HIGH LEVEL HAZARD SAFETY ANALYSIS VOL 2 OF 3

Main Category:	Safety & Failures
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SAF-142 EXAM PREVIEW

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Exam Preview:

1. According to the reference material, the Respirable Fraction (RF) identifies what fraction of the airborne aerosol can be inhaled and retained in the body.
   a. True
   b. False
2. Using Figure 5-2. Example Nuclear Materials Handling Facility, what type of facility would ion exchange gloveboxes or precipitation gloveboxes be found in?
   a. Lab
   b. Fuel Fabricator
   c. Purification
   d. Dissolution
3. According to the MAR for Waste Storage Area section of the reference material, the waste storage area provides temporary storage capacity for up to ___ 55-gallon drums of TRU waste.
   a. 20
   b. 30
   c. 40
   d. 50
4. According to the reference material, the vertical wind direction at the height of the release determines the initial direction of transport. The vertical wind direction used in Gaussian modeling is the average, or first moment, of a series of "instantaneous" wind direction measurements.
   a. True
   b. False

5. According to the ATMOSPHERIC STABILITY CLASSES section, which of the following stability classes corresponds to the description: Normally occurs at night or early morning with some cloud cover and with wind speeds in 2 to 5 m/s range.
    a. Class E: Slightly Stable
    b. Class A: Extremely Unstable
    c. Class C: Slightly Unstable
    d. Class G: Extremely Stable
6. Wind speed varies with height in the Planetary Boundary Layer (PBL). The wind profile of the PBL is generally linear in nature and is best approximated using the linear wind profile equation that accounts for surface roughness and atmospheric stability.
    a. True
    b. False
7. Using Table 6-1. Classification of Atmospheric Stability Based on Vertical Temperature Difference, which stability classification corresponds to an ambient temperature change in of $1.5 < \Delta T100m \leq 4.0$ °C/100m.
    a. Moderately Unstable
    b. Neutral
    c. Moderately Stable
    d. Extremely Stable
8. According to the reference material, in general, the rougher the terrain underneath the atmosphere moving above it, the more mechanical turbulence is generated and consequently the better the diffusion.
    a. True
    b. False
9. Using Table 5-1. Summary of Bounding ARF and RF Values, what is the respirable fraction (RF) for Superheated liquids ("flashing spray"), 50 °C – 100 °C superheat?
    a. 0.2
    b. 0.3
    c. 0.5
    d. 0.7
10. According to the Fire Event section of the reference material, the hazard identification states that ___ g of Pu metal fines, a pyrophoric hazard, is the maximum amount of metal contamination anticipated in impure oxide received for processing.
    a. 50
    b. 100
    c. 500
    d. 1,000

ACRONYMS

AC	Administrative Control or Alternating Current
ACGIH	American Conference of Government Industrial Hygienists
AED	Aerodynamic Equivalent Diameter
AEGL	Acute Exposure Guideline Level
AICC	Adiabatic, Constant-Volume Combustion
AIHA	American Industrial Hygienist Association
AMAD	Activity Median Aerodynamic Diameter
ANS	American Nuclear Society
ANSI	American National Standards Institute
APAC	Accident Phenomenology and Consequence
ARF	Airborne Release Fraction
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BC	Building Construction
BDBA	Beyond Design Basis Accident
BEBA	Beyond Evaluation Basis Accident
BEU	Beyond Extremely Unlikely
BLEVE	Boiling Liquid Expanding Vapor Explosion
BNL	Brookhaven National Laboratory
BR	Breathing Rate
BST	Building Source Term
CCPS	Center for Chemical Process Safety
CDC	Centers for Disease Control
CFAST	Consolidated Model of Fire and Smoke Transport
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CMM	Chemical Mixture Methodology
CR	Central Registry
CSE	Criticality Safety Evaluation
CTH	Cloud Top Height
CW	Co-located Worker
DBA	Design Basis Accident
DCF	Dose Conversion Factor
DDT	Deflagration to Detonation Transition
DF	Decontamination Factor
DG	Dense Gas
DNFSB	Defense Nuclear Facilities Safety Board
DOE	Department of Energy
DOS	Disk Operating System
DOT	Department of Transportation
DR	Damage Ratio
DSA	Documented Safety Analysis
DTA	Differential Thermal Analysis

EBA	Evaluation Basis Accident
EDE	Effective Dose Equivalent
EEGL	Emergency Exposure Guidance Level
EFCOG	Energy Facility Contractor Group
EG	Evaluation Guideline
EPA	Environmental Protection Agency
ERPG	Emergency Response Planning Guideline
EU	Extremely Unlikely
FDC	Flood Design Category
FDT	Fire Dynamics Tool
FGR	Federal Guidance Report
FHA	Fire Hazards Analysis
FMEA	Failure Modes and Effects Analysis
FTF	Filter Test Facility
FW	Facility Worker
GEP	Good Engineering Practice
GNB	Gaussian Neutrally Buoyant
GRF	German Research Foundation
HA	Hazard Analysis
HAZOP	Hazard and Operational Analysis
HC	Hazard Category
HCN	Health Code Number
HDBK	Handbook
HE	High Explosive
HEPA	High Efficiency Particulate Air
HPR	Highly Protected Risk
HRR	Heat Release Rate
HSDB	Hazardous Substances Data Bank
IACR	International Association of Cancer Registries
ICRP	International Council on Radiation Protection
IDLH	Immediately Dangerous to Life and Health
IEEE	Institute of Electrical and Electronics Engineers
ILA	Immediate Landscaped Area
INL	Idaho National Laboratory
IST	Initial Source Term
JFD	Joint Frequency Distribution
LANL	Los Alamos National Laboratory
LCF	Latent Cancer Fatality
LEL	Lower Explosive Limit
LET	Linear Energy Transfer
LFL	Lower Flammability Limit
LOC	Level of Concern
LPF	Leak Path Factor
LPG	Liquified Petroleum Gas

