pu) are also fissionable, both will be referred to as fissionable.) The amount of fission products and actinides produced by the excursion is a function of the total fissions from the criticality and the specific fissionable radionuclide involved and should be determined by an appropriate code such as ORIGEN2. The fraction that is at-risk of airborne suspension depends upon the physical form of the fissionable materials involved.

Background material used to determine the credibility of a potential criticality is provided in Appendix B - "Background Information and Screening Factors for the Potential of Inadvertent Nuclear Criticalities".

In the absence of credible scenarios or for screening purposes, the airborne release from nuclear excursions in various physical systems can be estimated using the equations which follow. The physical systems considered are solutions, fully moderated/reflected solids, dry solids, and large storage arrays.

Solutions

$$[(MAR_{cl} \times DR_{cl} \times ARF_{cl} \times RF_{cl}) + (MAR_{sl} \times DR_{sl} \times 5E\text{-}4 \times 1.0)]\ LPF$$

where: MAR_{cl} = inventory radionuclides from criticality in a solution calculated by computer code such as ORIGEN2 based on 1E+19 total fissions; or,
= [1E+19 fissions/1E+19 fissions] X table.[10]

[10] Tables from Reg. Guide 3.33 (Spent Commercial Nuclear Fuel solution), 3.34 (uranium) & 3.35 (plutonium) "Radioactivity of Important Nuclides Released From the Criticality Accident ..." also attached to this document (Tables 6.2-1a & -1b, -2 & -3).

DR_{c1} = damage ratio for material involved in criticality, 1.0.
ARF_{c1} = Airborne Release Fraction for solution criticality in NRC Reg Guides[11]: 1E+0 for noble gases, 2.5E-1 for radioiodines, 1E-3 for radioruthenium.
RF_{c1} = Respirable Fraction[12] materials generated by criticality ... materials generated all in gaseous phase and RF = 1.0.
MAR_{s1} = inventory radionuclides in solution prior to the nuclear excursion evaporated, curies.
DR_{s1} = Damage Ratio radionuclides in solution, 1.0.
LPF = LeakPath Factor for airborne material[13] ... different LPFs are necessary for gaseous radionuclides and airborne particulate materials.

Fully Moderated/Reflected Solids

A coherent solid cannot be moderated and solids < 100 μm in diameter must be intimately mixed with moderator to be fully moderated.

$$MAR_{c2} \times DR_{c2} \times ARF_{c2} \times RF_{c2} \times LPF$$

---

[11] ARF (Airborne Release Fraction) for:
fission product noble gases = 1.0
radioiodines and other radiohalogens that can be generated as vapors by accident conditions = 0.25
salts in liquid evaporated (assume 100 liter for large volume solution excursion) = 5E-4 non-volatile fission products (see Subsection 6.2.4.3)

[12] RF (Respirable Fraction) for:
noble gases = all the airborne material can be transported downwind and affects the exposure of the population, use 1.0
radioiodine = 1.0 (assume released as vapor)
salts in liquids evaporated during boildown of solution = 1.0

[13] LPF (LeakPath Factor) is assumed to be 1.0 for noble gases, 1.0 for radioiodine unless functional iodine removal devices are in the facility gaseous effluent exhaust system (use conservative estimate of removal efficiency). For particulate materials generated, if generated indoors and the airborne material from the excursion is released via the facility gaseous effluent exhaust system, use a LPF of 0.001 (filter efficiency of 99.9%) for the 1st stage of HEPA filtration and 0.002 (filter efficiency of 99.8%) for every stage thereafter or a conservative estimate of the transmission factor for other types of high efficiency particulate filtration (e.g., sand filters) in place.

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where: MAR_{c2} = inventory radionuclides from criticality in reflected/ moderated solids calculated by computer codes such as ORIGEN2 based on 1E+18 total fissions, or,
= [1E+18 fissions/1E+19 fissions] X table[10].
DR_{c2} = Damage Ratio for radionuclides generated by criticality, 1.0.
ARF_{c1} = Airborne Release Fraction[11] in NRC Reg Guides.
RF_{c1} = Respirable Fraction for airborne material in gaseous phase, 1.0[12].
LPF = LeakPath Factor for gaseous airborne material[13].

Dry Solids

$$[(MAR_{c3} \text{ X } DR_{c3} \text{ X } ARF_{c3} \text{ X } RF_{c3}) + (MARs3 \text{ X } DR_{c3} \text{ X } ARF_{s3} \text{ X } RF_{s3})] \text{ LPF}$$

where: MAR_{c3} = inventory of radionuclides generated by bare, dry metal criticality based on total fission yield of 1E+17 fission by computer code such as ORIGEN2; or,
= [1E+17 fissions/1E+19 fissions] X table[10].
DR_{c3} = Damage Ratio = A_s X 10-mm/Vol_f
where: A_s = surface area of fissionable material exposed to the air, mm
Vol_f = volume of fissionable material, mm[11].
ARF_{c3} = Airborne Release Fractions in Table 6-4; or,
= if using MAR values in NRC Reg Guide use ARFs[11] from that document.
RF_{c3} = Respirable Fraction, assume 1.0 for all materials.
MAR_{s3} = Inventory of fissionable material involved in criticality.
ARF_{s3} = Airborne Release Fraction for ignited, oxidized metal - natural convection, 5E-4.
RF_{s3} = Assume 1.0.
LPF = Need LPF for both gases/vapors and airborne particulate material[13].

Large Storage Arrays

$$MAR_{c4} \text{ X } DR_{c4} \text{ X } ARF_{c4} \text{ X } RF_{c4} \text{ X LPF}$$

where: MAR_{c4} = inventory radionuclides generated in solid materials based on total fission yield of 1E+20 fissions by computer code such as ORIGEN2; or,
= [1E+20 fissions/1E+19 fissions] X table[10].

DR_{c4} = Damage Ratio, assume all radionuclides generated at-risk.
ARF_{c4} = Airborne Release Fraction, if using values in Reg Guide as MAR, use values for ARF[11]. Unless substantial clad/ package failure is postulated, only gaseous/volatile materials are assumed to be made airborne.
RF_{c4} = Respirable Fraction[12], assume 1.0 for all airborne materials,
LPF = LeakPath Factor for gaseous materials[13].

6.2 DISCUSSION

6.2.1 Estimates of Total Fissions from Excursion

The excursion(s) postulated should be based upon a careful analysis of the various systems of concern. The credibility of the event should be based upon a formalized system such as Fault Tree Analysis using Monte Carlo techniques to determine the most probable and those sequences that are credible. Once the systems have been defined, various computer codes and simplified techniques are available to estimate the total fissions generated by the event (see Appendix B). In the absence of such a procedure where a credible scenario cannot be described but a criticality event must be addressed, total fission estimates based upon upper values from historical data for such systems (see Appendix B) are presented:

6.2.1.1 Solutions

Based upon the NRC rationale in Regulatory Guides (NRC April 1977; April 1979; July 1979), the following estimate for total fissions for a inadvertent nuclear criticality is recommended. For solutions in a vented vessel, 1E+19 total fissions (initial burst of 1E+18 fissions in 0.5 seconds followed successively at 10-minute intervals by 47 bursts of 1.9E+17 fissions for a total of 1E+19 fissions in 8 hours). For an excursion involving larger (>100 gallons) volumes, the excursion is assumed to be terminated by evaporation of 100 liters of solution.

6.2.1.2 Reflected/Moderated Solids

Based upon historical data on nuclear excursions that have occurred involving this physical system covered in Appendix B, an estimate of 1E+18 total fission in a single burst is assumed.

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6.2.1.3 Bare, Dry Solids

Based upon historical data for nuclear excursions that have occurred involving this type of physical system covered in Appendix B, an estimate of 1E+17 total fissions in a single burst is recommended.

6.2.1.4 Large Storage Arrays

Due to the lack of data on historical excursions involving this physical system, the estimate of 1E+20 total fission is based upon the combined data for storage arrays and reactor excursions covered in Appendix B.

6.2.2 Material-at-Risk

There are two potential sources of radionuclides for airborne suspension during a nuclear excursion - the radionuclides (fission products and actinides) generated by the reaction and the radionuclide (fissionable material) involved in the reaction. The radionuclides produced by the nuclear criticality are a function of the total fissions that are generated and the fissionable material (each type of fissionable material generates a different spectrum of fission products and actinides). The inventory of fissionable material provides both a screening factor (must exceed the critical mass for the form and radionuclide involved) and a source (if a criticality is postulated). The radionuclide inventory for the specific system should be calculated if possible by a computer code relevant for the physical system involved.

6.2.2.1 Solutions

The inventory of radionuclides (fission products and actinides) generated by the nuclear excursion involving a solution should be calculated by use of an appropriate computer code such as ORIGEN2 on the basis of a total yield of 1E+19 fissions. In the absence of access to a computer model such as ORIGEN2 or for screening purposes, the significant radionuclide releases from the various types of fissionable material can be estimated from:

- Tables 6-1 and 6-2, from NRC Reg Guide 3.33 (NRC April 1977) - 1E+19 fissions in 3.3% Enriched Fuel Irradiated to 33 000 MWd/MTU cooled 150 days in an acid solution.

- Table 6-3, from NRC Reg Guide 3.34 (NRC April 1979) - 1E+19 fission in unirradiated uranium Fuel in a 400 g U/liter acid solution.

Table 6-1. Assumed Fission Products and Transuranic Radionuclides in Spent Fuel Solution Prior to Nuclear Excursion (NRC April 1977)

Nuclide	Ci/L
Tritium	2.9E-1
Strontium-89	4.0E+1
Strontium-90	3.2E+1
Yttrium-90	3.2E+1
Yttrium-91	5.7E+1
Zirconium-95	1.2E+2
Niobium-95	2.2E+2
Ruthenium-103	3.7E+1
Rhodium-103m	3.7E+1
Ruthenium-106	1.7E+2
Rhodium-106	1.7E+2
Iodine-129	1.6E-5
Iodine-131	9.1E-4
Xenon-131m	1.4E-3
Cesium-139	9.0E+1
Cesium-137	4.5E+1
Barium-137m	4.2E+1
Cerium-1141	2.4E+1
Cerium-144	3.2E+2
Praseodymium	3.2E+2
Promethium-147	4.2E+1
Europium-154	2.3E+0
Plutonium-238	1.2E+0
Plutonium-239	1.4E-1
Plutonium-240	2.0E-1
Plutonium-241	4.8E+1
Americium-241	8.4E-2
Curium-242	6.3E+0
Curium-244	1.0E+0

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Table 6-2. Curies of Important Radionuclides Released During Nuclear Excursion Involving Spent Fuel Solution (NRC April 1977)

Nuclide	0 to 0.5 hr	0.5 to 8 hr	Total
Krypton-83m	3.7E+0	3.3E+1	3.7E+1
Krypton-85m	1.6E+1	1.5E+2	1.7E+2
Krypton-85	1.5E-4	1.4E-3	1.6E-3
Krypton-87	1.0E+2	9.0E+2	1.0E+3
Krypton-88	6.5E+1	5.9E+2	6.6E+2
Krypton-89	4.1E+3	3.7E+4	4.1E+4
Xenon-131m	3.8E-4	3.5E-3	3.9E-3
Xenon-133m	5.5E-2	4.9E-1	5.5E-1
Xenon-133	1.3E+0	1.2E+1	1.3E+1
Xenon-135m	1.1E+1	9.9E+1	1.1E+2
Xenon-135	1.6E+1	1.5E+2	1.7E+2
Xenon-137	3.8E+3	3.5E+4	3.9E+4
Xenon-138	1.2E+3	1.0E+4	1.1E+4
Iodine-129	4.2E-11	3.9E-10	4.3E-10
Iodine-131	1.8E-1	1.6E+0	1.8E+0
Iodine-132	6.7E-1	6.1E+0	6.7E+0
Iodine-133	3.5E+0	3.1E+1	3.5E+1
Iodine-134	4.8E+1		4.8E+2
Iodine-135	1.2E+1	1.0E+2	1.2E+2

Table 6-3. Curies of Important Radionuclides Released During Nuclear Excursion Involving Unirradiated, Unenriched Uranium Solution (400 g U/liter) (NRC April 1979)

Nuclide	Half-Life	Radioactivity, Ci			Egamma	Ebeta
		0 to 0.5 hr	0.5 to 8 hr	Total		
Krypton-83m	1.8 h	2.2E+1	1.4E+2	1.6E+2	2.6E-3	0
Krypton-85m	4.5 yr	2.1E+1	1.3E+2	1.5E+2	1.6E-1	2.5E-1
Krypton-85	1.7 yr	2.2E-4	1.4E-3	1.6E-3	2.2E-3	2.5E-1
Krypton-87	76.3 m	1.4E+2	8.5E+2	9.9E+2	7.8E-1	1.3E+0
Krypton-88	2.8 h	9.1E+1	5.6E+2	6.5E+2	2.0E+0	3.5E-1
Krypton-89	3.2 m	5.9E+3	3.6E+4	4.2E+4	1.6E+0	1.3E+0
Xenon-131m	11.9 d	1.1E-2	7.0E-2	8.2E-2	2.0E-2	1.4E-1
Xenon-133m	2.0 d	2.5E-1	1.6E+0	1.8E+0	4.1E-2	1.9E-2
Xenon-133	5.2 d	3.8E+0	2.3E+1	2.7E+1	4.6E-2	1.1E-1
Xenon-135m	15.6 m	3.1E+2	1.9E+3	2.2E+3	4.3E-2	9.0E-2
Xenon-135	9.1 h	5.0E+1	3.1E+2	3.6E+2	2.5E-1	3.7E-1
Xenon-137	3.8 m	6.9E+3	4.2E+4	4.9E+4	1.6E-1	1.8E+0
Xenon-138	14.2 m	1.8E+3	1.1E+4	1.3E+4	1.1E+0	6.2E-1
Iodine-131	8.0 d	1.2E+0	7.5E+0	8.7E+0	3.8E-1	1.9E-1
Iodine-132	2.3 h	1.5E+2	9.5E+2	1.1E+3	1.1E+0	5.0E-1
Iodine-133	20.8 h	2.2E+1	1.4E+2	1.6E+2	6.1E-1	4.1E-1
Iodine-134	52.6 m	6.3E+2	3.9E+3	4.5E+3	2.6E+0	6.1E-1
Iodine-135	6.6 h	6.6E+1	4.0E+2	4.7E+2	1.5E+0	3.7E-1

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- Table 6-4, from NRC Reg Guide 3.35 (NRC July 1979) - 1E+19 fissions in plutonium acid solution. Must exceed minimum single parameter concentration and mass limits for plutonium.

Although the tables do not consider the airborne release of the non-volatile radionuclides generated by the nuclear excursion, the radionuclides listed are assumed to be the significant radionuclides released from solutions are recommended for use.

6.2.2.2 Reflected/Moderated Solids

The inventory of radionuclides generated by an nuclear excursion involving reflected/moderated solids should be estimated by use of an appropriate computer code on the basis of a total yield of 1E+18 fissions. In the absences of such calculations or for screening calculations, the significant radionuclides released from reflected/moderated solids assumed to be the same as listed for solutions above modified by the ratio between the fissions yield (i.e., 1E-18 fissions/1E+19 fissions).

The inventory of fissionable material in solid form immersed in water is assumed to not be at risk of suspension under these conditions.

6.2.2.3 Bare, Dry Solids

The inventory of radionuclides should be calculated using an appropriate computer code on the basis of a total fission yield of 1E+17 fissions. In the absence of such calculations or for screening calculations, the important radionuclides released listed in Tables 6-1 through 6-4 may be used modified by the ratios between the fission yields (i.e. 1E+17 fissions/1E+19 fissions).

6.2.2.4 Large Storage Arrays

The inventory of radionuclides should be calculated by use of an appropriate computer code on the basis of a total yield of 1E+20 fissions. In the absence of such calculations or for screening purposes, the materials released listed in Tables 6-1 through 6-4 with appropriate modification (ratio of the fission yield, 1E+20 fissions/1E+19 fissions) may be used.

6.2.3 Damage Ratios

The fraction of the material-at-risk for each physical system that may be affected by the suspension mechanism varies with the physical system.

Table 6-4. Curies of Important Radionuclides Released During Nuclear Excursion Involving Plutonium Solutions (NRC April 1979)

Nuclide	Half-life	Radioactivity, Ci			Egamma	Ebeta
		0 to 0.5 hr	0.5 to 8 hr	Total		
Krypton-83m	1.8 h	2.2E+1	1.4E+2	1.6E+2	2.6E-3	0
Krypton-85m	4.5 yr	2.1E+1	1.3E+2	1.5E+2	1.6E-1	2.5E-1
Krypton-85	1.7 yr	2.2E-4	1.4E-3	1.6E-3	2.2E-3	2.5E-1
Krypton-87	76.3 m	1.4E+2	8.5E+2	9.9E+2	7.8E-1	1.3E+0
Krypton-88	2.8 h	9.1E+1	5.6E+2	6.5E+2	2.0E+0	3.5E-1
Krypton-89	3.2 m	5.9E+3	3.6E+4	4.2E+4	1.6E+0	1.3E+0
Xenon-131m	11.9 d	1.1E-2	7.0E-2	8.2E-2	2.0E-2	1.4E-1
Xenon-133m	2.0 d	2.5E-1	1.6E+0	1.8E+0	4.1E-2	1.9E-2
Xenon-133	5.2 d	3.8E+0	2.3E+1	2.7E+1	4.6E-2	1.1E-1
Xenon-135m	15.6 m	3.1E+2	1.9E+3	2.2E+3	4.3E-2	9.0E-2
Xenon-135	9.1 h	5.0E+1	3.1E+2	3.6E+2	2.5E-1	3.7E-1
Xenon-137	3.8 m	6.9E+3	4.2E+4	4.9E+4	1.6E-1	1.8E+0
Xenon-138	14.2 m	1.8E+3	1.1E+4	1.3E+4	1.1E+0	6.2E-1
Iodine-131	8.0 d	1.2E+0	7.5E+0	8.7E+0	3.8E-1	1.9E-1
Iodine-132	2.3 h	1.5E+2	9.5E+2	1.1E+3	1.1E+0	5.0E-1
Iodine-133	20.8 h	2.2E+1	1.4E+2	1.6E+2	6.1E-1	4.1E-1
Iodine-134	52.6 m	6.3E+2	3.9E+3	4.5E+3	2.6E+0	6.1E-1
Iodine-135	6.6 h	6.6E+1	4.0E+2	4.7E+2	1.5E+0	3.7E-1
Plutonium-238				5.9E-4		

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Table 6-4. Curies of Important Radionuclides Released During Nuclear Excursion Involving Plutonium Solutions (cont.) (NRC April 1979)

Nuclide	Half-life	Radioactivity, Ci			Egamma	Ebeta
		0 to 0.5 hr	0.5 to 8 hr	Total		
Plutonium-239				2.7E-5		
Plutonium-240				5.8E-5		
Plutonium-241				1.8E-2		
Plutonium-242				4.3E-7		
Americium-241				2.4E-5		

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6.2.3.1 Solutions

From the rationale followed in the NRC Reg Guides (NRC April 1977; April 1979; July 1979), it is assumed that all the radionuclides (those generated by the nuclear excursion and present in the spent fuel solution) are at risk.

6.2.3.2 Reflected/Moderated Solids

It is postulated that the radionuclides generated by the criticality and present as fissionable material are in the solid matrix. Heat generated by the excursion are assumed to be dissipated in the water surrounding the fissionable material. For powders (metal or ceramic oxide), all the non-condensible gases and volatile radionuclides (radioiodine) are assumed pass into the water and behave as these materials in solution criticalities. If the powder or pieces are covered by a cladding that is not damaged by the event, no radionuclides would be exposed to airborne suspension forces.

6.2.3.3 Bare, Dry Solids

It is postulated that the fraction of radionuclides in the portion of fissionable material (metal or ceramic oxide) melted and exposed to air are subjected to airborne suspension forces. The fraction melted based on the historical data is very limited (some metal may softens but does not melt and ceramic material is not expected to soften or melt under the conditions postulated for bare, dry solid excursions). It is assumed that the fissionable material in the outer 10 mm of surface exposed to the air melts/soften sufficiently to release some fraction of the non-volatile radionuclides. Therefore, the DR for radionuclides generated by the excursion and for the fissionable material are:

$$DR_{c3} = [A_s \text{ X } 10\text{-mm}]/Vol_f$$

where: DR_{c3} = Damage Ration for Bare, Dry Solids during a nuclear excursion.
A_s = Area of fissionable material exposed to air, mm.
Vol_f = Volume of fissionable material, mm^3

6.2.3.4 Large Storage Arrays

It is postulated that the cladding/packaging around the fissionable materials are punctured and not catastrophically ruptured. Therefore, it is assumed that the gaseous materials generated (noble gases and volatiles) are released but that the particulate materials are retained.

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6.2.4 Airborne Release Fraction and Respirable Fraction

6.2.4.1 Solutions

The rationale presented in the NRC Reg Guides (NRC April 1977; April 1979; July 1979) postulates that 1E+0 of the noble gas fission product, 2.5E-1 of the radioiodines, 1E-3 of any ruthenium radionuclides, and 5E-4 of the salt-content (fissionable material) of the solution evaporated liquid (100 liters for large systems) is recommended. Materials in the gaseous state, non-condensible gases and vapors of volatile materials, are all respirable and are assigned a RF of 1.0. In the absence of any data on the size distribution of the airborne particles from the evaporation of the salt solution, a RF of 1.0 is recommended.

6.2.4.2 Reflected/Moderated Solids

It is postulated that all the non-condensible gas and volatile (radioiodine) radionuclides are released into the liquid moderator. It is further postulated that 1E+0 of the non-condensible gas radionuclides and 2.5E-1 of the volatile (iodine) radionuclides are released from the moderator to the environment. As in Subsection 6.2.4.1, non-condensible gases and vapors of volatile materials are assigned a RF of 1.0.

6.2.4.3 Bare, Dry Solids

It is postulated that the airborne release of radionuclides from bare, dry solids will be bounded by the experimental airborne release fractions measured during heating of commercial nuclear fuel (irradiated, clad, ceramic oxide).

The fission and activation products formed by an excursion in a solid are enclosed within the matrix of the solid fissionable material. The fissionable solids that are generally found in DOE ex-reactor facilities are metal and ceramic oxides of the metals that may be clad in metal (e.g., aluminum, zircaloy, stainless steel). Because of the wide range of fissionable mixtures that may be used for fuel in the production, experimental, and test reactors at DOE sites each generating its own spectra of irradiation products, fuel (unirradiated or spent) are not covered in this discussion.

The products contained in the matrix of the solid fissionable materials are not exposed to the ambient environment and would not constitute a hazard to offsite individual unless released from the matrix. Of the 11 historical excursion involving metal system listed on Table B-10b (b), only 1 (with a total fission yield estimated at 4E+17 fissions) exhibited any melting of the metal. Warping/oxidation are listed as consequences of 3 additional events (total fission yields ranging from 6E+16 to 1E+17 fissions). Therefore, a limited amount of melting of the solid would be anticipated at the reference yield level of 1E+18 fissions.

Restrepo (April 1992) reviewed the post-NUREG-0772 research and experiments on fission product release rates from heated/melted spent fuel. The specific elements involved were categorized into 12 discrete chemical groups (as shown below in Table 6-5) based upon the similarity of their responses to thermal stress. "... release fractions within each group varied by as much as two to three orders of magnitude ... the geometric mean and standard deviation of the release fractions for each of those groups were obtained." The geometric mean of the airborne release for each chemical groups, rounded off to a single digit was selected as the release fraction for that group (except the noble gases) and is listed in Table 6.2-4. The Upper limit estimate for release was selected for the noble gases. Also, no release fractions are reported for chemical group 12 (boron) and, since its' behavior is similar to the trivalent group (chemical group 9), the release rate for the trivalent elements is used for the boron elements in Table 6-5.

Table 6-5. Release Fraction for Various Chemical Classes from Heated Spent Fuel (Restrepo 1991)

Group #	Group Name	Rep. Ele.	Elements in Group	ARF
1	Noble Gases	Xe	Xe, Kr, He, Ne, Ar, Rn, H	5.0E-1
2	Alkali Metals	Cs	Cs, Rb, Li, K, Fr, Na	2.0E-1
3	Alkali Earths	Ba	Ba, Sr, Mg, Ca, Ra, Be	3.0E-2
4	Halogens	I	I, F, Cl, Br, At	5.0E-2
5	Chalogens	Te	Te, S, Se, O, Po, N	7.0E-2
6	Platinoids	Ru	Ru, Rh, Pd, Os, Ir, Pt, Au, Ni	2.0E-3
7	Transition Metals	Mo	Mo, V, Cr, Fe, Co, Mn, Nb, Tc	3.0E-2
8	Tetravalent	Ce	Ce, Ti, Zr, Hf, Th, Pa, U, Np Pu	4.0E-4
9	Trivalent	La	La, Al, Sc, Y, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Bk, Cf	6.0E-4
10	Main Group I	Cd	Cd, Hg, Zn, As, Sb, Pd, Tl, Bi	4.0E-3
11	Main Group II	Sn	Sn, Ca, In, Ag	4.0E-3
12	Boron	B	B, Si, P, C	6.0E-4

Thus, 5E-1 of the noble gases is assumed to be released from the solid matrix to the moderator and 1.0 of the noble gases released to the moderator are released to the ambient environment around the moderator. Likewise, 5E-2 of the halogen (iodine) is released from the matrix to the moderator with 0.25 (1.25E-2 of the inventory) released from the moderator to the ambient environment. As with solutions, 5E-4 of all non-volatile materials released to the moderator are released to the ambient environment (e.g., Group #2 2E-1 X 5E-4 = 1E-4). The RFs of the airborne non-volatile materials are assumed to be 1.0. In as much as the excursion does not generate sufficient energy to fail the particulate filters on the exhaust system resulting in a further reduction of the airborne emission of the very small

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quantity of the non-volatile by 3 to 5 orders of magnitude, the contribution of the airborne non-volatile materials to the offsite consequences is generally ignored.

Other groupings of radionuclides are possible. For instance, ruthenium is rather unique in that it can readily form volatile oxides under the appropriate conditions. Ruthenium could be logically includes with the Transition Metal increasing it release fraction from 2E-3 to 3E-2 (greater than an order of magnitude increase). The ARF for the Alkali Metal is four times greater than for the Halogens and is difficult to justify. Generally, the elements in the Main Group I elements appear to be more volatile than those in the Main Group II element although both are assigned the same ARF. The role of cladding is critical for Chalogen (Group V) elements especially Te for which significant interactions are predicted in all but very oxidizing conditions. Barium releases as high as shown would only occur for very reducing conditions. The ARFs are those determined from the evaluation of most recent experiments on irradiated fuel heating and may not reflect responses for lesser levels of stress.

An RF of 1.0 is assigned to all ARFs in the absence of any data on the size distribution of the airborne material. If the airborne material is from condensation of vaporized solids, the value may well reflect the size distribution of the initial airborne material.

For the purpose of consistency and conservatism, it is recommended that the USNRC ARF (1E+0 for noble gases, 2.5E-1 for radioiodines) also be used for this system.

6.2.4.4 Large Storage Arrays

It is postulated that the packages/clad of the stored material is compromised to the extent that gaseous airborne materials are released. It is recommended that the NRC Reg Guide ARF be applied.

7.0 REFERENCES

Alonso, A., R. Bolado and Hontanon. July 1981. Aerosol Resuspension in the Reactor Cooling System of LWR's Under Severe Accident Conditions, EUR 13789 EN, Directorate-General for Science Research and Development, Joint Research Centre - Ispra Site.

Ammerich, M., A. Briand, J.C. Laborde, Ph. Mulcey and J. Savornin. 1989. "Contamination Releases From HEPA Filters Under High Temperature Conditions", Proceedings of the 20th DOE/NRC Nuclear Air Cleaning Conference (M.W. First, Ed), NUREG/CP-xxxx (CONF-xxxxxx), Harvard Air Cleaning Laboratory, Boston, MS.

ANSI. 1983. American National Standards for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, ANSI/ANS-8.1-1983, American Nuclear Society, La Grange Park, IL.

ANS. 1986. American National Standard - Criticality Accident Alarm System, ANSI/ANS-8.3-1986, American Nuclear Society, La Grange Park, IL.

ANS. 1987a. American National Standard - Guide for Nuclear Criticality Safety in the storage of fissile materials, ANSI/ANS-8.7-1987, American Nuclear Society, La Grange Park, IL.

ANS. 1987b. American National Standard - Nuclear Criticality Control and Safety of Plutonium-Uranium Fuel Mixture Outside Reactors, ANSI/ANS-8.12, American Nuclear Society, La Grange Park, IL.

Anspaugh, L.R., P.L. Phelps, N.C. Kennedy, J.H. Shinn and J.M. Reichman. 1976. "Experimental Studies on the Resuspension of Plutonium from Aged Sources at the Neveda Test Site." in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants - 1974 (R.J. Englemann and G.A. Sehmel, Ed.), CONF-740921, pp 727-743, National Technical Information Services, Springfield, VA.

Anspaugh, L.R., P.L. Phelps, G. Holladay and K.O. Hamby. 1970. "Distribution and Redistribution of Airborne Particulate from the Schooner Cratering Event", In Proceedings of the 5th Annual Health Physics Society Midyear Topical Symposium: Health Physics Aspects of Nuclear Facility Siting, 2:pp 428-446, Eastern Idaho Health Physics Society, Idaho Falls, ID.

Anspaugh, L.R., J.H. Shinn, P.l. Phelps and C. Kennedy. 1975. "Resuspension and Redistribution of Pu in Soils", Health Physics, 29:pp 571-582.

Arnold, P.M. September 1986. Characterization of Spent HEPA Filters From Rocky Flats Plant, AO 6629 UNIF, Rockwell International - Rocky Flats Plant, Golden, CO.

Ayer, J.E., A.T. Clark, P. Loysen, M.Y. Ballinger, J. Mishima, P.C. Owczarski, W.S. Gregory, B.D. Nichols. May 1988. Nuclear Fuel Cycle Accident Analysis Handbook, U.S.N.R.C. - Office of Nuclear Material Safety and Safeguards, Washington, DC 20555.
Aylor, D.E. 1976. "Resuspension of Particles from Plant Surfaces by Wind.", in Proceedings of the Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants – 1974 (R.J. Englemann and G.A. Sehmel, Ed.), CONF-740921, pp 791-812, U.S. Energy Research and Development Adminsitration, National Technical Information Services, Springfield, VA.

Ballinger, M.Y., J.W. Buck, P.C. Owczarski and J.E. Ayer. January 1988. Methods for Describing Airborne Fractions of Free Fall Spills of Powders and Liquids, NUREG/CR-4997 (PNL-6300), Pacific Northwest Laboratory, Richland, WA 99352.

Ballinger, M.Y. and W.H. Hodgson. December 1986. Aerosols Generated by Spills of Viscous Solutions and Slurries, NUREG/CR-4658 (PNL-5910), Pacific Northwest Laboratory, Richland, WA.

Ballinger, M.Y., S.L. Sutter and W.H. Hodgson. May 1987. New Data for Aerosols Generated by Releases of Pressurized Powders and Solutions in Static Air, NUREG/CR-4779 (PNL-6065), Pacific Northwest Laboratory, Richland, WA 99352.

Bennett, B.G. 1976. "Transuranic Element Pathways to Man", in Transuranium Nuclides in the Environment Symposium Proceedings, pp 376-383, U.S. Research and Development Administration and International Atomic Energy Agency.

Borkowski, R., H. Bunz and W. Schoeck. May 1986. Resuspension of Fission Products During Severe Accidents in Light-Water Reactors, KfK 3987 (EUR 10391 EN), Kernforschungszentrum Karlsruhe, Germany.

Braaten, D.A., R.H. Shaw and K.T. Paw U. 1986. "Particle Detachment in Turbulent Boundary Layer, Proceedings of the Second International Aerosol Conference - West Berlin, ...

Brockman, J.E. February 1985. "Range of Possible Resuspension and Reentrainment of Fission Product During Containment Depressurization", Appendix G of Uncertainty in Radionuclide Release Under Specific LWR Accident Condition, Volume II - TMLbeta' Analyses, SAND84-0410, Sandia National Laboratory, Albuquerque, NM.

Brown, R. and J.L. York. 1962. "Sprays Formed by Flashing Liquid Spray", A.I.Ch.E. Journal, 8:No. 2 pp 149-153.

Brunskill, R.T. 1967. "The Relationship Between Surface and Airbone Contamaination.", in Proceedings of Surface Contamination Symposium (B.R Fish, Ed.), pp 93-105, Pergamon Press, New York.

000235

Buijis, K., B. Chavane de Dalmassy and H.E. Schmidt. October 1983. "The Characterization of Radioactive Aerosols from Fires", Proceedings of the CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems in Nuclear Facilities, LA-9911-C Volumes I & II (CSNI Report No. 83), Los Alamos National Laboratory, Los Alamos, NM.

Carter, R.F. 1970. "The Measurement of Dust Levels in a Workshop Environment.", AWRE 028/70, United Kingdom Atomic Energy Authority, Aldermaston, Berkshire, England.

Carter, R.F. and K. Stewart. 1970. "On the Oxide Fume Formed by the Combustion of Plutonium and Uranium", Inhaled Particles III (Proceedings of an International Symposium, British Occupational Hygiene Society, London, 9/14-23/70), Unwin Brothers Limited - The Gresham Press, Old Working, Surrey, England.

Chambers, D.R., R.A. Markland, M.K. Clary and R.L. Bowman. October 1982. Aerosolization Characteristics of Hard Impact Testing of Depleted Uranium Penetrators, ARBRL-TR-02435, Ballistic Research Laboratory, Aberdeen Proving Grounds, MD 21005.

Chatfield, E.J. 1968. "The Generation of Particulate Aerosols From Plutonium Surfaces", Atmospheric Environment, 2:pp 97-101.

Chatfield, E.J. 1969. "Some Studies on the Aerosol Produced by the Combustion or Vaporization of Plutonium-Alkali Mixtures", Journal of Nuclear Materials, 32:pp 228-246.

Chepil, W.S. 1945. "Dynamics of Soil Erosion II -- Initiation of Soil Movement", Soil Science, 60:pp 397-411.

Clayton, E.D. June 1979. Anomalies of Nuclear Criticality, PNL-SA-4868, Rev 5, Pacific Northwest Laboratory, Richland, WA.

Cleaver, J.W. and B. Yates. 1973. "Mechanism of Detachment of Colloidal Particles From a Flat Surface in a Turbulent Flow", Journal of Colloid and Interface Science, 44:p 464.

Condit, R.H. October 1986. Plutonium Dispersal in Fires - Summary of What's Known, LLNL.

Corino, E.R. and R.S. Brodkey. 1969. "A Visual Investigation of the Wall Region in Turbulent Flow", Journal of Fluid Mechanic, 37:No. 1 ...

Corn, M. 1966. "Adhesion of Particles" in Aerosol Science (C.N. Davies, Ed), Academic Press, New York.

Corn, M. and F. Stein. July 1965. "Re-Entrainment of Particles From a Plane Surface" American Industrial Hygiene Association Journal, 26:pp 325-336.

Dahneke, B. January 1975. 'Kinetic Theory of the Escape of Particles From Surfaces", Journal of Colloid and Interface Sciences, 50:No. 1, pp 89-107.

Dempsey, E. and A.E. Kay. 1958. "Some Investigations on Plutonium Metal", Journal Institute of Metals, 4:p 379.

DOE. 2-8-90. Safety of Nuclear Facilities, DOE 5480.5, U.S. DOE -Office of Environment, Safety and Health, Washington, DC.

DOE. 2-8-90. "Derived Concentration Guides for Air and Water", Chapter III in Radiation Protection of the Public and the Environment, DOE Order 5400.5, U.S. D.O.E. -Office of Environment, Health and Safety, Washington, DC.

Eidson, A.F. and G.M Kanapilly. February 1983. Plutonium Aerosolization Studies: Phase I Final Report, ITRI - Lovelace Laboratory, Albuquerque, NM.

Eidson, A.F., H.C. Yeh and G.M. Kanapilly. 1988. "Plutonium Aerosol Generation in Reducing and Oxidizing Atmospheres", Journal of Nuclear Materials, 152:pp 41-52.

Einstein, H.A. 1942. "Formulas for the Transportation of Bed-Load", Trans. Am. Soc. Civil Eng., 107:pp 561-597.

Elder, J.C. and M.C. Tinkle. December 1980. Oxidation of Depleted Uranium Penetrators and Aerosol Dispersal at High Temperatures, LA-8610-MS, Los Alamos National Laboratory, Los Alamos, NM 87545.

Ettinger, H.J. 1974. "Resuspension of Particulates, in Aerosol Studies, Annual Report of the Biomedical and Environmental Research Program of the LASL Health Division, Januray through December 1974, LA-5883-PR pp 27-29, Los Alamos National Laboratory, Los Alamos, NM.

Fairchild, C.I. 1982. "Wind Tunnel Measurement of Ideal Particles", Atmospheric Environment, 16: ...

Fish, B.r., R.L. Walker, G.W. Royster and J.l Thompson. 1967. "Redispersion of Settled Particles.", in Proceedings of the Surface Contamination Symposium (B.R. Fish, Ed.), pp 75-81, Pergamon Press, New York.

Fish, B.R., T.D. Calton, C.F. Parrish, R.L. Walker and F.G. Karitoris. October 1966. "Adhesion of Particles", in Aerosol Physics, Health Physics Division Annual Report for Period Ending July 31, 1965, ORNL-4007, Oak Ridge National Laboratory, Oak Ridge, TN.

000237

Fromentin, A. January 1987. Dry Resuspension: State of the Art, DRAFT, Swiss Federal Institute for Reactor Research, Wuerenlingen, Switzerland.

Fromentin, A. September 1989.Particle Resuspension from a Multi-Layer Deposit by Turbulent Flow, PSI-Bericht Nr. 38, Paul Scherer Institut, Wuerenlingen, Switzerland.

Garger, YeK, V.P. Gavrilov and G.P. Zhukov. 1992. "Estimation of the Secondary Contamination of Resuspension within 30 km Zone of Chernobyl NPP and Its Comparison with Measured Data", Precipitation Scavenging and Atmosphere-Surface Exchange. Volume 3. Summer Volume: Applications and Appraisals (S.E. Schwartz and W.G.N. Slinn, Coordinators), Hemisphere Publishing Corp., Washington, DC.

Garland, J.A. 1982. "Some Recent Studies of the Resuspension of Deposited Materials from Soil and Grasses", Proceeding of the Fourth International Conference on Precipitation Scavenging, Dry Deposition, and Resuspension - St. Monica, ...

Garland, J.A. and K. Pigford. 1992. "Resuspension Following the Chernobyl Acident", Precipitation Scavenging and Atmosphere-Surface Exchange Volume 3. The Summer Volume: Applications and Appraisals (S.E. Schwartz and W.G.N. Slinn, Coordinators), K=Hemiphere Publishing Corp., Washington, DC.

Garner, F.H., S.R.M. Ellis and J.A. Lacey. 1954. "The Size Distribution and Entrainment of Drops", Trans. Inst. Chem. Eng., 32:p 222

Garner, F.H., S.R.M. Ellis and D.B. Shearn. 1959. "Entrainment in Evaporators", Trans. Inst. Chem. Eng., 37:p 247.

Gido, R.G. and A. Koestel. November 1978. "LOCA-Generated Drop Size Prediction - A Thermal Fragmentation Model", Transactions of ANS, 30:pp 371-372.

Gilchrist, R.l. (Project Manager), G.B. Parker and J. Mishima. March 1978. Radiological and Toxicological Assessment of an External Heat (Burn) Test of the 105-mm Cartridge, APFSDS-T, XM-744, PNL-2670, Pacific Northwest Laboratory, Richland, WA 99352.

Gilchrist, R.L. (Project Manager) and P.W. Nickola. January 1979. Characterization of Airborne Depleted Uranium From April 1978 Test Firings of the 105-mm, APFSDS-T, M735E1 Cartridge, PNL-2881, Pacific Northwest Laboratory, Richland, WA 99352.

Glauberman, H., W.R. Bootman and A.J. Breslin. 1967. "Studies on the Significance of Surface Contamination.", in Proceedings of the Surface Contamination Symposium (B.R. Fish, Ed.), pp 169-178, Pergamon Press, New York.

Glissmeyer, G.A. and J. Mishima. November 1979. Characterization of Airborne Uranium From Test Firings of XM774 Ammunition, PNL-2944, Pacific Northwest Laboratory, Richland, WA 99352.