MAR	Material at Risk
MAK-Wert	Maximale Arbeitsplatz-Konzentration
MOI	Maximally Exposed Offsite Individual
MW	Molecular Weight
NAC/AEGL	National Advisory Committee for Acute Exposure Guideline Levels
NARAC	National Atmospheric Release Advisory Center
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection
NDC	Natural Phenomena Hazard Design Category
NEPA	National Environmental Policy Act
NFDRS	National Fire Rating Danger System
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NNSA	National Nuclear Security Administration
NNSS	Nevada Nuclear Security Site
NOAA	National Oceanic and Atmospheric Administration
NPH	Natural Phenomena Hazard
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NTSB	National Transportation Safety Board
OSHA	Occupational Safety and Health Administration
PAC	Protective Action Criteria
PBL	Planetary Boundary Layer
PC	Performance Category
PDC	Precipitation Design Category
PEL	Permissible Exposure Level
PHA	Preliminary Hazard Assessment
PISA	Potential Inadequacy of the Safety Analysis
PNNL	Pacific Northwest National Laboratory
PRA	Probabilistic Risk Assessment
PrHA	Process Hazard Analysis
PSO	Program Secretarial Office
PUREX	Plutonium Uranium Redox Extraction
PWHA	Probabilistic Wind Hazard Assessment
RCRA	Resource Conservation and Recovery Act
REL	Recommended Exposure Level
RF	Respirable Fraction
RG	Regulatory Guide
RTECS	Registry of Toxic Effects of Chemical Substances
SAC	Specific Administrative Control
SAWG	Safety Analysis Working Group
SBAA	Safety Basis Approval Authority
SC	Safety Class
SCAPA	Subcommittee for Consequence Assessment and Protective Actions
SDC	Seismic Design Category

SDS	Safety Data Sheet
SFPE	Society of Fire Protection Engineers
SIH	Standard Industrial Hazard
SIZ	Structure Ignition Zone
SME	Subject Matter Expert
SMP	Safety Management Program
SNL	Sandia National Laboratories
SNM	Special Nuclear Material
SQA	Software Quality Assurance
SRDT	Solar Radiation Delta Temperature
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SS	Safety Significant
SSC	Structures, Systems, and Components
ST	Source Term
STD	Standard
STEL	Short-Term Exposure Level
STP	Standard Temperature and Pressure
TBP	Tri-Butyl Phosphate
TED	Total Effective Dose
TEDE	Total Effective Dose Equivalent
TEEL	Temporary Emergency Exposure Limit
TF	Topographical Feature
TLV	Threshold Limit Value
TNO	The Netherlands Organization
TNT	Trinitrotoluene
TRU	Transuranic
TSL	Technical Support Level
TSR	Technical Safety Requirement
TWA	Time-Weighted Average
UEL	Upper Explosive Limit
UFL	Upper Flammability Limit
UL	Underwriters Laboratories
USQ	Unreviewed Safety Question
V & V	Verification & Validation
VDC	Volcanic Design Category
VP	Vapor Pressure
WDC	Wind Design Category
WEEL	Workplace Environmental Exposure Limit
WIPP	Waste Isolation Pilot Plant

Note: Definitions related to the DOE hazard and accident analysis process can be found in 10 CFR §830.3, DOE-STD-3009-2014 (or other Part 830 safe harbor), or DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*. Other definitions related to accident phenomenology for evaluation of potential consequences, such as physical and chemical effects, are provided in references cited in the text.

5 SOURCE TERM ANALYSIS

5.1 INTRODUCTION

This chapter addresses development of source terms for accident analysis for the evaluation of consequences to the MOI, and also quantitative evaluation of consequences to the CW, when necessary. As noted in Footnote 4 for Table 2-8, Consequence Thresholds, consequences may be estimated using qualitative and/or semi-quantitative techniques for the hazard analysis. The source term is the amount of hazardous material released to the environment from a given confinement volume under the stress posed by a hypothetical phenomenological event. The source term initially released from confinement into process areas is also of interest for evaluation of consequences to FWs.

This chapter covers application of the five-factor formula presented in Figure 5-1: MAR, DR, ARF, RFs, and LPF, as described in the DOE-HDBK-3010-94. These parameters are evaluated in terms of the stresses imposed by internal events, external man-made events, and NPHs.

Examples of the type of thought processes, bounding assumptions, and overall methodologies used in parameter determination are also provided.

5.2 RADIOLOGICAL SOURCE TERM COMPONENTS

The amount of hazardous material released as a result of accident-imposed stresses is evaluated by a prescribed formula that considers the influence of those five factors. Figure 5-1 displays those factors and their relationships. The basic concept is as follows:

MARxDRxARF = Initial Source Term (IST)

ISTxLPF = Building Source Term (BST)

and

ISTxRF = IST that is respirable

IST (respirable) xLPF = BST that is respirable[40]

The material potentially available to be affected is the MAR. The DR represents that fraction of available material actually affected by the accident stresses. The ARF represents the fraction of material actually affected that is driven airborne, either as a gas or an aerosol. Together, these three factors define the amount of material in the air at the immediate point of release, or the IST. The airborne pathway is normally the exposure mechanism evaluated as it is the principle means by which exposures at a distance from the point of release can occur. Releases to large bodies of waters are a special case where the IST would reduce to simply the MARxDR, with the DR being expressed as a total fraction of material released or a leakage rate.