Graf, W.H. and E.R Acaroglu. 1968. "Sediment Transport in Conveyance Systems", Bull. Intern'l Assoc. Sci. Hydrol., 23(2):pp 20-39.

Gregory, W.S., R.A. Martin, P.R. Smith and D.E. Fenton. October 1983. "Response of HEPA Filters to Simulated Accident Conditions", Proceedings of the 17th DOE Nuclear Air Cleaning Conference (M.W. First, Ed), CONF-820833, Harvard Air Cleaning Laboratory, Boston, MS.

Hackney, S. 1983. "Fire Testing of HEPA Filters Installed in Filter Housings", Proceedings of the 17th DOE Nuclear Air Cleaning Conference (M.W. First, Ed.), CONF-820833, Harvard Air Cleaning Laboratory, Boston, MS.

Haggard, D.L., W.M. Herrington, C.D. Hooker, J. Mishima, M.A. Parkhurst, R.I. Scherpelz, L.A. Sigalla and D.E. Hadlock. July 1986. Hazard Classification Test of the 120-mm, APFSDS-T, M829 Cartridge: Metal Shipping Container, PNL-5928, Pacific Northwest Laboratory, Richland, WA 99352.

Hall, D. 1988. "Measurements of the Mean Force on a Particle Near a Boundary in Turbulent Flow", Journal of Fluid Mechanics, 187:pp 451-466.

Halverson, M.A., M.Y. Ballinger and G.W. Dennis. March 1987. Combustion Aerosols formed During Burning of Radioactively Contaminated Materials - Experimental Results, NUREG/CR-4736 (PNL-5999), Pacific Northwest Laboratory, Richland, WA.

Hanson, W.C., J.C. Elder, H.J. Ettinger, L.W. Hantel and J.W. Owens. October 1974. Particle Size Distribution of Fragments from Depleted Uranium Penetrators Fired Against Armor Plate Targets, LA-5654, Los Alamos National Laboratory, Los Alamos, NM 87544.

Haschke, J.M. July 1992. Evaluation of Source-Term Data for Plutonium Oxidation, LA-12315-MS, Los Alamos national Laboratory, Los Alamos, NM.

Healy, J.W. 1974. A Proposed Interim Standard for Plutonium in the Soils, LA-5483-MS, Los Alamos National Laboratory, Los Alamos, NM.

Heger, R., et al. 1982. "Bestimmung der Quellterme bei verfahrenstechnischen Operationen im Weideraufbeitungsprozess", KfK Nachrichten, 14 (3):p 143.

Heger, R. and Th. Waescher. 1983. "Charakteriserung der Aerosolemissionen im Bahaelterabgas einer Wiederaufarbeitungsanlage", Jahrestagung Jerntecknik, Berlin, Tagungsband, p 423.

Hooker, C.D., D.E. Hadlock, J. Mishima and R.L. Gilchrist. November 1983. Hazard Classification Test of the Cartridge, 120-mm, APFSDS-T, XM829, PNL-4459, Pacific Northwest Laboratory, Richland, WA 99352.

Hubbe, M.A. 1984. "Theory of Detachment of Colloidal Particles From Flat Surfaces Exposed to Flow", Journal of Colloid and Interface Sciences, 50: ...

Iranzo, E and S. Salvador. 1970. "Inhalation Risk to People Living Near a Contaminated Area." presented at the Second International Congress International Radiaition Protection Association, May 3-8, 1970, Brighton, England.

Jardine, L.J., W.J. Mecham, G.T. Reedy and M.J. Steindler. 1982. Final Report of Experimental Laboratory-Scale Brittle Fracture Study of Glass and Ceramics, ANL-82-39, Argonne National Laboratory, Argonne, IL.

Jette, S.J., J.A. Glissmeyer, J. Mishima, D.J. Sherwood and R.E. Williford. August 1989. Potential Aerosolization (Airborne Suspension) of Depleted Uranium During Test Firings, PNL-7137 Informal Letter Report, Pacific Northwest Laboratory, Richland, WA 99352.

Jette, S.J., J. Mishima and D.E. Hadlock. August 1990. Aerosolization of the M829A1 and XM900E1 Rounds Fired Against Hard Targets, PNL-7452, Pacific Northwest Laboratory, Richland, WA 99352.

John, W., D.N. Fritter and W. Winklmayr. 1991. "Resuspension Induced by Impacting Particles", J. Aerosol Sciences, 22:No. 22, pp 723-736.

Johnson, K.L., K. Kendall and A.D. Roberts. 1971. "Surface Energy and the Contact of Elastic Solids", Proceedings of the Royal Society, London, Series A, 324:pp 301-313.

Jones, I.S. and S.F. Pond. 1967. "Some Experiments to Determine the Resuspension Factor of Plutonium from Various Surfaces", in Proceedings of the Surface Contamination Symposium (B.R. Fish, Ed), pp 83-92, Pergamon Press.

Jordan, S. and W. Lindner. October 1983. "The Behavior of Burning Kerosine, Aerosol Formation and Consequences", Proceedings of the CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems, LA-9911-C Volumes I & II (CSNI Report No. 83), Los Alamos National Laboratory, Los Alamos, NM.

Jordan, S. and W. Lindner. February 1985. "Aerosols Released from Solvent Fire Accidents in Reprocessing Plants", Proceedings of the CSNI Specialists Meeting on Nuclear Aerosols in Reactor Safety (W.O. Schikarski and W. Shock, Ed.), KfK 3800 (CSNI Report No. 95), Kerforschungszentrum Karlsruhe, FRD.

Kalinske, A.A. 1947. "Movement of Sediment as Bed Load in Rivers", Trans. Am. Geophys. Union, 28:615.

Kanapilly, G.M. March 1982. Pu Aerosolization Studies, ITRI - Lovelace Laboratory, Albuquerque, NM.

Kataoka, I. and M. Ishii. April 1983. Mechanistic Modeling for Correlations for Pool Entrainment Phenomenon, NUREG/CR-3304 (ANL-83-37), Argonne National Laboratory, Argonne, IL 60439.

Knief, R.A. 1985. Nuclear Criticality Safety - Theory and Practice, American Nuclear Society, La Grange Park, IL.

Krey, P.W., R. Knuth, T. Tamura and L. Toonkel. 1976. "Interrelationships of Surface Air Concentrations and Soil Charcateristics at Rock Flats.", Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants - 1974 (R.J. Englemann and G.A. Sehmel, Ed.), CONF-740921, pp 744-756, U.S. Energy Research and Development Administration, National Technical Information Services, Springfield, VA.

Langer, G. November 1987. Simulated Seismic Event Release Fraction Data. Progress Report April 1986 - April 1987, RFP-4161, Rockwell International - Rocky Flats Plant, Golden, CO 80402-0464.

Langham, W.H. 1971. "Plutonium Distribution as a Problem in Environmental Sciences, Proceedings of Environmental Plutonium Symnposium (E.B. Fowler, R.W. Henderson and M.F. Milligan, Ed.), LA-4756, Los Alamos National Laboratory, Los Alamos, NM.

Larsen, R.I. August 1958. "The Adhesion and Removal of Particles Attached to Air Filter Surfaces", American Industrial Hygiene Association Journal, 19:pp 265-270.

Malet, J.C., G. Duverger de Cuy, R. Gasteiger and J. Janberg. April 1983. "Solvent Pool Fire Testing", Proceedings of the CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems in Nuclear Facilities, LA-8911-C Vol 1 & 2 (CSNI Report No. 83), Los Alamos National Laboratory, Los Alamos, NM.

Manowitz, B., R.H. Bretton and R.V. Horrigan. 1955. "Entrainment in Evaporators", Chem. Eng. Progress, 51 (7):p 313.

Martin, R.A., P.K. Tang, A.P. Harper, J.D. Novat and W.S. Gregory. October 1983. Material Transport Analysis for Accident-Induced Flow in Nuclear Facilities, NUREG/CR-3527 (LA-9913-MS), Los Alamos National Laboratory, Los Alamos, NM 87545.

000241

McLaughlin, T.P. 1991. Process Criticality Accident Likelihood, Consequences, and Emergency Planning, LA-UR-91-2325, Los Alamos National Laboratory, Los Alamos, NM 87545.

Mecham, W.J., L.J. Jardine, R.H. Pelto, G.T. Reedy and M.J. Steindler. October 1981. Interim Report of Brittle Fracture Impact Studies: Development of Methodology, ANL-81-27, Argonne National Laboratory, Argonne, IL.

Milham, R.C., J.F. Schubert, J.F. Watts, J.R. Boni and J.C. Corey. 1976. "Measured Plutonium Resuspension and Resulting Dose from Agricultural Operations on an Old Field at the Savannah River Plant in the Southeastern United States of America.", Transuranium Nuclides in the Environment, pp 409-421, International Atomic Energy Agency, Vienna, Austria.

Mishima, J. August 1964. A Review of Research on Plutonium Releases During Overheating and Fires, HW-83668, General Electric Company - HAPO, Richland, WA.

Mishima, J. December 1965. Plutonium Release Studies - I. Release From the Ignited Metal, BNWL-205, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J. November 1966. Plutonium Release Studies II. Release From Ignited, Bulk Metallic Pieces, BNWL-357, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J. June 1973. Interim Report: The Fractional Airborne Release of Dissolved Radioactive Materials During the Burning of 30 Percent Normal Tributyl Phosphate in a Kerosine-Type Diluent, BNWL-B-274, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J. and L.C. Schwendiman. October 1970. The Amount and Characteristics of Plutonium Made Airborne Under Thermal Stress, BNWL-SA-3379, Pacific Northwest Laboratory, Richland, WA.

Mishima, J. and L.C. Schwendiman. April 1973. Fractional Airborne Release of Uranium (Representing Plutonium) During the Burning of Contaminated Waste, BNWL-1730, Pacific Northwest Laboratory, Richland, WA.

Mishima, J. and L.C. Schwendiman. August 1973. Some Experimental Measurements of Airborne Uranium (Representing Plutonium) in Transportation Accidents, BNWL-1732, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J., L.C. Schwendiman and C.A. Radasch. July 1968. Plutonium Release Studies III. Release From Heated Plutonium Bearing Powders, BNWL-786, Pacific Northwest Laboratory, Richland, WA.

Mishima, J., L.C. Schwendiman and C.A. Radasch. November 1968. Plutonium Release Studies IV. Fractional Release From Heating Plutonium Nitrate Solutions in Flowing Air Stream, BNWL-931, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J., L.C. Schwendiman and J.E. Ayer. October 1978. Increment of Analysis - An Estimate of Airborne Release of Plutonium from Babcock and Wilcox Plant as a Result of Severe Wind Hazard and Earthquake, PNL-2812, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J., M.A. Parkhurst, R.I. Scherpelz and D.E. Hadlock. March 1985. Potential Behavior of Depleted Uranium Penetrators under Shipping and Bulk Storage Accident Conditions, PNL-5415, Pacific Northwest Laboratory, Richland, WA 99352.

Mitchell, R.N. and B.C. Eutsler. 1967. "A Study of Beryllium Surface Contamination and Resuspension.", in Surface Contamination Symposium Proceedings (B.R. Fish, Ed.), Pergamon Press, New York.

Myers, D.S., W.J. Silver, D.G. Coles, K.C. Lamson, D.R. McIntyre and B. Mendoza. 1976. "Evaluation of the Use of Sludge Containing Plutonium as a Soil Conditioner for Food Crops, in Transuranium Nuclides in the Environment, pp 311-323, International Atomic Energy Agency, Vienna, Austria.

Nelson, C.T. 1973. Resuspension Studies, AI-AEC-13108, Atomics International, ...

NRC. April 1977. Assumptions Used for Evaluating the Potential Radiological Consequences of Accidental Nuclear Criticality in a Fuel Reprocessing Plant, Regulatory Guide 3.33, USNRC - Office of Standards Development, Washington, DC.

NRC. April 1979. Assumption Used for Evaluating the Potential Radiological Consequences of Accidental Nuclear Criticality in Uranium Fuel Fabrication Plant, Regulatory Guide 3.34, USNRC - Office of Standards Development, Washington, DC.

NRC. July 1979. Assumption Used for Evaluating the Potential Radiological Consequences of Accidental Nuclear Criticality in a Plutonium Processing and Fuel Fabrication Plant, Regulatory Guide 3.35, USNRC - Office of Standards Development, Washington, DC.

Nyer, N.E., G.O Bright and R.J. McWhorter. 1965. "Reactor Excursion Behavior" in Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Vol 13. Nuclear Safety, United Nations, New York, NY.

Olsen, A.R., R.L. Hooper, V.O. Uotinen and C.L. Brown. July 1974. Empirical Method for Estimating the Total Number of Fissions From Accidental Criticality in Uranium and Plutonium Systems, BNWL-1840, Pacific Northwest Laboratory, Richland, WA.

000243

Parkhurst, M.A., J. Mishima, D.E. Hadlock and S.J. Jette. April 1990. Hazard Classification and Airborne Dispersion Characteristics of the 25-mm, APFSDS-T XM919 Cartridge, PNL-7232, Pacific Northwest Laboratory, Richland, WA 99352.

Parthenaides, E. and R.E. Passwell. 1970. "Erodibility of Channels with Cohesive Boundaries", J. Hydraulics Div., Proceedings of Am. Soc. Civil Eng., 96(H):pp 755-771.

Paxton, H.C. 1980. "Historical Perspective of Criticality Safety in the United States" in Proceedings od ANS Topical Meeting Nuclear Criticality Safety, SAND80-1675, Sandia National Laboratory, Albuquerque, NM.

Paxton, H.C., J.T. Thomas, D. Callihan and E.B. Johnson. June 1964. Critical Dimensions of Systems Containing U^{235}, Pu^{239}, and U^{233}, TID-7028, Los Alamos National Laboratory & Oak Ridge National Laboratory, Los Alamos, NM/Oak Ridge, TN.

Punjrath, J.S. 1972. "Mechanism of Small Particle Re-Entrainment from Flat Surfaces", Aerosol Sciences, 3: ...

Punjrath, R.F. and D.R. Heldman. 1973. "Mechanisms of Small Particle Reentrainment from Flat Surfaces", Aerosol Sciences, 3:pp 429-440.

Raabe, O.G., S.V. Teague, N.L. Richardson and L.S. Nelson. November 1978. "Aerodynamic and Dissolution Behavior of Fume Aerosols Produced During the Combustion of Laser-Ignited Plutonium Droplets in Air:, Health Physics, 35:pp 663-674.

Rader, D.J. and D.A. Benson. June 1986. Aerosol Production by High-Velocity Molten-Metal Droplets, SAND88-0678, Sandia National Laboratory, Albuquerque, NM 87185.

Reeks, M.W., J. Reed and D. Hall. May 1985a. On the Long Term Resuspension of Small Particles by a Turbulent Flow, Part I - A Statistical Model, TPRD/B/0638/N85, Central Electric Generating Board, Berkeley Nuclear Laboratory, Gloucesterhire, UK.

Reeks, M.W., J. Reed and D. Hall. May 1985b. On the Long Term Resuspension of Small Particles by a Turbulent Flow, Part II - Determination of the Resuspension Rate Constant for an Elastic Particle on a Surface Under the influence of van der Waals Forces, TPRD/B/0639/N85, Central Electric Generating Board, Berkeley Nuclear Laboratory, Gloucestershire, UK.

Reeks, M.W., J. Reed and D. Hall. June 1985a. On the Long Term Resuspension of Small Particles by a Turbulent Flow, Part III - Resuspension for Rough Surfaces, TPRD/B/0640/N85, Central Electric Generating Board, Berkeley Nuclear laboratory, Gloucestershire, UK.

Reeks, M.W., J. Reed and D. Hall. June 1985b. On the Long Term Resuspension of Particles by a Turbulent Flow, Part IV - CAGR Plant Application, TPRD/B/0641/N85, Central Electric Generating Board, Berkeley Nuclear Laboratory, Gluocestershire, UK.

Reek, M.W., J. Reed and D. Hall. 1988. "On the Resuspension of Small Particles by a Turbulent Flow", Journal of Physics, D, Applied Physics, 21:pp 574-589.

Restrepo, L. 1991. Building 771, Subteam 6 DRAFT Report, Chapter 7, Criticality Assessment, EG&G-RF, Golden, CO.

Restrepo, L.F. April 1992. The Annular Core Research Reactor (ACRR) Limiting Event Workers and Public Consequences, SAND91-0572, Sandia National Laboratory, Albuquerque, NM.

Roblyer, S.P. and P.C: Owczarski. 1992. Determining Wind Spray Release From Effluent Disposal Ponds Using AIRSOURCE Model, paper presented at Hazmacon '92, March 30-April 2, 1992, Long Beach, CA.

Royster, G.W. and B.R. Fish. 1967. "Techniques for Assessing 'Removable' Surface Contamination", Surface Contamination (B.R. Fish, Ed) pp 201-207, Pergamon Press, New York, NY.

Sackman, J.F. 1960. "The Atmospheric Oxidation of Plutonium Metal", Proceedings Conference Internationale Metallurgie du Plutonium, Grenoble, France.

SAND. September 1987. Appendix F "Preliminary Preclosure Safety Analysis", Site Characterization Plan Conceptual Design Report (H.R. MacDougall, L.W. Scully and J.R. Tillerson, Compilers), SAND84-2641 Vol 4, Sandia National Laboratory, Albuquerque, NM.

Schmitt, R.C. May 1975. "Carbon Microspheres as Extinguishing Agents for Fissionable Material Fires", Fire Protection, 11:pp 95-98.

Sehmel, G.A. 1973. "Particle Resuspension from an Asphalt Road Caused by Car and Truck Traffic", Atmospheric Environment, 7:pp 291 - 301.

Sehmel, G.A. 1979. Deposition and Resuspension Process, PNL-SA-6746, Pacific Northwest Laboratory, Richland, WA.

Sehmel, G.A. 1980. "Particle Resuspension: A Review", Environment International, 4:pp 107 - 127.

000245

Sehmel, G.A. and F.D. Lloyd. 1975. "Initial Particle Resuspension Rates – A Field Experiment Using Tracer Particles.", Pacific Northwest Laboratory Annual Report for 1974: Atmospheric Sciences, BNWL-1950-Pt 3, pp 203-207, Pacific Northwest Laboratory, Richland, WA.

Sehmel and Lloyd. 1976. "Resuspension Rates from a Circular Field Source", Annual Report 1975 to the USERDA Division of Biomedical and Environmental Research, Part 3, Atmospheric Sciences, BNWL-2000, Part 3, Pacific Northwest Laboratory, Richland, WA.

Sehmel, G.A. and F.D. Lloyd. 1976. "Particle Resuspension Rates", Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (R.D. Englemann and G.A. Sehmel, Ed), ERDA Symp. Series #38, Technical Information Center - Energy Research and Development Center (Now U.S. Department of Energy), Washington, D.C.

Sehmel, G.A. and M.M. Orgill. 1973. "Resuspension by Wind at Rocky Flats.", in Pacific Northwest Laboratory Annual Report for 1972: Atmospheric Sciences, BNWL-1751-Pt-1, pp 15-22, Pacific Northwest Laboratory, Richland, WA.

Shor, A.J., H.T. Ward, D. Miller and W.A. Rodger. 1957. "Radioactive Carry-Over from Borax III and Test Systems", Nucl. Sci. Eng., 2:pp 126-142.

Singer, J.M., E.R. Cook and J. Grumer. 1972. Dispersal of Coal and Rock Dust Deposits, BMRI-7642, Bureau of Mines, Washington, D.C.

Singer, J.M., M.E. Harris and J. Grumer. 1976. Dust Dispersal by Explosion-Induced Airflow, Entrainment by Air Blast, BMRI-8130, Bureau of Mines, Washington, D.C.

Skidmore, E.L. and N.P. Woodruff. 1968. Wind Erosion Forces in the United States and Their Use in Predicting Soil Loss, Agricultural Handbook No. 346, U.S. Department of Agriculture, Washington, D.C.

Spenser, H.W. 1976. 'Rapping Entrainment Studies", in Symposium on Particulate Control in Energy Processes (D.E. Blake, ED), ...

Steindler, M.J. and W.H. Seefeldt. 1980. "A Method for Estimating the Challenge to an Air Cleaning System", Proceeding of the 16th DOE Air Cleaning Conference (M.W. First, Ed.), Harvard Air Cleaning Laboratory, Boston, MS.

Stewart, K. 1963. "The Particulate Material Formed by the Oxidation of Plutonium", Progress in Nuclear Energy Series IV, Vol 5, pp 535-579.

Stewart, K. 1967. "The Resuspension of Particulate Material from Surfaces.", in Proceedings of the Surface Contamination Symposium (B.R. Fish, Ed.), pp 63-74, Pergamon Press, New York.

Stratton, W.F. September 1967. A Review of Criticality Accidents, LA-3611, Los Alamos National Laboratory, Los Alamos, NM.

Sutter, S.L. August 1980. Potential Airborne Release from Soil-Working Operations in a Contaminated Area, PNL-3498, Pacific Northwest Laboratory, Richland, WA 99352.

Sutter, S.L. May 1982. Accident Generated Particulate Materials and Their Characteristics – A Review of Background Information, NUREG/CR-2651 (PNL-4154), Pacific Northwest Laboratory, Riehland, WA 99352.

Sutter, S.L. August 1983. Aerosols Generated by Releases of Pressurized Powders and Solutions in Static Air, NUREG/CR-3093 (PNL-4566), Pacific Northwest Laboratory, Richland, WA 99352.

Sutter, S.L., J. Mishima and L.C. Schwendiman. June 1974. Fractional Airborne Release of Strontium During the Combustion of 30 Percent Normal Tributyl Phosphate in a Kerosine-Type Diluent, BNWL-B-358, Pacific Northwest Laboratory, Richland, WA.

Sutter, S.L., J.W. Johnston and J. Mishima. December 1981. Aerosols Generated by Free Fall Spills of Powders and Solutions in Static Air, NUREG/CR-2139 (PNL-3786), Pacific Northwest Laboratory, Richland, WA 99352.

Sutter, S.L., J.W. Johnston, J.A. Glissmeyer and G.F. Athey. January 1985. BTD Building Uranium Mass Balance Study, PNL-5344, Pacific Northwest Laboratory, Richland, WA 99352.

Thomas, J.T., Ed. June 1978. Nuclear Safety Guide, TID-7016, Revision 2, NUREG/CR-0095, Oak Ridge National Laboratory, Oak Ridge, TN.

Tuck, G. August 1974. "Simplified Methods of Estimating the Results of Accidental Solution Excursions", Nuclear Technology, 23:pp 177-188.

Waber, J.T., W.M. Olson, J.A.C. Davidson, P.M. French, E.N. Hodkin and M.J.F. Notley. 1960. Atmospheric Corrosion Tests of Several Delta-phase Alloys of Plutonium, Journal of Nuclear Materials, 3:p 201.

Walker, E. 1978. A Summary of Parameters Affecting the Release and Transport of Radioactive Material From an Unplanned Incident, Bechtel Inc., San Francisco, CA.

Wilsey, E.F. and E.W. Bloore. May 1989. M774 Cartridges Impacting Armor-Bustle Targets: Depleted Uranium Airborne and Fallout Material, BRL-MR-3760, Ballistics Research Laboratory, Aberdeen Proving Grounds, MD 21005-5066.

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Woodcock, E.R. 1966. Potential Magnitude of Criticality Accidents, AHSB (RP) R-14, United Kingdom Atomic Energy Authority.

Wright, A.L. and W.L. Pattison. 1984. 'Results from Simulated Upper-Plenum Aerosol Transport and Aerosol Resuspension Experiment", Proceeding of the CSNI Specialist Meeting on Nuclear Aerosols in Reactor Safety, ..., Karlsruhe, ...

Zimon, A.D. 1969. Adhesion of Dust and Powder (Translation by M. Corn), Plenum Press, New York.

DOE Office of Defense Programs (DP)

Jacty,
How does this impact the PSAR or Greg's SAR?
Numbers will be formally published in a DOE Handbook

DEFENSE PROGRAMS SAFETY SURVEY

AIRBORNE RELEASE FRACTIONS/ RATES RESPIRABLE FRACTIONS

Jofu Mishima, SAIC

Las Vegas Workshop - December 7, 1993

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Airborne Release Fractions/Rates and Respirable Fractions Used in DP Facilities Safety Survey

by

Jofu Mishima, SAIC-Richland, WA

Presented at the DP Safety Survey Workshop
Las Vegas Hilton
December 7, 1993

METHODOLOGY

1. Hazards Identification -

   * potential impact hazards: hazards in each area with significant inventory of radionuclides.
   * identifies candidate scenario for PHA.

2. Preliminary Hazards Assessment, PHA - screens scenarios.

   * identifies MARs.
   * assesses potential consequences: Relative Biological Hazards of Radionuclides; Recommended Values ARFs/ARRs and RFs.
   * Identifies "bounding" scenarios.

3. Engineering Analysis/Assessment - specifies behavior of determinant materials/systems involved in scenarios to identify:
   * Damage Ratios
   * Levels of Stress/Conditions generated by postulated event, determines the ARF/RF applicable.

4. Deterministic Accident Analysis - 5-component linear equation.

5. Estimate LeakPath Factors - intra- and extra-facility transport.

LIST OF HAZARDS COMMONLY FOUND IN FACILITIES

Heat Sources
- Electrical
- Steam
- Flames
- Solar
- Friction
- Chemical reactions
- Spontaneous

Cold Sources
- Cryogenic materials
- Ice, snow, wind, rain

Electrical Sources
- Capacitors
- Transformers
- Batteries
- Exposed conductors
- Static electricity
- Other high-voltage sources

Motion Sources
- Pulleys, belts, gears
- Shears, sharp edges, pinch points
- Vehicles
- Mass in motion

Radiant Sources
- Intense light
- Lasers
- Ultraviolet (UV)
- X-rays and ionizing radiation
- Infrared sources
- Electron beams
- Magnetic fields
- RF fields
- Nuclear criticality

Pressure Sources
- Confined gases
- Explosives
- Noise
- Chemical reactions
- Stressed mechanical systems

Chemical Sources
- Corrosive materials
- Flammable materials
- Toxic materials
- Reactive materials
- Pathogenic materials (virus, bacteria, etc.)
- Oxygen deficiency
- Carcinogenic materials

Gravity-Mass Sources
- Falling
- Falling objects
- Lifting
- Tripping, slipping
- Earthquakes

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RELATIVE RADIOLOGICAL IMPACTS OF
SELECTED AIRBORNE RADIONUCLIDES

Radionuclide	Halflife	DCG, uCi/ml	x:^{239}Pu[a]
H-3, water	12.2 y	1E-7 (inhal, w)	5E+6
elemental		2E-2 (inhal, w)	1E+12
C-14, org	5730 y	6E-9 (inhal, w)	3E+5
CO		4E-6 (inhal, d)	2E+8
CO2		5E-5 (inhal, d)	2.5E+7
Kr-83m	1.8 h	2E-4 (immersion)	1E+10
-85m	4.5 h	1E-7 (immersion)	5E+6
-85	10.7 y	3E-6 (immersion)	1.5E+8
-87	76.3 m	2E-8 (immersion)	1E+6
-88	2.8 h	9E-9 (immersion)	4.5E+5
-89	3.2 m	1E-8 (immersion)	5E+5
Sr-89	52 d	2E-9 (inhal, d)	1E+5
-90	28.1 y	5E-11 (inhal, d)	2.5E+3
Y-90m	3.1 h	3E-8 (inhal, w)	1.5E+6
-90	64 h	2E-9 (inhal, w)	1E+5
-91m	50 m	6E-7 (inhal, w)	3E+7
-91	58.5 d	4E-4 (inhal, w)	2E+4
Zr-95	65 d	6E-10 (inhal, d)	3E+4
Nb-95	35.2 d	6E-9 (inhal, w)	3E+5
Tc-99	2.12E+5 y	1E-8 (inhal, d)	5E+5
Ru-103	39.6 d	4E-9 (inhal, d)	2E+5
-106	367 d	2E-10 (inhal, d)	1E+4
Rh-103m		3E-6 (inhal, d)	1.5E+8
-106m	130 m	6E-8 (inhal, d)	3E+6
I-129	1.7E+7 y	7E-11 (inhal, d)	3.5E+3
-131	8.0 d	4E-10 (inhal, d)	2E+4
-132	2.3 h	4E-8 (inhal, d)	2E+6
-133	20.8 h	2E-9 (inhal, d)	1E+5
-134	52.6 m	1E-7 (inhal, d)	5E+6
-135	6.6 m	1E-8 (inhal, d)	5E+5
Xe-131m	11.9 d	2E-6 (immersion)	1E+8
-133m	2.0 d	6E-7 (immersion)	3E+7
-133	5.2 d	5E-7 (immersion)	2.5E+7
-135m	15.6 m	5E-8 (immersion)	2.5E+6
-135	9.1 h	8E-8 (immersion)	4E+6
-137	3.8 m	9E-8 (immersion)	4.5E+5
-138	14.2 m	2E-8 (immersion)	1E+6

Ce-141	33 d	2E-9 (inhal, w)	1E+5
-144	284 d	6E-11 (inhal, w)	3E+3
Pr-144	13.3 m	3E-7 (inhal, w)	1.5E+7
Cs-137	30.2 y	4E-10 (inhal, d)	2E+4
Pm-147	2.5 y	5E-10 (inhal, w)	2.5E+4
U-234	2.47E+5 y	4E-12 (inhal, d)	200
-235	7.1E+8 y	5E-12 (inhal, d)	250
-236	2.39E-7 y(?)	5E-12 (inhal, d)	250
-237	6.75 d	6E-9 (inhal, d)	3E+5
-238	4.51E+9 y	5E-12 (inhal, d)	250
-239	23.5 m	4E-7 (inhal, d)	2E+7
-natural		5E-12 (inhal, d)	250
Np-239	2.35 d	5E-9 (inhal, w)	2.5E+5
Pu-238	86 y	3E-14 (inhal, w)	1.5
-239	24400 y	2E-14 (inhal, w)	1.
-240	6580 y	2E-14 (inhal, w)	1.
-241	13.2 y	1E-12 (inhal, w)	50
-242	3.79E+5 y	2E-14 (inhal, w)	1.
-243	4.98 h	8E-8 (inhal, w)	4E+6
-244	8E+7 y	2E-11 (inhal, w)	1.
Am-241	458 y	2E-14 (inhal, w)	1.

Radionuclide = specific radionuclide
Half Life = duration over which 1/2 of activity present will radioactively decay.
DCG = Derived Concentration Guide from DOE 5400.5 2-8-90 as uCi/ml exposure pathway -
inhal = inhalation & immersion, Clearance Class DCG based upon -
d = day [clearance halftime <1 day];
w = week [clearance halftime 1-10 days];
y = year [clearance halftime of >100 d].
x:^{239}Pu = an indication of the number of curies of the radionuclide that must be released to have the same offsite radiological impact of releasing 1 curie of ^{239}Pu.

ACCIDENT EVALUATION

Building Source Term = MAR X DR X ARF X RF X LPF

Where: MAR = Material-at-Risk, Inventory of radionuclides at risk of release in discrete physical location in scenario, Ci radionuclide.

DR = Damage Ratio, fraction of MAR impacted by postulated event.

ARF = Airborne Release Fraction, Fraction of MAR X DR suspended by accident generated stress during postulated event.

RF = Respirable Fraction, fraction of ARF in respirable form (for particles, the fraction of ARF as particles 10 micrometers AED and less[1]).

LPF = LeakPath Factor, the fraction of particles airborne that will be transported by the local flow field to the opening to the next volume (e.g. LPF in enclosure, in operating area, in exhaust ducting, in building corridors).

AED - Aerodynamic Equivalent Diameter - the diameter of a sphere of density 1 g/cm^3 that exhibits the same aerodynamic behavior (commonly the terminal velocity) as the particle in question.

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NON-CONDENSIBLE GASES

* Release mechanism: loss of containment/confinement; for spent fuel, appears to be migration from generation site to interstice of grain boundaries and release to surfaces, "gap release" upon loss of cladding but may be due to some degree to fuel pellet fragmentation.

* material released as a gas and percolate through water. Carried by local flow field.

VAPORS (Condensible Gases)

* Release mechanism: conditions to generate vapor (i.e. temperature, chemical environment).

* Material released in gaseous state and carried by local flow conditions. May revert to solid (homogeneous or heterogeneous condensation) upon loss of conditions to maintain vapor (temperature). Vapors generated by chemical interactions (e.g. iodine, ruthenium) may be chemically active.

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LIQUIDS

* Two types:
  - aqueous (solutions, slurries, viscous liquids).
  - organic, combustible (only values for thermal stress - combustion).

* Release mechanism:
  - aqueous: drop formation and suspension in vapor flux/local flow field for aqueous under stress; drops may evaporate during transport reducing particle size during transport, grow by condensation of miscible liquids, deposit depending on conditions; drops are sphere with a density close to 1 g/cm^3 and most closely approach predictable behavior.
  - organic, combustible: evaporation/drop formation and suspension for solvent; for non-volatile solutes/slurries, size reduction by loss of solvent (burned or evaporated); drops are sphere but density may vary from 1 g/cm^3, solute particle highly variable.

* Stresses covered:
  - Thermal: aqueous - boil/pressurize, can form "flashing sprays"; organic - burn
  - Explosive:
    A. shock - fragment (microsecond reaction, detonation if chemical source).
    B. blast - drop formation (millisecond to second reaction, rapid burning, deflagration if chemical source).
  - Pressure (liquid less than boiling):
    A. vent below liquid surface - spray.
    B. vent above liquid surface - above or below critical freeboard distance.
  - Free-Fall/Shock-Impact: drop formation by fragmentation.
  - Aerodynamic Entrainment: drop formation by wave action.

AQUEOUS LIQUIDS

Thermal Stress - heating

- Flowing air, no bubbles	ARF 3E-5; RF 1.0
- Flowing air, boiling	ARF 2E-3; RF 1.0

Explosive Releases

- Shock effects	[1]
- Blast effects (Accelerated velocity)	ARF 4E-3/hr X t; RF 1.0[2]

Venting Pressurized Liquids

- Vented above the liquid level, <bp

- pre-pressurized liquids -

* Density near 1g/cm^3	ARF 2E-3; RF 0.3
* Conc. soln. heavy metal, density >1.3 g/cm^3	ARF 1E-3; RF 0.4

- unpressurized liquids -
(vent above critical freebaord height)

(vent less than critical freeboard height)
use Schrock et al. (August 1986) to determine the gas fraction in vented gas based on stratified 2-phase flow

- Vented below liquid level, 3.25-mm diam. orifice, <1.4 MPa pressure	ARF 1E-4; RF 1.0
- Superheated liquids ("Flashing Spray"), >50 C above solvent bp	ARF 1E-1; RF 0.7

AQUEOUS LIQUIDS (cont)

Free-Fall Spill

- Solutions
  - * fall distance <3m — AEF 2E-4; RF 0.7
  - * fall distance >3m — [3]

- Slurries, <3m fall, <40% solids — ARF 5E-5; RF 0.8

- Viscous liquids, > 8 cp, <3-meters fall distance — ARF 3E-5; RF 0.7

Aerodynamic Entrainment (Resuspension)

- Indoors, hard unyielding surface (nominal air velocities) — ARR 4E-7/hr; RF 1.0

- Indoors, cover debris or static conditions (static conditions) — ARR 4E-8/hr; RF 1.0

- Outdoors, large pool, windspeed <13.4 m/s — ARR 4E-6/hr; RF 1.0

- Outdoors, soil, windspeed <22.4 m/s — ARR 9E-5/hr; RF 1.0

ORGANIC COMBUSTIBLE LIQUIDS

Thermal Stress, combustion with/without aqueous layer:

- Non-Condensible gases	ARF 1E+0; RF NA
- Volatile radionuclides, under all conditions	ARF 1E+0; RF NA
- Non-volatiles	
* Small pool fire, quiescent burning	ARF 1E-2; RF 1.0
* Large pool, vigorous burning	ARF 3E-2; RF 1.0
* Burned to dryness	ARF 1E-1; RF 1.0
* Outdoors, aq. soln or a.d. salts under burning fuel, non-heat conducting surface	ARF 5E-3; RF 0.4
* Outdoors, aq. soln. or a.d. salts under burning fuel, heat conducting surfaces	ARF 2E-1; RF 0.3

[No experimental data on behavior of organic, combustible liquids to other suspension mechanisms. Apply factors for response aqueous solutions in preceeding section for comparable stresses for remaining phenonenon.]

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SOLIDS

* Types:
  - Pyrophoric (Reactive) Metals (plutonium, uranium);
  - Solids that undergo brittle fracture (vitrified waste/glass, aggregate); and,
  - Powders

* Release Mechanism: particle formation/deagglomeration, suspension, transport by local flow field.

* Airborne materials governed by aerosol physics:
  - variable shapes/rarely spheres (condensed fumes);
  - powders difficult to deagglomerate;
  - variable densities (theoretic to agglomerated mass); can be reactive (e.g. condensed metal vapor).

* Stresses: (as with liquids)
  Principal stresses impacting various forms:
  - Reactive Metals: thermal/oxidation; shock/material fragmentation.
  - Solids/brittle fracture: thermal-air/UO_2; shock/fragmentation; free-fall spill & shock-impact/fragmentation.
  - Powders: thermal (reactive and inert cpd)/suspension by convection; blast/aerodynamic entrainment (deep bed) by impulse; pressure (vent above or below powder surface)/Bernoulli's effect or entrainment; free-fall spill + shock-impact/aerodynamic entrainment (deep bed); aerodynamic entrainment (deep bed).