[40] The "respirable BST" that represents the MARxDRxARF/RFxLPF has been called the "five-factor formula" and is generally presented as the "Source Term (ST)" when describing the input to the radiological consequence analysis for inhalation dose calculations.

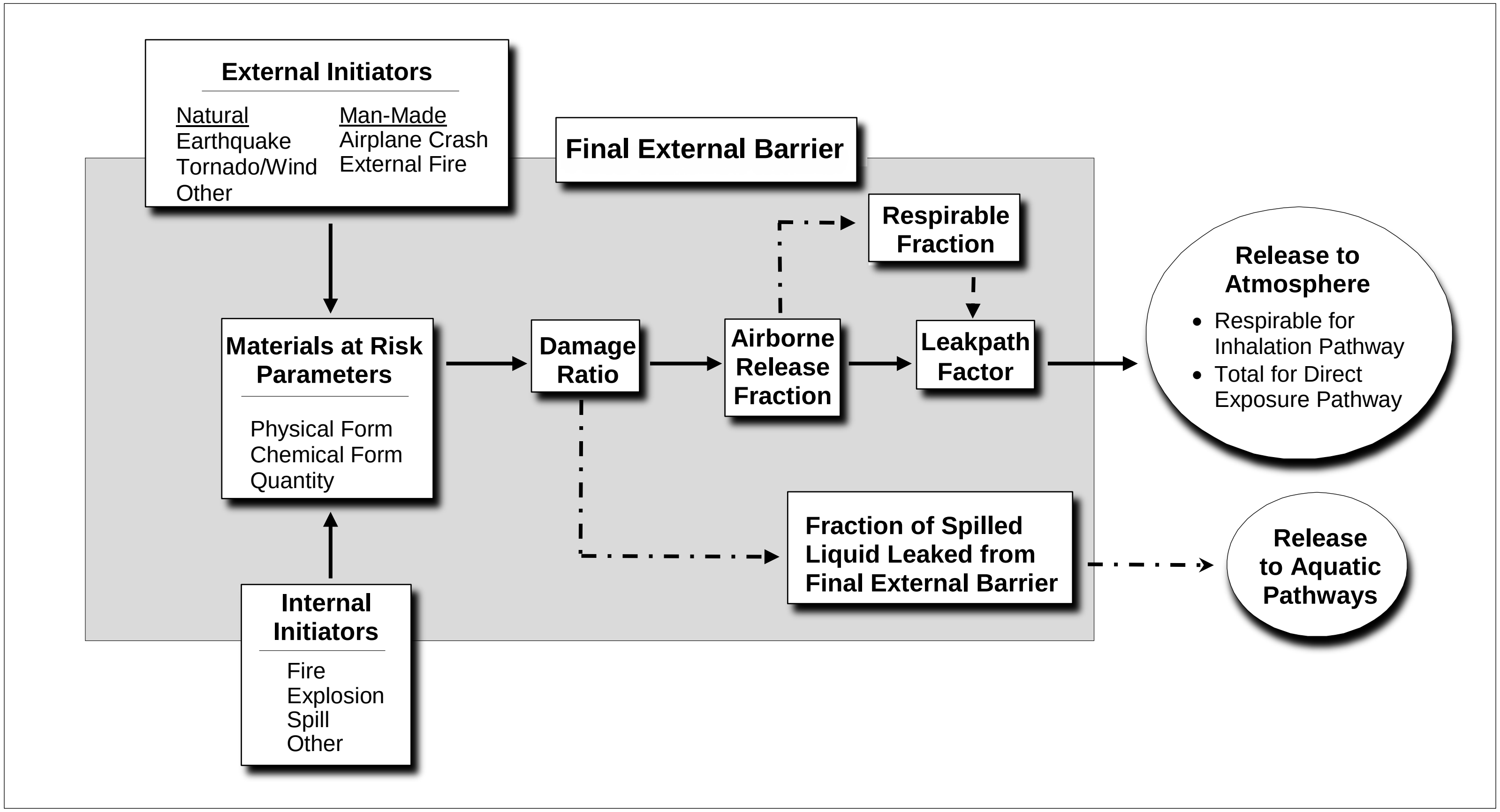

Figure 5-1. Five Factors Formula.

The RF identifies what fraction of the airborne aerosol can be inhaled and retained in the body. The responsible portion of the IST is of major interest for nuclear material handling operations as, with the exception of MAR such as tritium gas, fission products, or high energy gamma sources, most materials of concern (e.g., plutonium, uranium) are alpha-emitting radionuclides. These present no significant dose hazard outside the body. For gases, of course, the IST and the IST respirable amount are the same.

An LPF accounts for source term depletion due to filtration or deposition (“plateout”) as the source term migrates through various layers of confinement. By far the most common application of LPF is HEPA or sand filtration in exhaust ventilation. Applying all relevant LPFs yields the amount of material released to the environment, sometimes called the BST as most handling operations occur inside fixed facilities. The LPF is of interest for mitigated analysis, and is set to unity for unmitigated analysis.

5.2.1 MATERIAL AT RISK

5.2.1.1 OVERVIEW OF REQUIREMENTS, GUIDANCE, AND PRACTICES FOR IDENTIFYING MAR

DOE-STD-3009-2014, Section 3.2.4.1, provides the following direction regarding MAR:

> The MAR is the bounding quantity of radioactive material that is available to be acted upon by a given physical stress from a postulated accident. The MAR may be the total inventory in a facility or a portion of this inventory in one location or operation, depending on the event. MAR values used in hazard and accident analysis shall be consistent with the values noted in hazard identification/evaluation, and shall be bounding with respect to each accident being evaluated.

This concept is considered equally applicable to hazardous chemicals.

The MAR value assigned should be consistent with the DSA hazard identification[41] documented for a given facility or operation. That is, the DSA hazard identification used some basis to determine the maximum hazardous material accumulation foreseeable. The MAR should use that same basis. If it does not, absent some compelling explanation, the basis for either the hazard identification or the MAR designation, or both, becomes suspect. Therefore, if some compelling explanation for a discrepancy does exist, it is preferable to document the rationale for the discrepancy in both the summary section of the DSA hazard identification results and in the DSA hazard evaluation or accident analysis section.

Specifying the amount of a given material foreseeable is based on physical possibility, procedural or other administrative limits, or sampling/historical data. Physical possibility is most often used as a basis with regard to fixed volumes, such as storage vessels. In these cases, the maximum volume of material present can be precisely specified. However, there is still a need to specify the concentrations of the different radionuclides within that volume, in order to determine a bounding MAR.

Administrative limits dominate the assignment of MAR values for radioactive material handling in glovebox-type environments. These environments are constructed to allow operations within the confinement, as opposed to serving as simple holding volumes. Normal practice is to assess specific workstations, glovebox vessels, and storage containers, in terms of batch sizes, process parameters, and

[41] Note that the DSA hazard identification values are is not necessarily the same as the initial data generated in the hazard identification activity itself. As noted in Section 2.2.2, Hazard Data Recording, the DSA hazard identification may identify bounding MAR values as opposed to maintaining a plethora of inventory limits.

criticality safety or other procedural limits.

Statistical sampling or historical data are primarily used for waste-handling and environmental cleanup activities. While some waste-handling operations will have physical upper limits for a given storage vessel such as a drum, much of the radioactive material of concern is mixed with debris, liquid or dirt and is present in very dilute concentrations. A vessel's inventory is estimated by specific process knowledge and is not exaggerated by using the full capacity with concentrated material. Likewise, the condition of residual material in cleanup efforts may not support precise specification of the quantities involved. A theoretical reconstruction based on historical data, measurement, sampling, or some combination of these is required. This is consistent with the statistical treatment of TRU waste allowed in DOE-STD-5506-2007, *Preparation of Safety Basis Documents for Transuranic (TRU) Waste Facilities,* as discussed later in this chapter.

Sometimes for simplification of accident analysis calculations it is beneficial to introduce the concept of surrogate compositions. For example, the concept can be used to establish a common inventory or tracking basis for a dose calculation. It can provide a process for accepting new material while remaining within the bounds of the accident analyses, thus allowing operational flexibility while complying with the safety basis and source strength administrative control limits. A DSA identifies and protects any significant assumptions used in deriving surrogate compositions (e.g., the fraction of combustible waste forms in TRU waste inventories, or the fraction of highly dispersible powders in glovebox operations). See Section 8.2.6, Plutonium Equivalent Curies (PE-Ci), for a further discussion of dose equivalent technique.

5.2.1.2 EXAMPLES FOR IDENTIFYING MAR

Figure 5–2 offers a simplified representation of a nuclear materials handling facility modeled off the example plutonium recovery facility in DOE-HDBK-3010-94. It consists of three glovebox processing rooms: a metal dissolution line, an ion exchange and precipitation room containing two gloveboxes, and a fuel fabrication room containing four gloveboxes. There are also two gloveboxes in a laboratory, one for handling solid samples and the other for handling liquids. Waste is stored in 55-gallon drums in a waste handling room. Finally, there are three storage vessels outside the facility: a chlorine gas supply to the laboratory, and sulfamic acid and nitric acid storage tanks. A MAR is developed for each of these operations. It is important to account for the potential accumulation of MAR throughout the process area, including piping.