REACTIVE METALS
(can attain self sustaining oxidation at moderately elevated temperatures)

Thermal Stress - heating

- Plutonium	
* room temperature oxidation	
unalloyed Pu (dry air)	ARR 2E-6 micrograms Pu/cm^2-hr; RF 0.7
(100% RH)	ARR 7E-3 micrograms Pu/cm^2-hr; RF 0.7
delta-phase (dry air)	ARR 7E-8 micrograms Pu/cm^2-hr; RF 0.7
(100% RH)	ARR 6E-4 micrograms Pu/cm^2-hr; RF 0.7
* oxidation at elevated temperatures	ARF 3E-5 X fract. oxid.; RF 0.04
* self sustained oxidation, natural convection	ARF 5E-4; RF 0.5
* disturbed surfaces, high turbulence, violent airborne reaction, falling molten metal drops	ARF 1E-2; RF 1.0
* explosive reaction molten metal, rapid vapor formation	ARF 1E+0; RF 0.5
- Uranium	
* complete oxid. metal, 0 to 20 cm/s gas flow, >500° C	ARF 1E-3; RF 0.6[6][a]
* falling molten drops/disturbed surface	ARF 6E-3; RF 1.0[6][b]
* explosive dispersal of molten metal	ARF 1E+0; RF 1.0[6][b]

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REACTIVE METALS (cont)

Explosive Release	
- Shock effects	[1]
- Blast effects	(no significant effects postulated)
Venting of Pressurized Gases Over Metal	(may suspend powdery surface corrosion)
Free-Fall Spill/Crush-Impact	
- spill of molten metal	(see falling molten drops above)
Aerodynamic Entrainment (resuspension)	(use values for release from room temperature oxidation of Pu)

SOLIDS THAT UNDERGO BRITTLE FRACTURE
(e.g. Aggregates, Glasses)

Thermal Stress - heating — oxidation of UO_2 to other oxides
spent commercial nuclear fuel, "gap" release

Explosive Releases

- Shock effects — (No data available)
  (Steindler-Seefeldt correlation, crush-impact energy/volume model)

- Blast effects — (No data available)

Venting of Pressurized Gases Over Solid — [See Aerodynamic Entrainment (Resuspension) of Surface Contamination]

Free-Fall Spill, Crush-Impact

$$PULF = 2E\text{-}4 \times density \times g \times h \times [J/10^7\ g\text{-}cm/s^2]$$

Where: 2E-4 = coefficient, cm^3/Joule
density = specimen density, g/cm^3
g = gravitational acceleration, ~960 cm/s^2 at sea level
h = fall distance, cm

Spent commercial nuclear fuel "gap" release

Aerodynamic Entrainment (Resuspension) — [See Aerodynamic Entrainment (Resuspension of Surface Contamination]

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POWDERS

Thermal Stress, <1000° C, natural convection:

- non-reactive compounds — ARF 6E-3; RF 0.01[6]
- reactive compounds (except PuF_4) — ARF 1E-2; RF 0.001
- PuF_4 — ARF 1E-3; RF 0.001

Explosive Releases

- Shock effects — (No data available)
- Blast effects
  * Accelerated airflow, parallel to surface, <0.14 MPa (20 psi) — ARF 5E-3; RF 0.3
  * deflagration above, limited volume reactants ("unconfined" vapor cloud), 0.14 to 0.34 MPa (50 psi) — ARF 1E-1; RF 0.7[6]
  * deflagration above, large volume reactants, >0.34 MPa, strong flow directly impacts material/severe turbulence — ARF 1E+0; RF 1.0[6]

Venting Pressurized Powders, <3.4 MPa (500 psi)
ARF 1E-1; RF 0.5

Free-Fall Spill, Crush-Impact/Shock-Vibration

- free-fall spill
  * airflow normal to fall direction, <1 m/s
    - fall distance <3m — ARF 2E-3; RF 0.3
    - fall distance >3m — [7]
  * airflow normal to fall direction, >1 m/s
    dispersed powder into flowing air — ARF 0.0134U + 0.00543 (U = local windspeed, m/s)
    RF 1.0
- shock-vibration — ARF 1E-3; RF 0.1

POWDERS (cont)

Aerodynamic Entrainment (Resuspension)

- thick beds, homogeneous surface	ARR 4E-5/hr; RF 1.0
- thick beds, buried under debris or indoors static volume	ARR 4E-6/hr; RF 1.0
- turbulence generated by falling debris	ARF 1E-2; RF 0.2
- vehicular traffic through or by freshly deposited powder	ARR 1E-2/pass; RF 1.0

SURFACE CONTAMINATION
sparse particle deposit on combustible substrate

Thermal Stress - burning	
- contained mixed waste	ARF 5E-4; RF 1.0[6]
- uncontained	
* cellulosics	ARF 1E-2; RF 1.0[6]
* plastics (except polystyrene)	ARF 4E-2; RF 0.2[6]
* polystyrene (polyethylene, IX resin)	ARF 1E-2; RF 0.9[6]
- airflow through burning mass, >1 m/s	ARF 4E-1; RF 1.0[6]
Explosive Release	
- Shock effects	ARF 1E-3[11]; RF 1.0[6] [1]
- Blast effects	
* Accelerated airflow	ARF 1E-3[11]; RF 1.0[6]
Venting of Pressurized Gases Over Solid	(no data available)
Free-Fall Spill, Shock-Vibration	
- free-fall spill	(no data available)
- shock-vibration	ARF 1E-3; RF 1.0[6]
Aerodynamic Entrainment (Resuspension)	
- nominal flow conditions, <5 m/s	ARR 4E-5/hr; RF1.0[6]
- buried under debris, indoors static conditions	ARR 4E-6/hr; RF 1.0[6]

SURFACE CONTAMINATION

sparse particle deposit on hard, unyielding, non-combustible substrate

Thermal Stress - heating	(heating inert powder on heterogeneous surface)
Explosive Releases -	
- Shock effects	[1]
- Blast effects	ARF 1E-3; RF 1.0[6]
Venting of Pressurized Gases Over Solid -	ARF 1E-1; RF 1.0[6]
Free-Fall Spill, Crush-Impact/Brittle Fracture, Shock-Vibration	
- free-fall spill	(no data available)
- crush-impact/brittle fracture	[5]
- shock-vibration	ARF 1E-3; RF 1.0[6]
Aerodynamic Entrainment (Resuspension) -	
- nominal flow conditions	ARR 4E-5/hr; RF 1.0
- buried under debris, indoor static condition	ARR 4E-6/hr; RF 1.0

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SURFACE CONTAMINATION
Material accumulated on HEPA filters

Thermal Stress - heating	ARF 1E-4; RF 1.0[6]
Explosive Releases - High Pressure (blowout)	
- Dynamic	ARF 2E-6; RF 1.0
- Static	ARF 1E-2; RF 1.0
Venting of Pressurized Gases Through Filter	
Free-Fall Spill, Crush-Impact	
- free-fall spill	(no data available)
- crush-impact (vibration)	
* uncontained (unenclosed)	ARF 1E-2; RF 1.0[6]
* contained (enclosed)	ARF 5E-4; RF 1.0[6]

LEGEND

[1] Assume mass inert material fragmented and made airborne as particles or droplets airborne as RF equal to TNT Eq.
[2] An ARR of 4E-3/hr is applied for the number of seconds estimated for the impulse to pass over the deposited material.
[3] See Ballinger et als. 1/88.
[4] Plutonium oxidation rate - use value in Table 4.2-2 (Stewart 1963) or 0.2 g PuO_2/cm^2 exposed metal surface per minute for self-sustained oxidation (Haschke July 1992).
[5] Fraction of brittle solids and aggregates fragmented into particles 10 micometers AED and less (respirable fraction), PULF, is:

$$PULF = 2E\text{-}4 \times density \times g \times h \times [J/10^7\ g\text{-}cm/s^2]$$

Where: 2E-4 = coefficient, cm^3/Joule
density = specimen density, g/cm^3
g = gravitational acceleration, ~960 cm/s^2 at sea level
h = fall distance, cm

[6] Limited to RF in source powder.
[7] PSPILL, see subsect. 4.C.4.c.
[8] Tables from Reg. Guide 3.33 (Spent Commercial Nuclear Fuel solution), 3.34 (uranium) & 3.35 (plutonium) "Radioactivity of Important Nuclides Released From the Criticality Accident ..." also attached to this document (Tables 6.2-1a & -1b, -2 & -3).
[9] ARF (Airborne Release Fraction) for:
* fission product noble gases = 1.0
* radioiodines and other radiohalogens that can be generated as vapors by accident conditions = 0.25
* salts in liquid evaporated (assume 100 liter for large volume solution excursion) = 5E-4
* non-volatile fission products (see subsect.6.2.4.3)

LEGEND (cont)

[10] RF (Respirable Fraction) for:

* noble gases = all the airborne material can be transported downwind and affects the exposure of the population, = 1.0
* radioiodine = 1.0
  (assume released as vapor).
  salts in liquids evaporated during boildown of solution = 1.0

[11] Possible additional thermal stress (burning) from high temperatures generated by explosion.

[12] LPF (LeakPath Factor) is assumed to be 1.0 for noble gases, 1.0 for radioiodine unless functional iodine removal devices are in the facility gaseous effluent exhaust system (use conservative estimate of removal efficiency). For particulate materials generated, if generated indoors and the airborne material from the excursion is released via the facility gaseous effluent exhaust system, use a LPF of 0.001 (filter efficiency of 99.9%) for the 1st stage of HEPA filtration and 0.002 (filter efficiency of 99.8%) for every stage thereafter or a conservative estimate of the transmission factor for other types of high efficiency particulate filtration (e.g. sand filters) in place.

[a] >95% uranium in "Y" solubility class with remainder in "D" solubility class.

[b] 50% uranium in "Y" solubility class and 50% in "D" solubility class.

INADVERTENT NUCLEAR CRITICALITIES

Solutions, large volume systems (>100 gallons in vented vessel)

Building Source Term = $[(MAR_{c1} \times DR_{c1} \times ARF_{c1} \times RF_{c1}) + (MAR_{s1} \times DR_{s1} \times 5E\text{-}4 \times 1.0)]$ LPF

where: MAR_{c1} = inventory radionuclides from criticality in a solution calculated by computer code such as ORIGEN2 based on 1E+19 total fissions; or,
= [1E+19 fissions/1E+19 fissions] X table[8].

DR_{c1} = damage ratio for material involved in criticality, 1.0.

ARF_{c1} = Airborne Release Fraction for solution criticality in NRC Reg Guides[9]: 1E+0 for noble gases, 2.5E-1 for radioiodines, 1E-3 for radioruthenium and 5E-4 for dissolved non-volatiles.

RF_{c1} = Respirable Fraction[10] materials generated by criticality ... materials generated all in gaseous phase, RF = 1.0.

MAR_{s1} = inventory radionuclides in solution prior to the nuclear excursion evaporated, Ci.

DR_{s1} = Damage Ratio radionuclides in solution, 1.0.

LPF = LeakPath Factor for airborne material[12] ... different LPFs are necessary for gaseous radionuclides and airborne particulate materials.

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INADVERTENT NUCLEAR CRITICALIIES

Fully moderated/reflected solids - (a coherent solid can not be moderated and solids <100 micrometers in diameter must be intimately mixed with moderator to be fully moderated.)

Building Source Term = MAR_{c2} X DR_{c2} X ARF_{c2} X RF_{c2} X LPF

where: MAR_{c2} = inventory radionuclides from criticality in reflected/moderated solids calculated by computer codes such as ORIGEN2 based on 1E+18 total fissions, or,
= [1E+18 fissions/1E+19 fissions] X table[8].

DR_{c2} = Damage Ratio for radionuclides generated by criticality, 1.0.

ARF_{c1} = Airborne Release Fraction[9] in NRC Reg Guides.

RF_{c1} = Respirable Fraction for airborne material in gaseous phase, 1.0[10].

LPF = LeakPath Factor for gaseous airborne material[12].

INADVERTENT NUCLEAR CRITICALITIES - Bare, Dry Solids

Building Source Term = $[(MAR_{c3} \times DR_{c3} \times ARF_{c3} \times RF_{c3}) + (MARs3 \times DR_{c3} \times ARF_{s3} \times RF_{s3})]$ LPF

where: MAR_{c3} = inventory of radionuclides generated by bare, dry metal criticality based on total fission yield of 1E+17 fission by computer code such as ORIGEN2; or,
= [1E+17 fissions/1E+19 fissions] X table[8].

DR_{c3} = Damage Ratio = A_s X 10-mm/Vol_f

where: A_s = surface area of fissionable material exposed to the air, mm;
Vol_f = volume of fissionable material, mm^3.
ARF_{c3} = Airborne Release Fractions in Table 6.2-4; or,
= if using MAR values in NRC Reg Guide use ARFs[9] from that document.

RF_{c3} = Respirable Fraction, assume 1.0 for all materials.

MAR_{s3} = Inventory of fissionable material involved in criticality.

ARF_{s3} = Airborne Release Fraction for ignited, oxidized metal - natural convection, 5E-4.

RF_{s3} = Assume 1.0.

LPF = Need LPF for both gases/vapors and airborne particulate material[12].

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INADVERTENT NUCLEAR CRITICALITIES - Large Storage Arrays

Building Source Term = MAR_{c4} X DR_{c4} X ARF_{c4} X RF_{c4} X LPF

where: MAR_{c4} = inventory radionuclides generated in solid materials based on total fission yield of 1E+20 fissions by computer code such as ORIGEN2; or,
= [1E+20 fissions/1E+19 fissions] X table[8].

DR_{c4} = Damage Ratio, assume all radionuclides generated at-risk.

ARF_{c4} = Airborne Release Fraction, if using values in Reg Guide as MAR, use values for ARF[9]. Unless substantial clad/package failure is postulated, only gaseous/volatile materials are assumed to be made airborne.

RF_{c4} = Respirable Fraction[10], assume 1.0 for all airborne materials.

LPF = LeakPath Factor for gaseous materials[12].

ATTACHMENT A

DEFENSE PROGRAMS NUCLEAR FACILITIES SAFETY SURVEY

AIRBORNE RELEASE FRACTIONS

Prepared by

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June 12, 1991

DP NUCLEAR FACILITIES SAFETY SURVEY

AIRBORNE RELEASE FRACTIONS (ARFs)

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June 12, 1991

DEFENSE PROGRAMS NUCLEAR FACILITIES SAFETY SURVEY AIRBORNE RELEASE FRACTIONS (ARFs)

INTRODUCTION

An Airborne Release Fraction (ARF) is a coefficient used to estimate the amount of a radioactive material that can be suspended in air and available for transport under a specific set of accident conditions. Radioactive materials are found in all physical forms (non-condensible gases, vapors, liquids and solids). ARFs for liquids and solids should be specified in terms of both a fraction (e.g. 0.01 = 1E-2 = 1%) and a size distribution [e.g. 0.5 (50%) 10 micrometers Aerodynamic Equivalent Diameter (AED) or 0.5 "respirable" fraction (RF). With an estimate of the Material-at-Risk (MAR) and Damage Ratio (DR), the ARF is used to estimate the IST (Instantaneous Source Term) - the amount of radioactive material at the point of origin available for transport to the building-environment interface (e.g. stack, breach in structure, open doorway). The estimates of ARFs applicable to various accident generated mechanisms for the suspension of radioactive materials is based upon experimental data for specific types and levels of stresses/force. Care must be used in applying the ARFs 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 the powder is released into flowing gas in a dispersed fashion. In most cases, extrapolations of the values to encompass levels well beyond those covered in the experiments are not valid.

AIRBORNE RELEASE FRACTIONS

A. NON-CONDENSIBLE GASES

Most radionuclides in the form of non-condensible gases are stored/held under pressure and physical constraints (e.g. tritium and noble gases in spent fuel held in the fuel matrix and cladding, cylinders of gases used in the laboratory). Non-condensible gases generated during nuclear criticalities are the exception. In either case, essentially all the gas is considered released upon the loss of gas-tight physical constraint. For very large containers (e.g. relatively gas-tight metal vessels) that are breached but maintain their physical integrity (e.g. compromised by loss of piping), the fraction of gas overpressure may be considered instantaneously released (e.g. for a gas initially at 2 atmospheres absolute/1 atmosphere gage, 5E-1 of the gas may be considered instantaneously released).

B. VAPORS (Condensible Gas)

Vapors (materials in gaseous form due to local conditions) may result from two phenomena - chemical reaction and temperature. Some vapors result from chemical reactions that

generate a volatile compound (e.g. halogens in a reducing, acidic environment). Many chemically volatile compounds are reactive and can be lost in transit by reaction with materials found along its path to the facility/environment interface. Under most conditions, the ARF assumed for vapors is 1.0. If the local conditions are not adequate for quantitative vaporization of all the material (e.g. inadequate chemical reactants, inadequate temperature), the ARF is the fraction of the material converted to vapor form. Loss for chemically reactive materials is difficult to quantify due to the uncertainty of the materials encountered along the pathway, the kinetics of these reactions, and the transport of the vapors to the surfaces. A "conservative" value is to assume all the material released is transported to the facility/environment interface without loss unless engineered emission control devices (e.g. for radioiodine - impregnated charcoal filters, silver substituted zeolite filters, silver nitrate coated ceramic saddles) are present for removal of the specific material.

For temperature-sensitive vapors (e.g. metal vapors generated at high temperatures, tritiated water vapors), the amount of material volatilized can be estimated by the amount of heat energy present and/or generated by the event. Similarly, condensation may also be calculated by heat transfer at the surfaces or by homo-or heterogenous condensation in air. Parenthetically, the mass flux of vapors to cool surface (diffusiophoresis) can be an effective mechanism to sweep small diameter (submicrometer) particles from the air.

C. LIQUIDS

In order for a liquid to be made airborne, the bulk liquid must be subdivided into particles/-droplets small enough to be entrained in the local airflow and be injected into the flow.

1. Aerodynamic Entrainment - liquids can be made airborne by the passage of air over its surface and the droplet formation by wave formation and capillary action of the liquid up the sides of the container. An indication of the ARF for this type of condition at very low velocities can be gained from the entrainment of plutonium solution in air at velocities from 10 to 100 cm/s passing over the surface (Mishima, Schwendiman and Radasch November 1968). The entrainment was from a very shallow pool (~2 to 4 mm) of limited diameter (~2.5 cm) using dense solution. Evaporation periods lasted from 2 h to 24 h with temperatures from ambient (~21 C) to 100 C. The fraction of plutonium entrained ranged from <2E-10 to 3E-5. For entrainment at ambient temperature with an evaporation period of 24 h, the ARF ranged from <2E-10 to 2.5E-9. The ARFs measured are listed in Table I (attached) from that document. Using an ARF of 1E-8 appear to be conservative for the range of conditions covered in the experiments (air velocity up to 100 cm/s, temperatures up to 100 C with quiescent heating not boiling). Based upon the low air velocities used in the experimental study and the size of the apparatus, all the airborne material is assumed to be in the respirable size fraction.

   Aerodynamic entrainment (resuspension) at higher air velocities for UNH (uranium nitrate hexahydrate) solution from various surfaces were measured in wind tunnel experiments (Mishima and Schwendiman August 1973). Measurements were made

TABLE I

FRACTIONAL RELEASE DURING AIR DRYING OF CONCENTRATED PLUTONIUM NITRATE SOLUTIONS

(Using 0.72g Plutonium as a source)

Run No.	Temp. (°C)	Air Velocity (cm/sec)	Sampling Time Evap. (hr)	Sampling Time Residue (hr)	Weight Percent Plutonium Found In: Containment Vessel Wash	Condensate + Wash	Sweep Air During Evaporation	Sweep Air Following Evaporation
01*	Ambient	10	24		0.0033	8.7×10^{-3}	$<10^{-7}$	--
02*	75	10	5	20	0.00027	9.5×10^{-8}	$<10^{-6}$	$<10^{-6}$
03	100	10	2	4	0.0046	1.7×10^{-6}	0.001	3×10^{-7}
04	Ambient	50	24	24	0.00035	4.5×10^{-7}	2.5×10^{-7}	1×10^{-7}
05	100	50	1-1/2	3	0.027	1.4×10^{-4}	0.003	6×10^{-7}
06	90	50	2	4-1/2	0.00051	5.4×10^{-6}	5.3×10^{-5}	1×10^{-6}
07	Ambient	100	24	24	0.020	7.5×10^{-8}	$<2 \times 10^{-8}$	$<2 \times 10^{-8}$
08	50	100	2	4	0.00045	9.4×10^{-6}	1.3×10^{-5}	$<2 \times 10^{-8}$
09	90	100	1-1/2	4	0.00013	9.4×10^{-5}	5.7×10^{-5}	3×10^{-6}

* 0.86 g plutonium used during these runs.

(Mishima, Schwendiman and Radasch November 1968)

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at velocities of 2.5 mph and 20-23 mph 1-ft above the smooth, sandy soil with and without vegetation, stainless steel, and road-like asphalt surfaces (see Table III from the reference, attached). The ARFs for 2.5 mph are only for soil and are bounded by a value of 6E-5/h. Use of the factor for short time frames (< 100 hours) would not introduce serious error due to the depletion of the source. For time period exceeding 100 hours, the reduction of the source must be accounted for from the entrainment of material. At 20 mph, the ARF from soil are bounded by a value of 8E-5/h. The size of the airborne material is considered to be 100% in the respirable size fraction.

2. Free-Fall Spill of Liquid (Sutter, Johnston and Mishima December 1981) - liquids spilled onto a hard, unyielding surface can be subdivided into drops by the instability/shear stress at the surface of the liquid during the fall and by impact upon striking the surface. Experiments have been performed to determine the airborne fraction from the free-fall spill of aqueous solutions with a density near 1.0 (uranine) and 1.7 g/cc (uranium nitrate hexahydrate, UNH). Material that may represent airborne material deposited on the walls were measured in some experiments. The fall distance was limited (less than 3 meters) and the initial dispersion of the material was uncontrolled (released by inverting a glass beaker holding the liquid). The ARFs for the uranine solution under these conditions ranged from 6E-6 to 1.6E-4 (Table A.2 from the reference, attached) and 1E-6 to 2E-5 for the UNH (Table A.4 attached). The fraction of the source airborne as particles 10 micrometers AED and less ranged from 2E-6 to 8.3E-5 for the uranine solution (Table B.2 attached) and 2E-7 to 1.3E-5 for UNH (Table B.4 attached). Both the fraction airborne and the fraction in the respirable size range appear to vary with fall distance and source size. A conservative value for the ARF for aqueous solution with a density near 1 would be 1E-4 with 0.5 in the respirable size range. For TRU solution with greater densities, an ARF of 2E-5 with 0.2 in the respirable size range appears to be conservative.

Experiment were also performed to measure the ARFs from the free-fall spill of viscous solutions and slurries (Ballinger and Hodgson December 1986). Figure 6 from that reference shows the ARF as a function of viscosity. For solutions that have a viscosity >8 centipoise, the ARFs are less than 6E-6 (Tables B.1 & B.2 from the reference, attached) with 0.9 of the airborne material in the respirable size fraction. For slurries with 25% to 51% solids and specific gravities ranging from 1.123 to 1.407, the ARFs are bounded by 5E-5 (Table B.3 attached) with 0.8 of the airborne material in the respirable size fraction (Table B.4 attached).

3. Venting of Pressurized Liquids,

   a. Depressurization of Free Volume Above Liquid Surface - sudden depressurization of aa liquid allows the release of dissolved/trapped gases. This sudden release of gases may result in the formation of bubbles that can form very small drops upon collapse. Figure 3.1 from Ballinger, Sutter and Hodgson (May 1987) illustrates the relationship between the amount of

TABLE II

URANIUM RESULTS -- ENGINEERING SCALE EXPERIMENTS

Uranium Form Used	Wind Speed	AERODYNAMIC ENTRAINMENT Expt. No.	Wt. Percent Source Airborne (hours sampled)	Less Than[1] 10 microns	PETROLEUM FIRE Expt. No.	Wt. Percent Source Airborne (hours sampled)	Less Than[1] 10 microns
Smooth Sandy Soil							
UO_2	low[2]	2	0.43 6 hrs.	56	3+	0.63 6 hrs.	5
		22a	0.042 24 hrs.	54	22b	0.048 1 hr.	72
		22c*	0.0092 24 hrs.	54			
	moderate[3]	1	2.3 24 hrs.	75			
		23a	24.4 24 hrs.	40	23b	0.34 0.3 hrs.	62
		23c*	1.0 24 hrs.	68			
Air Dried[4] UNH	low[2]	4b	0.0069 24 hrs.	74	5+	0.0074 5.5 hrs.	64
		8b	0.0054 24 hrs.	77	9+	0.004 5 hrs.	18
	moderate[3]	6b	0.93 24 hrs.	22	7+	0.12 7 hrs.	32
		26b*	1.1 24 hrs.	64			
UNH[5]	low[2]	4a	0.049 6 hrs.	76	10+	0.0017 5.5 hrs.	75
		8a	0.012 24 hrs.	84			
	moderate[3]	6a	0.039 20 hrs.	60	26a	0.54 0.13 hrs.	40
Vegetation							
UO_2	low[2]	11	0.046 24 hrs.	82	12+	0.014 6 hrs.	91
	moderate[3]	13	1.0 24 hrs.	40	14+	3.1 6 hrs.	19
UNH[5]	low[2]	--	-- --	--	16+	0.096 6 hrs.	78
	moderate[3]	--	-- --	--	15+	0.2 6 hrs.	86
Stainless Steel							
UO_2	low[2]	17b*	0.09 4.8 hrs.	83	17a	0.12 0.12 hrs.	66
	moderate[3]	25a	7.6 24 hrs.	14	25b	1.3 0.13 hrs.	7
		25c*	0.7 24 hrs.	42			
UNH[5]	low[2]	19b*	0.023 6 hrs.	76	19a	1.1 0.22 hrs.	40
	moderate[3]	18b*	2.6 5 hrs.	30	18a	11.4 0.17 hrs.	34
Road-Like Surface							
UO_2	low[2]	21b*	0.14 6 hrs.	62	21a	0.041 0.37 hrs.	70
UNH[5]	moderate[3]	20b*	0.063 5 hrs.	50	20a	0.24 0.20 hrs.	60

[1] Percent airborne less than 10 microns aerodynamic equivalent diameter.
[2] Approximately 2.5 mph.
[3] In range of 20 to 23.5 mph.
[4] Dried in flowing air at stated velocity for a minimum of 24 hours.
[5] Uranyl Nitrate Hexahydrate.
* Residue after gasoline fire.
\+ During and immediately following a gasoline fire.

(Mishima and Schwendiman August 1973)

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TABLE A.2. Airborne Releases of 10 g/ℓ Uranine Solution, Releases Resulting from a Free Fall Spill in Static Air

Run	Source Volume cc	Source Weight Uranine g	Spill Height m	Uranine Airborne g	Estimated Total Wall Deposition g	Percent Collected On Wall	Calculated Total Mass Airborne g	Weight Percent Mass Airborne
30	500	5	3	1.94×10^{-4}	ND		1.94×10^{-2}	0.0039
31				1.567×10^{-4}	1.55×10^{-4}	49.7	1.57×10^{-2}	0.0031
32				1.534×10^{-4}	6.79×10^{-5}	30.8	1.53×10^{-2}	0.0031
33				2.79×10^{-4}	4.58×10^{-4}	39.1	2.79×10^{-2}	0.0056
34				2.55×10^{-4}	3.02×10^{-4}	15.4	2.55×10^{-2}	0.0051
35				1.63×10^{-4}	2.41×10^{-4}	32.4	1.63×10^{-2}	0.0033
40[a]				2.04×10^{-4}	4.31×10^{-5}	17.4	2.04×10^{-2}	0.0041
41[a]				1.85×10^{-4}	7.35×10^{-6}	3.8	1.85×10^{-2}	0.0037
55	1000	10		1.270×10^{-3}	1.23×10^{-4}	9.7	1.27×10^{-1}	0.013
58	1000	10	1	3.037×10^{-4}	ND		3.0374×10^{-2}	0.003
59	1000	10	3	8.0237×10^{-4}	5.079×10^{-5}	6.0	8.0237×10^{-2}	0.008
60[b]	125	1.25	3	2.00×10^{-4}	ND		2.00×10^{-2}	0.016
61	500	5	1	2.913×10^{-5}	ND		2.913×10^{-3}	0.0004
62	125	1.25	1	7.7685×10^{-6}	ND		7.7685×10^{-4}	0.0006
63	125	1.25	3	4.147×10^{-5}	ND		4.147×10^{-3}	0.003

(a) Spill initiated by pulling stopper
(b) High release due to splashes
ND Not Detectable

(Sutter, Johnston and Mishima December 1981)

TABLE A.4. Airborne Releases of 208.7 g/ℓ Uranium Solution, Releases Resulting from a Free Fall in Static Air

Run	Source Volume, cc	Source Weight Uranium, g	Spill Height, m	Uranium Airborne, μg	Weight Percent Airborne	Total Mass Airborne[a], g
1	1000	208.7	3	2271.4	0.0011	1.85×10^{-2}
2	125	26.1	1	141.1	0.0005	1.15×10^{-3}
3	500	104.4	1	137.5	0.0001	1.12×10^{-3}
4	125	26.1	3	346	0.0013	2.82×10^{-3}
5	1000cc H_2O		3	22.7		
6	500	104.4	3	1067.6[b]	0.0013	1.12×10^{-2}
7	1000	208.7	1	223.2	0.0001	1.82×10^{-3}
8	125	26.1	3	514	0.0020	4.19×10^{-3}
9	500	104.4	1	161.5	0.0002	1.32×10^{-3}
10	1000cc H_2O		3	42.36		
11	125	26.1	1	43.4	0.0004	3.50×10^{-4}
12	1000	208.7	1	254.0	0.0001	2.07×10^{-3}
13	1000	208.7	3	2378.2	0.0011	1.94×10^{-2}
14	500	104.4	3	1412.5	0.0014	1.15×10^{-2}

(a) Calculated using solution density of 1.7 g/cc.
(b) Q2 dropped and contaminated. Collection estimated at 313 μg would raise the value to 1380.6. The weight percent airborne and total mass airborne were calculated using this value.

(Sutter, Johnston and Mishima December 1981)

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TABLE B.2. Median Aerodynamic Equivalent Diameter Particle Size Generated by a Free Fall Spill in Static Air, 10 g/ℓ Uranine Solution

Run	Source Volume, cc	Uranine Weight, g	Spill Height, m	Median Diameter, μm	σg	Percent of Collection 10 μm and Less	Weight Percent of Source Airborne 10 μm and Less
30	500	5	3	8.0	3.5	56	0.0022
31				11.0	2.8	44	0.0014
32				4.5	2.4	80	0.0025
33				4.8	2.6	82	0.0046
34				5.4	2.6	74	0.0038
35				4.8	3.0	70	0.0023
40				7.3	3.2	59	0.0024
41				6.8	3.1	64	0.0024
55	1000	10		11.5	3.1	45	0.0058
58	1000	10	1	8.6	4.1	53	0.0016
59	1000	10	3	10.0	2.6	50	0.0040
60	125	1.25	3	9.2	3.7	52	0.0083
61	500	5	1	6.0	2.1	62	0.0002
62	125	1.25	1	4.2	1.8	72	0.0004
63	125	1.25	3	7.2	3	63	0.0019

(Sutter, Johnston and Mishima December 1981)

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TABLE B.4. Median Aerodynamic Equivalent Diameter Particle Size Generated by a Free Fall Spill in Static Air, 208.7 g/ℓ Uranium Solution

Run	Source Volume, cc	Spill Height, m	Median Diameter, μm	σg	Percent 10 μm and Less	Weight Percent of Airborne 10 μm and Less
1	1000	3	34	4.1	21	0.0002
13	1000		32	3.6	19	0.0003
6	500		4.2[a]	2.2	99.4	0.0013
14	500		34	2.1	16	0.0002
4	125		20	7	36	0.0005
8	125		30	6	26	0.0005
7	1000	1	9.6	5	51	0.00005
12	1000		40	5.8	24	0.00002
3	500		2.3	1.9	85	0.00009
9	500		27	6.6	30	0.00006
2	125		3.2	2.3	62	0.0003
11	125		5.0	7.8	61	0.0002

(a) Collected in second half of run, so the size distribution is in smaller range, not used in analysis

(Sutter, Johnston and Mishima December 1981)

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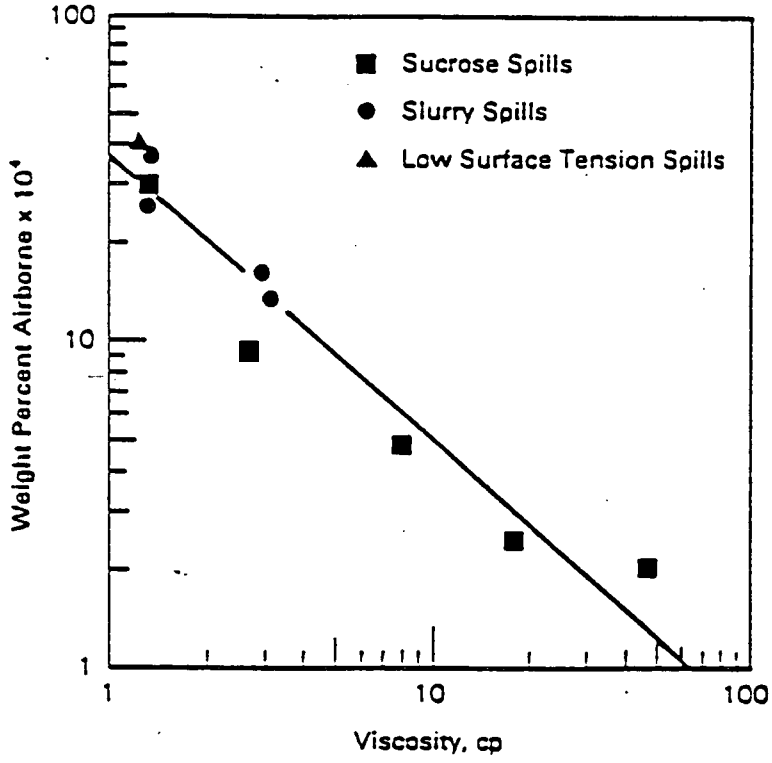

FIGURE 6. Weight Percent Airborne Versus Viscosity for Sucrose, Slurry, and Low Surface Tension Spills

(Ballinger and Hodgson December 1986)

APPENDIX B

EXPERIMENTAL DATA

TABLE B.1. Mass Airborne from Sucrose Solution Spills (source volume = 1 L, source height = 3 m)

Concentration, percent sucrose	Uranine Collected, mg	Total Solution Airborne, mg	Measured Weight Percent Airborne x 10^4
0	0.54	32.4	32.2
0	0.49	28.2	28.0
22	0.12	8.0	7.3
22	0.19	12.2	11.1
40	0.07	4.6	3.8
40	0.10	6.8	5.7
49	0.05	3.4	2.7
49	0.04	2.7	2.1
56	0.03	2.0	1.6
56	0.04	3.0	2.3

TABLE B.2. Size of Particles Produced by Sucrose Solution Spills

Concentration, percent sucrose	Aerodynamic Mass-Median Diameter, μm	σ_g	Percent <10 μm	Measured Weight Percent Airborne x 10^4 that is <10 μm
0	7.0	5.8	59	19.0
0	4.3	7.2	74	20.7
22	4.8	7.7	70	5.1
22	2.7	7.5	76	8.4
40	1.6	10.0	80	3.0
40	0.6	28.0	83	4.7
49	2.2	5.5	78	2.1
49	1.6	4.6	90	1.9
56	1.9	7.7	84	1.3
56	0.6	10.0	89	2.0

TABLE B.3. Mass Airborne from Slurry Spills (source volume = 1 L, height = 3 m)

Slurry Number	Uranine Collected, mg[a]	Total Solution Airborne, mg	Measured Weight Percent Airborne
1	0.15[a]	9.8	0.0009
2	0.20[a]	12.7	0.0011
3	0.14	10.9	0.0009
3	0.27	21.1	0.0018
4	0.85	61.4	0.0046
4	0.57	36.6	0.0027
5	0.41	32.2	0.0030
6	0.31	22.5	0.0016

(a) One of the filters dropped to the floor and became contaminated. Based on the other runs it was assumed that 23% of the total mass would have come from this filter.

TABLE B.4. Size of Particles Produced by Slurry Spills

Slurry Number	Aerodynamic Mass Median Diameter, μm	σ_g	Percent <10 μm	Measured Weight Percent Airborne x 10^4 that is <10 μm
1	2.3	8.0	73	0.0007
2	4.7	6.1	64	0.0007
3	2.1	7.1	77	0.0007
3	2.5	8.4	76	0.0014
4	3.0	3.8	78	0.0036
4	3.1	5.6	81	0.0022
5	2.6	7.8	78	0.0023
6	4.7	6.9	72	0.0012

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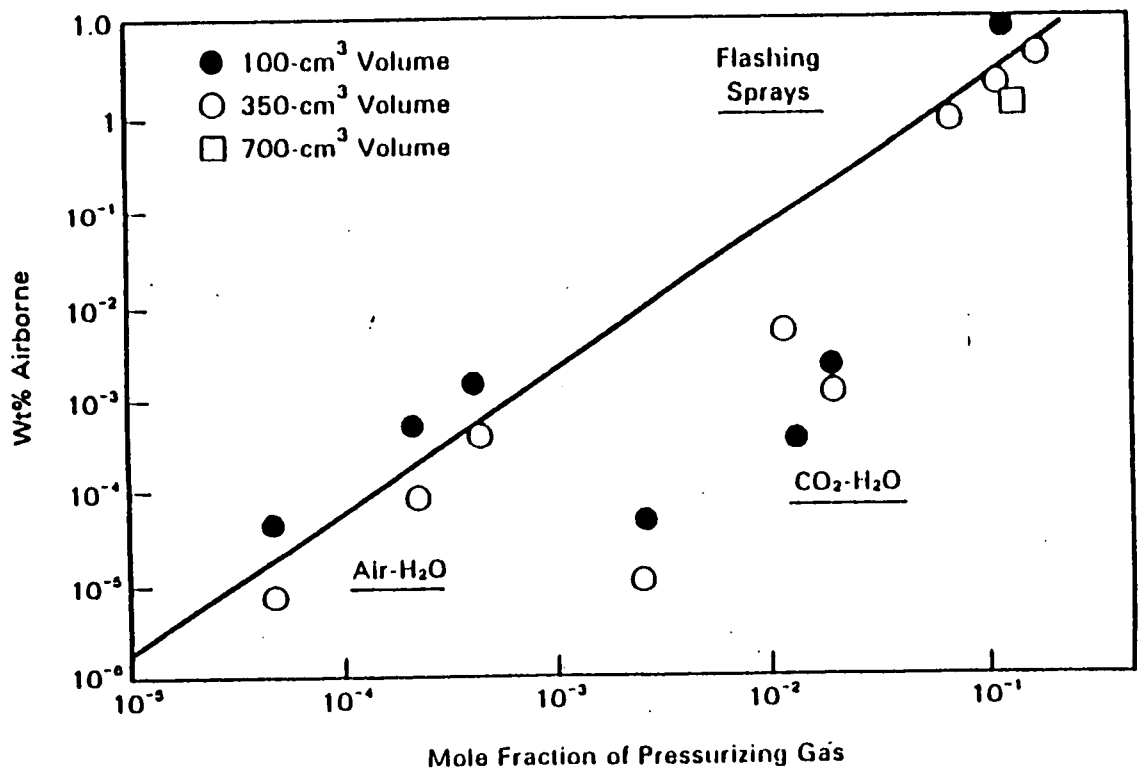

FIGURE 3.1. Weight Percent Airborne as a Function of Mole Fraction of Pressurizing Gas

(Ballinger, Sutter and Hodgson May 1987)

gas/vapor released and the fraction airborne. Experiments were performed to measure the ARF as a result of venting pressurized volumes of liquids (aqueous solutions)(Sutter August 1983). The average ARF as a function of pressure, solution density and source size are shown in Table 8 (tabulated as weight percent, 0.05 wt/o = 5E-4 fraction)(attached) from the reference and plotted in Figure 10. The ARF increases with pressure and decreases with density and source size. The size distribution for the various experiments are tabulated in Tables B.4 and B.5 in Appendix B (attached) from the reference. For the uranine solution (lower density liquid), the fraction of airborne material in the respirable size range was approximately 0.8. For the UNH (higher density liquid) the fraction of the airborne material in the respirable size fraction was approximately 0.6.

b. Depressurization via Breach Under the Liquid Surface (Spray)(Mishima, Schwendiman and Ayer October 1978) - if the container holding a pressurized liquid is breached, the liquid can escape in a variety of ways. For the purposes of airborne suspension, a conservative assumption would be the pressurized release of the liquid via a very fine hole as occurs in a commercial spray nozzle. The size distribution of some commercial spray nozzles as a function of orifice diameter and upstream pressure were shown in Figure 6 (attached) from Mishima, Schwendiman and Ayer (October 1978). It is not anticipated that drops formed from breaches, cracks, leaks would generate finer drop size distribution than equipment specifically designed for that purpose. The size distribution of the liquid drops decrease with orifice diameter and increasing upstream pressure. Using the fraction of droplets in the respirable size range generated by a device designed to generate fine liquid drops (spray nozzle) as the ARF (1E-4 with 100% of the airborne material in the respirable size range) appears to be a conservative value. For other size fractions, the values can be inferred from the 0.086-inch diameter spray nozzle values at 100 psig upstream pressure.

c. Venting of Super-Heated Solutions, "Flashing Spray" (Ballinger, Sutter and Hodgson, May 1967) - liquids heated above the boiling temperature of the liquid-solvent-diluent, flash (the jet of liquid released breaks up into fine droplets) upon release from the bulk vaporization of the liquid. Aqueous solutions were heated to pressures of 57 psig (~134 C), 124 psig (~161 C) and 240 psig (~202 C) using source volumes of 700 cu-cm, 350 cu-cm and 100 cu-cm. The liquid was released from the open top of the ~4-inch diameter apparatus via a double rupture disk arrangement. The fraction airborne increased with initial pressure and decreasing source size. The greatest ARF, 8.5 E-2, was measured at 124 psig using a 100 cu-cm source. Approximately 69% of the airborne material was in the respirable size fraction. The ARF and RF depend upon the amount of heat available and the heat needed to vaporize the solvent. The greater the fraction of solvent that can be flashed, the larger the ARF and RF. The ARFs and RFs measured are tabulated in Tables 3.6 and 3.7 (attached), respectively, from that reference.