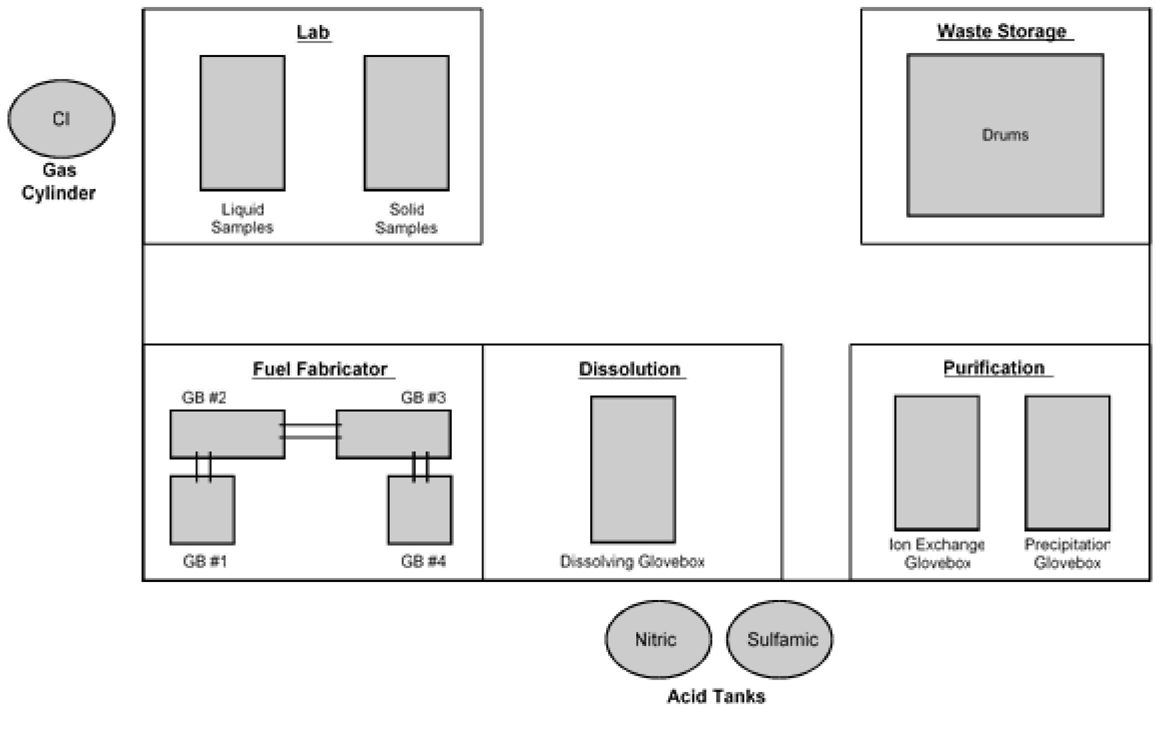

Figure 5-2. Example Nuclear Materials Handling Facility.

Note that the following discussion is for example only, and none of the fictitious quantities cited are intended to represent actual operations in any weapons complex facility.

MAR in External Storage Tanks

Simple physical possibility, with some reference to procedural limits, is used to identify the MAR for these operations. Suppose the chlorine source is a standard vendor-supplied compressed gas cylinder containing 30 pounds of chlorine. As the cylinder volume is fixed and its pressure is monitored by the supply manifold, it is not reasonable to presume a quantity of material greater than 30 pounds based on the unlikely possibility of the vendor overcharging the cylinder. Likewise, if the external acid supply tanks are sized to hold 3,000 gallons, that is maximum volume potentially present. Procedural limits factor into defining the operating concentrations desired. If 32 percent by weight nitric acid and 15 percent by weight sulfamic acid are what is supplied, these would be the values used to define density, and volatility.

Chlorine: 30 pounds in gaseous form

Nitric Acid: $3{,}000\text{gal} \times 1\text{ft}^3/7.48\text{gal} \times 74\text{lb/ft}^3 = 30{,}000$ lb of solution
$30{,}000$ lb of solution $\times\ 0.32 = 9{,}600$ lb of acid

Sulfamic Acid: $3{,}000\text{gal} \times 1\text{ft}^3/7.48\text{gal} \times 75\text{lb/ft}^3 = 30{,}000$ lb of solution
$30{,}000$ lb of solution $\times\ 0.15 = 4{,}500$ lb of acid

MAR for Dissolution Glovebox

The metal dissolution glovebox holds a small spray chamber, a 30-liter acid storage tank, a heat exchanger, a small pump, and various piping and valves. Single plutonium metal shapes are then placed in the spray chamber and dissolved by a heated acid spray recirculated from the slab tank via the following reaction:

$$Pu + 3NH_2SO_3H \rightarrow Pu^{+3} + 3NH_2SO_3^{-1} + 1.5H_2 \qquad \textbf{Equation 5-1}$$

In this case, the glovebox volume is capable of holding a great deal more material than practical operating considerations will allow. Therefore, the MAR is derived from administrative limits.

Suppose a criticality safety evaluation determined that the criticality limit for the acid storage tank is 100 g of plutonium per liter. A volume of 30 liters would then allow 3,000 g of plutonium. But further suppose that the actual pieces to be dissolved each individually contain a maximum plutonium inventory of 750 g. The critical discriminator would then be how the process is operated. If four 750 g pieces are allowed to be dissolved before the dissolving solution is sent out of the glovebox, the bounding MAR values would be as follows:

3,000 grams in liquid form, or

750 grams in solid form, or

whatever combination of both forms could result in the bounding radiological consequences.

On the other hand, if only one item can be dissolved at a time, after which the acid tank solution is sent out of the box, then 750 g of plutonium could represent a reasonable bounding value. For each accident scenario, the analyst would assume the material is in the form (liquid or solid) that maximizes the consequences for that scenario. Or the bounding value could be 1,000 grams if this limit is being normalized with the limits of other operations to provide for TSR consistency. Further, the limit might even be 2,000 grams for the entire glovebox to normalize glovebox TSR limits. There are multiple potential answers depending on how the operation is run and how material limits are apportioned.

Potential administrative burdens on facility management should be considered as well. Suppose the limit had been set at 750 g. If a campaign of unusual shapes ranging in mass up to 1,000 g becomes necessary, and there is no way to split the units into two pieces, a facility might again choose to assign a larger MAR limit for flexibility. The key point is that the limit allowed is the amount analyzed. Within reasonable bounds, there is flexibility to assume more MAR in the accident analysis than is expected to be present during operating campaigns with individual high process inventories.

MAR from Fuel Fabrication

This process takes as feedstock purified oxide powders from the ion exchange and precipitation process which takes the plutonium-bearing dissolution product. Fuel fabrication consists of four gloveboxes containing a variety of milling, blending, sintering, and fuel matrix formation stations. Assume there are 13 distinct operating stations with operating limits as follows:

Operating Limit	Number of Stations
1,000 grams	4
2,000 grams	3
3,000 grams	6

These limits yield a cumulative quantity of 28 kg of plutonium oxide for the overall room. The way in which the process is operated, however, could affect that conclusion. Suppose the process is a semi-batch operation run in campaigns. Three thousand grams (the feed of four dissolving operations) may be entered into glovebox #1, and 3,000 more grams entered when the first batch has progressed to glovebox #3. After the completion of this second batch, the process is then shut down for material control and accountability cleanup. If that is the case, then the overall MAR figure for the fabrication room could decrease to 6 kg of plutonium oxide. Again, the MAR assumed in accident analysis is a function of how facility management chooses to control the operation, and the MAR assumptions may require protection and coverage in the TSRs.

Note that to the degree individual accidents are sufficiently localized so as to affect only a subset of stations, the scenario-specific MAR might also be only a fraction of the overall total. Given the nature of the operation, there may also be a point in processing beyond which the material is no longer at risk from phenomena threatening the entire room, for example, after incorporation into a ceramic matrix. The accident analysis needs to consider station-specific form in order to fully assess vulnerability.

MAR for Waste Storage Area

The waste storage area provides temporary storage capacity for up to thirty 55-gallon drums of TRU waste. The drum limit for disposal is 80 PE-Ci. Based the fact that no drums from this facility have ever approached that level, the facility has an internal restriction of 10 PE-Ci/drum, but managed as 300 PE-Ci as a facility limit. The historical database for the facility, which covers a period of 15 years and includes a statistically significant amount of data, indicates the 95th percentile drum loading is 3.0 PE-Ci, the 50th percentile loading is 0.2 PE-Ci, and the mean loading is 0.4 PE-Ci.

Based on a maximum capacity of 30 drums, the MAR can range from a minimum of 6 PE-Ci (based on 50th percentile loading) to a maximum of 2,400 PE-Ci (based on disposal limit), while the mean loading is about 12 PE-Ci for the entire facility. That considerable range requires common sense parsing. At a minimum, the internal limit of 10 PE-Ci/drum or 300 PE-Ci for the facility is an acceptable MAR assumption for accident analysis. This is also a case where the use of statistical sampling or historical data should be considered. Even the 95th percentile drum loading is a factor of three less than the local facility limit, and the average loading is a factor of 25 less. DOE-STD-5506-2007, Table 4.3.2-1, Bounding MAR Limits for TRU Waste Operations 4, provides a statistical algorithm on how to address multiple drum accidents, except where drums with the highest inventories are commingled are segregated from the general population. Administrative controls may be (and generally are) required to protect the

MAR assumptions for a group of drums or other containers, if the analysis does not assume that every drum is loaded at the maximum allowable level. This applies to the use of the Standard 5506 statistical method, as well as other methods that do not assume the maximum inventory for each container.

The use of statistical sampling and historical data (acquired knowledge) is common in cases of old waste storage areas or environmental restoration where detailed nondestructive assay records do not exist. One such example is the case at Rocky Flats where plutonium residues had built up in ventilation ducting over many years. Prior to cleaning out this material, selected samples were taken to characterize the range of physical forms and chemical composition. This data was augmented by nondestructive assay measurements of radiation levels along the length of the ductwork to arrive at workable estimates of material holdup quantities. In such cases, reasonable conservatism is needed to provide a bounding estimate that is unrealistic.

5.2.2 DETERMINING THE DAMAGE RATIO (DR)

5.2.2.1 OVERVIEW OF REQUIREMENTS, GUIDANCE, AND PRACTICES

The DR is the fraction of material that is actually affected by the accident-generating conditions. DOE-HDBK-3010-94 notes that some degree of ambiguity can result from overlapping definitions of MAR and DR. A given DSA should use one consistent definition throughout. A DR of 1.0 is used unless there is an applicable standard or technical basis for a smaller value. For example, DOE-STD-5506-2007 contains specific DRs (and associated MAR guidance) that may be used in TRU waste operations.

If a qualified container is assessed to survive the postulated accident scenario (i.e., container test requirements exceed the accident environment) then a DR of zero is assigned since there is no release. If the qualified container does not survive the accident conditions, a DR of 1.0 is usually assigned, unless technical justification is provided for a lesser value.

There is an intrinsic interdependence between the definitions of MAR and DR. In simplest terms, the overall area impacted by an event, as well as the magnitude of any energy release, determines what material is impacted. But that can also be thought of as determining what materials are available to be acted upon.

This distinction is made clear by considering two cases. The first is an explosion that affects only one room in a large facility and does not have the capacity to generate a large fire. Most analyses will focus only on that one room. They will not consider material in other rooms, as by definition such material is not at risk, and thus not part of the MAR.

The second case is a seismic event that shakes the entire facility and topples various weak gloveboxes throughout the facility. In this case, analyses identify material in every room as MAR, specifying DRs over the range of zero (e.g., if seismically qualified) to one for each specific case. Because the event affects the entire facility, it is deemed necessary to demonstrate that every potential source of release has been considered. Or, in simpler terms, the practical limits of what could be MAR are not self-evident from the scenario definition itself.