TABLE 8. Average Weight Percent Airborne from Pressurized Liquid Release

Pressure, psig	350 cm^3 Source		100 cm^3 Source	
	Uranine	UNH	Uranine	UNH
500	0.05	0.025	0.15	0.08
250	0.01	0.01	0.06	0.05
50	0.0008	0.0004	0.005	0.002

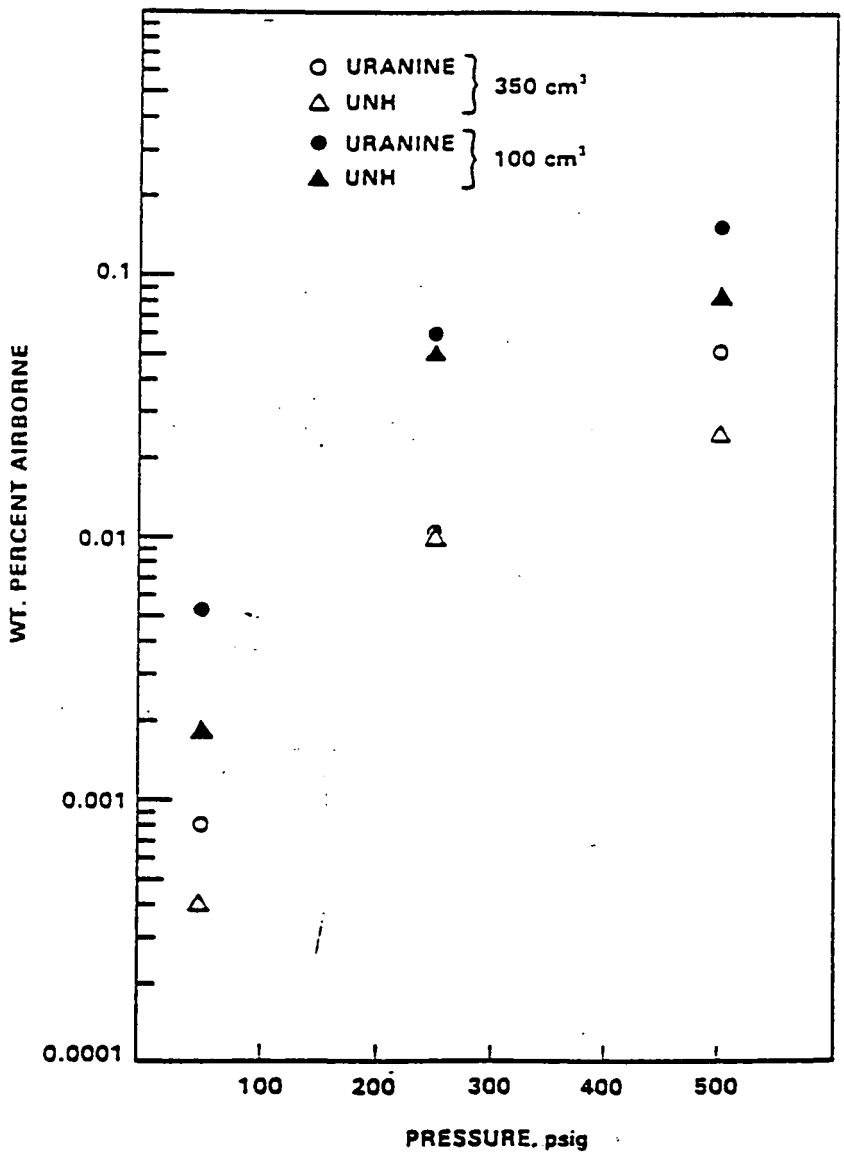

FIGURE 10. Average Weight Percent of Liquid Airborne as a Function of Pressure

(Sutter August 1983)

TABLE B.4. Median AED of Particles Produced by Pressurized Releases of Uranine Solutions

Source, cm^3	Rep.	Run	psig	Median Diameter, um	σ_g	% 10 µm and Less	wt% of Source that becomes Airborne 10 µm and Less
350	1	1	500	4	3	86	0.05
	2	13	500	4.3	2.4	85	0.03
	1	6	250	4	1.6	98	0.007
	2	14	250	3.6	3	84	0.01
	1	4	50	1.5	3	83	0.0003
	2	8	50	2.1	4	87	0.001
100	1	7	500	4	3	90	0.16
	2	12	500	4.0	4	70	0.08
	1	3	250	2.4	4	78	0.03
	2	9	250	4	3.6	77	0.05
	2	11	50	2.1	4	80	0.004

(Sutter August 1983)

000295

TABLE B.5. Median AED of Particles Produced by Pressurized Releases of UNH

Source, cm^3	Rep.	Run	psig	Median Diameter, µm	σg	% 10 µm and Less	wt% of source that Becomes Airborne 10 µm and Less
350	1	1	500	17	4.0	34	0.0074
	2	8		14	2.9	37	0.0103
	1	5	250	45	5.9	20	0.0018
	2	10		12	2.9	45	0.0040
	1	4	50	3	4.8	76	0.0002
	2	12		5	5.2	70	0.0003
100	1	6	500	14	2.5	46	0.0314
	2	9		14	2.9	38	0.0362
	1	3	250	14	2.7	36	0.0160
	2	11		11	4.6	45	0.0264
	1	2	50	6	7.5	61	0.0010
	2	13		8	4.6	60	0.0011

(Sutter August 1983)

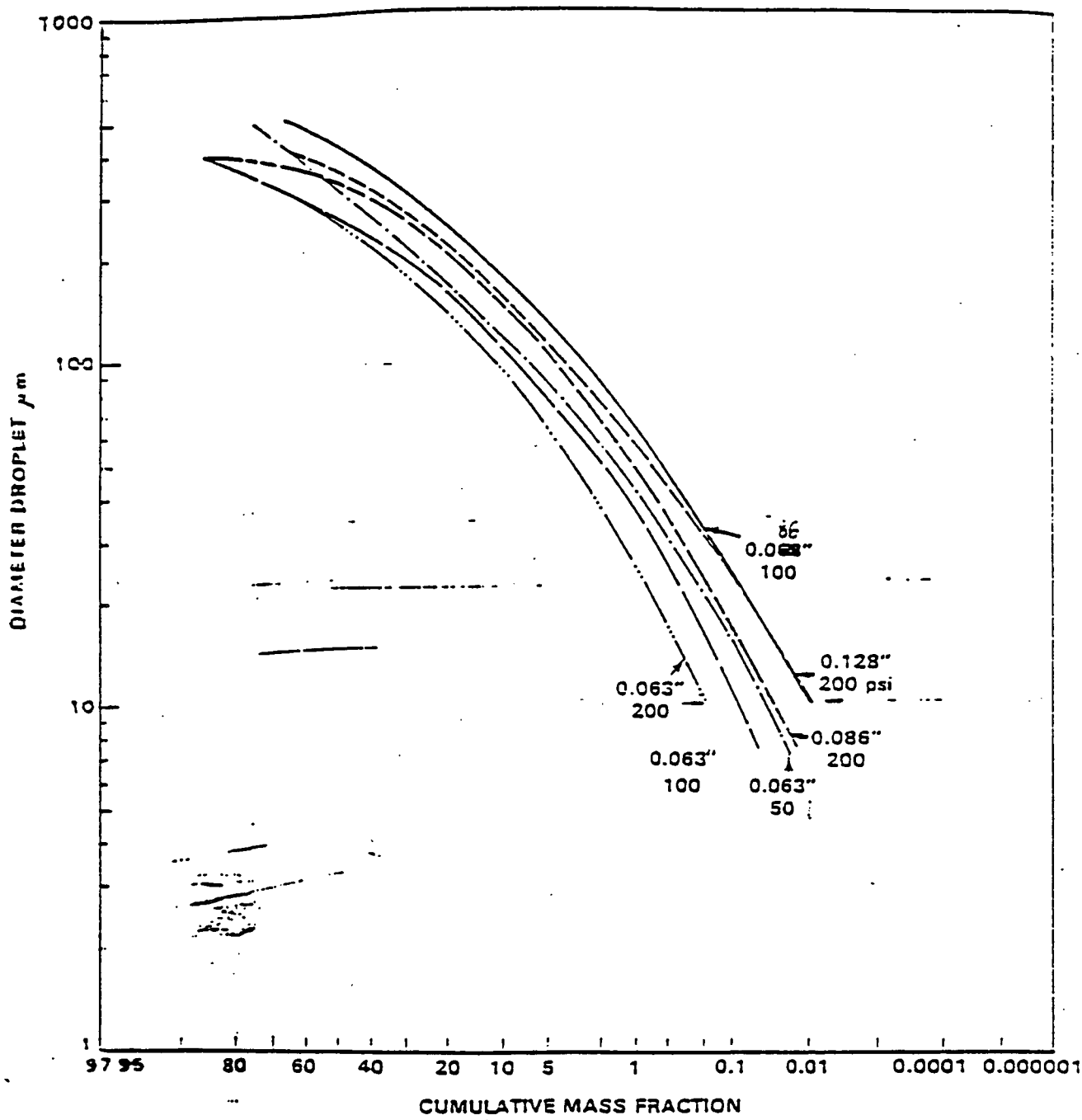

FIGURE 6. Mass Fraction vs Droplet Diameters for Sprays as a Function of Orifice Diameter and Upstream Pressure

(Mishima, Schwendiman and Ayer October 1978)

TABLE 3.6. Weight Percent Uranine Airborne from Flashing-Spray Releases

Chamber Pressure, psig	700-cm^3 Source	350-cm^3 Source	100-cm^3 Source
240		4.96	
124	1.51	2.22	8.51
57		0.89	

TABLE 3.7. Median AED of Particles Generated by Flashing-Spray Releases

Chamber Pressure, psig	700-cm^3 Source		350-cm^3 Source		100-m^3 Source	
	AMMβ μm	σ_g	Ammβ μm	σ_g	Ammβ μm	σ_g
240			6.25	2.7		
124	5.9	2.6	7.7	2.7	6.4	3.3
57			8.4	5.6		

(Ballinger, Sutter and Hodgson May 1987)

002299

FRACTIONAL AIRBORNE RELEASE OF SELECTED ISOTOPES IN 30 PERCENT n-TRIBUTYL PHOSPHATE IN A KEROSINE-TYPE DILUENT DURING COMBUSTION

Element	Percent Of Source Airborne[1]			
	Self Sustaining Burning Up To The Point of Spontaneous Extinguishment[2]		Self-Sustaining Burning But Heat Added With A Propane Torch In A Later Stage, Taken To Dryness	
	1 cfm	2 cfm	1 cfm	2 cfm
Uranium (∿ 270 g/l)	0.027%	0.023%		0.3 %
Cesium (∿ 0.2 ppm)	0.22 %	0.25 %	0.19 %	1.0 %*
Cerium (∿ 0.2 ppm)	0.74 %	0.56 %	0.77 %	0.71%*
Zirconium (∿ 0.2 ppm)	0.65 %*	ND	0.55 %*	0.24%*
Iodine (∿ 0.2 ppm)	65.7 %*	65.3 %*	81.7 %*	84.3 %* 82.8 %* 83.3 %*

[1] Activity measured in all samples except residue.

[2] Experiment ended when flame self-extinguished. Usually 5 to 10 ml of liquid remained.

* Percent of total activity collected.

ND Not Detectable

(Mishima December 1965)

nitric acid resulted in surface disturbance. The ARF for uranium dissolved in the combustible liquid increased with uranium concentration ranging from 2E-3 to 3E-2. All the airborne radionuclides appeared to be in the respirable size fraction. An additional 6E-2 fraction could be made airborne if the liquid were evaporated to dryness (difficult with TBP).

SOLIDS, Bulk

1. Aerodynamic Entrainment (Resuspension) - aerodynamic entrainment from a coherent, bulk solid would be limited to the surface dust unless the solid is eroded by the airflow. The phenomena would be similar to suspension of a powder from a hard, unyielding surface. For large pieces that project beyond the boundary layer, entrainment due to "wake effect" may be a significant process. No experimental data for the resuspension/aerodynamic entrainment from a coherent monolith of material have been reported. Appears would depend upon the characteristics of the material and conditions (e.g. iron surface will rust with time and environment and the rust particles may be entrained by air blowing over the surface). It is assumed for the purposes of analysis that no significant airborne release occurs unless experimental data is available to quantify the ARF/RF for the phenomenum.

2. Crush-Impact, Fragmentation by Brittle Fracture - brittle materials (e.g. glass, aggregate) can be fragmented when impacted or crushed. Jardine et al. (1982) performed experiments to measure the fraction and size distribution generated by the impact of various materials resting on a unyielding surface. The degree of fragmentation and the size distribution are a function of the material, the strength/age of the material, and the energy input per volume (Mecham et als. October 1981). The fraction in the size range 10 micrometers AED and less was empirically correlated with the energy input (J/cu-cm) in subsect. 5.1.3, Appendix F in Vol. 4 of SAND (September 1987) as:

$$PULV = A\ P\ gh$$

where: PULV = fraction pulverized into 10 Micrometer and less size range P gh
A = empirical correlation, 2E-4 cu-cm/J (J = g-cm/s)
P = specimen density, g/cu-cm
g = gravitational acceleration, ~960 cm/s2 at sea level
h = height, cm

Use of this correlation to estimate the RF and the very conservative assumption that all the RF is made airborne by the impact is recommended.

3. Subdivision by Oxidation, Metal with Self-Sustaining Reactions - many metals generate heat from the oxidation reaction. Metal that attain a self sustaining reaction at ambient temperature are called pyrophoric. Some nuclear metal (uranium, plutonium) can achieve a self-sustaining reaction at elevated temperature

4. Explosive Dispersion of Aqueous Solutions (Ayer et als. May 1988) - Steindler and Seefeldt provide an empirical correlation to experimental data on the fragmentation of metals and aqueous solution by detonations [energy releases in microseconds with brisance(shattering effect)]. The experiments covered mass ratios (mass of inert shattered to TNT Eq.) of 1 to 10 and probably should not be applied to ratios greater than 50. The experiments were conducted with the condensed phase explosive embedded or contiguous to the material affected. Estimates of the ARF and size distribution for various mass ratios up to 1000 are provided in Appendix C of Ayer et al. (May 1988) for a SGD (Standard Geometric Deviation, the slope of the line on log probability plot) of 8. The SGD is much greater than normally assumed (SGD 2) and provide greater fractions in the larger size ranges (an unconservative assumption for the assessment of radiological impacts). The fractions in various size ranges and the total fraction aiborne for MR 1-50 for a SGD of 2 are tabulated in Appendix B using the computer code DETIN.

5. Combustion of Contaminated Combustible Liquids - radionuclides are present in combustible liquids during liquid-liquid extraction processes and during decontamination procedures. In some cases, the radionuclides can be in an aqueous solution under a burning organic layer. The combustion of a liquid is a heterogenous reaction - heat from the flame radiates back to the liquid surface resulting in the evaporation of more fuel vapor that entrains air until a combustible mixture is attained and is ignited. The suspension of non-volatile materials appears to result from formation of drops of the bulk liquid. If the conditions are such that the surface film of the liquid is minimally disturbed, very little of the non-volatile components will be suspended from the bulk liquid. As the surface of the liquid is disturbed by turbulence of the vapor generation, the capillary action at the edge of the liquid, and the evolution of water vapors from the aqueous solution trapped beneath the organic layer, the suspension of non-volatile components increases. If the evolution of water vapors is very rapid, a large volume of the aqueous layer may be ejected and quench the fire. Combustion is quenched when the oxygen concentration diminishes to 17.5% to 11% (generally flaming combustion ceases at oxygen concentrations of approximately 16%)(Malet et al 1983, Jordan and Lindner 1982 & 1983).

For quiescent fire (relatively undisturbed liquid surfaces), the ARFs measured by Mishima (1973) for the combustion of 30% TBP in a kerosine-type diluent are applicable: non-volatiles 1E-2; volatiles 1.0. The measured values are tabulated in a table (attached) from that document. All the airborne material is in the respirable fraction although the volatile (generally iodine but may include other halogens, ruthenium and possibly some cesium compounds) may condense on pre-existing airborne particles and behave like the host particle thereafter. The effect can not be readily characterized and the conservative assumption is that all the material is respirable.

Jordan and Lindner (1982 & 1983) performed large scale burning experiments using TBP-kerosine mixtures with and without an aqueous phase. The decomposition of

dependent upon surface to volume ratio and heat transfer condition. The matrix spacing for the some oxides is sufficiently different than the metal phase spacing that the oxide is non-adherent and can be made airborne in the convection currents from the metal/oxide surface. Carter and Stewart (1970) surveyed experiments to determine the ARF for plutonium under fast reactor processing conditions. Table IV (attached) from that reference lists the geometric mean and 95% confidence values for various degrees of disturbance at the surface of the material. For the ARF for oxidation after ignition (includes melting) of plutonium metal, the mean ARF is 7E-6 with a 95% confidence value of 1E-4. These are in agreement with ARFs measured by Mishima (Table III, December 1965 and Table I & Fig 5 November 1966 attached) for the airborne releases during the oxidation after ignition of small, cylindrical pieces (3E-6 to 5E-5) where the convective flow is small due to the lesser heat generation and during the oxidation after ignition of large pieces (4E-6 to 5E-4). The values in Table IV Carter and Stewart (1970) correspond to the geometric mean value and 95% confidence value. Therefore, it is recommended that for small individual pieces oxidizing in still air (apparently less disturbance at the surface) an ARF of 1E-5 be assumed with 100% of the airborne material in the respirable size range. For situations involving the self-sustained oxidation of larger metal pieces (> 100 g) or the self-sustained oxidation in turbulent atmosphere (effect of other burning material at same location), an ARF of 1E-4 to 5E-4 with 0.3 of the airborne material in the respirable size range. This value also is in agreement with the ARF (5E-4) recommended from experiments involving 200 g of plutonium metal suspend over a gasoline fire (Mishima 1964). For molten plutonium metal drops falling 0.75 m or less or molten metal with some disturbance, and ARF of 1E-2 is recommended with 0.01 in the respirable size range (Carter and Stewart). The fraction in the respirable size range for the two situations generating the highest ARFs (partial disruption of molten Pu into droplets and vapor formation from droplets/exploding wire dispersal) are shown in Table II from Carter and Stewart (1970) indicate RF of 0.004 and 0.03. All the above are only applied during the oxidation of the metal. Suspension after oxidation from the pile of oxide is covered below.

Similar values for uranium metal are also found in Carter and Stewart (1970).

4. Explosion, Metal - Materials can react explosively from internally generated stress (e.g. rapid heating, chemical reactions in composite/aggregate materials). Carter and Stewart (1970) experimentally determined the ARF by an exploding wire technique for plutonium. An ARF of 5E-1 is reported with 3% of the airborne material in the respirable size range (see Tables II and IV from that reference).

Steindler and Seefeldt (1980) provided an empirical correlation to experimental data for the fragmentation of metals surrounding a detonation. The ratio of the mass of the explosive material, as Equivalent (mass) of TNT, to the mass of the inert materials absorbing energy is the Mass Ratio (MR) and the fragmentation of a metal was discussed in subsect. C.4 above. The correlation covers a MR of 1-10 and can probably be extended to an MR of 50.

TABLE II. COMPARISON BETWEEN EXPLODING WIRE AEROSOL AND DROPLET FUME IN LIQUID SUSPENSION

PuO_2 size in nm	Exploding wire dispersed in water: (1)	Droplet fume dispersed in acetone: (1) (2)
< 300	0·95	0·90
< 100	0·49	0·47
< 30	0·02	0·12
< 10	0·004	0·03
< 5	0·003	0·02

Notes: (1) Fraction Pu in suspension by centrifuge.
(2) Fume from droplets at 600 °C.

TABLE IV. SUMMARY OF SOURCE FRACTIONS INVOLVED IN AEROSOL FORMATION

	Fraction of source released as aerosol < 10 μm unit density	
	Plutonium	Uranium
Ignition and burning in air	7×10^{-6} (a) 1×10^{-4} (b)	$1 \cdot 1 \times 10^{-4}$ (a) $3 \cdot 6 \times 10^{-4}$ (b)
Melting	7×10^{-6} (a) 1×10^{-4} (b)	(1)
Partial Disruption of liquid into droplets (2)	$3 \cdot 5 \times 10^{-3}$ (a) 1×10^{-2} (b)	$1 \cdot 9 \times 10^{-3}$ (a) 6×10^{-3} (b)
Vapour formation from droplets	About 0·5	

Notes: (a) Geometric mean. (b) 95% confidence limit.
(1) Massive U does not melt after ignition unless there is an external heat supply. Heat losses cause self extinguishing unless some form of insulation (oxide) is present.
(2) Height of fall approximately 0·75 m.

(Carter and Stewart 1970)

TABLE III

FRACTIONAL RELEASE FROM UNALLOYED PLUTONIUM RODS DURING OXIDATION AND COOLING

Run		Time (Min)	Temperature Range (°C)	Air Velocity (cm/sec)	Airborne w/o	Cumulative w/o
A	Oxidation & Cooling	155	Ambient-900	3.3	2.8×10^{-6}	2.8×10^{-6}
B	Oxidation & Cooling	74	Ambient-560	13.5	3.1×10^{-5}	3.1×10^{-5}
C	Oxidation	46	Ambient-650	50	3.8×10^{-5}	
	Cooling	29	Ambient-610	50	1.5×10^{-5}	5.3×10^{-5}
D	Oxidation & Cooling	146	Ambient-650	3.3	4.1×10^{-6}	4.1×10^{-6}
E	Oxidation	73	Ambient-560	3.3	7.8×10^{-6}	
	Cooling	80	Ambient-550	3.3	1.8×10^{-5}	2.6×10^{-5}
F	Oxidation	77	Ambient-560	20	2.6×10^{-6}	
	Cooling	40	Ambient-540	20	5.2×10^{-7}	3.1×10^{-6}

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PLUTONIUM RELEASED DURING THE OXIDATION OF LARGE METAL PIECES ABOVE IGNITION TEMPERATURES

Run No.	Weight Plutonium (grams)	Weight Pu Released (grams)	Weight % Plutonium Released	Total Time Sampled (min)	Release Rate (w/o hr)
1	569.8	0.268	4.9×10^{-2}	90	3.2×10^{-2}
2	1770	0.257	1.4×10^{-2}	45	1.9×10^{-2}
3	997	0.034	3.4×10^{-3}	22	4.5×10^{-3}
4	455.5	0.00132	3.9×10^{-4}	60	2.9×10^{-4}

(Mishima November 1966)

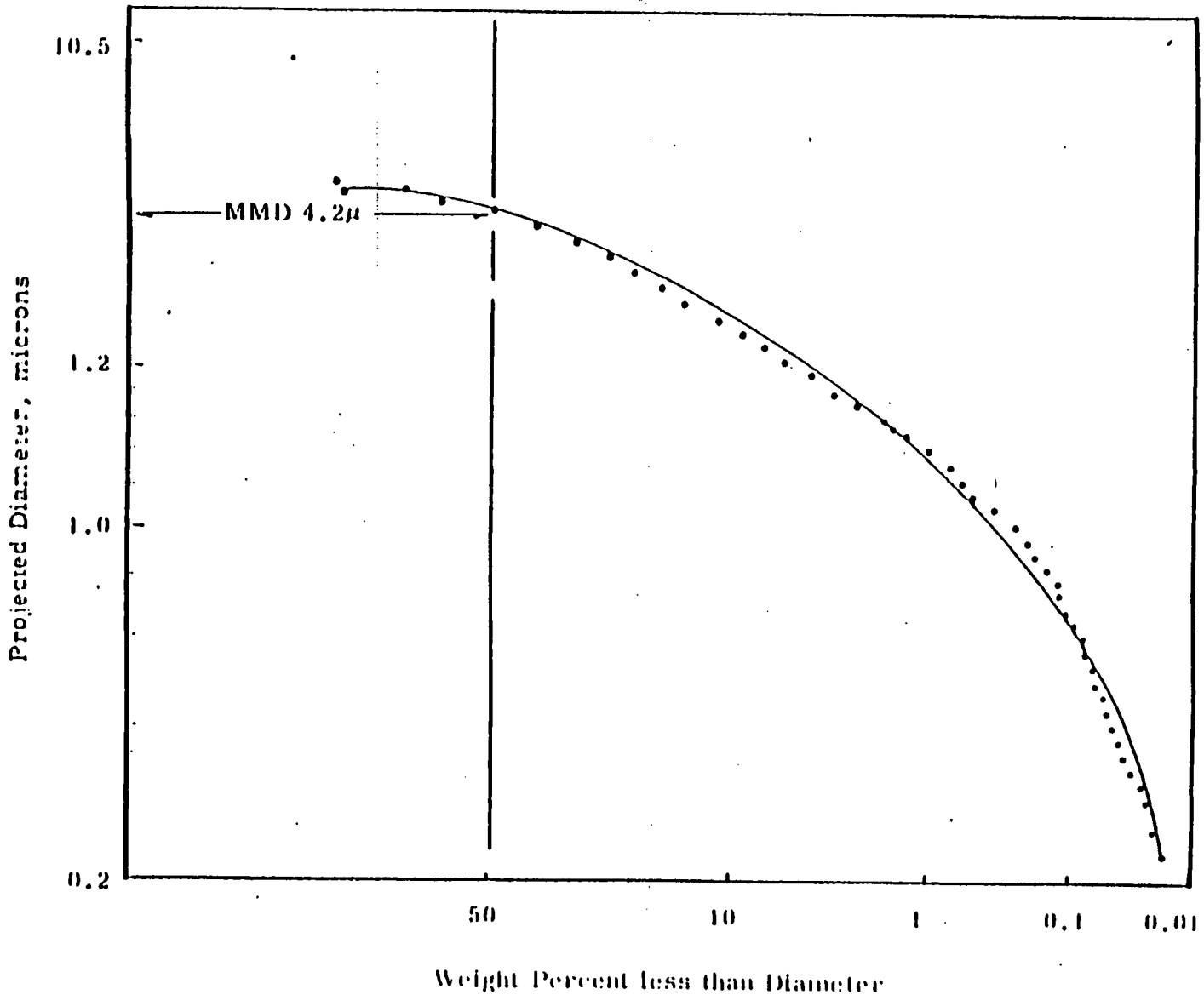

FIGURE 5
Particle Size Distribution by Weight of Oxide Entrained in Run 2

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5. Burning of Contaminated. Combustible Solids - Contaminants on solid, combustible materials can be suspended by the destruction of the substrate during the formation of pyrolyzates or smoldering combustion and entrained in the vapor flow/convective currents generated. Various experimental studies have been performed to measure the ARF during the burning of contaminated solid materials (Mishima and Schwendiman October 1970, June 1973; Halverson, Ballinger and Dennis March 1987). Most of the experimental configurations exposed the burning contaminated materials directly to flowing air (see Table II & III from Mishima & Schwendiman October 1970, attached). In one study (Mishima and Schwendiman April 1973), a mixture (uranium dioxide powder + UNH on cellulosics, rubber and plastic) wrapped in plastic in a sealed cardboard carton were burned to self-extinguishment (see Table II Mishima & Schwendiman April 1973, attached). Neither represents well the current packaging for TRU waste (55-gal metal drums with plastic liners).

For packaged mixtures of combustible material with uranium dioxide powder, UN and air-dried UNH burned in static air to self-extinguishment, the ARFs (including an fraction found deposited on the walls) ranged from 3E-5 to 2E-3. ARFs based solely on airborne concentration ranged from 3E-5 to 5.3E-4. No estimate were given for the fraction in the respirable size range. The ARFs measured are listed in Table II from Mishima and Schwendiman (April 1973) attached.

At low air velocities (< 100 cm/s) not directly impacting the burning material, the ARFs measured for Pu nitrate dried on wood, cellulosics and rubber ranged from 1E-4 to 1E-2 with no indication of the respirable fraction. In studies to define the ARF for specific combustible materials using uranium dioxide powder and UNH, air was passed directly through the burning mass (> 100 cm/s) and an ARF for uranium dioxide powder ranged from 1.6E-2 to 3.8E-1 with no RF reported. ARFs for uranium dioxide powder and UNH liquid from burning of specific materials has been measured (see Fig 2 Halverson, Ballinger and Dennis, March 1987, attached). From a mixture of combustibles materials, ARFs ranging from 4E-4 to 9E-4 were measured. The values are in agreement with earlier values for burning of mixtures in a cardboard carton to self-extinguishment, 3E-5 to 5E-4. A bounding value of 1E-3 is recommended for burning in self-induced convective flow or at low (< 100 cm/s) air velocities. No estimates for RF are available and a conservative value of 100% is assumed. ARFs/RFs from burning poly methylmethacrylate ranged from 7E-3/0.83 to 5E-2/0.95. The ARF/RF for burning polystyrene were 2E-3 to 8E-3/0.90; for burning polychloropene were 4E-3 to E-2/0.16; and for burning cellulosics 7E-5 to 3E-3/0.40 to 0.47. The recommended bounding values are listed in the summary table at the end of this document.

6. HEPA Filters

a. Release of Collected Contamination During Failure by Crush-Impact, Enclosed: the contamination collected in the HEPA filter is assumed to be in the form of fines sufficiently small in diameter to be airborne. The filters on the glovebox impacted by debris are postulated to be broken by the shock

TABLE II

FRACTIONAL RELEASE DURING BURNING OF FLAMMABLE MATERIALS CONTAINING PLUTONIUM NITRATE

Initial Activity dpm	Flammable Material Used	Duration Of Flame min.	Max. Flame Temperature °C	Percent Collection Filter
4.47×10^5	3 grams Coarse Fir Shavings	1.7	430	0.83
	10 grams Corrugated Cardboard	12	450	1.0
	5 grams Rubber -- Surgeon's Gloves	7	600	0.07
	5 grams Rubber -- Surgeon's Gloves	9	460	0.19
9.10×10^6	3 grams Coarse Fir Shavings	1.2	450	0.41
	10 grams Corrugated Cardboard	6.2	480	0.05
	3 grams Rubber + 3 grams Corrugated Cardboard	3.7	480	0.08
	5 grams Rubber -- Surgeon's Gloves	6.2	430	0.62
	5 grams Cheesecloth	6.2	520	0.43
	10 grams Corrugated Cardboard	6.2	585	0.12
	5 grams Cheesecloth	6.7	525	0.52
	3 grams Coarse Fir Shavings	3.7	500	1.0
	5 grams Rubber -- Surgeon's Gloves	5	610	0.02
	5 grams Rubber -- Surgeon's Gloves	7.2	675	0.08
	3 grams Coarse Fir Shavings -- on bed of sand	3	400	<0.01
	1/2" diam. Fir Plug -- on bed of sand	5.2	420	0.07

(Mishima and Schwendiman October 1970)

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FRACTIONAL RELEASE DURING BURNING OF COMBUSTIBLE MATERIAL CONTAINING URANIUM COMPOUNDS

(Area of Pyrex combustion chamber 57 cm^2, 3" OUT × 30" long, aluminum chimney, particles collected on 4" diameter glass fiber filters.)

Combustible Material Used	Uranium Compound Used	Duration Of Flame (min)	Nominal* Velocity Chamber (cm/sec)	Percent Uranium Entrained	Percent Uranium Carried To Filter
10 grams Tissue Paper (Kleenex)	0.32 gram U as Dioxide†	3.7	104	40	34
	0.24 gram U as Dioxide†	6	46	36	33
	0.29 gram U as Nitrate††	2.5	104	14	0
	0.11 gram U as Dioxide†	3.5	104	55	30
10 grams Cheesecloth	0.12 gram U as Dioxide†	2	104	35	20
	0.37 gram U as Dioxide†	2.1	104	44	35
	2.92 gram U as Nitrate††	7.7	104	0.4	0.2
	3.63 gram U as Dioxide†	1.7	104	37	33
	1.33 gram U as Dioxide†	3.2	46	10	7
	0.29 gram U as Nitrate††	2.5	46	1.4	3.4×10^{-4}
	0.29 gram U as Nitrate††	3.1	104	0.7	0.05
10 grams Corrugated Cardboard	0.17 gram U as Dioxide†	2.6	46	20	12
	0.76 gram U as Dioxide†	3.5	104	0.3	0.0
	0.29 gram U as Nitrate††	13	104	1.4	1.3
	2.92 gram U as Nitrate•	7	104	1.1	0.2
	2.42 gram U as Nitrate•	7	46	0.2	0.1
	2.42 gram U as Nitrate•	2.9	104	0.1	0.1
	1.31 gram U as Dioxide†	2.0	46	2.4	1.6
	0.26 gram U as Dioxide†	1.7	104	12	12
Combined Waste**	4.02 gram U as Nitrate††	--	104	1.0	0.0
	2.30 gram U as Dioxide†	6.4	104	17.6	9.0
	4.02 gram U as Nitrate††	4.6	46	0.1	5.4×10^{-4}
	1.22 gram U as Dioxide†	4.2	46	12.5	6.4

* Volume airflow through chamber ÷ cross sectional area.

** 5 grams cheesecloth + 3 grams tissue paper in polyethylene bag sealed in 2" × 2" × 3" corrugated cardboard box with masking tape.

† As powder.

†† As UNH solution.

• Air dried.

(Mishima and Schwendiman October 1970)

000309

TABLE II

FRACTIONAL AIRBORNE RELEASES OF URANIUM DURING THE BURNING OF CONTAMINATED WASTE

Experiment No.	Uranium Compound Used	Weight Uranium Used (grams)	Waste Config.	Fractional Airborne Release (% of Uranium Used As Source)		Percent Uranium Recovered	Percent Uranium Recovered In			
				Max. Airborne Concentration	Wall Deposition		Residue	Floor	Walls	Airborne
FW-1	UO_2	9.1	1	0.053	0.040	70	98.2	1.7	0.06	0.07
FW-2	a.d.UNH	25.5	1	0.003	0.045	80	99.9	0.06	0.008	0.003
FW-3	UNH	25.5	2	0.0083	0.011	85	99.5	0.46	0.013	0.01
FW-4	UNH	25.5	1	0.0047	0.11	177	99.9	0.01	0.06	0.003
FW-5	UO_2	64.1	2	0.017	0.23	69	98.6	0.9	0.5	0.02
FW-6	UO_2/UNH	51	2	0.0041	0.0033	89	99.9	0.08	0.004	0.005
FW-7	UNH	25.5	2	0.0030	0.0094	85	99.9	0.1	0.01	0.004
FW-8	UO_2	50.2	3	0.0052	0.010	74	99.3	0.7	0.01	0.007
FW-9	a.d.UNH	25.5	3	0.015	0.016	65	99.9	0.07	0.03	0.06
FW-10	UNH	51	3	0.015	0.0029	66	99.7	0.3	0.004	0.02
FW-11	UO_2	51.6	2	0.015	0.024	91	99.4	0.5	0.03	0.008
						$\bar{x}$ 97				

UNH -- Uranyl nitrate hexahydrate solution

a.d.UNH -- Air dried following addition to waste as UNH solution.

(Mishima and Schwendiman April 1973)

000310

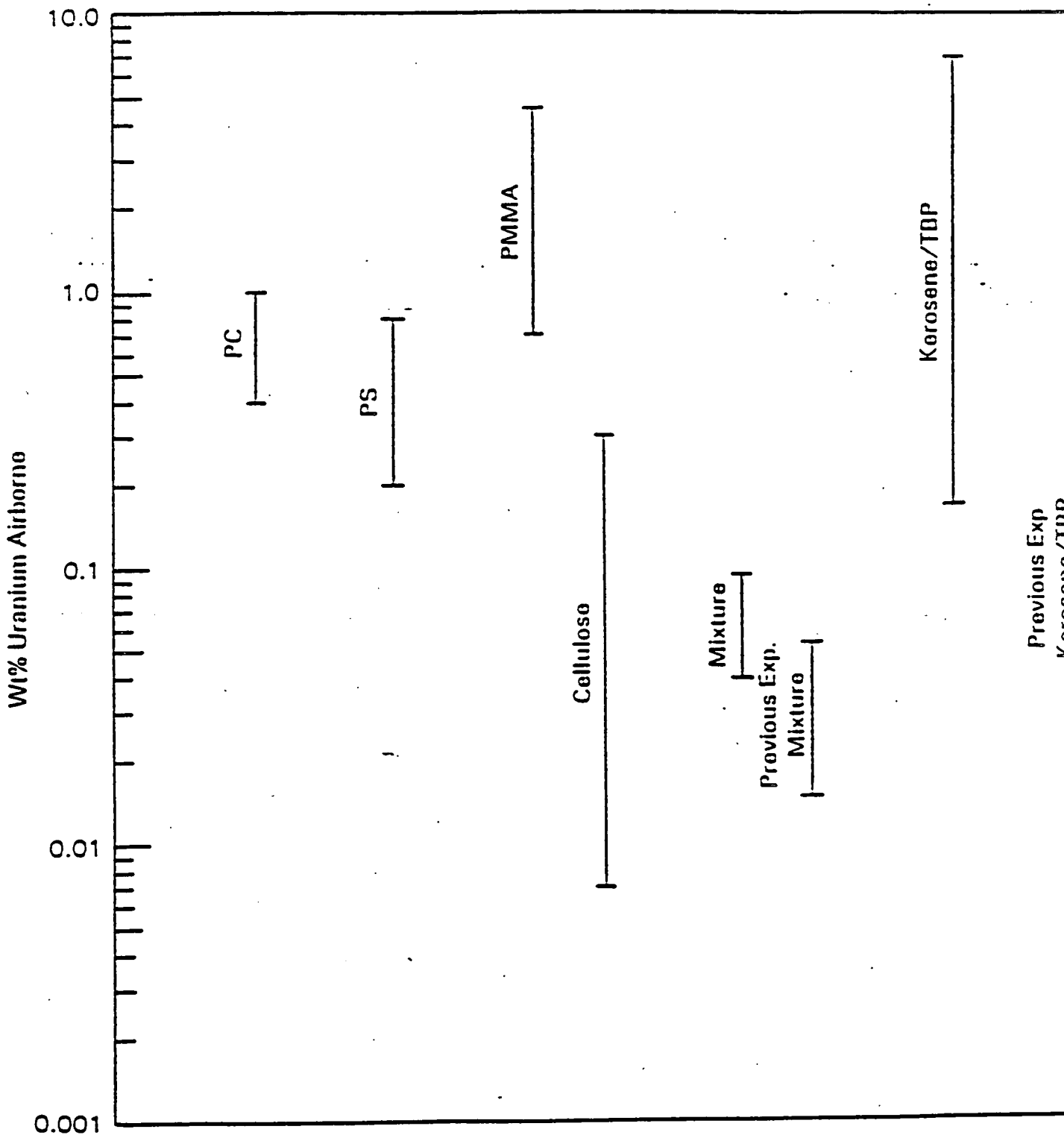

FIGURE 2. Results from Burning Contaminated Combustibles

(Halverson, Ballinger and Dennis March 1973)

from the impact massive materials (e.g. structural fragments, equipment) upon the filter enclosure.

Test to measure the amount of particulates from the handling of spent filter were performed at Rocky Flats Plant (Arnold 1986). Plastic wrapped glovebox filters of two sizes (8" X 8" X 3" and 8" X 8" X 6") were propelled 3-ft to a unyielding surface at least ten times. The particulate material generated by the impacts were collected and classified into fractions as required by storage facility criteria (<200 micrometers and < 10 micrometers in diameters). Three of four batches of filter contained appreciable quantities of Pu with the fourth measured at 1 g Pu in four filters. The values for < 10 micrometers diameter material generated ranged from 0 to 0.0018 wt/o (0 to 1.8E-5 fractions) based upon total waste matrix (filter) weight. The composition of the particles (e.g. Pu oxide, inert dust, glass fiber fragments) were not defined. The mass of particulate ranged from 0 to 35 g for individual filters with 63% (12 of 19) of the filters releasing no measurable quantity of particles. Thus, it does not appear that shock generates many particles in the respirable size fraction. If the mass of all the particles 10 micrometer in diameter and less are considered Pu oxide only, the mass would only represent 2.8E-3 fraction of the total Pu oxide mass present. On this basis, an ARF of 3E-3 with 100% of the material in the respirable fraction for the glovebox filter would certainly bound the release.

b. Release of Contamination by Failure of HEPA Filter by Crush-Impact, Unenclosed: the airborne release from catastrophic failure of uncontained-HEPA filter crushed are assumed similar to those for the crushing of HEPA filters described in Arnold (1986). The fraction of materials in various size fraction generated (fragments of media and collected materials) ranged from 5E-5 to 7E-2 for particles 212 micrometers LLD (Least Linear diameter, sieve) and 0 to 1.3E-3 for particles < 10 micrometers PD (Projected Diameter). A reasonably conservative average value for the material that could be airborne from the crushing of HEPA filter is ARF 1E-2/RF 0.5.

c. Release of Collected Contamination from Blowout of HEPA Filter by Pressure Pulse - very limited experimental data has been reported on the release of collected contamination as a result of the failure of glass fiber media HEPA filters from a dynamic pressure pulse. Gregory et als. February 1983) reported the release of 0.341, 1E-6 & 2 E-6 of the collected solid particles for high-flow HEPA filter during explosive transient. The large release from the first filter was attributed to media that was slightly crease prior to the test. If the high value is discounted, an ARF/RF of 2E-6/1.0 would bound the data.

d. Release of Collected Contamination from Blowout of HEPA Filter by Static Pressure - Gregory et als. (October 1983) also performed tests on from standard (1000 cfm) glass fiber media HEPA filters. The break pressure for

standard HEPA filters ranged from 1.32 to 2.91 psig with a mean value of 2.37 psig. High flowrate HEPA filter demonstrated lower structural capacity with break pressures ranging from 1.3 to 2.3 psig with a mean value of 1.6 psig. Removal efficiency of the standard HEPA filters for 0.46 micrometer diameter polystyrene latex beads upon tornado condition degraded from the 99.97% for a clean filter under normal conditions to 98.9%. The release of the approximately 1 kg of 0.46 micrometer diameter PSL collected for 1 type of standard HEPA filters was 1.46% & 0.71 with a mean value of 0.935%. An ARF/RF of 9E-3/1.0 is recommended.

e. Loss of Mat by Flame/Heat Intrusion - the ARF from the heat induced damage to a HEPA filter is estimated to be very small based on the following reasoned judgement. HEPA filters resisted temperature as high as 825 C for period of tens of minutes before loss of efficiency and 500 C for in access of 45 min (Hackney 1983). The filter media is very fine diameter glass fiber that soften and melt when heated and, thus, tend to retain materials adhering to the fibers. The release rate for several types of HEPA filter in flowing air at elevated temperatures less than required to induce failure (up to 400 C) are very low (Ammerich et als. 1989).