This relationship between MAR and DR may seem trivial. There have, however, been multiple analyses that have stumbled over it. MAR has been defined imprecisely enough that DRs for a given form were credited when that form had already been stricken from the MAR, and DRs greater than zero were applied to material not ultimately at risk. In the former case, the DR is effectively credited twice, yielding a nonconservative source term; in the latter, it is effectively omitted so that the source term is excessively conservative. The relationship between MAR and DR is pointed out to emphasize the need for precise definition of each with reference to the other. Either unaffected material is not considered MAR, or it is and assigned a DR of zero. Likewise, material with a DR greater than zero should be identified as MAR. The simplest convention for avoiding confusion is to identify all material within the structural subdivision affected by the accident (e.g., glovebox, room, wing) as MAR. DR values of zero are then assigned for material not impacted in any significant fashion as justified in the scenario description.

DR values are based on the response of MAR form and available shielding to the stress imposed, as attenuated by any distances involved. In many cases, the nature of the stress-to-distance, stress-to-shielding, or stress-to-form relationship is simple enough to assign a DR from general engineering knowledge or historical experience. Ion exchange exotherms are a well-understood potential in certain operations, sufficiently so that many have been re-engineered to eliminate or minimize that possibility. If vitrified waste, or even hardened cement containing waste, waste is co-located in a room with an ion exchange glovebox, these can be quickly eliminated as MAR is significantly impacted by the exotherm for all but the most unusual of circumstances. Likewise, spilling a plutonium nitrate solution from one glovebox is not going to affect material in other gloveboxes.

When the nature of the stress relationship is not so simple, engineering estimates of type and level of stress are performed in conjunction with assessments of structural strength for available shielding and confinement. Seismic assessments determine whether a given glovebox will remain stable or fall over, and whether massive objects in the overhead will impact the glovebox either way. Fire modeling (see Section 4.2) can estimate whether or not temperatures necessary for combustion of bulk metal will occur for an extended period of time. Blast calculations (see Section 4.3) can determine if a steel vessel at a given distance will remain intact. All of this information may be needed to define a DR of zero, one, or any fraction in between.

5.2.2.2 EXAMPLES

Examples are provided in the following subsections to illustrate the thought process for determining DRs. These are not bounding default recommendations, and use in a DSA will require appropriate justification in context with the scenario being analyzed.

Fire Event

The hazard identification states that 100 g of Pu metal fines, a pyrophoric hazard, is the maximum amount of metal contamination anticipated in impure oxide received for processing. The nuclear criticality limit is 2,000 g if an entire feed can contain nothing but metal fines, but the maximum anticipated amount from historical records is 100 g. Therefore, the DR is 0.05. Note that this assumption may require protection by a TSR administrative control. It would also be acceptable to use a DR of 1.0 with a MAR of 100 g. Another potential hazard to analyze is whether the pyrophoric event could affect other MAR, such as bulk metal, if it is also allowed to be present in this process. For example, the pyrophoric event could ignite the bulk metal or ignite nearby combustibles, leading to a larger fire involving more MAR in nearby gloveboxes. In this case, different DRs would be developed for this additional MAR.

Explosion Event

Assume four liquid tanks holding plutonium nitrate solution. The location of the tanks is split, with two each being located on opposite sides of a large room. There is a significant amount of intervening equipment between them.

The tanks are physically sized to hold 200 liters of solution. At a nominal operating concentration of 30 g Pu/l, the tanks could physically hold 6 kg. The operational flow sheet for the process; however, indicates that each batch contains only 1 kg of plutonium. The operating limit specified in procedures is 1.5 kg.

Assume that under certain conditions, any tank can experience a runaway reaction that overpressures the tank to failure. However, each is operated independently, so that a common cause for multiple over-pressurizations simultaneously does not exist. How should the MAR and DR be defined?

The starting MAR would be 1.5 kg Pu per tank. This is the allowable limit, irrespective of the fact that only 1 kg of Pu is expected per tank. If facility management does not desire to analyze 1.5 kg of Pu per tank, the operational limit should be lowered. Facility management may also choose to analyze a higher value, say 2 kg of Pu per tank, for future flexibility. There is no obligation, however, to assume 6 kg of Pu per tank simply because one could physically do that. That conclusion is no different than a glovebox example, where one works with the practical limits established as opposed to calculating how much solid material could physically be crammed into the box at a given density. The important point is to establish a conservative bounding estimate that is not unrealistic. Since the 1.5 kg of Pu is much less than the physical limit of 6 kg, a TSR Administrative Control may be necessary to protect this assumption unless process upsets cannot exceed the 1.5 kg operating limit.

Accordingly, each tank contains 1.5 kg Pu for the DSA analysis. The next question to answer is what happens to that material? The liquid in the tank where the runaway reaction occurs will experience an over-pressurization release phenomena. What happens to the other tanks is a function of two variables: (1) location, and (2) the violence of the original tank failure.

There are two tanks on the same side of the room. If the first tank merely experiences a localized weld failure (DR of 1.0 for over-pressurization only), the second tank on that side of the room should not be damaged (DR of zero). On the other hand, if the first tank bursts violently into multiple pieces (DR of 1.0 for over-pressurization and DR of 1.0 for free-fall spill of the remaining solution), and the second tank is directly adjacent, it is reasonable to consider whether the second tank could be punctured (DR of 1.0 for free-fall spill). The answer to that question would be determined by mechanical engineering calculations. For example purposes, assume the second tank would be punctured if the engineering calculation is not performed.

The final matter to consider is the two tanks on the opposite side of the room. If the room is large, and the process equipment occupying the floor space between forms a natural barrier, assume that an engineering calculation has been performed that establishes that the remaining two tanks are unaffected; therefore, a DR of 0.0. That is an acceptable conclusion for an unmitigated analysis given that no specific preventive or mitigative capability is being credited. The relative locations of the tanks are physical facts, and the process they serve intrinsically requires equipment located on the intervening floor space.