HEPA filter that both unused and removed from service due to high differential pressures (clogged) were tested using solid particles at a range of temperatures less than required for failure. The efficiencies of the filters prior to testing for 1.8 micrometers particles ranged from 99.97% to 99.9999989%. Two high flow (2000 cfm) and one at 1000 cfm HEPA filters with glass fiber media and various sealant and gasket materials were tested. No releases were found at temperatures below 150 C (175 C for 1 of the high flow filters). For the 1000 cfm type filter, the release rates for temperatures from 175 and 190 started at 1E-6/min and reduced to 5E-8/min within 1 hour (the lower limit of detection was 2E-8/min). The high flow HEPAs were tested to temperatures of 200 C and 250 C with release rates starting at 2E-4/min and 2E-5/min and reducing to 3E-7 in 60 min and 2E-8/min in 30 min. There was no release of contamination from a oven-fired, mineral sealant, high flow type filter at temperatures up to 350 C and the release in other types of HEPA filters is associated with the emission of smoke (binder, degradation of inert dust on filter, pyrolysis of sealant and gaskets). Thus, it appears that the heat-induced release from 1000 cfm HEPA filter prior to failure may be as high as 1E-5. The RF is assumed to be 1.0 without an experimental basis. ARFs for high-flowrate HEPA filter may be an order of magnitude higher (1E-4).

E. SOLIDS, Powder

1. Aerodynamic Suspension (Resuspension) - aerodynamic entrainment of powders from surfaces depends upon many factors; the speed and direction of the airflow; the size and distribution of the powder contaminant; the characteristics of the surface

(e.g. powder bed like soil, canopy like vegetation, surface roughness for hard-unyielding surfaces like steel, concrete); etc. Sehmel (1980), in his review of resuspension factors for mechanical and aerodynamic stresses, list values extending over 8 orders of magnitude (see Fig 2 from that reference attached). In experiments, Sehmel (1973) measured an entrainment rate of 1E-1 per pass by a vehicle driven through material deposited on an asphalt road at 50 mph. Mishima and Schwendiman (August 1973) measured aerodynamic entrainment of depleted dioxide powder, air-dried UNH, and residues from fires from various surfaces at wind velocities of 2.5 and 20 mph approximately 1-ft above the surface (see Table III from that reference attached).

Based upon experimental measurements over a 1-year duration from materials deposited on the ground at Hanford, Sehmel and Lloyd (1974) suggested resuspension rates for powders from 1E-8/s to 1E-10/s. No size fractions were designated but 100% respirable is assumed. These values are comparable to resuspension factors of 1E-3/meter to 1E-5/meter assuming a 24-hour sampling period. The values apply to resuspension from soil under average meteorological conditions.

For aerodynamic suspension of powder from various surfaces (soil, soil with vegetation cover, stainless steel and asphalt) at wind speeds up to 6 mph (2.5 mph corrected for wind speed measured at normal height of 10 m), a ARF of 5E-3 was measured over a 6-h period with 50% in the respirable size fraction. At higher wind speeds (50 mph at normal measurement height), an ARF of 2.5E-1 in 24-hours with an RF of 0.4 were measured. The fraction of the source in the respirable size fraction can not exceed the fraction of respirable powder in the source unless some mechanism can be postulated to subdivide the particles while on the surface.

2. Free-Fall Spills - Experiments were performed to measure the fractional airborne release of powders [TiO_2,density 4.2 g/cu-cm; DUO (Depleted uranium dioxide), density 10.96 g/cu-cm] during the free-fall spills of powders (Sutter, Johnston and Mishima December 1981). The measured values for the airborne release are tabulated in Tables A.1 & A.3 (attached) from that reference and the size distribution of the airborne materials are tabulated in Tables B.1 & B.3 are also attached. Fig. C.1 (attached) from the reference shows the size distribution of the powders used. Experimental data on the ARFs from the free fall spill of dense powders (uranium dioxide) indicate a maximum value of 7E-4 with AMAD (Activity Median Aerodynamic Diameter) of 20.8 micrometer. The average values for ARFs for a 10-ft fall distance for a material with a lesser density (4.2 g/ml) was ~ 1E-3. Calculations outlined in Ballinger et als. (January 1988) indicate a ARF of 2E-3 for the fall height of 15-ft. Based on the above for a fall distance of 3-m or less, an ARF of 2E-3 with 0.2 of the airborne material in the respirable fraction is recommended. For fall distances >3-m, the procedure outlined in Sect. 4 of Ballinger et als. (January 1988) or the computer code PSPILL can be used.

REFERENCE	LOCATION	STRESS
MITCHELL AND FUTSLER, 1967	ROOM	SWEEPING, VIG
CALC. FROM BRUNSKILL, 1967	ROOM	WALKING
CALC. FROM BRUNSKILL, 1967	CHANGE ROOM	CHANGING
GLAUBERMAN et al., 1967	ROOM	FAN, DOLLY
CARTER, 1970	ROOM	MACHINING
CARTER, 1970	WORK	STACKING SHEETS
GLAUBERMAN et al., 1967	ROOM	FAN
BRUNSKILL, 1967	CHANGE ROOM	WALKING
STEWART, 1967	MARALINGA TRIALS	STIRRED DUST
GLAUBERMAN et al., 1967	ROOM	AFTER TESTS
GLAUBERMAN et al., 1967	ROOM	FAN, DOLLY
FISH et al., 1967	ROOM	SWEEPING, LT.
STEWART, 1967	MARALINGA TRIALS	VEHICLE, 0.3 m
GLAUBERMAN et al., 1967	URANIUM FACILITY	NO CIRCULATION
STEWART, 1967	MARALINGA TRIALS	WALKING
GLAUBERMAN et al., 1967	ROOM	DOLLY
STEWART, 1967	C.D. TRIALS	WORK, ENCLOSED
STEWART, 1967	ROOM	FAN
GLAUBERMAN et al., 1967	Pu FACILITY	NO CIRCULATION
FISH et al., 1967	ROOM	SWEEPING, VIG.
LANGHAAR, 1971	NEVADA TEST SITE	VEHICHAR
STEWART, 1967	MARALINGA TRIALS	CAR, LANDROVER
JONES AND POND, 1967	ROOM	36 STEPS/MIN
FISH et al., 1967	ROOM	WALKING
STEWART, 1967	MONTE BELLO ISLANDS	VEHICLE, 2ND DAY
STEWART, 1967	MONTE BELLO ISLANDS	VEHICLE, 4TH DAY
STEWART, 1967	AUSTRALIAN DESERT	INSIDE VEHICLE
CALC. FROM MILLHAM et al., 1976	FIELD	MOVING
JONES AND POND, 1967	ROOM	18 STEPS/MIN
FISH, et al., 1967	ROOM	WORK, LIGHT
CALC. FROM MILLHAM et al., 1976	FIELD	PLANTING, DISKING
JONES AND POND, 1967	ROOM	36 STEPS/MIN
CALC. FROM MILLHAM et al., 1976	FIELD	SUBSOILING
STEWART, 1967	MONTE BELLO ISLANDS	VEHICLE, 7TH DAY
STEWART, 1967	C.D. TRIALS	WORK, OPEN
STEWART, 1967	AUSTRALIAN DESERT	VEHICLE TAILBOARD
STEWART, 1967	MARALINGA TRIALS	VEHICLE, 1-2 DAY
CALC. FROM BENNETT, 1976	NEW YORK	FALLOUT CONCS.
CALC. FROM MILLHAM et al., 1976	FIELD	TRACTOR, DOWNWIND
JONES AND POND, 1967	ROOM	18 STEPS/MIN
CALC. FROM TRANZO AND SALVADOR, 1970	PALMARES, SPAIN	NEARLY FARMING
STEWART, 1967	AUSTRALIAN DESERT	WALKING
CALC. FROM MILLHAM et al., 1976	FIELD	TRACTOR CAB
MILLHAM et al., 1976	FIELD	TRACTOR
CALC. FROM MYERS et al., 1976	STUDIE	ROTOTILLING
JONES AND POND, 1967	LABORATORY	NO MOVEMENT
CALC. FROM MILLHAM et al., 1976	FIELD	FERTILIZING
STEWART, 1967	MARALINGA TRIALS	WIND
ANSPAUGH et al., 1970	NEVADA TEST SITE	
STEWART, 1967	SANDY-GRASS	
STEWART, 1967	SANDY-DEBRIS	
STEWART, 1967	MONTE BELLO ISLANDS	
SEHMEL AND ORGILL, 1973	ROCKY FLATS	
CALC. FROM TRANZO AND SALVADOR, 1970	PALMARES, SPAIN	
LANGHAAR, 1971	NEVADA TEST SITE	
STEWART, 1967	PAVING STONES	
CALC. FROM BENNETT, 1976	NEW YORK-FALLOUT	
STEWART, 1967	SANDY-CLEARED	
SEHMEL AND LLOYD, 1975	HANFORD	
CALC. BY BENNETT, 1976	NEW YORK-U	
HAMILTON CALC. BY BENNETT, 1976	UNITED KINGDOM U	
KREY et al., 1976	ROCKY FLATS	
ANSPAUGH et al., 1975	NEVADA TEST SITE	

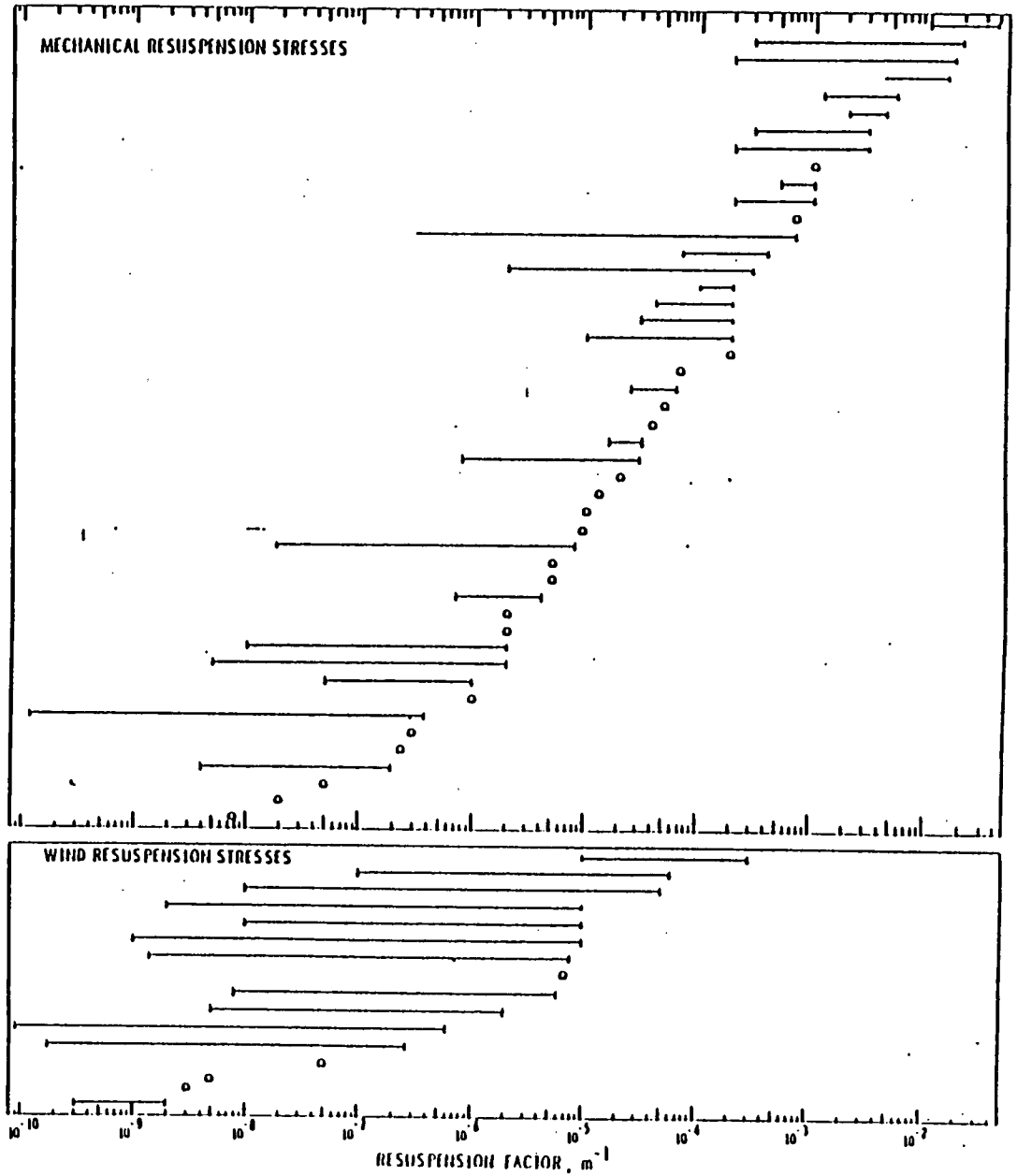

Fig. 2. Resuspension factor ranges from mechanical and wind resuspension stresses.

000345

TABLE A.1. Airborne Releases of TiO_2 Powder Traced with Uranine, Releases Resulting from a Free Fall Spill in Static Air.

Run	Weight g	Spill Height m	Uranine Airborne g	Uranine Wall Deposition, g: 1 m	Uranine Wall Deposition, g: 3 m	Uranine Total g	Percent Deposited On Wall	Calculated Mass Airborne g	Calculated Total Mass Airborne and Deposition g	Weight Percent Airborne	Weight Airborne and Deposition
37	471.9	3	2.85×10^{-3}	1.87×10^{-5}	2.9615×10^{-3}		3.8	0.9105	0.9462	0.19	0.20
38	450.4		4.38×10^{-4}	3.44×10^{-5}	1.10×10^{-5}	4.83×10^{-4}	9.4	0.1475	0.1628	0.033	0.036
39	431.1		3.07×10^{-4}	5.29×10^{-5}	5.25×10^{-5}	4.12×10^{-4}	25.6	0.0850	0.1151	0.020	0.027
42	460.0		1.17×10^{-3}	5.90×10^{-5}	7.41×10^{-5}	1.30×10	10.2	0.3900	0.4333	0.09	0.094
43	100		1.35×10^{-3}	1.92×10^{-4}	1.18×10^{-4}	1.66×10^{-3}	18.7	0.1194	0.1469	0.12	0.15
44	100		1.01×10^{-3}	7.71×10^{-5}	4.00×10^{-5}	1.13×10^{-3}	10.3	0.0990	0.1108	0.099	0.11
47	1000		6.403×10^{-3}	2.357×10	1.64×10^{-4}	6.803×10^{-3} [a]	5.9	1.480	1.5725	0.15	0.15
48	1000		3.742×10^{-3}	2.263×10^{-4}	1.464×10^{-4}	4.1147×10^{-3}	9.1	0.9659	1.062	0.096	0.11
49	25		2.926×10^{-4}	1.445×10^{-5}	2.95×10^{-5}	3.3655×10^{-4}	10.8	0.0240	0.0276	0.10	0.11
50	25		1.855×10^{-4}	ND	5.58×10^{-6}	1.911×10^{-4}	2.9	0.01656	0.0171	0.07	0.08
45	441.1	1	1.40×10^{-6}	7.45×10^{-5}	1.21×10^{-4}	1.60×10	11.6	0.0345	0.0391	0.008	0.008
46	451		1.81×10^{-4}	1.59×10^{-5}	7.49×10^{-6}	2.04×10^{-4}	12.9	0.0360	0.0406	0.008	0.009
51	25		3.7882×10^{-5}	ND	ND	3.7882×10^{-5}	ND	0.0030	--	0.01	--
52	25		5.0123×10^{-5}	ND	ND	5.0123×10^{-5}	ND	0.0040	--	0.02	--
53	1000		2.2477×10^{-3}	5.06×10^{-5}	4.10×10^{-5}	2.34×10^{-3}	3.9	0.4984	0.5188	0.05	0.05
54	1000		1.0052×10^{-3}	1.39×10^{-5}	4.965×10^{-7}	1.10×10^{-3}	1.3	0.1742	0.1766	0.017	0.018
56	1000	0	5.3340×10^{-6}			5.3340×10^{-6}		0.0009			
57	1000		3.6031×10^{-6}			3.6031×10^{-6}		0.0006			

(a) Calculate from 1 sq ft deposition sample.
(b) Ceiling deposition 1.98×10^{-5} g not included.

(Sutter, Johnston and Mishima December 1981)

000316

7638

TABLE A.3. Airborne Releases of DUO Powder, Releases Resulting from a Free Fall Spill in Static Air

Run	DUO Weight, g	Spill Height, m	Total DUO Airborne, g	Weight Percent Airborne
1	1000	3	0.23122	0.023
2	100	1	0.00337	0.003
3	500	1	0.01924	0.004
4	100	3	0.00350	0.004
5	1000g TiO_2	1	0.000100[a]	
6	500	3	0.17579	0.04
7	1000	1	0.05589	0.006
8	100	3	0.04489	0.04
9	500	1	0.03081	0.008
10	1000g TiO_2	3	0.000211[a]	
11	100	1	0.00670	0.007
12	1000	1	0.07703	0.008
13	1000	3	1.19463	0.12
14	500	3	0.54383	0.11

(a) TiO_2 standard indicated 0.00011 g interference in uranium quality assurance tests. Therefore this collection is not significant.

(Sutter, Johnston and Mishima December 1981)

000317

TABLE B.1. Median Aerodynamic Equivalent Diameter Particle Size Generated by a Free Fall Spill in Static Air, Traced TiO_2 Powder

Run	Source Weight, g	Spill Height, m	Median Diameter, μm	σg	Percent of Collection 10 μm and Less	Weight Percent of Source Airborne 10 μm and Less
37	471.9	3	21.0	6.2	34	0.065
38	450.4		5.8	5.6	62	0.020
39	431.1		16.0	6.6	40	0.008
42	460		17.2	6.9	40	0.036
43	100		27.0	7.5	31	0.037
44	100		13.0	5.9	46	0.046
45	441	1	15.3	7.7	41	0.033
46	451	1	16.8	6.5	42	0.034
47	1000	3	36.0	6.7	25	0.038
48	1000		17.0	7.4	40	0.038
49	25		9.6	3.7	50	0.050
50	25		9.8	4.7	50	0.035
51	25	1	4.7	2.7	62	0.006
52	25		7.2	3.1	58	0.012
53	1000		9.1	2.8	53	0.027
54	1000		16.5	5.9	40	0.068

(Sutter, Johnston and Mishima December 1981)

TABLE B.3. Median Aerodynamic Equivalent Diameter Particle Size Generated by a Free Fall Spill in Static Air, DUO Powder

Run	Source Weight, g	Spill Height, m	Median Diameter, μm	σg	Percent 10 μm and Less	Weight Percent of Source Airborne 10 μm and Less
1	1000	3	3.1	5.1	25	0.006
13	1000		10.5	3.9	49	0.059
6	500		6.1	3.1	70	0.028
14	500		16	5.2	38	0.042
4	100		<0.1	50	91	0.004
8	100		12.0	3.2	44	0.017
7	1000	1	11.0	2.75	46	0.003
12	1000		9.6	3.2	50	0.004
3	500		3.2	3.5	83	0.003
9	500		9.5	2.6	52	0.004
2	100		0.65	5.2	93	0.003
11	100		11.5	2.9	51	0.004

(Sutter, Johnston and Mishima December 1981)

000319

Particle Size

The size distributions of the source powders were determined using sedimentation methods that record the cumulative mass settled in a column of liquid. These are shown in Figure C.1. The mass median diameter (MMD) of the TiO_2 was 1.7 µm; DUO, 1.0 µm; σg was 2 for both powders. Ninety-five percent of the TiO_2 powder was between 0.425 and 6.8 µm, MMD; the DUO between 0.25 and 4.0 µm. Using theoretic density of 4.26 g/cc for TiO_2, 10.76 g/cc for DUO, aerodynamic diameters of 3.5 and 3.3 µm, respectively, were calculated. The DUO was thus a somewhat finer powder as tabulated in Table C.2. A size distribution considered representative of dry PuO_2 powders (Schwendiman 1977) is included for comparison.

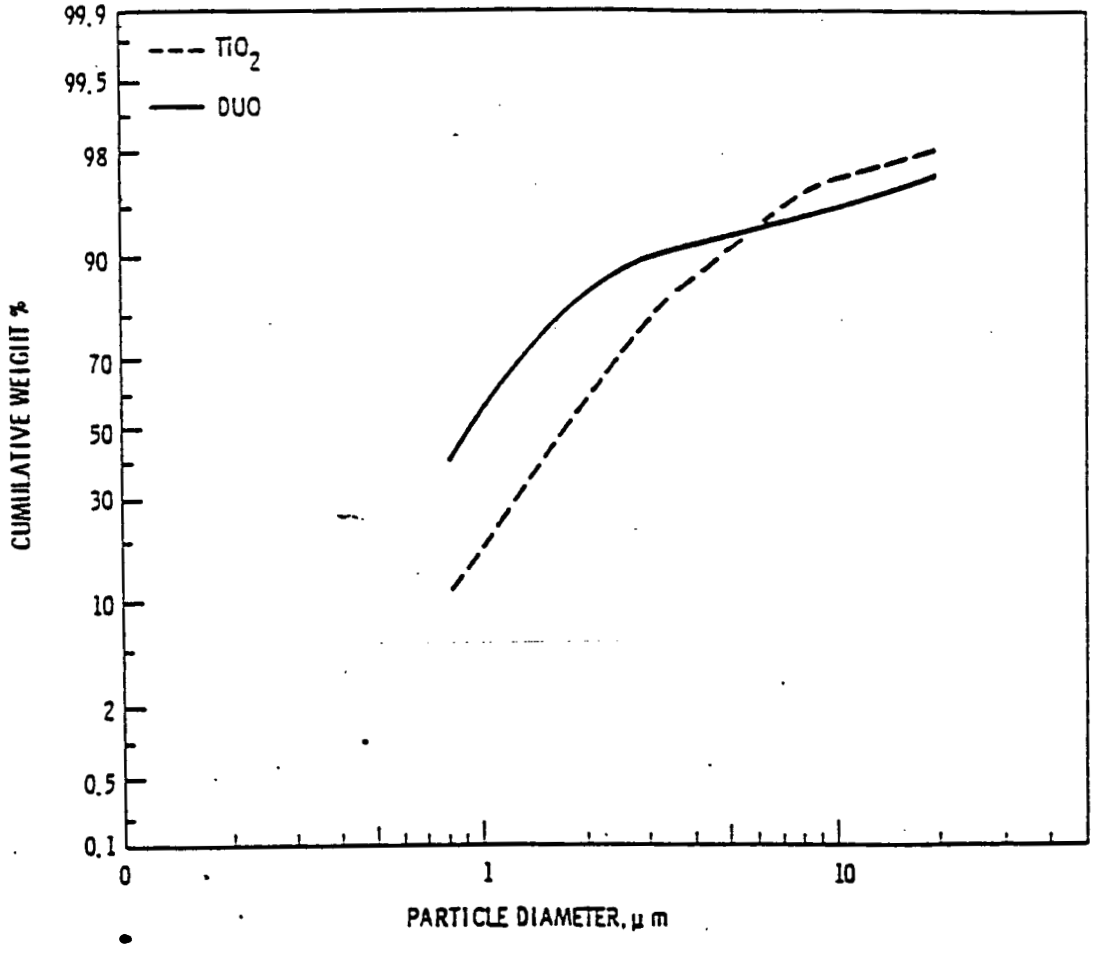

FIGURE C.1. Titanium Dioxide and Uranium Dioxide Particle-Size Distribution

(Sutter, Johnston and Mishima December 1981)

3. Venting of Pressurized Powder -

a. Venting of Pressurized Powders - if the gases around and in a powder are compressed during pressurization, the gases expand rapidly during venting and result in the airborne dispersal of the powder. Experimental data for the airborne release of 2 powders with varying densities (TiO_2 4.2 g/cu-cm & UO_2 10.96 g/cu-cm) for two masses-at-risk have been reported (Sutter August 1983; Ballinger, Sutter & Hodgson May 1987). Initially, tests were performed using pressure to 1000 psig but significant masses of powder were impacted and adhered to the ceiling of the 10-ft tall containment vessel compromising the measurement of the fraction airborne. Although tests performed at 500 psig appeared to be affected somewhat by the same phenomena, the effects at this and lower pressure did not appear to be affected significantly. For the same pressures, the airborne releases measured for the small mass-at-risk (100 g) were approximately twice those measured for the larger mass-at-risk (350 g) and may indicate that surface to volume ratio may influence the release fraction. The ARFs for the less dense material for the two masses-at risk pressurized to 50 psig to 500 psig ranged from 3.6E-2 to 2.95E-1 increasing with pressure with RFs from 0.42 to 0.62 for 100 g source and ARFs from 6.2E-3 to 9.8E-2 with RFs from 0.38 to 0.64 for 350 g sources (Tables A.2 & B.2 Sutter August 1983). For the denser material for the two masses-at-risk and initial pressurizations from 9 psig to 500 psig, the ARFs and RFs for 100 g sources ranged from 3E-4 to 2.1E-1 and 0.25 to 0.54, respectively. For the 350 g sources, the ARF/RFs ranged from 5E-5 to 9E-2/0.31 to 0.42 (Table A.1 & B.1 Sutter August 1983; Tables A.3 & B.3 Ballinger, Sutter and Hodgson May 1987). Thus, the ARFs appear to decrease with density of the material, decrease with increasing initial mass, and increase with pressure. In as much as the experimental masses are much smaller than commonly found in nuclear processes, the bounding value recommended for the ARF/RF for powders pressurized to 500 psig would be 1E-1/0.6. If the level of pressure can be determined, the appropriate ARF/RF can be selected from the tables attached.

b. Venting of Pressurized Gases Through Powders - in certain situations, pressurized gases (e.g. stored compressed gases, gases pressurized by the heating of a closed vessel, gases pressurized by explosive events) may be vented through powder beds. Experiments were performed to measure the ARFs and RFs from venting pressurized gases (50 psig to 500 psig) through 100 g & 350 g masses of TiO_2 powder. The ARFs ranged from 8.2E-2 to 2.87E-1 for the 100 g source with RFs from 0.48 to 0.71 and ARFs from 4.5E-2 to 1.09E-1 for the 350 g source with RFs from 0.46 to 0.88 (Tables A.3 & B.3 Sutter August 1983). For the conditions described subsect. E.3.a above, the recommended bounding ARF/RF for pressures upon to 500 psig are 1.1E-1/0.9.

TABLE A.2. Mass Airborne from Pressurized Releases of TiO_2 Powder

Source, g	Rep.	Run	psig	Weight, g	Average, wt g	wt% Airborne	Avg wt% Airborne
350	1	5[a]	1000	15.8805	15.8805	4.5	4.5
	1	4	500	21.3782		6.1	
	2	16	500	34.2035	27.7909	9.8	7.9
	1	3	250	10.1143		2.89	
	2	14	250	26.4866	18.3005	7.6	5.2
	1	2[a]	100	3.2783	3.2783	0.94	0.94
	1	1	50	2.1848		0.62	
	2	15	50	12.5796	7.3822	3.6	2.1
100	1	7[a]	1000	12.3933	12.3933	12.4	12.4
	1	13	500	29.4976		29.5	
	2	18	500	18.7731	24.1354	18.8	24.1
	1	11	250	19.8395		19.8	
	2	9	250	16.5683	18.2039	16.7	18.2
	1	10[b]	189	11.0536	11.0536	11.1	11.1
	1	6	50	3.6082		3.6	
	2	7	50	5.1346	4.3714	5.1	4.4
50	1	8[a]	50	0.51	0.51	1.0	1.0

(a) Single value only
(b) Premature rupture

(Sutter August 1983)

TABLE B.2. Median AED of Particles Produced by Pressurized Releases of TiO_2

Source, g	Rep.	Run	psig	Median Diameter, um	σg	%10 um or Less	wt% of Source that Becomes Airborne 10 um and Less
350	1	5[a]	1000	7.0	4.1	64	2.9
	1	4[b]	500				
	2	16	500	15, 12	10.7, 8.6	40, 44	3.9, 4.3
	1	3[b]	250				
	2	14	250	14	8.5	44	3.3
	1	2[b]	100				
	1	1[b]	50				
	2	15[c]	50	20, 16	13, 10.3	38, 48	1.4, 1.7
100	1	7[a]	1000	5.6	8.2	60	7.4
	1	13	500	4.6, 4.2	6.3, 5.5	68, 72	20.1, 21.2
	2	18	500	6.9, 5.0	6.0, 6	54, 66	10.1, 12.4
	1	11	250	10, 8.3	9.5, 5.7	50, 54	9.9, 10.7
	2	9	250	17, 6.4	14, 5.8	42, 61	6.9, 10.1
	1	10[d]	189	14, 10	10.8, 4.5	44, 50	4.9, 5.5
	1	6	50	8.2	5.9	54	1.9
	2	17	50	9.2, 6.8	5.1, 4.3	52, 60	2.7, 3.1
50	1	8[e]	50	12	8.6	48	0.5

(a) Exploratory at 1000 psig
(b) Impactor overloaded
(c) Data based on 2 impactors where two sizes are shown
(d) Run originally set for 250 psig, went off prematurely
(e) Exploratory at 50 psig and using 50 g traced TiO_2

(Sutter August 1983)

000323

TABLE A.1. Mass Airborne from Pressurized Releases of DUO Powder

Source g	Rep.[a]	Run[b]	psig	Weight, g	Average, wt g	wt% Airborne	Avg wt% Airborne
350	1	1	500	29.7028		9	
	2	13	500	30.7083	30.2056	9	9
	1	6	250	19.1341		6	
	2	14	250	21.9318	20.5330	6	6
	1	4	50	7.0006		2	
	2	88	50	6.7570	6.8788	2	2
100	1	7	500	21.2210		21	
	2	12	500	18.3406	19.7814	18	20
	1	3	250	12.6345		13	
	2	98	250	13.3580	12.9963	13	13
	1	2	50	3.3166		3	
	2	11	50	3.7947	3.5557	4	4

(a) This is the replicate identification number
(b) Run number, used to identify experiment since they were done in a random sequence.

(Sutter August 1983)

TABLE B.1. Median AED of Particles Produced by Pressurized Releases of DUO

Source, g	Rep.	Run	psig	Median Diameter, um	σg	wt% 10 µm or Less	wt% of Source that Becomes Airborne 10 um and Less
350	1	1	500	16	3.0	34	3.0
	2	13	500	16	3.0	31	2.7
	1	6	250	12	2.1	42	2.3
	2	14	250	18	3.0	29	1.8
	1	4	50	16	3.0	33	0.7
	2	8B	50	21	4.8	31	0.6
100	1	7	500	10	2.5	49	10.4
	2	12	500	18	4.0	38	7.0
	1	3	250	9	2.2	54	6.8
	2	9B	250	12	1.9	38	5.1
	1	2	50	13	2.9	41	1.4
	2	11	50	25	4.2	25	1.0

(Sutter August 1983)

000325

TABLE A.5. Mass Airborne from Low-Pressure DUO Releases

Source Mass, g	Pressure, psia	Uranium Collected, g	Wt% Airborne	Total Mass not Ejected from Chamber, g	Mass Ejected but not Airborne, g
350	24.5	0.610	0.174	24.4	325.0
	17.5	0.387	0.111	50.1	299.4
	9.0	0.017	0.005	269.6	80.4
100	24.5	0.302	0.302	21.1	78.7
	17.5	0.63	0.63	65.5	34.4
	9.0	0.03	0.03	75.9	24.1

TABLE A.6. Median AED of Particles Producted by Low-Pressure DUO Releases

Source Mass, g	Pressure, psia	Median Diameter, µm	σ_g	% 10 µm and Less	Wt% of Source that Becomes Airborne and is 10 µm and Less
350	24.5	38	9.3	35	0.061
	17.5	19	6.5	60	0.067
	9.0	6	6.0	61	0.003
100	24.5	24	7.5	42	0.127
	17.5	6	4.6	72	0.045
	9.0	7	4.8	62	0.02

(Ballinger, Sutter and Hodgson May 1987)

TABLE A.3. TiO_2 Powder Airborne, Powder Release Above Chamber (PRAC)

Source, g	Run	psig	Weight, g	wt% Airborne
350	1	500	38.2198	10.9
	5	250	36.6774	10.5
	4	50	15.8639	4.5
100	6	500	28.7369	28.7
	3	250	21.3226	21.3
	2	50	8.1773	8.2

(Sutter August 1983)

000327

TABLE B.3. Median AED of Particles Produced by TiO_2 Powder Releases Above Chamber (PRAC)

Source, g	Run	psig	Median Diameter, µm	σg	%10 µm and Less	Avg wt% of Source that Becomes Airborne and is 10 µm and Less
350	1	500	20[a]	11.8	54	
			9	7	40	5.1
	5	250	11	5.5	48	
			5	3.6	72	6.3
	4	50	12	9.2	46	
			2.4	3.8	88	3.0
100	6	500	11	7.7	48	
			4.3	4.0	71	17.1
	3	250	10.1	5.3	48	
			6.2	4.4	65	12.0
	2	50	8.4	6.5	53	
			6	7.0	68	5.0

(a) Based on two impactor samples

(Sutter August 1983)

4. Explosive Release - an ARF and RF of 7.6E-2 and 0.14 were measured for the suspension of UO2 powder from a stainless steel surface for a wind velocity of 23 mph 1-ft above the surface (comparable to a 50 mph under normal wind speed measurements) in a 24-hour period (see Table III Mishima and Schwendiman August 1973, attached). In the case of explosion-generated air velocities, the duration of the peak velocity is in terms of milliseconds. Approximately 60% of the resuspended powder (4.56E-2) was made airborne during the 1st hour of the wind (Figure 16, Mishima and Schwendiman August 1973, attached). If resuspension is linear over the initial hour, the ARF would be 7.6E-4 per minute. On this basis, reasonably conservative values for the ARF and RF for the suspension of a powder from a smooth, unyielding surface by the pressure impulse generated (gas flow parallel to surface) by an explosion appear to be 5E-3 and 0.2 respectively. If the compressed gases are vented through the powder as in subsect. E.3.b above, the ARF/RF (1.1E-1/0.9) for that scenario should be applied.

5. Surface Contamination -

   a. Aerodynamic Entrainment (Resuspension) - the aerodynamic suspension (resuspension) of powders was discussed in subsect. E.1.

   b. Suspension of Powder-like Surface Contamination by Shock/Vibration - if shock/vibration is applied to a non-reactive material whose surface is contaminated with a powder, the shock/vibration may dislodge the powder. Some factor that may affect the suspension are the frequency/amplitude of the shock/vibration, the size distribution of the powder, the coating of the surface with condensed moisture or organic vapors, the gas velocity and direction flowing over the contamination, and characteristics of the surface (e.g. relationship between particle size of powder and surface roughness). No known experimental data for the suspension of powder contamination from surfaces from shock/vibration. Mishima, Schwendiman and Ayer (October 1978) estimated an ARF of 1E-3 with a RF of 1.0. In lieu of directly applicable experimental data for this phenomena, the ARF/RF is recommended for use.

   c. Suspension of Powder-like Contamination by Heating of Non-Combustible Surfaces- the flexing (expansion and contractions) of metal and other non-combustible surfaces may eject some particles contaminating their surfaces. An ARF of 2.5E-4/s (0.9/h) with a MMD of 2.5 micrometers for the airborne material is found in NUREG/CR-1320. The experimental basis for the value are found in Table VI, VIII & X (attached) from Mishima, Schwendiman and Radasch (November 1968). The average of all ARFs for experiments at a temperature of 700 C & an air velocity of 100 cm/s is 2E-3/h. The MMD stated in Geometric Diameter (the linear diameter of the particle) and, since the theoretic density of PuO2 is 11.46 g/cu-cm, the MMD in AED is >80 micrometers. The RF estimated from the size distribution plots in the

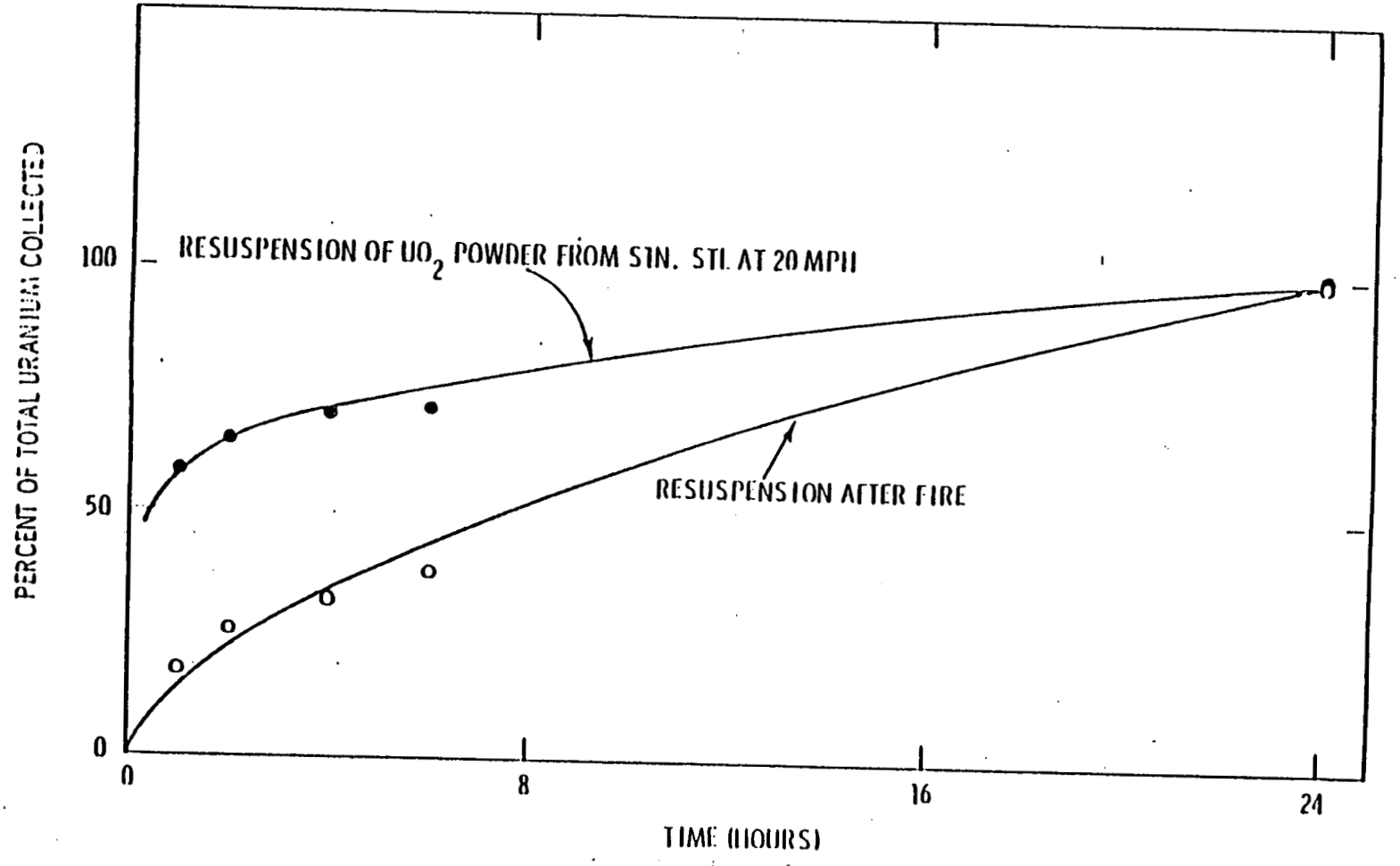

FIGURE 16. AERODYNAMIC ENTRAINMENT OF URANIUM DIOXIDE POWDER FROM A STAINLESS STEEL SURFACE AT AN AIR VELOCITY OF 20 MPH

(Mishima and Schwendiman August 1973)

BNWL-1732
7638
000330

0001331

TABLE VI. Partially Oxidized Plutonium Oxalate Release Rates (in wt%/hr)

Temperature, °C	Sample Type	Nominal Air Velocity Through Chimney 10 cm/sec	50 cm/sec	100 cm/sec
Ambient	A	0.051	$<4 \times 10^{-3}$	$<4 \times 10^{-3}$
	B	4.6×10^{-3}	$<4 \times 10^{-3}$	0.66
400	A	--	--	0.057
	B	--	--	0.0075
700	A	--	--	0.735
	B	--	--	0.041
1000	A	0.25	0.62	0.82*
	B	0.023	$<4 \times 10^{-3}$	0.057*

A *Particles carried through chimney (collected on glass fiber filter).*

B *Particles entrained but deposited on chimney walls (collected on 0.003-in. mild steel shimstock liner).*

* *Average of two runs.*

(Mishima, Schwendiman and Radasch July 1968)

TABLE VIII. Plutonium Oxalate Release Rates (in wt%/hr)

Temperature, °C	Sample Type	Nominal Air Velocity Through Chimney 10 cm/sec	50 cm/sec	100 cm/sec	
Ambient	A	<0.004	<0.004	<0.004	0.073
		<0.004	<0.004	0.38	0.54
	B	<0.004	<0.004	0.006	0.025
		<0.004	0.0096	0.023	0.036
400	A	--	--	0.48	
	B	--	--	0.016	
700	A	0.0044	<0.004	0.90	
	B	<0.004	<0.004	0.047	
1000	A	<0.004	0.007	0.25	
	B	<0.004	0.005	0.075	

A *Particles carried through chimney (collected on glass fiber filter).*

B *Particles entrained but deposited on chimney walls (collected on 0.003 in. mild steel shimstock liner).*

(Mishima, Schwendiman and Radasch July 1968)

000332

7638

000333

TABLE X. Plutonium Fluoride Release Rates (In wt% released per hour)

Temperature, °C	Sample Type	Nominal Air Velocity Through Chimney 10 cm/sec	50 cm/sec	100 cm/sec
Ambient	A	$<4 \times 10^{-3}$	$<4 \times 10^{-3}$	$<4 \times 10^{-3}$ $<4 \times 10^{-3}$
	B	$<4 \times 10^{-3}$	$<4 \times 10^{-3}$	$<4 \times 10^{-3}$ $<4 \times 10^{-3}$
400	A	--	--	0.0073
	B	--	--	$<4 \times 10^{-3}$
700	A	--	--	0.022
	B	--	--	0.048
1000	A	$<4 \times 10^{-3}$	$<4 \times 10^{-3}$	0.05 0.02
	B	$<4 \times 10^{-3}$	$<4 \times 10^{-3}$	0.016 $<4 \times 10^{-3}$

A *Particles carried through chimney (collected on glass fiber filter).*

B *Particles entrained but deposited on chimney walls (collected on 0.003 in. mild steel shimstock liner).*

(Mishima, Schwendiman and Radasch July 1968)

document indicate a value ~0.0005 (0.05 wt/o). Therefore, an ARF of 2E-3 per hour/RF 0.01 appears to be very conservative.

F. CRITICALITIES

In many instances, viable scenarios for the occurrence of a nuclear criticality in a facility can not be postulated although the possibility of an occurrence is required. For these instances, the U.S.N.R.C. has provided calculations of the source term for criticalities in various classes of facilities (fuel reprocessing, uranium fuel fabrication, and plutonium fuel fabrication and processing plants)(USNRC 1977, 1979a, 1979b). The release of radionuclides to the cell/enclosure/room for each type of facility is shown in Table 1 and the assumptions shown in Appendix A.1, A.2 & A.3.

REFERENCES

Ammerich, M., A. Briand, J.C. Laborde, Ph. Mulcey and J. Savornin. 1989. "Contamination Releases From HEPA Filters Under High Temperature Conditions", Proceedings of the 20th DOE/NRC Nuclear Air Cleaning Conference (M.W. First, Ed), NUREG/CP-xxxx (CONF-xxxxxx), Harvard Air Cleaning Laboratory, Boston, MS.

Arnold, P.M. Characterization of Spent HEPA Filters From Rocky Flats Plant, AO 6629 UNIF, Rockwell International - Rocky Flats Plant, Golden, CO.

Ayer, J.E., A.T. Clark, P. Loysen, M.Y. Ballinger, J. Mishima, P.C. Owczarski, W.S. Gregory, B.D. Nichols. May 1988. Nuclear Fuel Cycle Accident Analysis Handbook, U.S.N.R.C. - Office of Nuclear Material Safety and Safeguards, Washington, DC 20555.

Ballinger, M.Y., J.W. Buck, P.C. Owczarski and J.E. Ayer. Januray 1988. Methods for Describing Airborne Fractions of Free Fall Spills of Powders and Liquids, NUREG/CR-4997 (PNL-6300), Pacific Northwest Laboratory, Richland, WA 99352.

Ballinger, M.Y. and W.H. Hodgson. December 1986. Aerosols Generated by Spills of Viscous Solutions and Slurries, NUREG/CR-4658 (PNL-5910), Pacific Northwest Laboratory, Richland, WA.

Ballinger, M.Y., S.L. Sutter and W.H. Hodgson. May 1987. New Data for Aerosols Generated by Releases of Pressurized Powders and Solutions in Static Air, NUREG/CR-4779 (PNL-6065), Pacific Northwest Laboratory, Richland, WA 99352.

Buijis, K., B. Chavane de Dalmassy and H.E. Schmidt. October 1983. "The Characterization of Radioactive Aerosols from Fires", Proceedings of the CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems in Nuclear Facilities, LA-9911-C Volumes I & II (CSNI Report No. 83), Los Alamos National Laboratory, Los Alamos, NM.

Carter, R.F. and K. Stewart. 1970. "On the Oxide Fume Formed by the Combustion of Plutonium and Uranium", Inhaled Particles III (Proceedings of an International Symposium, British Occupational Hygiene Society, London, 9/14-23/70), Unwin Brothers Limited - ^The Gresham Press, Old Working, Surrey, England.

Hackney, S. 1983. "Fire Testing of HEPA Filters Installed in Filter Housings", Proceedings of the 17th DOE Nuclear Air Cleaning Conference (M.W. First, Ed), CONF-820833, Harvard Air Cleaning Laboratory, Boston, MS.

Gregory, W.S., R.A. Martin, P.R. Smith and D.E. Fenton. October 1983. "Response of HEPA Filters to Simulated Accident Conditions", Proceedings of the 17th DOE Nuclear Air Cleaning Conference (M.W. First, Ed), CONF-820833, Harvard Air Cleaning Laboratory, Boston, MS.

Jardine, L.J., W.J. Mecham, G.T. Reedy and M.J. Steindler. 1982. Final Report of Experimental Laboratory-Scale Brittle Fracture Study of Glass and Ceramics, ANL-82-39, Argonne National Laboratory, Argonne, IL.

Jordan, S. and W. Lindner. October 1983. "The Behavior of Burning Kerosine, Aerosol Formation and Consequences", Proceedings of the CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems, LA-9911-C Volumes I & II (CSNI Report No. 83), Los Alamos National Laboratory, Los Alamos, NM.

Jordan, S. and W. Lindner. February 1985. "Aerosols Released from Solvent Fire Accidents in Reprocessing Plants", Proceedings of the CSNI Specialists Meeting on Nuclear Aerosols in Reactor Safety (W.O. Schikarski and W. Shock, Ed.), KfK 3800 (CSNI Report No. 95), Kerforschungszentrum Karlsruhe, FRD.

Mecham, W.J., L.J. Jardine, R.H. Pelto, G.T. Reedy and M.J. Steindler. October 1981. Interim Report of Brittle Fracture Impact Studies: Development of Methodology, ANL-81-27, Argonne National Laboratory, Argonne, IL.

Mishima, J. August 1964. A Review of Research on Plutonium Releases During Overheating and Fires, HW-83668, General Electric Company - HAPO, Richland, WA.

Mishima, J. December 1965. Plutonium Release Studies - I. Release From the Ignited Metal, BNWL-205, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J. November 1966. Plutonium Release Studies II. Release From Ignited, Bulk Metallic Pieces, BNWL-357, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J. June 1973. Interim Report: The Fractional Airborne Release of Dissolved Radioactive Materials During the Burning of 30 Percent Normal Tributyl Phosphate in a Kerosine-Type Diluent, BNWL-B-274, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J. and L.C. Schwendiman. October 1970. The Amount and Characteristics of Plutonium Made Airborne Under Thermal Stress, BNWL-SA-3379, Pacific Northwest Laboratory, Richland, WA.

Mishima, J. and L.C. Schwendiman. April 1973. Fractional Airborne Release of Uranium (Representing Plutonium) During the Burning of Contaminated Waste, BNWL-1730, Pacific Northwest Laboratory, Richland, WA.

Mishima, J. and L.C. Schwendiman. August 1973. Some Experimental Measurements of Airborne Uranium (Representing Plutonium) in Transportation Accidents, BNWL-1732, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J., L.C. Schwendiman and C.A. Radasch. July 1968. Plutonium Release Studies III. Release From Heated Plutonium Bearing Powders, BNWL-786, Pacific Northwest Laboratory, Richland, WA.

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Mishima, J., L.C. Schwendiman and C.A. Radasch. November 1968. Plutonium Release Studies IV. Fractional Release From Heating Plutonium Nitrate Solutions in Flowing Air Stream, BNWL-931, Pacific Northwest Laboratory, Richland, WA 99352.

Mishima, J., L.C. Schwendiman and J.E. Ayer. October 1978. Increment of Analysis - An Estimate of Airborne Release of Plutonium from Babcock and Wilcox Plant as a Result of Severe Wind Hazard and Earthquake, PNL-2812, Pacific Northwest Laboratory, Richland, WA 99352.

SAND. September 1987. Appendix F "Preliminary Preclosure Safety Analysis", Site Characterization Plan Conceptual Design Report (H.R. MacDougall, L.W. Scully and J.R. Tillerson, Compilers), SAND84-2641 Vol 4, Sandia National Laboratory, Albuquerque, NM.

Sehmel, G.A. 1973. "Particle Resuspension from an Asphalt Road Caused by Car and Truck Traffic", Atmospheric Environment, 7:pp 291 - 301.

Sehmel, G.A. 1980. "Particle Resuspension: A Review", Environment International, 4:pp 107 - 127.

Sehmel, G.A. and F.D. Lloyd. 1976. "Particle Resuspension Rates", Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (R.D. Englemann and G.A. Sehmel, Ed), ERDA Symp. Series #38, Technical Information Center - Energy Research and Development Center (Now U.S. Department of Energy), Washington, D.C.

Steindler, M.J. and W.H. Seefeldt. 1980. "A Method for Estimating the Challenge to an Air Cleaning System", Proceeding of the 16th DOE Air Cleaning Conference (M.W. First, Ed.), Harvard Air Cleaning Laboratory, Boston, MS.

Sutter, S.L. August 1983. Aerosols Generated by Releases of Pressurized Powders and Solutions in Static Air, NUREG/CR-3093 (PNL-4566), Pacific Northwest Laboratory, Richland, WA 99352.

Sutter, S.L., J.W. Johnston and J. Mishima. December 1981. Aerosols Generated by Free Fall Spills of Powders and Solutions in Static Air, NUREG/CR-2139 (PNL-3786), Pacific Northwest Laboratory, Richland, WA 99352.

USNRC. April 1977. Assumptions Used for Evaluating the Potential Radiological Consequences of Accidental Nuclear Criticality in a Fuel Reprocessing Plant, Regulatory Guide 3.33, U.S. Nuclear Regulatory Commission - Office of Standards Development, Washington, DC 20555.

USNRC. July 1979a. Assumptions Used for Evaluating the Potential Radiological Consequences of Accidental Nuclear Criticality in a Uranium Fuel Fabrication Plant, U.S. Nuclear Regulatory Commission - Office of Standards Development, Washington, DC.

USNRC. July 1979b. Assumption Used for Evaluating the Potential Radiological Consequences of Accidental Nuclear Criticality in a Plutonium Processing and Fuel Fabrication Plant, U.S. Nuclear Regulatory Commission - Office of Standards Development, Washington, DC.

SUMMARY TABLE
AIRBORNE RELEASE FRACTIONS

Materials/Mechanisms	Parameter	ARF*	RF+	References
A. NON-CONDENSIBLE GASES -	Loss of Containment	1E+0	NA	
B. VAPORS (Condensible Gases) -	Evolution (chemical reactants, temperature)	1E+0	NA	
C. LIQUIDS				
1. Aerodynamic Entrainment (Resuspension)	<100 cm/s	1E-8^	1.0	Sehmel & Lloyd '76
	<20 mph	8E-5	1.0	Mishima & Schwendiman 8/73
2. Free-Fall Spill	<3 meters	1E-4	0.5	
	>3 meters	(see Ballinger et als. January 1988)		
Slurries	<3 meter, <50% solids	5E-5	0.9	Ballinger & Hodgson 12/86
Viscous Solutions	<3 meters, >8 centipoise	6E-6	0.8	Ballinger & Hodgson 12/86
3. Venting Pressurized Liquids				
a. above liquid level				
	density ~1/<500 psig	1.5E-3	0.8	Sutter 8/83
	density ~1.3/<500 psig	2.5E-4	0.6	Sutter 8/83
b. below liquid level				
	diameter opening <0.25"	1E-4	1.0	Mishima et als. 10/78
a. superheated liquids ("flashing spray)	240 psig/202 C	1E-1	0.7	Ballinger at als. 5/87
4. Explosive Dispersal	Mass Ratio <50 (see Appendix B)			Ayer et als. 10/88
5. Burning Combustible Liquids				
quiescent burning	volatiles	1E+0	NA	Mishima et als.
	Non-volatiles	1E-2	1.0	
burning large volumes	Non-volatiles	3E-2	1.0	Buijis et als. 10/83
complete dryness	Non-volatiles	1E-1	1.0	Buijis et als. 10/83

* ARF - Airborne Release Fraction (e.g. 0.0001 = 1E-4)

\+ RF - Respirable Fraction: fraction of airborne particles in the size range of 10 micrometers or less AED.

^ ARF for aerodynamic suspension of materials based upon source that is continually depleted with time. At an ARF of 1E-8/s, the source is 1% depleted in approximately 12 days.

D. SOLIDS, Bulk

1. Aerodynamic Entrainment (Resuspension)		NSAR		
2. Crush-Impact, Brittle-Fracture		PULV		SAND 9/87
3. Oxidation				
<Ignition Temperatures		7E-6 X FO**	1.0	Carter & Stewart '70
Self-Sustained	small pieces, <100 g/ quiescent -	1E-5	1.0	
	large metal pieces >100 g, turbulent	5E-4	0.3	Mishima & Schwendiman 4/73
	some disturbance of molten metal	1E-2	1.0	Carter & Stewart '70
4. Explosive Dispersal, Metal	internal explosive forces (expl. wire)	5E-1	0.01	Carter & Stewart
	detonation/MR# <50	(see Appendix B)		Ayer et al. 5/88
5. Burning of Contam'd Combustible Solid	mixtures, air velocity <100 cm/s	1E-3	1.0	Mishima & Schwendiman 4/73
	PMMA, low air vel	5E-2	1.0	Halverson et als. 3/87
	PS, low air vel	1E-2	0.2	"
	PC, low air vel	1E-2	0.9	"
	cellulosic, low air velocity	5E-5	0.5	"
	mixture - powder, >100 cm/s through burning mass	4E-1	!	Mishima & Schwendiman 10/70
	mixture - liquid, air through burning mass	1E-1	0.1	Mishima & Schwendiman 10/70

** FO - Fraction of metal oxidized during event

MR - Mass Ratio = mass inert (g, lb)/TNT Eq of explosive force (g, lb)

! The respirable fraction airborne can not exceed the amount of respirable particles in the powder contaminant unless some mechanism exists for subdivision of the powder (most non-volatile radionuclides form inert, ceramic metal oxides).

PMMA - polymethylmethacrylate (lucite used to make clear panes for windows, etc.).

PS - polystyrene (plastic used to make many types of containers, furniture, equipment and ion exchange resin beads).

PC - polychloropene (elastomer used for gloves, gaskets).

cellulosics like paper, cardboard, wood, etc.

6. HEPA Filter				
a. Crush-Impact	enclosed	3E-3	1.0	Arnold 9/86
	unenclosed	1E-2	0.5	"
b. Blowout	dynamic pressure	2E-6	1.0	Gregory et als. 10/83
	static pressure	9E-3	1.0	Gregory et als. 10/83
c. Flame/Heat	prior to failure	1E-5	1.0	Ammerich et als. '89

E. SOLIDS, Powder

1. Aerodynamic Entrainment (Resuspension)	average met conditions	1E-8/s to 1E-10/s	1.0	Sehmel & Lloyd '76
	<6 mph	5E-3 (6 hours)	0.5!	Mishima & Schwendiman 8/73
	<50 mph	2.5E-1 (1st hour)	0.4!	"
2. Free-Fall Spill	<3-meter fall	2E-3	0.2!	Sutter et als. 12/81
	>3-meter fall	(see Ballinger et als. 1/88)		
3. Venting Powders				
a. Pressurized Powders		1E-1	0.6	Sutter 8/83 Ballinger et als. 5/87
b. Pressurized Gases Through Powders		1.1E-3	0.9	Sutter 8/83
4. Explosive Dispersal	parallel flow	5E-3	0.2	
5. Surface Contamination, powder on smooth, unyielding, non-reactive surfaces ...				
a. Aerodynamic entrainment		(see subsect. E.1)		
b. Suspension by shock/vibration		1E-3	1.0	
c. Suspension by heat		2E-3/h	0.01	

Nuclear Criticality

1. Fuel Processing Plant	USNRC Reg Guide 3.33 April 1977
2. Uranium Fuel Fabrication	USNRC Reg Guide 3.34 July 1979a
3. Plutonium Processing and Fuel Fabrication	USNRC Reg Guide 3.35 July 1979b

* Total fraction airborne in respirable size fraction due to aerodynamic entrainment (resuspension) can not exceed total fraction of particles in respirable fraction in source powder unless mechanism for particle subdivision can be shown.

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EPA-450/3-87-026

Hazardous Waste Treatment, Storage and Disposal Facilities (TSDF) — Air Emission Models

Emission Standards Division

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Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park NC 27711

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2. Compute the decay constant, λ (mo^{-1}) (Equation (6-13)):

$$\lambda = 2.63 \times 10^{6}\ E_i^*/M_{oi}$$

$$\lambda = (2.63 \times 10^{6})(0.413\ g/s)/1.50 \times 10^{10}\ g$$

$$\lambda = 7.25 \times 10^{-5}\ mo^{-1}\ .$$

3. Compute the instantaneous emission rate, E_i, in Mg/yr, after 1 yr (Equation (6-12)):

$$E_i(t) = 31.56\ E_i^*\ \exp(-\lambda t)$$

$$E_i = (31.56)(0.413\ g/s)\ \exp(-7.25 \times 10^{-5}\ mo^{-1} \times 12\ mo)$$

$$E_i = 13.0\ Mg/yr\ .$$

i. Compute the average emission rate in the first year, E_{Ai}, in Mg/yr (Equation (6-15)):

$$E_{Ai}(t) = \frac{31.56\ E_i^*}{\lambda t}\left[1 - e^{-\lambda t}\right]$$

$$E_{Ai} = \frac{(31.56)(0.413\ g/s)}{(7.25 \times 10^{-5}\ mo^{-1})\ (12\ mo)}\left[1-\exp\left[-12\ mo \times 7.25 \times 10^{-5}\ mo^{-1}\right]\right]$$

$$E_{Ai} = 13.0\ Mg/yr\ .$$

6.3 FIXATION PITS

6.3.1 Emission Model Equations

The open dump model is used to estimate air emissions of the constituent of interest from open waste sources that, for the duration of the emission calculation, may be considered to have an effectively constant concentration of the constituent of interest in the waste surface layer. An example of such sources is waste fixation pits (the fixation operation is of short duration, approximately 2 h, and includes stirring the mixture).

It is the purpose of this section to describe the model, its history, and inherent assumptions.

A previous EPA study[28] that identified and evaluated models for estimating emissions from hazardous waste TSDF identified only one model (the open dump model) pertaining directly to uncovered waste. The open dump model is based originally upon the work of Arnold,[29] who applied unsteady-state diffusion theory to the case of diffusion into still air at constant pressure from a liquid surface at which the concentration of a volatilizing liquid remained constant. Convection was assumed to be absent. (This configuration, referred to as the "semi-infinite column," can be approximated in practice by the vaporization of a liquid into a cylinder of sufficient height such that vapor does not reach the top during the experiment.) Arnold's solution provided the cumulative vapor release from the surface as a function of time. Arnold noted, however, that the Fick's law solution was not rigorously correct because Fick's law does not account for the displacement of the inert gaseous medium (air) by the volatilizing vapor. Arnold thus presented the Fick's law solution with a correction factor (derived from a more rigorous treatment) to account for this effect:

$$V = 2y^{*}A\sqrt{\frac{Dt}{\pi F_v}} \qquad (6\text{-}16)$$

where

V = volume of vapor released at ambient pressure and temperature, cm^3

y^* = equilibrium mole fraction of the volatilizing constituent in the gas phase at the liquid-gas interface

A = area of the liquid surface, cm^2

D = diffusivity of volatilizing constituent in air, cm^2/s

t = time, s

F_v = correction factor for Fick's law

π = 3.1416.

The correction factor, F_v, is dependent solely upon y^*. It is presented in tabular form in Table 6-3 and in graphical form in Figure 6-1.

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TABLE 6-3. FICK'S LAW CORRECTION FACTOR[30] AS A FUNCTION OF y^*

y^*	F_v
0	1
0.05	0.9635
0.10	0.9268
0.15	0.8900
0.20	0.8527
0.25	0.8152
0.30	0.7774
0.35	0.7391
0.40	0.7004
0.45	0.6613
0.50	0.6215
0.55	0.5810
0.60	0.5398
0.65	0.4976
0.70	0.4540
0.75	0.4088
0.80	0.3616
0.85	0.3112
0.90	0.2546
0.95	0.1893
1	0
x	y

$$m = \frac{RISE}{RUN} = \frac{\Delta y}{\Delta x} = \frac{(.7391 - .2546)}{(.35 - .90)} = \frac{.4845}{-.55} = -.881$$

$$y = mx + b$$

$$.7391 = (-.881)(.35) + b$$

$$1.0475 = b$$

thus $y = (-.881)x + 1.0475$

or $F_v = (-.881)y^* + 1.0475$

F_v Approximation

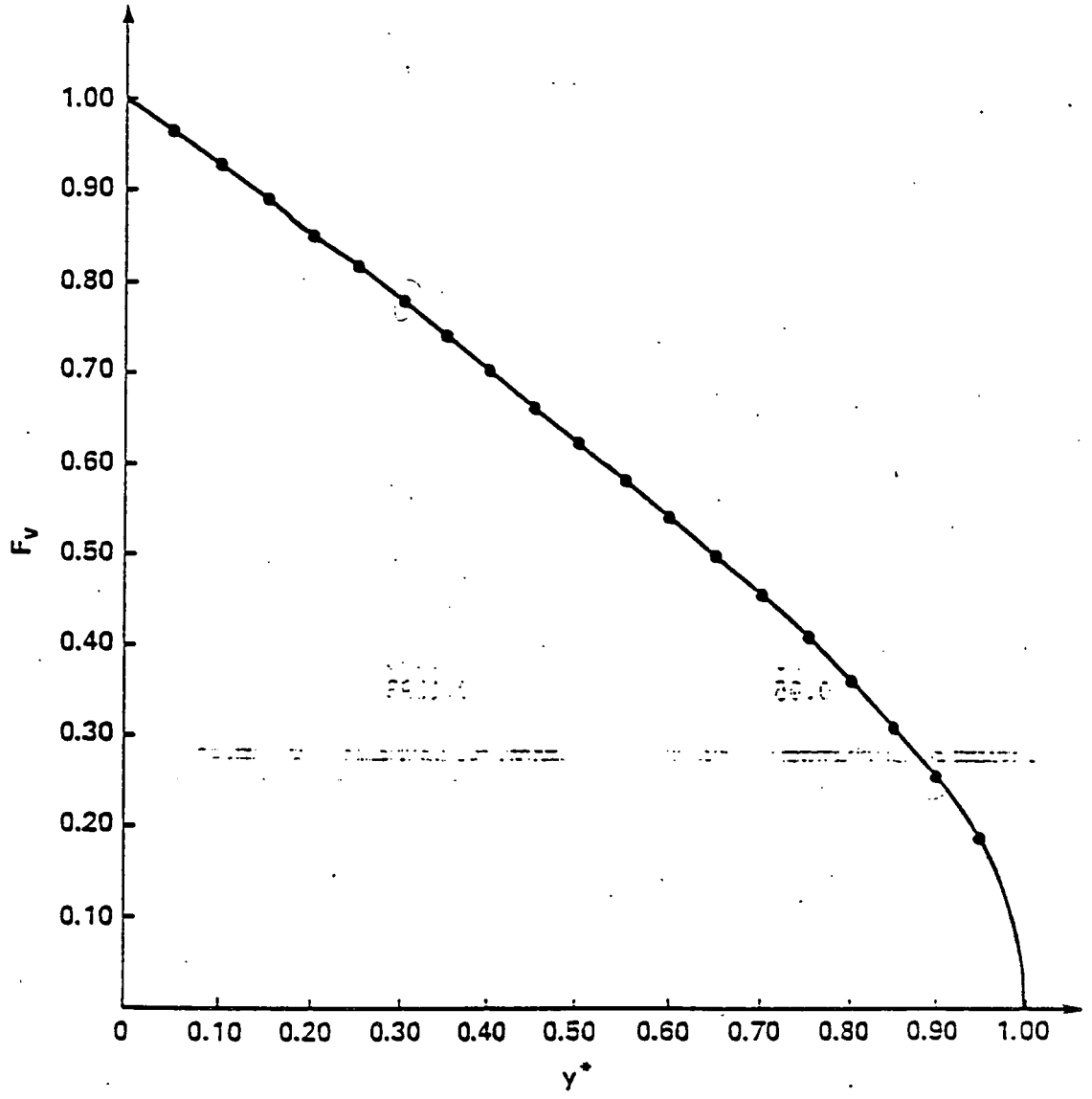

Figure 6-1. Fick's law correction factor F_v as a function of y^*.[31]

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The equation was subsequently modified,** as indicated by Shen,[32] to yield an expression for the average rate of vapor release in terms of windspeed. Shen generalized the expression to account for more than one constituent in the liquid through the incorporation of a weight fraction term for the constituent of interest. (Subsequent analysis indicates that this term is expressed more accurately as a mole fraction of the constituent of interest.)

The resulting equation may thus be expressed as:

$$\left.\frac{dV_i}{dt}\right|_{avg} = 2y_i^* w \sqrt{\frac{D_i l U}{\pi \bar{r}_v}} \qquad (6\text{-}17)$$

where

$\left.\frac{dV_i}{dt}\right|_{avg}$ = average emission rate of the constituent of interest from the surface at ambient pressure and temperature, cm^3/s

y_i^* = equilibrium mole fraction of the i-th constituent in the gas phase

w = width of volatilizing surface perpendicular to the wind direction, cm

l = length of volatilizing surface, parallel to the wind direction, cm

U = windspeed, cm/s.

The calculation of y_i^* varies (for a multicomponent liquid), depending upon whether volatilization from the liquid is governed by Raoult's law or Henry's law. If Raoult's law applies (i.e., if the waste is a two-phase liquid or an organic liquid):

$$y_i^* = X_i P_i^* / P_o \qquad (6\text{-}18)$$

**Modifications included (1) taking the time derivative (to produce a rate expression), (2) making a change of variables by substituting t = x/U (an expression for time expressed in terms of position "x" along the length of the dump and windspeed U), and (3) integrating along the length of the surface to yield the total emission rate. The change of variables represents an attempt to deal with convective air flow.

where

X_i = mole fraction of the i-th constituent in the organic phase

where

$X_i = (C_i/MW_i)/[C_i/MW_i + C_{oil}/MW_{oil}]$

where

C_i = weight fraction of constituent i in the original waste liquid

MW_i = molecular weight of constituent i, g/g mol

C_{oil} = weight fraction of oil carrier-liquid in the original waste liquid

MW_{oil} = molecular weight of oil carrier-liquid (g/g mol)

P_i^* = pure component vapor pressure of the i-th constituent, mm Hg

P_o = atmospheric pressure, mm Hg.

If Henry's law applies:

$$y_i^* = 55{,}555\ X_i H_{ci} \qquad (6\text{-}19)$$

where

X_i = mole fraction of constituent i in the aqueous liquid

where

$X_i = (C_i/MW_i)/[C_{H_2O}/18 + C_i/MW_i]$

where

C_i = weight fraction of constituent i in the original waste liquid

C_{H_2O} = weight fraction of water in the original waste liquid

MW_i = molecular weight of constituent i, g/g mol

H_{ci} = Henry's law constant for the i-th constituent in the liquid, $m^3 \cdot atm/mol$

55,555 = conversion factor, g mol water/m^3.

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The volumetric emission rate (cm^3/s) presented in Equation (6-17) pertains to the pure constituent of interest only (per the principle of partial volumes) at ambient pressure (total pressure) and temperature. The mass emission rate of the constituent of interest may be obtained by multiplying by its gas density, as computed from the ideal gas law:

$$\rho_i = \frac{P_o MW_i}{RT} \tag{6-20}$$

where

ρ_i = gas density of the pure constituent of interest at system pressure and temperature

P_o = total system pressure (ambient pressure), mm Hg

MW_i = molecular weight of constituent i, g/g mol

R = ideal gas constant, 62,300 mm Hg•cm^3/g mol•K

T = ambient temperature, K.

The open dump equation in its final form is thus presented as:

$$E_i = \frac{2P_o MW_i y_i^* w}{RT} \sqrt{\frac{D_i l U}{\pi F_v}} \tag{6-21}$$

where

E_i = emission rate of the constituent of interest from the emitting surface, g/s.

Table 6-4 summarizes the model equations.

The open dump model is quite sensitive to the pure component vapor pressure (P_i^*) or Henry's law constant (H_i) for the constituent of interest, the mole fraction of the constituent in the waste (X_i), the molecular weight of the constituent (MW_i), the width of the pit (w) (assumed to be in the direction perpendicular to the wind flow), and the ambient temperature (T). However, because of the wide range of likely values for parameters such as vapor pressure, Henry's law constant, mole fraction of the constituent in the waste, and temperature, these four parameters may have the greatest impact on model sensitivity.

TABLE 6-4. OPEN DUMP MODEL

Emission rate equations

$$E_i = \frac{2\ P_o\ MW_i\ y_i^* w}{RT} \sqrt{\frac{D_i l U}{\pi F_v}}$$

$y_i^* = 55{,}555\ X_i H_{ci}$ (dilute aqueous waste); $y_i^* = \frac{X_i\ P_i^*}{P_o}$ (two-phase liquid or organic liquid waste)

$X_i = (C_i/MW_i)/(C_{H_2O}/18 + C_i/MW_i)$ (dilute aqueous waste liquids)

$X_i = (C_i/MW_i)/(C_i/MW_i + C_{oil}/MW_{oil})$ (two-phase liquid or organic liquid waste)

Variable	Description	Data source
E_i	Emission rate of constituent i, g/s	Calculated
y_i^*	Equilibrium mole fraction of constituent i in the gas phase (dimensionless)	Calculated
P_o	Atmospheric pressure, mm Hg	Literature
MW_i	Molecular weight of constituent i, g/g mol	Data base
MW_{oil}	Molecular weight of oil carrier-liquid in the original waste liquid, g/g mol	Definition or estimated
l	Length of dump in the direction of wind flow, cm	Definition
C_i	Weight fraction of constituent i in the waste liquid (dimensionless)	Definition
C_{H_2O}	Weight fraction of water in the original waste liquid (dimensionless)	Definition
C_{oil}	Weight fraction of oil in the original waste liquid (dimensionless)	Definition
w	Width of dump in the direction perpendicular to the wind flow, cm	Definition
P_i^*	Pure component vapor pressure of constituent i, mm Hg	Data base
R	Universal gas constant, 62,300 mm Hg•cm^3/g mol•K	Literature

(continued)

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TABLE 6-4 (continued)

Variable	Description	Data source
X_i	Mole fraction of constituent i in the aqueous liquid (for dilute aqueous waste) or in the organic phase (for two-phase or organic liquid waste) (dimensionless)	Calculated
D_i	Diffusivity of constituent i in air, cm^2/s	Data base
U	Windspeed, cm/s	Definition
T	Temperature, K	Definition
H_{ci}	Henry's law constant for constituent i, $atm \cdot m^3/g\ mol$	Literature
F_v	Fick's law correction factor (a function of y_i^*)	Tabulated

COMPOUND NAME	DIFF. AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
ACETALDEHYDE	1.24E-01	20.8	8.005	1600.017	291.809
ACETONE	1.24E-01	56.2	7.117	1210.595	229.664
ACROLEIN	1.05E-01	53.0	2.337833		
ACRYLONITRILE	1.22E-01	77.4	7.038	1232.53	222.47
ALLYL ALCOHOL	2.64E-01	97.0	1.367406		
BENZENE	8.80E-02	80.1	6.905	1211.033	220.79
BENZYL CHLORIDE	7.50E-02	179.4	0.082788		
BUTANOL-1	8.00E-02	117.7	7.476	1362.39	178.77
CARBON DISULFIDE	1.04E-01	46.3	6.942	1169.11	241.59
CARBON TETRACHLORIDE	7.80E-02	76.8	6.9339	1242.43	230
CHLOROBENZENE	7.30E-02	132.0	6.978	1431.05	217.55
CHLOROFORM	1.04E-01	61.2	6.493	929.44	196.03
CHLOROPRENE	1.04E-01	59.4	6.161	783.45	179.7
CRESOL(-m)	7.40E-02	202.0	7.508	1856.36	199.07
CRESOL(-o)	7.40E-02	190.8	6.911	1435.5	165.16
CRESOL(-p)	7.40E-02	203.0	7.035	1511.08	161.85
CRESOLS	7.40E-02	195	-0.34469		
CRESYLIC ACID	7.40E-02	225.0	-0.52289		
CUMENE (isopropylbenzene)	6.50E-02	153.0	6.963	1460.793	207.78
CYCLOHEXANONE	7.94E-02	157.0	0.681266		
DICHLOROBENZENE(1,2) (-o)	6.90E-02	179.0	0.176097		
DICHLOROBENZENE(1,4) (-p)	6.90E-02	173.4	0.079184		
DICHLOROETHANE(1,2)	1.04E-01	83.4	7.025	1272.3	222.9
DIMETHYL NITROSAMINE	1.04E-01	153			
DIOXIN	1.04E-01				
EPICHLOROHYDRIN	8.60E-02	117.0	1.230494		
ETHYLACETATE	7.32E-02	77.0	7.101	1244.95	217.88
ETHYLBENZENE	7.50E-02	136.2	6.975	1424.255	213.21
ETHYLENEOXIDE	1.04E-01	10.7	7.129	1054.54	237.76
ETHYLETHER	7.40E-02	34.5	6.92	1064.07	228.8
FORMALDEHYDE	7.40E-02	-14.0	7.195	970.6	244.1
FREONS	1.04E-01	-29.8	3.699106		
HEXACHLOROBUTADIENE	5.61E-02	215.0	-0.82393		
HEXACHLOROCYCLOPENTADIENE	5.61E-02	234.0	-1.09155		
ISOBUTYL ALCOHOL	8.60E-02	107.9	1.000036		
MALEIC ANHYDRIDE	9.50E-02	200.0	-4.00014		
METHANOL	1.50E-01	65.0	7.897	1474.08	229.13
METHYL ACETATE	1.04E-01	54.0	7.065	1157.63	219.73
METHYL ETHYL KETONE	8.08E-02	79.6	6.97421	1209.6	216
METHYL ISOBUTYL KETONE	7.50E-02	115.8	6.672	1168.4	191.9
METHYLENE CHLORIDE	1.01E-01	39.8	7.409	1325.9	252.6
METHYLNAPHTHALENE (1)					
NAPHTHALENE	5.90E-02	218.0	7.01	1733.71	201.36
NITROBENZENE	7.60E-02	210.8	7.115	1746.6	201.8
NITROSOMORPHOLINE	5.90E-02	225			
PHENOL	8.20E-02	182.0	7.133	1516.79	174.95
PHOSGENE	1.08E-01	8.2	6.842	941.25	230
PHTHALIC ANHYDRIDE	7.10E-02	284.0	8.022	2568.5	0
POLYCHLORINATED BIPHENYLS	1.04E-01				
PROPYLENE OXIDE	1.04E-01	33.9	2.719846		
PYRIDINE	9.10E-02	115.5	7.041	1373.8	214.98
TETRACHLOROETHANE(1,1,2,2)	7.10E-02	146.2	6.631	1228.1	179.9
TETRACHLOROETHLYENE	7.20E-02	121.4	6.976	1386.92	217.53
TOLUENE	8.70E-02	110.7	6.954	1344.8	219.48
TRICHLORO(1,1,2)TRIFLUOROETHANE(1,2,2)	7.80E-02	48.0	6.88	1099.9	227.5
TRICHLOROETHANE(1,1,1)	7.80E-02	73.0	8.643	2136.6	302.8
TRICHLOROETHYLENE	7.90E-02	87.0	6.518	1018.6	192.7
TRICHLOROFLUOROMETHANE	8.70E-02	23.8	6.884	1043.004	236.88
VINYL CHLORIDE	1.06E-01	-13.9	3.425008		
VINYLIDENE CHLORIDE	9.00E-02	31.9	6.972	1099.4	237.2
XYLENE(-m)	8.70E-02	144.4	6.998	1474.679	213.69

EXHIBIT A-2 (continued)

Table 2

Computation of Emission Rate According to EPA Method

Release Conditions:

Outdoor release of 220 gal benzene at 70° F

Surface area of spill 340 m^2 (Table 6.2-5)

Diameter of spill area is calculated as:

$$r^2 = \frac{340}{\pi}$$

$$r = 10.4 \text{ m}$$

$$d = 20.8 \text{ m}$$

Wind velocity is 2 m/sec (Table 6.2-4)

Equation:

$$E_i = \frac{2P_o MW_i Y_i^* L}{RT} \left[\frac{D_i Wu}{\pi F_v} \right]^{0.5}$$

where

P_o = atmospheric pressure, 760 mm Hg

MW_i = molecular weight, 78.1 g/mole

Y_i^* = equilibrium mole fraction of the volatilizing constituent in the gas phase at the liquid-gas interface

L = length of spill perpendicular to spill, 2080 cm

R = universal gas constant, 62,300 mm Hg·cm^3/g mole°K

T = 298°K

D_i = diffusion coefficient in air, 0.088 cm^2/sec

W = width of spill parallel to wind direction, 2080 cm

u = surface velocity over liquid, 200 cm/sec

F_v = Fick's Law correction factor (a function of Y_i^*) 0.92 as taken from EPA (1987)

Table 2 (Continued)

$$Y_i^* = X_i \frac{P_i}{P_o}$$

where

X_i = mole fraction, assumed 1 for single compound
P_i = vapor pressure of benzene, 95.2 mm Hg
P_o = atmospheric pressure, 760 mm Hg
Y_i^* = 0.125

$$E_i = \frac{2(760)(78.1)(0.125)(2080)}{(62300)(298)} \left[\frac{(0.088)(2080)(200)}{\pi(0.92)}\right]^{0.5}$$

E_i = 186.8 g/sec

Expressed as per m^2: $\frac{186.8}{340\ m^2}$ g/sec = 0.55 g/sec/m^2

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WESTINGHOUSE ENVIRONMENTAL
MANAGEMENT COMPANY OF OHIO

Safety Procedures	Title: Preparation of Safety Assessments	SP-A-01-013 Department: IRS&T Section: N&SS
Authorization:		Supersedes: Rev. 0 Rev. Date: 09/16/92

1.0 PURPOSE

The purpose of this procedure is to assign responsibilities and establish the procedure to perform safety assessments (SAs) for all Department of Energy (DOE) operations at the Fernald Environmental Management Project (FEMP). The SA documentation process shall be used as follows to:

- Identify potential hazards early in the design phase of a proposed DOE operation;
- Determine whether or not a proposed or existing DOE operation is a Nuclear Facility and, if so, what type of Special Facility category applies to it;
- Set the preliminary design criteria for proposed DOE operations;
- Determine the hazard classification of all existing and proposed DOE operations;
- Determine the rigor of safety analysis documentation required for a given DOE operation and the subsequent safety documentation review and approval levels; and
- Determine the authorization level required to start-up new DOE operations.

2.0 SCOPE

This procedure establishes a methodology and provides guidance for the preparation of SAs, and applies to the design and operation of all facilities or activities which are managed by the Westinghouse Environmental Management Company of Ohio (WEMCO). This procedure is for use by originators of the SAs.

3.0 DEFINITIONS

3.1 Design Basis Accident (DBA) - Postulated accidents or natural forces, and resulting conditions, for which the confinement structure, systems, components, and equipment must meet their functional goals.

These "Safety Class Items" are necessary to ensure the capability to:

a. Safely shut down operations, maintain the plant in a safe shutdown condition, and maintain integrity of the final confinement barrier of radioactive or other hazardous materials;

b. Prevent or mitigate the consequences of accidents; or

c. Monitor releases that could result in potential off-site exposures.

Design Basis Accidents include Design Basis Earthquakes. Design Basis Fires, Design Basis Floods, and Design Basis Tornados (or Wind), as well as factors governing other types of accident scenarios such as nuclear criticality or explosion. (DOE 6430.1A)

3.2 Design Basis Criticality (DBC) - A nuclear criticality event that is the most severe design basis accident of that type applicable to the area under consideration. (inferred by DOE 6430.1A)

3.3 Design Basis Earthquake (DBE) - An earthquake that is the most severe design basis accident of this type, and that produces the vibratory ground motion for which the items designated as SC-1 for that facility are designed to remain functional. A DBE is equivalent to a "safe shutdown earthquake." (DOE 6430.1A)

3.4 Design Basis Explosion (DBEX) - An explosion that is the most severe design basis accident of that type applicable to the area under consideration. (inferred by DOE 6430.1A)

3.5 Design Basis Fire (DBF) - A fire that is the most severe design basis accident of this type. In postulating such a fire, failure of automatic and manual fire suppression provisions shall be assumed except for those Safety Class Items that are specifically designed to remain available (structurally or functionally) through the event. (DOE 6430.1A)

3.6 Design Basis Flood (DBFL) - A flood that is the most severe design basis accident of that type applicable to the area under consideration. (DOE 6430.1A)

3.7 Design Basis Tornado (DBT) - A tornado that is the most severe design basis accident of that type applicable to the area under consideration. Criteria for DBT may be related to that of DBW for a given facility. (DOE 6430.1A)

3.8 Design Basis Wind (DBW) - A wind that is the most severe design basis accident of that type applicable to the area under consideration. Criteria for DBW may be related to that of DBT for a given facility. (DOE 6430.1A)

3.9 DOE Operations - All activities for which DOE has assumed ES&H responsibility, regardless of whether or not there is a facility involved. Thus, the transportation of hazardous materials is included in this definition. Those activities for which DOE has assumed ES&H responsibility can be determined by the contract provisions. (DOE 5481.1B)

3.10 Facility - Buildings and other structures, their functional systems and equipment, and other fixed systems and equipment installed therein; outside plant, including site development features such as landscaping, roads, walks, and parking areas; outside lighting and communications systems; central utility plants; utilities supply and distribution systems; and other physical plant features. Generally, a facility is a collection of buildings, processing equipment, and other supporting units (e.g. SOPS) which:

a. Share a common mission,

b. Are under single operational management,

c. Share a common discharge point (e.g. stack), or

d. Are located within the same area (e.g. fence, yard, pad, etc.).

The Facility Hazard Classification shall be designated for a facility based upon this definition. See also, "Segment." (DOE 6430.1A)

3.11 Facility Use Category - The category assigned to a facility which determines the structural design requirements that facility must meet. Category determination is based upon the importance assigned to the function of the facility or the hazard presented by the facility. These Facility Use Categories, which may be applied to nuclear and non-nuclear facilities alike, are as follows:

a. General Use - Facilities which have a non-mission dependent purpose, such as administration buildings, cafeterias, storage, and maintenance and repair facilities which are plant or grounds oriented. Design for General Use Facilities falls under aegis of the Uniform Building Code.

b. Important or Low Hazard - Facilities which have mission dependent use (e.g., laboratories, production facilities, and computer centers) and emergency handling or hazard recovery centers (e.g., hospitals, fire stations).

c. Moderate Hazard - Facilities where confinement of contents is necessary for public or employee protection. Examples would be

uranium enrichment plants, or other facilities involving the handling or storage of significant quantities of radioactive or hazardous materials.

d. High Hazard - Facilities where confinement of contents and public and environmental protection are of paramount importance (e.g., facilities handling substantial quantities of in-process plutonium or fuel reprocessing facilities). Facilities in this category represent hazards with potential long-term and widespread effects. (UCRL-15910) R

3.12 Generally Accepted - Hazards which are routinely encountered in industry and accepted without question by the vast majority of persons. Included in this category are hazards commonly associated with General Use Facilities. (DOE 5481.1B, Inferred by UCRL-15910)

3.13 General Use Facilities - Facilities which have a non-mission dependent purpose, such as administration buildings, cafeterias, storage, maintenance, and repair facilities which are plant or grounds oriented. General Use facilities normally involve hazards which are considered Generally Accepted. (UCRL-15910, Inferred by DOE 5481.1B)

3.14 Hazard Classification - The screening process used to ensure that the depth and rigor of safety analysis required for any DOE operation is proportional to the risk presented by that operation. These hazard classes, which are applied to nuclear and non-nuclear facilities alike, are as follows:

a. Generally Accepted - Those operations which present hazards which are routinely encountered in industry and accepted without question by the vast majority of persons.

b. Low - Those operations which present minor on-site and negligible off-site impacts to people or the environment.

c. Moderate - Those operations which present considerable potential on-site impacts to people or the environment, but at most only minor off-site impacts.

d. High - Those operations with the potential for on-site or off-site impacts to large numbers of persons or for major impacts to the environment. (DOE 5481.1B)

3.15 Limits - Several established limits are used to delineate the boundaries between the different hazard categories for both on-site and off-site. These limits are applied as a screening mechanism and do not represent absolute risk. Among these limits are:

a. Threshold Limit Values (TLVS) - TLVs refer to airborne concentrations of substances and represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects.

b. Immediately Dangerous to Life and Health (IDLH) - The maximum airborne concentration of a substance to which a healthy worker can be exposed for 30 minutes and escape without suffering irreversible health effects or escape-impairing symptoms.

c. Lethal Dose (LD50) - The dose level to a target population which is expected to result in the death of 50-percent of the population.

3.16 Non-Standard Hazards - Hazards which are not routinely encountered or accepted in the course of everyday living by the vast majority of the general public. DOE operations which present non-standard hazards are categorized as High, Moderate, or Low Hazard facilities via the Hazard Classification process. (Inferred by DOE 5481.1B)

3.17 Nuclear Facility - A facility whose operations involve radioactive materials in such form and quantity that a significant nuclear hazard potentially exists to the employees or the general public. Included are facilities that:

a. Produce, process, or store radioactive liquid or solid waste, fissionable materials, or tritium;

b. Conduct separations operations;

c. Conduct irradiated materials inspection, fuel fabrication, decontamination, or recovery operations; or

d. Conduct fuel enrichment operations. Incidental use of radioactive materials in a facility operation (e.g., check sources, radioactive sources, and X-ray machines) does not necessarily require the facility to be included in this definition. Accelerators and reactors and their operations are not included in this definition. (DOE 5480.5)

DOE 6430.1A "General Design Criteria" further clarifies this definition by specifying the types of facilities that are to be considered as nuclear facilities in Division 13, "Special Facilities," 1300-1.1 which covers non-reactor nuclear facilities and explosives facilities. (DOE 6430.1A)

3.18 Preliminary Hazard Analysis (PHA) - An analytical tool usually used early in the life of a project to identify hazards, potential causes and consequences, and preventive/mitigative measures. (MIL-STD-882B) | R

3.19 Project Authorization (PA) - A document which describes a proposed project and requests approval by valid authority.

3.20 Safety Analysis - A documented process to:

a. Provide systematic identification of hazards within a given DOE operation; | R

b. Describe and analyze the adequacy of measures taken to eliminate, control, or mitigate identified hazards; and

c. analyze and evaluate potential accidents and their associated risks. (DOE Order 5480.23) R

3.21 Safety Analysis Report - A report which documents the adequacy of safety analysis for a nuclear facility to ensure that the facility can be constructed, operated, maintained, shut down, and decommissioned safely and in compliance with applicable laws and regulations. (DOE Order 5480.23) R

3.22 Safety Assessment (SA) - A brief, factual, and objective document which determines if activities involve hazards -- other than those standard to industry -- that require elimination, control, or mitigation, thereby establishing the need for a safety analysis report. R

3.23 Safety Class Items - Systems, components, and structures, including portions of process systems, whose failure could adversely affect the environment or the safety and health of the public or workers. Determination of classification is based on analysis of the potential abnormal and accidental scenario consequences as presented in the Safety Analysis Report. Safety Class Items provide functional and/or structural integrity for mitigation of event severities up to and including Design Basis Accidents. Safety Class Items were formerly referred to as Safety Systems and Design Features for Safety. (DOE 6430.1A, DOE/TIC-11603) R

3.24 Segment - A distinct portion of a Facility. The following engineering criteria shall be considered in the division of a facility into distinct segments:

a. Structural independence,

b. Process independence (e.g. isolation of process and support systems),

c. Proximity, and

d. Other factors related to common cause.

3.25 Special Facilities - Specific types of facilities that are to be considered as nuclear facilities. These facilities are listed in DOE 6430.1A "General Design Criteria," Division 13, Section 1300-1.1 (refer to Attachment A). (DOE 6430.1A)

4.0 RESPONSIBILITIES

4.1 Manager, Environmental Management (EM) - Has primary responsibility for implementation of the Safety Analysis Documentation Program. R

4.2 Manager, Nuclear and System Safety (N&SS) - Responsible for an evaluation of existing and proposed facilities to determine the risk of operation and for generation of the resultant SAs and SARs.

4.3 Chair - ISR Committee - Presides over an objective and independent multi-disciplinary review of Safety Analysis Documentation to ensure that the various documents are thorough, accurate, and are consistent with each other and satisfy the requirements of this program.

4.4 All Staff Managers - Support the Safety Analysis Documentation Program by providing information essential in the preparation of Safety Assessments for projects and facilities under their jurisdiction. R

5.0 GENERAL

There are two decisions that are made early in the life cycle of a new project, to significant modification to an existing plant or process, or to the initial analysis of an existing plant or process that are of importance to the iterative design and safety analysis processes. They are:

a. Will the project or existing facility be classified as a Nuclear Facility subject to the Special Facility design requirements of DOE Order 6430.1A, Division 13 (and the "-99" sections of the other divisions of 6430.1A); and the requirements of DOE Order 5480.5; and

b. What is the Facility Hazard Classification (Generally Accepted, Low, Moderate, or High) for both nuclear and non-nuclear facilities?

The concepts applied in these two questions are also related to two other concepts: Facility Use Category and Safety Class Items. Because of the important interactive relationship between the design, construction, and operation process and the safety analysis process, one must have a clear understanding of each of these concepts and their interrelationship.

5.1 DOE Orders and Implications

The requirements for the Safety Analysis and Review System are contained in DOE 5481.1B, and DOE Order 5480.23. The purpose of the Safety Analysis and Review System, as stated in DOE 5481.1B, is "to establish requirements for the preparation and review of safety analyses of Department of Energy (DOE) operations, including identification of hazards, their elimination or control, assessment of the risk, and documented management authorization of the operation. Detailed requirements for the review and authorization processes for nuclear facilities and reactors are addressed in DOE 5480.5 and DOE 5480.6." R

The extent of applicability of the Safety Analysis and Review System is defined in DOE 5481.1B, Chapter II, which reads as follows:

a. DOE operations, as defined, embraces all activities for which DOE has assumed ES&H responsibility, regardless of whether or not there is a facility involved. Thus, the transportation of hazardous materials is included. Those activities for which DOE has assumed ES&H responsibility can be determined by the contract provisions.

b. Recognizing that no activity is without some degree of risk, and that certain routine risks are accepted without question by the vast majority of persons (e.g., machine shops which do not handle hazardous materials, cars for personal transportation), the applicability of this Order has been limited to those DOE operations that involve hazards that are not routinely encountered and accepted in the course of everyday living by the vast majority of the general public.

By definition, the FEMP is a DOE operation. Therefore, the requirements of the Safety Analysis and Review System are applicable to the FEMP.

DOE Order 5481.1B provides further guidance for the categorization of DOE operations into three hazard classes. This screening process serves to ensure that the depth and rigor of safety analysis required for any operation is proportional to the risk presented by that operation.

These hazard classes are:

a. Low - Those (operations) which present minor on-site and negligible off-site impacts to people or the environment;

b. Moderate - Those (operations) which present considerable potential on-site impacts to people or the environment, but at most only minor off-site impacts;

c. High - Those (operations) with the potential for on-site or off--site impacts to large numbers of persons or for major impacts to the environment.

It should be noted that the extent of safety analysis required for a given facility may be specified by other DOE Orders, thus superseding this decision-making process for some facilities. For example, low level radioactive waste treatment facilities (such as the Advanced Wastewater Treatment Facility) or long-term, low-level radioactive waste storage facilities, automatically (without regard to hazard level) require a SAR per Chapter III of DOE Order 5820.2A, RADIOACTIVE WASTE MANAGEMENT.

DOE 5481.1B further requires that existing facilities or operations be compared against current design criteria. Where safety analysis demonstrates a degree of risk from lack of compliance to those criteria, appropriate backfitting of those facilities or operations to eliminate,

control, or mitigate those risks must be undertaken. The continued operation of those facilities or operations without backfitting must be justified. The current technical criteria to which this comparison must be made is found in DOE 6430.1A, GENERAL DESIGN CRITERIA.

The assignment of the Nuclear Facility designation per DOE 5480.5 has definite impacts relative to the application of DOE 6430.1A. In general, DOE 6430.1A applies to all DOE facilities. However, certain criteria apply only to "those facilities identified as Special Facilities." In general, the criteria for Special Facilities are considered to be good design practices for dealing with radioactive materials (e.g. ventilation systems, containment philosophy). Thus, for each Nuclear Facility (regardless of Facility Hazard Classification) the intent is that the requirements related to Special Facilities be addressed for applicability. The expectation is that all applicable design requirements be met, unless justification for not meeting a specific criterion is provided in the SAR (refer to DOE 6430.1A).

Certain key structural design criteria are dependent upon the hazard class of a facility. In the case of a proposed facility, an SA would determine those criteria which must be incorporated into the structural design of the project and the subsequent engineered systems or features which are determined to be Safety Class Items. An existing facility would be evaluated to determine the criteria to which it must be compared in the subsequent SAR.

5.2 Purpose of the Safety Assessment Process

The SA is the first step in the safety documentation process. The findings of a SA determine the future course of action for safety documentation. The SA is a brief, factual, and objective document that determines if facilities involve hazards that require elimination, control, or mitigation, thereby establishing whether or not further documentation, in the form of a SAR is needed. SAs shall be prepared in conformance with information provided in DOE Order 5481.1B and other applicable DOE Orders, using the guidance provided by this procedure and FMPC-2116. | R

It is required that an SA be prepared for all FEMP facilities, projects, and activities to determine and document the presence of hazards unique to DOE operations or not readily accepted by the public or commonly encountered by industry. If a project/activity is subdivided into subprojects or a work breakdown structure (WBS), an SA may be prepared for each subproject or element of the WBS (as needed). If the SA identifies the facility/operation as Moderate-hazard or High-hazard, detailed accident analyses shall be performed, using accepted methodology, and documented in a formal PSAR, and subsequent FSAR/OSR document. When a PSAR is required, an FSAR/OSR will also be required. | R

DOE approval is required for PSARs and FSARs/OSRs. SAs for projects are normally submitted for DOE review along with the Conceptual Design Report or Project Authorization. The PSAR is begun during the Conceptual

Design Report phase of a project, evolves as the project design is developed, and is submitted with the Design Criteria. The PSAR forms the basis of the subsequent FSAR/OSR document. The FSAR/OSR document is submitted approximately two months prior to anticipated start-up of the subject facility or facility modification.

It is essential that non-standard hazards are identified early in the design process for new facilities and operations, or for modifications to existing facilities and operations, to allow for adequate funding for the incorporation of Safety Class Items as part of the original facility design criteria. Early identification of hazards also allows for development of appropriate administrative controls and other operational prerogatives that will complement facility design to reduce the risk of operation.

SAs prepared for existing facilities are used to identify the need for (or possible existing presence of) Safety Class Items or Administrative Controls needed to achieve an adequate level of safety. When a need has been identified, the subsequent safety documentation (an FSAR) may serve as a basis to prepare design changes. No PSAR is required for an existing facility. When modifications are made to an existing facility where an FSAR is already in existence, that FSAR will be revised on a timely basis such that the revisions are in place prior to operating the facility as modified. The following determinations shall be made in an SA:

a. The types of non-standard hazards (if any) associated with the facility;

b. The Facility Hazard Classification (Generally Accepted, Low, Moderate, or High) based upon the non-standard hazards presented by the facility;

c. The nature of the facility (i.e. is the facility a non-reactor nuclear facility and, if so, what type of Special Facility category applies?);

d. The structural design criteria, based upon the Facility Hazard Classification and the type of Special Facility; and,

e. The adequacy of the existing safety documentation (if any) for the facility as relates to both the Facility Hazard Classification and the backfitting requirements of DOE 5481.1B.

5.3 Facility Identification and Segmentation

The first step in the safety assessment process is to identify the facility in question. For a project involving the construction of a new facility, this may entail nothing more than defining the size of the "box" to be drawn around the project. If a project involves the modification of an existing facility, the project must be assessed based

upon its impact on the existing facility. Several factors affect the decision on what constitutes a facility. This decisionmaking process becomes complicated when considering how best to analyze complex, multi-purpose facilities. In general, a facility is regarded as a collection of buildings, processing equipment, and other supporting units (e.g. SOPS) which:

a. Share a common mission,

b. Are under single operational management,

c. Share a common discharge point (e.g. stack), or

d. Are located within the same area (e.g. fence, yard, pad, etc.) or building structure.

A facility may be divided into several distinct segments. The following engineering criteria shall be considered in the division of a facility into distinct segments:

a. Structural independence,

b. Process independence (e.g. isolation of process and support systems),

c. Proximity, and

d. Other factors related to common cause.

The object of dividing a facility into segments is to apply the higher levels of structural design criteria only to those portions of a facility which truly require them. In order for the segmentation of a facility to work correctly, the failure of a segment cannot adversely impact the survivability of other segments within the facility which have been assigned higher levels of structural design criteria.

An example of a properly segmented facility is as follows. The proposed (fictitious) Omega Facility at the FEMP is designed to be a finishing, inspection, and shipping facility for enriched (2.5%U) uranium metal reactor components. The facility is comprised of four distinct units, all of which contribute to the common mission of the facility. These are:

a. An administrative office area, designated "W";

b. A metals finishing, inspection, packaging, and storage area, designated "X";

c. A gamma radiography cell, designated "Y"; and

d. A satellite RCRA accumulation shed and shipping pad, designated "Z".

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Each area is proposed to be structurally independent of the others. Common walls will be designed to the highest hazard level of the contiguous areas. The failure of one area will not cause the failure of an adjoining area with a higher Facility Hazard Classification. This design allows each of the areas (W, X, Y, and Z) to be considered as separate segments.

If a facility is divided into segments, each segment will be subjected to the Facility Hazard Classification process, and the structural design criteria will be identified separately for each. The overall Facility Hazard Classification will be based upon the highest Facility Hazard Classification of its component segments. The SAR for a facility shall include all of the segments within the facility boundary.

5.4 Guidelines for Hazard Identification

The next step in the SA process is to identify the raw, unmitigated, non-standard hazards presented by the proposed or existing facility. The purpose of this exercise is to determine the sources of unwanted energies which may impact upon the workers, public, or environment. The potential hazards are usually identified from lists of potentially hazardous materials, energy sources, and equipment. A list of this type of information for use as a reference source is presented as Attachment B.

Identifying hazards typically consists of a "brainstorm" process where no attempt is made to analyze "on-the-spot" any of the identified hazards. Strong consideration should be given to a team approach using appropriate knowledgeable people from various organizations in the brainstorming session. No credit is taken for mitigating factors such as engineered systems or structures (including Safety Class Items) or personnel actions. The result is a raw list of potential hazards which the analyst will screen to identify those source terms to be used in the Facility Hazard Classification process.

The screening technique most applicable to this initial analysis of a project or existing facility is the Preliminary Hazard Analysis (PHA). The PHA is part of the U.S. Military Standard System Safety Program Requirements (MIL-STD-882B). The PHA is used to recognize hazards early, thus saving time and cost which could result from major plant backfitting if hazards are discovered at a later stage. Many chemical companies use a similar procedure under a different name. It is generally applied during the conceptual design phase of a process plant, and can be very useful in site selection.

The PHA is a precursor to further hazard analyses. It provides a cost-effective, early-in-plant-life method for hazard identification. The PHA is intended for use in the preliminary phase of plant development where past experience provides little or no insight into any potential safety problems. e.g. a new plant-with a new process.

The PHA focuses on the hazardous materials and major plant elements since few details of the plant design are available, and there is likely not to be any information on procedures. The PHA is also considered to be a review of where energy can be released in an uncontrolled manner. This is where the PHA is also suitable for the initial screening of existing plants and processes, where a review of unmitigated hazard is necessary before determining whether mitigators are adequately provided for that facility.

The PHA consists of formulating a list of the hazards related to:

a. Raw materials, intermediate and final products, and their reactivity,

b. Plant equipment,

c. Interface among system components,

d. Operating environment (operational goals, performance requirements, etc.),

e. Operations (test, maintenance, etc.),

f. Facility, and

g. Safety equipment.

These Hazards are then analyzed by determining the Causes and Major Effects resulting from each cause. The radiological, chemical, and other hazard information is then used to determine the Facility Hazard Classification by utilizing the methodology stated in Section 5.5.

Where Mitigative Measures have been identified for these Causes in the design or are present in the existing facility, these are also listed in a PHA. However, as stated before, no credit is claimed for these items in the analysis.

Where Mitigative Measures have not been identified for these Causes in the design or in the existing facility, then guidance for appropriate mitigators should be provided in the "Conclusions" section of the SA. These are derived from DOE Orders (e.g. DOE 6430.1A), DOE guidance documents (DOE/TIC-11603, Rev. 1), engineering standards and judgement, and past, related/relevant experience.

5.5 Guidelines for Facility Hazard Classification

Facility Hazard Classification is based on the hazard potential of the activity in question without consideration of any mitigation such as would be provided by the structure of the facility or engineered safety features. However, it is implicit that at least a conceptual design of the process and location be utilized in making the determination. This is necessary to ensure that the appropriate physical forms and

quantities of materials, as well as site-specific conditions such as meteorology, are considered. It is also necessary to ensure that all of the energies available for dispersing toxic or radioactive materials are considered.

The DOE order defines low, moderate, and high hazard classes based on the potential for impact both on-site and off-site. The assignment of these hazard classes is based on the assumption that the facilities being reviewed involve hazards not routinely encountered and accepted by the public (i.e. "non-standard" hazards). Hazards which are routinely encountered and accepted by the public are categorized as "standard" or "generally accepted" hazards. A list of those types of facilities which may usually be categorized as "generally accepted" is given as Attachment C. The definitions for low, moderate, and high are vague and do not provide clear-cut dividing lines between hazard classes. The more specific modeling, assumptions, and numerical criteria presented below are intended to clarify the DOE definition and provide supportable, quantifiable criteria.

The impacts to be considered in this process shall consist of radiological impacts, non-radiological impacts (e.g. release of toxic materials), and unplanned nuclear criticalities.

Because the Facility Hazard Classification does not consider mitigating factors (i.e. facility structure, engineered safety features, or administrative controls), the proposed dividing lines between hazard classes can be misinterpreted as being approval of unacceptable consequences from operation of the facility. This is not the case. Rather, the Facility Hazard Classification assures the appropriate level of review of the raw hazard and the factors proposed to mitigate the raw hazard. It is not an indication of acceptability of risk, as risk is not determined at this stage of the safety analysis process.

The interaction between Facility Hazard Classification and facility design is discussed in Section 5.5.2. In brief, the hazard class of a facility, through its relation to the Facility Use Category, defines structural design criteria for those features which can affect the mitigation of the hazard. This would include both the features which directly provide mitigation and those whose failure could cause a failure of the mitigating feature. This is essentially the equivalent of Safety Class Items. The design of those features which do not affect the mitigation of hazards is not influenced by the Facility Hazard Class.

In general, the methodology employed to determine the Facility Hazard Classification shall evaluate accidents using site-specific parameters such as climatology, hydrology, and seismology, as well as the physical constraints inherent in the process, such as material form and particle size.

5.5.1 Assumptions and Models for Facility Hazard Classification

As the Facility Hazard Classification shall be based upon the numerical criteria specified in Section 5.5.1.4, it will be necessary to perform numerical analyses to quantify the hazards. The assumptions and models recommended here are generally very conservative, and the resultant hazard values are expected to be much greater than consequence values typically presented in SARS. The following assumptions and models are recommended for the Facility Hazard Classification process.

5.5.1.1 General Assumptions:

a. A facility may be divided into portions or segments for the purpose of Facility Hazard Classification if the hazard sources in the facility can be clearly separable by structural division and there is no synergism between the hazard sources.

b. The analysis shall be performed for each portion or segment, and the resulting Facility Hazard Classification shall be the basis for determining the structural design requirements per DOE 6430.1A.

c. If a facility consists of segments with a different Hazard Classification for each segment, the highest Hazard Class for the segments shall be the overall Facility Hazard Classification for the purpose of implementing DOE 5481.1B.

5.5.1.2 Assumptions and Models for Radiological and Chemical Hazards:

a. Hazard source inventories shall be based on the maximum processing and storage capacities.

b. Inherent physical, chemical, and radiochemical characteristics associated with hazard source materials shall be considered for the atmospheric or aqueous dispersion analysis.

c. The parameters suggested in NUREG 1320 may be used to quantify carryover fractions from source materials to transport media. The parameters below may be considered for carryover fractions if NUREG 1320 cannot be readily applied. Note that these carryover fractions may be increased or decreased by chemical or physical characteristics as stated in b. above.

Source Material	Gaseous Pathway	Liquid Pathway
Gaseous	1.0	0.0
Liquid	0.1	1.0
Solid (unconsolidated)	0.01	0.1
Solid (consolidated)	0.001	0.01

NOTE: An unconsolidated solid means that the hazard sources (e.g., radionuclides or chemicals) are not physically or chemically bound to a medium, and are thus dispersable. Examples of unconsolidated solids would include powders, granular materials, and friable solids. A consolidated solid means that the hazard sources are physically or chemically bound to a medium, and thus are not readily available for dispersion. Examples of consolidated solids would be cemented or vitrified waste and massive uranium metal.

d. No credit shall be taken due to engineered features (Safety Class Items or others) or administrative controls.

e. A downwind distance of 100 meters is recommended for an on-site receptor for calculation of atmospheric dispersion factors. Other downwind distances for the on-site receptor may be considered if site-specific conditions warrant other distances (e.g. if nonoccupational personnel were to be located within the 100 meter distance of the process facility in question, then the lesser distance would be acceptable for the dispersion model.

f. The atmospheric factors representing the worst sector of site boundary shall be used for the off-site receptor.

g. For both on-site and off-site atmospheric dispersion, short-term (0-8 hours) dispersion characteristics shall be used assuming the atmospheric stability classes and wind speeds of:

1) Pasquill F with a wind speed of 2 m/s -assumption is that a Design Basis Earthquake levels the facility and breaches all confinements. Credible mixing of solid materials due to wind-pile interaction at low wind speeds should be factored into source term development.

2) Pasquill C with a wind speed of 31 m/s -assumption is that a Design Basis Wind levels the facility and breaches all confinements.

3) Pasquill A with a wind speed of 31 m/s -assumption is that a Design Basis Wind levels the facility and breaches all confinements.

4) Pasquill A with a wind speed of 62 m/s -assumption is that a Design Basis Tornado levels the facility and breaches all confinements.

h. All releases shall be assumed at ground level, and building wake effects and plume-terrain interaction shall not be considered.

i. The release duration shall be consistent with the basis for the atmospheric dispersion (i.e. 0-8 hours). Total inventories of hazard source shall be assumed to be available for potential release to atmosphere.

j. Atmospheric dispersion models shall be consistent with those models described in TID-24190 (Meteorology and Atomic Energy.') In general, for dispersion of radionuclides, GENII will be used to determine the total committed effective dose (chronic) for the radiological impact, and the downwind concentrations (acute) for the toxicological impact. If GENII is not available, then Air Dose will be used to determine the total committed effective dose (chronic) for the radiological impact, and HARMII will be used to determine the downwind concentrations (acute) for the toxicological impact. For dispersion of nonradionuclide chemicals, HARMII will be used to determine the downwind concentrations (acute) for the toxicological impact.

k . General parameters presented in ICRP 30 shall be used for radiological dose calculation.

5.5.1.3 Special Assumptions and Models for Criticality Hazard:

a. Inherent nuclear and chemical properties and geometrical configuration of the source materials shall be considered in determining whether the criticality hazard exists or not.

b. The following distances shall be assumed for the calculation of direct dose due to a criticality accident:

On-site: 100 meters or other site-specific distances
Off-site: Shortest site boundary distance

c. Fission yield values recommended in LA-10294-MS shall be used for calculation of direct dose.

5.5.1.4 Facility Hazard Classification Rating Criteria:

The numerical Facility Hazard Classification criteria shall be based upon radiological, chemical, and other non-standard hazard considerations for on-site and off-site receptors and the environment.

It should be emphasized that the numerical criteria presented do not represent expected consequences or risks for on-site or off-site personnel or the environment. Rather, these values represent potential hazards at on-site and off-site locations without the benefit of any engineered systems or administrative controls. Therefore, the realistic values of risks or consequences due to radiological or chemical releases will be several orders of

magnitude less than the values presented when credits are taken for those engineered systems and administrative controls.

The hazard rating criteria are different for on-site and off-site receptors for a given Facility Hazard Classification. This premise relates back to the DOE guidelines listed in DOE 5481.1B, where impacts to on-site personnel are more substantial than those to off-site personnel for a given Facility Hazard Classification. Therefore, the rating criteria for on-site receptors are skewed higher relative to the off-site receptors to reflect this. Thus, a given release can cause an on-site measurement which may be determined in the Low range, that could be Moderate or High if such a measurement were recorded at the off-site receptor. Normally, one would expect a Facility Hazard Classification for an off-site receptor to be at or below that determined for an on-site receptor. However, a number of factors can cause a reversal of this situation, where a release scenario may yield a lower Facility Hazard Classification for an on-site receptor than for the off-site receptor. This may be due to the "less tolerant' hazard rating criteria for the off-site receptor, as well as other factors involved in the modelling of the release, such as lofting, stack height, and vapor cloud buoyancies. This is why an examination of both receptors is important in determining the Facility Hazard Classification.

Nuclear criticalities are treated specially for the purposes of this procedure. The two special criteria for the case of a nuclear criticality event are:

a. If a criticality potential exists, the facility or segment of facility shall be designated as a Moderate Hazard facility at a minimum.

b. If the potential direct dose due to a criticality is greater than 100 rems for the on-site receptor or greater than 5 rems for the off-site receptor, then the facility or segment of facility shall be designated a High Hazard facility.

The bases for the selection of the numerical values presented in Attachment-D are provided below.

Radiological Hazard Criteria - The Radiological Hazard value is assumed to be the sum of the Dose Equivalent from external exposure and the Committed Effective Dose Equivalent received by a single individual at the receptor location as e result of the accident.

On-Site:

High --

The lower bound of this range (x > 100 rem) represents approximately one-fourth the LD50 (450 rem) for instantaneous exposure per individual for a flash burst.

Moderate --

The upper bound of this range (x ≤ 100 rem) corresponds to one-half the Nuclear Regulatory Commission guidance criteria for a High Radiation Area (100 mrem/hr x 2000 workhrs x 1/2 - 100 rem/yr). The lower bound of this range (x > 5 rem) takes up where the upper bound of the Low Hazard category leaves off.

Low --

The upper bound of this range (x ≤ 5 rem) corresponds to the limit of annual occupational exposure specified in DOE 5480.11 and equates to one-half the Nuclear Regulatory Commission guidance criteria for a Radiation Area (5 mrem/hr x 2000 workhrs x 1/2 - 5 rem/yr). The lower bound of this range (x > background) is dependent upon the naturally occurring background radiation, which is site-specific.

Off-Site:

High --

The lower bound of this range (x > 5 rem) corresponds to the limit of annual occupational exposure specified in DOE 5480.11.

Moderate --

This range (0.5 rem < x ≤ 5.0 rem) corresponds to Nuclear Regulatory Commission guidance criteria for accepted ratio of worker to general public dose assessments.

Low --

The upper bound of this range (x ≤ 0.5 rem) corresponds to Nuclear Regulatory Commission guidance criteria for accepted ratio of worker to general public dose assessments. The lower bound of this range (x>background) is dependent upon the naturally occurring background radiation, which is site-specific.

Chemical Hazard Criteria - The Chemical Hazard ranges are based upon the health effects of the chemicals of interest upon human populations at given reference standards (TLVs and IDLHS).

On-Site:

High --

The lower bound of this range is y > (5)IDLH. Concentrations greater than five times the IDLH value will most likely result in many fatalities. This roughly corresponds to the personnel impacts presented by "Other Hazards, High, On-Site."

Moderate --

The upper bound of this range is y ≤ (5)IDLH. The (5)IDLH concentration was achieved by dividing (10)IDLH by 2. The value (5)IDLH roughly corresponds to the LC25 for a chemical [assuming (10)IDLH corresponds to the LC50 - reference Section 7.16]. The lower bound of this range (y ≤ IDLH) takes up where the upper bound of the Low Hazard category leaves off. This range roughly corresponds to the personnel impacts presented by "Other Hazards, Moderate, On-Site.'

Low --

The upper bound of this range is y ≤ IDLH. Per the NIOSH definition, IDLH levels are those concentrations to which a person may be exposed during a 30-minute escape window without experiencing any escape-impairing or irreversible health effects. The lower bound of this range is Y > background, which is dependent for each chemical on the naturally occurring concentration. For most chemicals, this concentration is zero. This range roughly corresponds to the personnel impacts presented by "Other Hazards, Low, On-Site."

Off-Site:

High --

The lower bound of this range is y >IDLH. Concentrations greater than the IDLH value will result in fatalities or other serious injuries. This range roughly corresponds to the personnel impacts presented by "Other Hazards, High, Off-Site."

Moderate --

The range for this category is TLV < y ≤ IDLH. Concentrations between the TLV and the IDLH will likely

result in minor injuries to personnel. This range roughly corresponds to the personnel impacts presented by "Other Hazards, Moderate, Off-Site."

Low --

The upper bound of this range is y ≤ TLV. The TLV is the concentration at which healthy people may be exposed for 8 hours a day for 40 hours a week without experiencing any adverse health effects. Since a two-hour exposure is postulated, no adverse effects are expected. The lower bound of this range is Y > background, which is dependent for each chemical on the naturally occurring concentration. For most chemicals, this concentration is zero. This range roughly corresponds to the personnel impacts presented by "Other Hazards, Low, Off-Site."

Note: If IDLH values are not available for the subject chemicals, a value of 500 times the Permissible Exposure Limit (PEL) shall be used as the IDLH level (reference Section 7.16).

Other Hazards - This category includes all other nonstandard hazards which may result in injury or death. The personnel impacts are roughly derived from the impacts as stated in DOE 5481.1B for the different hazard classes.

High --

"Those (operations) with the potential for on-site or off-site impacts to large numbers of persons..." Large numbers of fatalities on-site would be expected at the point where some fatalities began occurring off-site due to the proximity of on-site personnel to the accident scene. Off-site personnel will, in nearly all cases, be separated by a considerable distance from an accident scene in comparison to on-site personnel. In the same vein, large numbers of serious injuries would be expected on-site when any serious injuries began to occur off-site.

Therefore, large numbers of fatalities and serious injuries and fatalities and/or some serious injuries equates to the DOE criteria for "on-site or off-site impacts to large numbers of personnel."

Moderate --

"Those (operations) which present considerable potential on-site impacts to people ... but at most only minor off-site impacts." The FEMP criteria for some fatalities and/or multiple serious injuries equates to the DOE criteria for considerable on-site impacts." The FEMP criteria for

some minor injuries equates to the DOE criteria for "minor off-site impacts.'

Low --

"Those (operations) which present minor on-site and negligible off-site impacts to people..." Some serious injuries on-site were included in this category because it is believed that any facility can be expected to be vulnerable to this level of hazard in the normal course of operating. A "minor" impact on-site may then be interpreted differently than a 'minor' impact off-site. Therefore, some serious injuries and/or multiple minor injuries equates to "minor on-site impacts." No injuries equates to "negligible off-site impacts."

5.5.2 Design Impacts of Facility Hazard Classification

The Facility Hazard Classification determines the specification of certain structural design requirements. The basic concept is that a higher hazard classification requires higher structural integrity (e.g. higher tornadic/wind loadings, higher seismic loading) to help prevent unwanted consequences from occurring. In other words, the greater the hazard, the greater the need for preventive/mitigative designs and actions. Thus, the Facility Hazard Classification affects the design of a facility. This design impact will ultimately affect the risk which that facility will present when constructed and operated. It is through this mechanism that acceptable risk evolves from unmitigated hazard.

Structural design requirements for DOE facilities (both nuclear and non-nuclear) are contained in DOE 6430.1A, Section 0111. DOE 6430.1A references several Lawrence Livermore National Laboratory documents:

a. UCRL-15910, Design and Evaluation Guidelines for DOE Facilities Subjected to Natural Phenomena Hazards, (Interim) 1989;

b. UCRL-53526, Natural Phenomena Hazards Modeling Project: Extreme Wind/Tornado Hazard Models for DOE Sites, 1985; and

c. UCRL-53582, Natural Phenomena Hazards Modeling Project: Seismic Hazards Models for DOE Sites, 1984.

These documents specify for each DOE site the design loading requirements (earthquake, wind/tornado) as a function of four Facility Use Categories. These categories are: General Use, Important or Low Hazard, Moderate Hazard, and High Hazard.

Table 2-2 in UCRL-15910 shows the correspondence between the Facility Use Categories and the Facility Hazard Classification in the DOE 5481.1B system. This comparison is as follows:

COMPARISON OF CLASSIFICATION SYSTEMS

UCRL-15910	DOE 5481.1B
General Use	(Generally Accepted)
Important or Low Hazard	Low Hazard
Moderate Hazard	Moderate Hazard
High Hazard	High Hazard

Note that the category "Generally Accepted" has been added to the DOE 5481.1B list to account for those DOE operations which involve hazards which are routinely encountered or accepted in the course of everyday living by the vast majority of the general public. This category compares favorably to the UCRL-15910 category of General Use. On that basis, a direct correspondence is established between the UCRL-15910 and the DOE 5481.1B facility categories. Thus, determination of the Facility Hazard Classification automatically determines the Facility Use Category of the facility in question.

The Facility Use Category is dependent upon the mission of, as well as on the hazard presented by, the facility in question. For example, a hospital, police station, fire station, or emergency operations center could be classified akin to an administrative building or cafeteria due to the lack of nonstandard hazards. But because these facilities play an important role in a site's mission (i.e. emergency response and accident mitigation) the guidelines in UCRL-15910 for Facility Use Category have placed them in the Low or Important category, rather than in the General Use category. Therefore, guidelines available to the designer may elevate the importance of certain facilities from a mission perspective, rather than due to the Facility Hazard Classification. However, the converse is not true. That is, mission should not be used to justify a lower Facility Use Category where the Facility Hazard Classification indicates otherwise.

A single Facility Use Category need not be applied to the facility as a whole if the facility has been properly divided into distinct segments. If the facility has been segmented, the Facility Use Category and design criteria may differ for each segment. The advantage of this is that the entire facility need not be designed to meet the higher design standards which may only be applicable to a small portion of it.

For example, assume that an administrative office area located within a uranium processing facility has been designated as a segment of that facility. The office segment may then only be required to meet the structural design criteria of the Uniform Building Code for the seismic zone applicable to the site, whereas analysis has shown that the rest of the facility (the other segment) is required to meet the structural design criteria for a Moderate Facility Use Category. However, for this to be correct, it must be shown that the failure of the office area segment at the lower level of structural design criteria will not impact upon other segments of the facility. In other words, if the office area segment fails to survive a DBA for the other segment of the facility, and the failure of the office area adversely impacts the survivability

of that other segment, then the determination of facility segments was not properly executed. The segments chosen in this case are not sufficiently segregated according to the guidelines provided in Section 5.3. In order for the choice of facility segments to be correct, failures of segments cannot adversely impact other segments within the facility which have been assigned higher Facility Use Categories.

The Facility Use Category for a given facility or segment of a facility determines certain structural design criteria. These criteria are site-specific. If this information has not been established for a given site, then criteria presented for that site in the UCRL documents listed above may be used.

5.5.3 Facility Hazard Classification -- Summary

The Facility Hazard Classification established per the direction of this procedure is used for four purposes: (1) to satisfy the Facility Hazard Classification requirement of DOE 5481.1B, (2) to determine the Facility Use Category and its associated structural design requirements, as specified in DOE 6430.1A, (3) to determine the rigor and depth of subsequent safety analysis documentation (if required), and its level of review and approval, and (4) to establish the level of authorization required for facility start-up.

5.6 Nuclear Facility Determination

DOE 5480.5 defines a "nuclear facility" as:

> A facility whose operations involve radioactive materials in such form and quantity that a significant nuclear hazard potentially exists to the employees or the general public. Included are facilities that:
> (1) produce, process, or store radioactive liquid or solid waste, fissionable materials, or tritium;
> (2) conduct separations operations;
> (3) conduct irradiated materials inspection, fuel fabrication, decontamination, or recovery operations; or
> (4) conduct fuel enrichment operations.
> Incidental use of radioactive materials in a facility operation (e.g., check sources, radioactive sources, and X-ray machines) does not necessarily require the facility to be included in this definition. Accelerators and reactors and their operations are not included in this definition.

DOE 6430.1A, GENERAL DESIGN CRITERIA, further clarifies this definition by specifying the types of facilities that are to be considered as nuclear facilities in Division 13, "Special Facilities," 1300-1.1 which covers non-reactor nuclear facilities and explosives facilities. General requirements for Non-reactor Nuclear Facilities are contained in Division 13 and throughout other Divisions in what are called "-99 systems" or "-99 requirements". That designation refers to the facility categorization numbering format for special facilities. Those Special

Facilities that are categorized as non-reactor nuclear facilities or explosives facilities in Division 13 are listed in Attachment A. For these categories of non-reactor nuclear facilities, Section 1300 design requirements apply in addition to the general requirements (including "-99 requirements") contained in the other divisions of DOE 6430.1A.

In an SA, the facility in question must be compared to both the definition in DOE 5480.5 and the Special Facilities categories of 6430.1A. If the facility meets any of these criteria, it is a Nuclear Facility. A facility need not be a currently-defined Special Facility per DOE 6430.1A in order to qualify as a nuclear facility.

For example, a facility which stores thorium compounds, or depleted or natural uranium compounds, in quantities sufficient to constitute a radiological hazard to the workers, the environment, or the general public could arguably be classified as a nuclear facility, though no Special Facility category exists to further define this situation. The presence of nuclear materials in quantities sufficient to categorize a facility as Low, Moderate, or High Hazard per the Radiological Hazard Criteria (discussed in Section 5.5.1.4) would warrant its treatment as a nuclear facility.If a facility is divided into a number of segments, and those segments each meet the requirements of a different Special Facility definition, then the segments will each be considered to be the Nuclear Facility for which they qualify. The overall facility will then be the sum of the different Special Facilities. For the purposes of design, as in the case of Facility Hazard Classification and structural design criteria, each segment will be required to meet the design criteria specific to its Special Facility category, rather than the facility is a whole being required to meet the criteria of all of its segments.In this way, design requirements are confined to the areas for which they are pertinent, rather than designing an entire facility to meet criteria which may be applicable to only a discreet portion of it.

5.7 Design Basis Accidents (DBAS)

Design Basis Accidents are postulated accidents or natural forces, and resulting conditions, for which those aspects of the confinement structure, systems, components, and equipment which have been designated as Safety Class Items must meet their functional goals. Design Basis Accidents include Design Basis Earthquake, Design Basis Flood, Design Basis Tornado, and Design Basis Wind, as well as Factors governing certain types of facility-specific accident scenarios such as Design Basis Fire, Design Basis Criticality, or Design Basis Explosion. Safety Class Items provide functional and/or structural integrity for mitigation of event severities up to and including DBAS.

The Facility Hazard Classification determines certain design values applicable to the facility in question. As discussed in Section 5.5.2, the Facility Hazard Classifications are used to establish the Facility Use Category. The Facility Use Category determines the structural design requirements for the facility. And the structural design requirements

form the basis of many of the DBAs for a facility (i.e. DBE, DBT, and DBW).

Special facility components, systems, and structures shall be designed, fabricated, erected, and tested to standards and quality commensurate with the hazards and potential consequences associated with both the facility and the role of each component, system, and structure in mitigating the consequences of accidents.

Safety Class Items are systems, components, and structures, including portions of process systems, whose failure could adversely affect the environment or the safety and health of the public or workers. Determination of whether or not certain components are to be classified as Safety Class Items is based on analysis of the potential abnormal and accidental scenario consequences as presented in the Safety Analysis Report for the facility in question.

Safety Class Items provide functional and/or structural integrity for mitigation of event severities up to and including DBAS. The DBAs for a facility will affect the selection of those Safety Class Items later identified in the SAR. Those Safety Class Items must then be designed or, in the case of an existing facility, proven to have been designed to survive the DBA criteria.

Safety Class Items are identified generically for classes of nuclear facilities in Nonreactor Nuclear Facilities: Standards and Criteria Guide, DOE/TIC-11603, Rev. 1, U.S. Department of Energy, and in DOE 6430.1A. These types of Safety Class Items may be referred to in the "Conclusions" section of the SA (refer to Attachment D) for a project to provide guidance to the facility designers. The lack of these systems may be discussed in the conclusion of the SA for an existing facility.

5.9 SAR Content and Format

The adequacy of the existing safety documentation (if any) for the facility as relates to both the Facility Hazard Classification and the backfitting requirements of DOE 5481.1B shall be determined in the SA. This is done to ensure that the extent of safety analysis required or applied to any operation is proportional to the hazard presented by that operation. The level of safety documentation, and the subsequent review and approval levels for that documentation, are dependent upon the Facility Hazard Class. If the existing Safety Documentation is inadequate for the facility, this shall be so stated in the "Conclusions" section of the SA, accompanied by a statement as to the appropriate level of Safety Documentation for the facility.

5.10 SA Auditable Files

DOE Order 5480.5, paragraph 9.c., requires that the performance of the safety documentation system shall be recorded in sufficient detail to permit contractor management and DOE to evaluate its effectiveness. Actions taken on any recommendations resulting from reviews, audits, R

inspectins, appraisals, and surveillance shall be included in these records. Therefore, copies of interdepartmental and intradepartmental review comments and resolution shall be included in the official Safety Assessment files, which are maintained by the N&SS manager, along with the applicable, issued Safety Assessment. R

6.0 PROCEDURE

Procedures and instructions for the process of requesting, reviewing, and approving Safety Assessments for existing facilities and different types of projects are provided in FMPC-2116, Topical Manual for Implementing FMPC Policies and Procedures for System Safety Analysis. Content, format, and generic guidance for the preparation of Safety Assessments is provided in Attachment D, and is to be used in conjunction with the information provided in Section 5.0 above.

7.0 APPLICABLE DOCUMENTS

7.1 DOE Order 5480.1B, ENVIRONMENT, SAFETY, AND HEALTH PROGRAM FOR DEPARTMENT OF ENERGY OPERATIONS.

7.2 DOE Order 5480.5, SAFETY OF NUCLEAR FACILITIES.

7.3 DOE Order 5480.23, NUCLEAR SAFETY ANALYSIS REPORTS R

7.4 DOE Order 5481.1B, SAFETY ANALYSIS AND REVIEW SYSTEM.

7.5 DOE OR 5481.1B, SAFETY ANALYSIS AND REVIEW SYSTEM.

7.6 DOE Order 5820.2A, RADIOACTIVE WASTE MANAGEMENT.

7.7 DOE Order 6430.1A, GENERAL DESIGN CRITERIA. R

7.8 FMPC-209, "Independent Safety Review Committee Charter."

7.9 FMPC-721, "Plant Test Authorization."

7.10 FMPC-2116, Topical Manual for Implementing FEMP Policies and Procedures for System Safety Analysis.

7.11 DOE/TIC-11603 (Rev. 1), Nonreactor Nuclear Facilities: Standards and Criteria Guide.

7.12 Threshold Limit Values and Biological Exposure Indices for 1988-1989, American Conference of Governmental Industrial Hygienists; Cincinnati, Ohio; 1988.

7.13 NUREG-1320. Nuclear Fuel Cycle Facility Accident Analysis Handbook, U.S. Nuclear Regulatory Commission.

7.14 ICRP 30, "Limits for Intakes of Radionuclides by Workers."

7.15 LA-10294-MS, "A Guide to Radiological Accident Considerations for Siting and Design of Nonreactor Nuclear Facilities."

7.16 TID-24190, "Meteorology and Atomic Energy."

7.17 Technical Guidance for Hazard Analysis -- Emergency Planning for Extremely Dangerous Substances, Appendix D, pp. D-1 through D-27; U.S. Environmental Protection Agency, Federal Emergency Management Agency, and U.S. Department of Transportation; December 1987.

7.18 UCRL-15910, "Design and Evaluation Guidelines for DOE Facilities Subjected to Natural Phenomena Hazards," 1988.

7.19 UCRL-53526, "Natural Phenomena Hazards Modeling Project: Extreme Wind/Tornado Hazard Models for DOE Sites," 1985.

7.20 UCRL-53582, "Natural Phenomena Hazards Modeling Project: Hazards Models for DOE Sites," 1984.

7.21 DOE/TIC-11603, Rev. 1, Nonreactor Nuclear Facilities: Standards and Criteria Guide, U.S. Department of Energy; September 1986.

7.22 MIL-STD-882B, "Military Standard System Safety Program Requirements," 30 March 1984.

7.23 Guidelines for Hazard Evaluation Procedures, The Center for Chemical Process Safety of the American Institute of Chemical Engineers (AICHE, CCPS), 1985.

8.0 FORMS USED

None.

9.0 ATTACHMENTS

9.1 Attachment A - DOE 6430.1A Division 13 - Categories for Special Facilities, Non-Reactor Nuclear Facilities

9.2 Attachment B:
Table B-1 - Hazard Categories
Table B-2 - Hazardous Materials
Table B-3 - Energy Sources

9.3 Attachment C - Projects and Facilities Usually Defined as "Generally Accepted" for Hazard Classification Purposes

9.5 Attachment D - Safety Assessment Content and Format

ATTACHMENT A

DOE 6430.1A DIVISION 13 - CATEGORIES FOR SPECIAL FACILITIES
NON-REACTOR NUCLEAR FACILITIES

The following types of non-reactor nuclear facilities are classified as Special Facilities in Division 13 of DOE 6430.1A "General Design Criteria." For these categories of facilities, Section 1300 design requirements apply in addition to the general requirements (including "-99" requirements) contained in the other divisions of DOE 6430.1A. Facilities at the FEMP must be classified according to the criteria applicable to each of these types of facilities. Not all of the Special Category non-reactor nuclear facilities listed below are applicable to the FEMP.

Section 1304 Plutonium Processing and Handling Facilities (PPHF)

PPHFs include facilities principally dedicated to processing and handling plutonium in substantial quantities, e.g., to be used in nuclear explosives production, nuclear reactor fuel assemblies, or heat source packages. What constitutes a 'substantial quantity' depends on the quantity of each isotope, the physical and chemical form, and the specific process involved. A consideration of the hazard determines whether the facility should be classified as a PPHF. These criteria shall be used for facilities processing and handling other transuranic radionuclides, such as americium, curium, neptunium, and californium. The activity and mass criteria stated above shall apply.

Section 1305 Plutonium Storage Facilities (PSF)

These criteria shall be applied in the planning and design of PSF that will contain strategic (Category I as defined in the DOE 5632 series) amounts of plutonium. They are not applicable to 'in process' or "in use" material, to material in assembly cells for use in weapons, or to material that is packaged in accordance with the requirements of DOE 5480.3 and is awaiting transportation or has been received and is awaiting disposition. However, these criteria do apply to joint storage with other transuranic elements and uranium. The stored plutonium can be in the form of a solid, liquid, or gas. These general design criteria shall also be considered for application to facilities storing other transuranic radionuclides, such as neptunium and californium.

Section 1306 Unirradiated Enriched Uranium Storage Facilities (UEUSF)

This section is specifically applicable to dry type UEUSF used for the storage of UEU. The UEU may be in the form of a solid, liquid, or gas. (Dry refers to the absence of water such as in storage ponds for irradiated reactor assemblies. The UEU itself may be in the form of a solution.)

Section 1318 Uranium Enrichment Facilities (UEF)

This section is applicable to facilities that enrich uranium by the gaseous diffusion, gas centrifuge, or AVLIS process. UEFs include:

- Storage capability for incoming feed material
- A sampling station
- A feed system
- Equipment for the enrichment process
- A product withdrawal system
- A tails withdrawal system
- Product packaging, storage, and shipping areas
- Cleaning and decontamination areas
- Assembly/disassembly areas
- Maintenance and storage areas
- A central control station
- A complex to provide technical services and administration.

These criteria shall apply to all the levels of uranium-235 enrichment. The following are three popular assay levels of uranium-235 enrichment:

- Reactor grade assay (2.5 to 5 percent)
- High enrichment assay (5 to 94 percent)
- Very high enrichment assay (above 94 percent).

Section 1319 Uranium Processing and Handling Facilities (UPHF)

A UPHF is a facility that receives feed material from sources such as a conversion facility, a reprocessing facility, or fuel/target storage facility. It processes, handles, and produces such products as UO_2, UF_6, uranium metal, reactor fuel assemblies, target assemblies, and nuclear weapons components. This section is not process specific. It is applicable to facilities that process and handle uranium; however, it is principally directed at facilities that process and handle uranium enriched in U-235.

Section 1320 Irradiated Fissile Material Storage Facilities (IFMSFS)

IFMSFs are self-contained installations for storage of highly radioactive fissile material (e.g., spent fuel and target elements) that has been exposed to a neutron flux usually in a nuclear reactor. The irradiated material is properly clad or canned when received such that leakage from the assemblies is minimized and remains within specified limits. The IFMSF stores the material in a manner that ensures the integrity of the cladding or canning. The stored material is shipped to facilities such as a reprocessing facility, hot laboratory, or high-level solid radioactive waste facility. This section applies to water pool type or dry type of storage facility. Spent fuel storage facilities that are part of a reactor facility are not covered by this section. They are covered by DOE 5480.6.

Section 1321 Reprocessing Facilities

A reprocessing facility recovers uranium, plutonium, and other selected fission products from irradiated fissile fuel material and target material, and separates them from each other and from any remaining actinides and fission products.

Section 1322 Uranium Conversion and Recovery Facilities

Uranium conversion facilities receive feed materials such as UF6, uranyl nitrate or UO3, process these materials chemically and produce uranium metal, UO2, and UF6- Uranium recovery facilities receive and handle scrap feed materials that are of different types, shapes, sizes, uranium contents, and enrichments. The kind of scrap and therefore the process to facilitate recovery of uranium may vary as frequently as daily. This section is not process-specific. It is principally directed at facilities that produce products that are feed materials for uranium processing and handling facilities and those facilities that receive scrap from uranium processing and handling facilities for the purpose of recovering the uranium.

Section 1323 Radioactive Liquid Waste Facilities (RLWFI)

RLWFs are used to store, treat, and dispose of the range of liquid wastes generated by DOE nuclear facilities and reactor facilities. This waste includes low-level, high-level, and transuranic-contaminated (to include enriched uranium and uranium-233) liquid waste. These radioactive liquid waste facilities may be separate facilities or they may be an adjunct to another type of nuclear facility (e.g., a high-level waste processing line associated with a reprocessing facility). The environmental, and safety, and health concerns to be addressed to fulfill the design requirements for these facilities vary significantly according to the nature of the waste, the waste management techniques that are implemented, and the characteristics of the facility site.

Note: If the facility being assessed is determined to be a Radioactive Liquid Waste Facility, it automatically requires a SAR (in the case of a project, a PSAR/FSAR) per DOE Order 5820.2A "Radioactive Waste Management."

Section 1324 Radioactive Solid Waste Facilities

Radioactive solid waste facilities store, treat, and dispose of the range of solid waste generated by DOE nuclear facilities and reactor facilities. This waste contains high-level, low-level, and transuranic-contaminated solid waste including radioactive mixed waste. These radioactive solid waste facilities may be separate facilities or they may be adjunct to another type of nuclear facility (e.g., a high-level solid waste storage facility associated with a reprocessing facility). The environmental, safety, and health concerns to be addressed to fulfill the design requirements for these facilities vary significantly according to the nature of the waste, the waste management techniques that are implemented, and the characteristics of the facility site.

Note: If the facility being assessed is determined to be a Radioactive Solid Waste Facility, it automatically requires a SAR (in the case of a project, a PSAR/FSAR) per DOE Order 5820.2A "Radioactive Waste Management."

Section 1325 Laboratory Facilities (Including Hot Laboratories

Hot laboratories include those facilities where hot cells, glove boxes, hoods, and other similar enclosures are used for such laboratory work as isotope production, inspection of spent reactor fuel, prototype processes, metallurgical testing, etc., and are included under the general category of "Laboratory Facilities." Per DOE 5480.5, incidental use of radioactive material in the operation of the facility (e.g., check sources, radioactive sources, and x-ray machines) would not necessarily qualify a laboratory as a nuclear facility.

Section 1326 Tritium Facilities

A tritium facility is a facility that processes, handles, or stores large inventories of tritium in either gaseous, oxide, or hydride forms. Examples of these facilities include tritium target processing facilities, tritium storage facilities, tritium loading facilities and fusion gas test loops. A facility shall be classified as a tritium facility rather than a laboratory-scale facility based on the quantity of tritium involved and the scope of tritium handling/processing operations as determined by a safety analysis.

Section 1328 Fusion Test Facilities

These requirements are primarily concerned with the potential radiological hazard because of the intense neutron radiation associated with fusion machine operation, activated structural and blanket material, in some cases, activated nuclides in the atmosphere of the test cell, and, in the case of tritium fusion facilities, because of the radioactive material inventory of the facility consisting mostly of tritium. It should be noted that some fusion facilities use deuterium rather than tritium as the fuel. Because these facilities do not produce significant radiation fields or contain significant quantities of radiative materials, the application of the criteria provided in this section to these types of fusion facilities shall be considered on a case-by-case basis.

Examples of fusion facilities are facilities that include magnetic confinement and inertial confinement fusion devices. Fusion devices of interest range from experimental machines that are intended to operate below the break-even point, to experimental or demonstration facilities that are intended to operate at or beyond the break-even point. It is recognized that an electric power-producing fusion reactor will not exist for many years, and technical advancements during this period can have a significant impact on safety considerations related to such facilities.

Potential hazards that shall be considered in the design of a fusion facility include intense magnetic fields, an intense radiation source, activation products, cryogenic fluids, high-voltage electric power systems, tritium, and

some facilities, laser light. The tritium inventory in a fusion machine and associated primary systems may contain as much as 10 to 100 grams of tritium for small experimental to large demonstration facilities. Tritium processing systems may contain up to 100 grams of tritium, and storage facilities several thousand grams of tritium. Therefore, the total tritium inventory of a fusion facility may range up to 109 curies.

ATTACHMENT B
TABLE B-1
HAZARD CATEGORIES

Category	Event
Fire/Explosion	Ignition of flammables, explosives, combustibles (See Table A-2 examples). Unexpected or uncontrolled reaction due to evaporation, volatilization, leak, material error, unknown ignition sources, etc.
Loss of Containment	Breach of system/container due to material failure, over-pressurization, thermal stress, corrosion, chemical reaction, mechanical damage, etc. Failure of glove, glovebox, cell,storage, container, etc.
Loss of Confinement	Filter failure due to degradation, fire, overloading, etc. Failure to install filter.
Injury to Operating Personnel	Contact with hazardous materials (See table A-2 for examples) due to breach of containment, spill, evaporation, volatilization, leak, etc. Contact with energy sources (See Table A-3 for examples).

Category	Event
Nuclear Criticality	Failure due to chemical effects - corrosion (change in vessel dimensions, leakage, dissolution of poison), extraction into undetected phase, moderation (affinity of materials for water), fire/explosion/pressure (geometry change), precipitation or dissolution of fissionable material, etc. Failures due to human error - overbatching, improper spacing, improper material identification, transfer and valving errors (wrong materials, unsafe geometry, flooding), additions or interspersion of moderators, errors in analytical data. inventory, container volume or dimension, container arrangement, slab height, loss of services, etc. Failures due to thermal effects - evaporation, freezing, melting or condensation (to cause changes in concentrations, geometry, moderation, etc.), thermal shock (to cause equipment damage), etc. Failures due to mechanical effects - load failures, natural phenomena, siphons to unsafe geometry equipment, failure of piping carrying material (water, oil, etc.), impact of moving equipment to change configuration or reflection. failure of valves.
Interfaces	Failures in interfaces between subsystems, systems, equipment, personnel, and any combinations thereof. Material compatibility. Electromagnetic interference. Inadvertent activation. Fire/explosion initiation and propagation. Loss of services (power, water, air, etc.). Logistics/transportation.

Category	Event
Waste Disposal	System/equipment failures. Inadequate for type and/or volume of waste. No means of disposal available due to regulations, lack of technology, etc.
Maintenance	Maintenance requirements outside of ALARA philosophy. Hazardous conditions created by extended/frequent downtimes.
Extrinsic Hazards	Effects of nearby operations, facilities, traffic, etc. Failures due to natural phenomena effects of DBE, DBFL, DBT, DBW, volcanic activity, lightning, snow, etc.

TABLE B-2
HAZARDOUS MATERIALS

Category	Type
Radioactive	All radionuclides.
Fissionable	233U. 235U. 238Pu. 237No. 241Am
Alkali Metal	Na. NaK. Li
Toxic	Examples: Methanol, acetone, fluorides, carbon monoxide, lead, ammonia, asbestos, trichloroethylene, pesticides, herbicides, insecticides, bacteria, beryllium and compounds. chlorine, decontamination solutions, arsenic compounds, cyanides, acids, bases, organic solvents, oils. heavy metals. etc.
Corrosive	Examples: Acids, bases, ozone, decontamination solutions. etc.
Asphyxiant	Examples: Inert gases or vapors (e.g., argon, nitrogen, helium), hydrogen, ethane, low oxygen areas (e.g., pits. tunnels. tanks).
Explosive	Examples: Powdered metals, hydrogen, acetylene, propane, volatile liquids, nitrates, peroxides, methane, ozone, picric acid, gases, fuels, squibs, caps, primer cord. dynamite. etc.
Combustible/flammable	Examples: Paper, rags, boxes, roofing, floors, walls, pyrophoric metals and chemicals, wood, gasoline, oils, paint thinner, solvents, alcohols, gases (hydrogen, methane, ethane, etc.), fuels, pyrophoric reactions. greases. spray paint. etc.
Oxidizing	Examples: Oxygen, permanganates, dichromates, chromates, nitrates, nitric acid, nitrous acid. ozone. etc.

TABLE B-3
ENERGY SOURCES

Group	Initiator	Examples
Potential	Electrical	High Voltage Electrostatic Battery banks Diesel units High lines Transformers Wiring Switchgear Underground wiring Cable runs Service outlets and fittings Pumps Motors Heaters Power tools Small equipment
	Gravitational	Ladders Suspended loads Human effort Stairs Lifts Cranes Trucks Slings and lift fixtures Hoists Elevators Jacks Scaffolds and ladders Crane cabs Pits Excavations Elevated doors Canals Vessels Natural phenomena: Rain accumulation Snow accumulation

Group	Initiator	Examples
	Pressure	Boilers Heated surge tanks Autoclaves Test loops and facilities Gas bottles - compressed gases Pressure vessels Coiled springs Stressed members Gas receivers Natural phenomena: Straight line winds Tornadic depressurization Earth/hydraulic
Kinetic	Linear	Cars Conveyors Compactors Crushers Trucks Buses Fork lifts Carts Dollies Railroad Surfaces Obstructions Shears Presses Crane loads in motion PV blowdown Power-assisted driving tools Robot-assisted operations Natural phenomena: Earthquake Straight line winds Tornado Wind-borne missiles Flood
	Rotational	Centrifuges Motors Pumps Fans Laundry equipment Gears Shop equipment (grinders, saws, brushes, etc.) Robot-assisted operations Natural phenomena: Tornado

Group	Initiator	Examples
Radiant	Ionizing	alpha, beta, gamma, x-ray, and neutron from: Vaults Temporary storage areas Receiving areas Shipping areas Casks Burial grounds Storage racks Canals and basins Dollies Trucks Hand carrying Cranes Lifts Shops Hot cells Assembly areas Inspection areas Test rigs Laboratories Pilot Plants Radioactive sources Contamination Radiography equipment and sources Irradiated equipment Fusion experiments

Group	Initiator	Examples
	Nonionizing	Electromagnetic: Electric Furnace Blacklight (Magniflux) Laser Welding Electric arc - other high current circuits Electron beam Accelerators Microwave Magnetic Thermal: Furnaces Boilers Steam lines Lab and pilot plant equipment Solar Acoustical: Equipment noise Ultrasonic cleaners
Other	Nonionizing	Thermal: Convection Heavy metal weld preheat Exposed steam pipes Electric heaters Fire boxes Leading melting pot Electric wiring and equipment Furnaces

ATTACHMENT C
PROJECTS AND FACILITIES USUALLY DEFINED AS
"GENERALLY ACCEPTED" FOR HAZARD CLASSIFICATION PURPOSES

1. Parking lots, storage yards, railroad spurs, and new roads.

2. Routine resurfacing of roads and railroad repair.

3. Re-roofing.

4. HVAC modifications not related to containment systems for hazardous materials.

5. Modifications to noncritical utility systems such as:
   a. Sanitary water distribution system,
   b. Water treatment plant,
   c. Utility pole replacements,
   d. Burial of power lines,
   e. Coal and ash handling systems, or
   f. Wells and raw water supply systems.

6. Structural, electrical, and service piping modifications (including sprinkler system modifications) in administrative buildings, such as instrument and machine shop areas that are non-process related (decontamination areas are not included).

7. Building additions and new buildings to serve administrative, non-process, or research functions.

8. Telecommunications systems.

9. Lighting systems.

10. Fencing.

11. Security equipment and facilities (Covered by Security Vulnerability and Risk Assessment).

12. Metering for energy conservation and utilities monitoring.

13. Motor vehicles and heavy mobile equipment not to be used for transporting hazardous materials.

14. Standard machining tools (not involving fissile or radioactive materials) such as:
    a. Lathes,
    b. Boring mills, or
    c. N/C drills.

15. Elevator installations.

16. ADP equipment with no process control functions.

ATTACHMENT C (cont)

17. Scales (with possible exception of those used for nuclear material withdrawal).

18. Cooling tower fan motor replacements.

19. Furnaces used to heat buildings.

20. Laboratory equipment such as:
    a. Mass spectrometers,
    b. X-ray diffraction equipment, or
    c. Mechanical test and inspection equipment.

21. Storage facilities (except those used for fissile, radioactive, or hazardous materials).

22. Environmental sampling stations.

23. Meteorological stations.

24. RCW pump replacements.

25. Screens for cooling tower basins.

26. Instrument shop equipment.

27. Standard sanitary landfills.

ATTACHMENT D
EXAMPLE OF SAFETY ASSESSMENT CONTENT AND FORMAT

WEMCO-FEMP SAFETY ASSESSMENT

Date

FEMP FACILITY, PROJECT, OR SUBPROJECT	GIVE NAME OF FACILITY, PROJECT, OR SUBPROJECT TO BE ASSESSED(GIVE THE IDENTIFICATION NUMBER OF THE PROJECT, SUBPROJECT,WORK ORDER, RES, OR PTA IN PARENTHESIS, IF APPLICABLE)

1. FACILITY AND LOCATION: Give the building number (or, if no building number applies, then the name of the structure or work) and its location on site. Provide a site map showing the location of the building (structure, work) in relation to the other buildings on site.

2. SEGMENT LOCATIONS WITHIN FACILITY: Give the location within the facility of the segments which are to be assessed. Provide a building layout drawing(s) and reference column lines where possible and appropriate.

3. DESCRIPTION OF OPERATION: Briefly describe the operation of the facility segments. Include drawings of major equipment, show equipment locations, and provide process flow diagrams. Equipment, engineered features, or administrative controls which are essential for the safe operation of the facility (i.e. those items which are responsible for reducing the risk presented by non-standard hazards associated with the facility) should be identified. Non-standard equipment or operating parameters associated with this operation should be described. Unique or extraordinary equipment or parameters may include high-speed rotating equipment, fire and explosion hazards, unique electrical problems (e.g. high-energy plasma experiments), high-pressure equipment, high-energy lasing equipment, operations involving robots or artificial intelligence, or other uncommon equipment or operating parameters not routinely encountered and accepted by the public.

4. MAJOR EQUIPMENT FOR THE OPERATION: List the major equipment involved in the operation of the facility. Briefly describe the equipment at the system level and indicate the functional purpose of each system.

5. NUMBER AND CLASSIFICATION OF OPERATING PERSONNEL: List the number and job classifications of the operating personnel for the facility. Include the number of supervisory personnel directly responsible for the operation. Particular attention should be given to the minimum number of personnel necessary for the safe operation of the facility and the maximum number that would be affected by a major process accident.

6. INTERACTION WITH OTHER FACILITIES: List other facilities with which this facility interfaces. Examples of interfaces would include any connections via wiring, piping, or foundation, as well as shipper/receiver relationships for raw materials, intermediate materials, finished products, or waste. Include adjoining facilities

which have a credible possibility of impacting upon this operation, or which may be impacted by an accident at this facility. Ownership of the facility being evaluated versus its interfaces with other facilities should be established in this section.

7. NUCLEAR/RADIOACTIVE MATERIALS: The intent of this section is to identify the nuclear or radioactive materials which may: a) be used to generate source terms for radionuclide dispersion models; b) present direct radiation hazards; or c) pose nuclear criticality concerns. List the types of nuclear or radioactive materials and the quantities involved in the operation or stored in the facility. Discrete quantities of materials, such as the amount in a given storage tank or container or "in process" in equipment (such as in a reduction furnace), should be estimated. Give the total amount (or throughput values per unit time) of such materials present in the facility. Contaminated building materials, soils, equipment, or other similar substances should not be listed, unless such substances have been rendered into a form suitable for treatment or storage in, or shipment from the facility that is the subject of this assessment.

8. TOXIC AND FLAMMABLE SUBSTANCES: The intent of this section is to identify the toxic and flammable materials which may: a) be used to generate source terms for chemical dispersion models; b) present health hazards to operating personnel or others in the vicinity; or c) pose instability, flammability, or reactivity hazards. Provide a list of all hazardous materials and the quantities stored or involved in the operation of this facility. Include in this list all hazardous materials in adjoining facilities which have a credible possibility of impacting upon this facility (e.g., a release of H2 in Building 54 and subsequent explosion could impact upon the operation of the P-2 Furnace in Building 37, causing a release of uranium from the P-2 Furnace). The relevant health effects of these materials, and the hazards they pose (instabilities, flammabilities, reactivities) should be discussed. Discrete quantities of materials, such as the amount in a given storage container or "in process" in equipment, should be estimated. Give the total amount (or throughput values per unit time) of such materials present in the facility. Health, flammability, reactivity, and instability information should be obtained from accepted reference works (e.g., standards and publications by ACGIH, NIOSH, NFPA, etc.).

9. UNIQUE/UNUSUAL SAFETY PROBLEMS: The purpose of this section is to identify those aspects of the facility that involve hazards that are not routinely encountered and accepted in the course of everyday living by the vast majority of the general public. Those hazards shall then be assessed to determine the hazard classification of the facility.

Everything stated in this section shall be supported by information which has been provided by previous sections of the assessment. Where extensive calculations have been generated to support a position, those calculations shall be provided as an attachment to the assessment. Dispersion codes, KENO models, and other reference works shall be cited in Section 11 of this Attachment D.

A. PRELIMINARY HAZARD ANALYSIS -- This subsection of the assessment is used to document the Preliminary Hazard Analysis as described in Section 5.4 of this procedure. The format of the table to be used is shown below.

Hazard	Cause(s)	Major Effect(s)	Mitigative Measures

Information provided in Attachment B should be used as a guide to determine if all hazards are described. Only Mitigative Measures stated in the design or present in the existing facility are listed.

B. RADIOLOGICAL SOURCE TERMS -- This subsection of the assessment is used to determine the radiological source terms for the facility. It is also used to identify the potential for a nuclear criticality accident and the hazard it presents.

Assumptions: Use the assumptions as detailed in Section 5.5.1 of this procedure.

A dispersion model (e.g., Air Dose-EPA or GENII) shall be used to provide personnel exposures (in rem) for the selected radionuclide(s) on-site and off-site. These Dose Equivalent (or 'X") values will be used in determining the Facility Hazard Classification by referring to the Radiological Hazard column of the table presented in Attachment D. Where the calculated "X" value falls into a Radiological Hazard range, the corresponding Hazard Category shall apply.

C. CHEMICAL SOURCE TERMS -- This subsection of the assessment is used to determine the chemical source terms for the facility.

Assumptions: Use the assumptions as detailed in Section 5.5.1 of this procedure.

A dispersion model (e.g., HARMII or other accepted gaussian plume or chemical-specific model) shall be used to provide personnel exposures to the selected chemical(s) on-site and off-site. These dose (or "Y") values will be used in determining the Facility Hazard Classification by referring to the Chemical Hazard column of the table presented in Attachment D. Where the calculated "Y' value falls into a Chemical Hazard range, the corresponding Hazard Category shall apply.

D. OTHER NON-STANDARD HAZARDS -- This subsection of the assessment is used to identify other non-standard hazards associated with the facility. Included in this category are failures of high-speed rotating equipment, fire and explosion hazards, unique electrical problems (e.g. high-energy plasma experiments), failures of high pressure equipment, high-energy lasing hazards. operations involving robots or artificial intelligence, or other uncommon hazards not routinely encountered and accepted by the public. These are hazards which may present special problems apart from radiological or chemical dose concerns. Where these hazards may also involve radiological and/or chemical releases, discussion of those

results will be covered in Sections 9.B and 9.C of the Safety Assessment.

The projected injuries and fatalities associated with each type of non-standard hazard will be used in determining the Facility Hazard Classification by referring to the Other Hazards column of the table presented in Attachment D. Where the projected injuries/fatalities value falls into an Other Hazards range, the corresponding Hazard Category shall apply.

E. NON-REACTOR NUCLEAR FACILITY DETERMINATION -- This subsection of the assessment is used to determine if the subject facility is a nonreactor nuclear facility. If the facility in question meets the definition of 'nuclear facility" which appears in DOE 5480.5, "Safety of Nuclear Facilities,' Section 5.f; or it satisfies one of the categories of "Special Facilities' given in DOE 6430.1A, "General Design Criteria," Division 13, then it is a Nuclear Facility. A facility meets the definition of "nuclear facility" if it is a Low, Moderate, or High hazard facility for Radiological Hazard or Environmental (Radiological) Hazard per the Facility Hazard Classification process.

If the facility being assessed meets any of the Special Facility criteria stated in DOE 6430.1A, Division 13, this section of the assessment shall state which type(s) of nuclear facility the facility falls under and why. The determination will be made by Segment, if the facility has been segmented. If the facility does not meet any of these criteria, and does not satisfy the definition of "nuclear facility," the assessment shall state "The (name of facility) does not qualify as a 'nuclear facility' per the definitions and criteria specified in DOE Orders 5480.5 and 6430.1A.'

10. EXISTING SAFETY DOCUMENTATION: Provide a list of all safety documentation (Safety Assessments, Safety Studies, Safety Analysis Reports, and Operational Safety Requirements documents) which has been generated for this facility. The state of the documentation shall be noted (i.e., Approved, Draft, etc.). An evaluation shall be made to determine if existing safety documentation is adequate based upon the hazard classifications arrived at in Section 9 and the requirements of the DOE Orders referenced in Section 11.A through F. Where the documentation is shown to be inadequate, provide examples of the deficiencies.

11. CONCLUSIONS: This section shall provide the results of the investigation conducted in Sections 9 and 10 of the Safety Assessment. Everything stated in Section 11 shall be supported by information which has been provided by preceding sections.

A. FACILITY HAZARD CLASSIFICATION -- State the Facility Hazard Classification, as determined in Sections 9.B through 9.D. The Facility Hazard.Classification for the facility corresponds to the highest Facility Hazard Classification arrived at in the investigation, unless otherwise noted and justified. For example,

if three "Low" and one "Moderate" determinations were made for a facility, the Facility Hazard Classification for that facility would be the highest, or "Moderate." If the facility was divided into segments for the purpose of the Facility Hazard Classification process, detail each segment and the highest Facility Hazard Classification arrived at for that segment.

If only standard industrial hazards could be identified, then a statement to that effect shall be made.

B. NON-REACTOR NUCLEAR FACILITY DETERMINATION -- State the type(s) of DOE non-reactor nuclear facility applicable to the subject facility or its Segments. If none are applicable, state "The (name of facility) does not qualify as a 'nuclear facility' per the definitions specified in DOE Orders 5480.5 and 6430.1A."

C. SAFETY DOCUMENTATION -- State whether or not further safety documentation is required, and the type of documentation necessary. Base this conclusion upon the Facility Hazard Classification as presented in Section 12.A, and relate it to the required documentation level presented by the table in Attachment D of this procedure. Other applicable criteria, as required by DOE Orders, may require otherwise (e.g., DOE 5820.2A).

D. DESIGN CRITERIA -- State the structural design criteria the facility is required to meet due to its Facility Hazard Classification. If the facility was divided into segments for the Facility Hazard Classification process, the design criteria determined by the highest classification for each segment shall be applied to that segment. Other design criteria may be required by DOE 6430.1A if the facility or segment is a "nuclear facility"/"Special Facility". These criteria shall also be listed. Deficiencies in the provision of Mitigative Measures in the design of the project or the existing facility should be noted, with recommended additions utilizing the guidance provided in Section 5.4 of this procedure.

12. REFERENCES: Any information derived from documents (textbooks, regulations, design documents, DOE Orders, drawings, procedures, handbooks, letters, etc.) which appears in the text of the Safety Assessment must be referred to this section with standard end-note format.

13. SAFETY ASSESSMENT PREPARED BY: The signature of the Safety Analysis Engineer is required to verify that the Safety Assessment is ready for approval.

CONCURRENCE: The signature of the cognizant project engineer and/or area supervisor is required to verify that the facility and/or project descriptions presented in the Safety Assessment are accurate.

14. APPROVALS: The approval signatures will vary depending upon the type of project or existing facility being assessed. More detailed guidance for Safety Assessment approvals is provided in FMPC-2116.

ISSUE AND REVISION RECORD

DATE OF ISSUE	REVISION NUMBER	AFFECTED PAGES	REASON FOR CHANGE
5/03/90	0		Original issue of procedure
9/21/92	1	4, 5, 6, 7, 9, 10, 26, 27, & 50.	Response to CAR 92-021, convert to WordPerfect 5.1, eliminate references to cancelled DOE/OR-901 and replace with the applicable current reference, change Section 4.0 Responsibilities to reflect organizational changes, and editorial changes.