Alternatively, as previously discussed, the analyst could choose to state that the tanks on the opposite side of the room are not MAR for this particular accident scenario. Other subtleties could come into play as well. If, for the purposes of this example, it is not physically possible to generate a puncture in the adjacent tank at low levels, because half the tank is located in a pit, then only 50 percent of the adjacent tank contents could spill. The spill release DR for that tank may then be given a value of 0.5.

In the mitigated scenario, of course, the DRs can change significantly. For example, if one credits a pressure relief system designed to handle the runaway reaction, there may be no release at all. Or there may be a smaller release depending on the ultimate destination of the pressure relief outlet.

A final consideration is human error. That is not a consideration in this scenario as developed, but suppose the potential for human error to drain one of these tanks in a spill scenario was examined. At only two hundred liters, if there is a plausible way to initiate a spill by erroneous draining, the entire tank is usually assumed to spill. This is because although it might be noticed and the process stopped, the available volume relative to typical pump capacities can result in emptying the tank relatively quickly. A DR less than 1.0 would thus be inappropriate. On the opposite extreme, assume one is evaluating a legacy liquid waste storage tank holding over two million liters of solution. At some point, the cumulative level of human error required to drain the entire tank can become willfully egregious. There is no requirement to analyze scenarios that become physically ridiculous, so a reasoned basis for the maximum portion of the tank that might be drained is acceptable.

Determining DR for Spill Event – Powder Spill from example 7.3.1 in DOE-HDBK-3010-94: As discussed in that Handbook, the DR for a powder spill event is usually 1.

Liquid Spill from example 7.3.2 DOE-HDBK-3010-94: A spill can occur from a piping or vessel leak due to corrosion, or inadvertent damage from an activity such as maintenance or an unrelated accident. If the leak in a line is small, or a leak in a vessel is above the vessel bottom, not all of the material would be spilled. For the sake of simplicity, a leak large enough and situated so as to allow all of the liquid to drain from confinement is postulated (i.e., DR = 1.0).

Liquid Spray: The use of a centrifugal pump for liquid circulation generates positive pressure. While the pressure is not high in this small process, it is sufficient to produce liquid spray and thus a different release stress than the vacuum transfer systems in other dissolution lines. A pump seal, flange failure, or even a piping leak could cause spray generation. The maximum amount of material available in solution is 1,200 g of plutonium if all of the metal is dissolved. The DR will probably not be 1.0 even if no operator intervention occurs as the pump eventually shuts off from loss of net positive suction head after sufficient liquid is lost. The distinction, however, could be minor; therefore a DR of 1.0 is used for the sake of simplicity in this example.

Exothermic Event

The ion exchange process is located in the purification room shown in Figure 5-2, receiving feed solutions from the dissolving tanks and sending the processed liquid streams to annular holding tanks; both sets of tanks being located in other rooms. The process consists of three ion exchange columns in series in a glovebox with support equipment and piping. The columns themselves are 6-inch diameter, 5.5-foot tall Pyrex cylinders with flanged heads on the top and bottom. Each column holds approximately 24 liters of Dowex 21-K anion resin, or equivalent. This activity involves liquid plutonium solutions and plutonium absorbed on solid resins. The source term for the ion exchange exotherm is a function of MAR distribution as DRs are variable and there are competing release mechanisms for solid and liquid phases, with no constant ratio of plutonium between the phases depending on whether in the loading or eluting cycle. At the completion of a loading cycle almost 6,000 g of plutonium are absorbed in the beds with a maximum of 6,500 g allowed. Assume that no other MAR in the adjacent precipitation glovebox is affected by an explosion in the ion exchange glovebox.

First, if the temperature of the liquid flowing from the affected column to the next column in line is sufficiently high, it may initiate a resin exotherm in the next column. Secondly, when the affected column ruptures, historical experience and understanding of the phenomena indicate that at least some of the resin from the damaged column will continue to burn on the glovebox floor.

How much will burn depends on whether the spilled resin is piled on the glovebox floor to maintain local temperature above the autoignition temperature. If a large amount of resin burns, the heat generated may be sufficient to initiate resin exotherm reactions in the undamaged columns. This effect is not certain and there are historical incidents where an exotherm in one column was followed by a fire with no subsequent exotherm in adjacent columns. With respect to the Hanford exotherm incident discussed in Section 4.5 above, the presence of a significant amount of uncharred resin was reported after the incident. Finally, the other columns may be damaged in the initial explosion, shattered by shrapnel from the damaged column, in which case spilled resin may burn, but pressurization of multiple columns is not possible.

Therefore, depending on how many columns are assumed to be affected by a given stress, the first potential factor of the DR is 0.33, 0.67, or 1.0. A second potential factor is, at least for solids, how far the process is into a loading or elution cycle. For example, if only 2,000 g are loaded per operational limits that are protected by a TSR AC, the DR is 2,000/6,500 = 0.31. If both potential factors are used, they need to be defined together so that “double-counting” does not occur.

Earthquake Event

Figure 5–3 is a reproduction of Figure 5–2 with the additional designation of a structural collapse zone along the south wall vulnerable to a seismic event. The affected equipment includes half of the dissolution glovebox and the final glovebox (No. 4) in the fuel fabrication line. A seismic study indicates all other gloveboxes and major equipment have sufficient margin to survive the seismic stress.

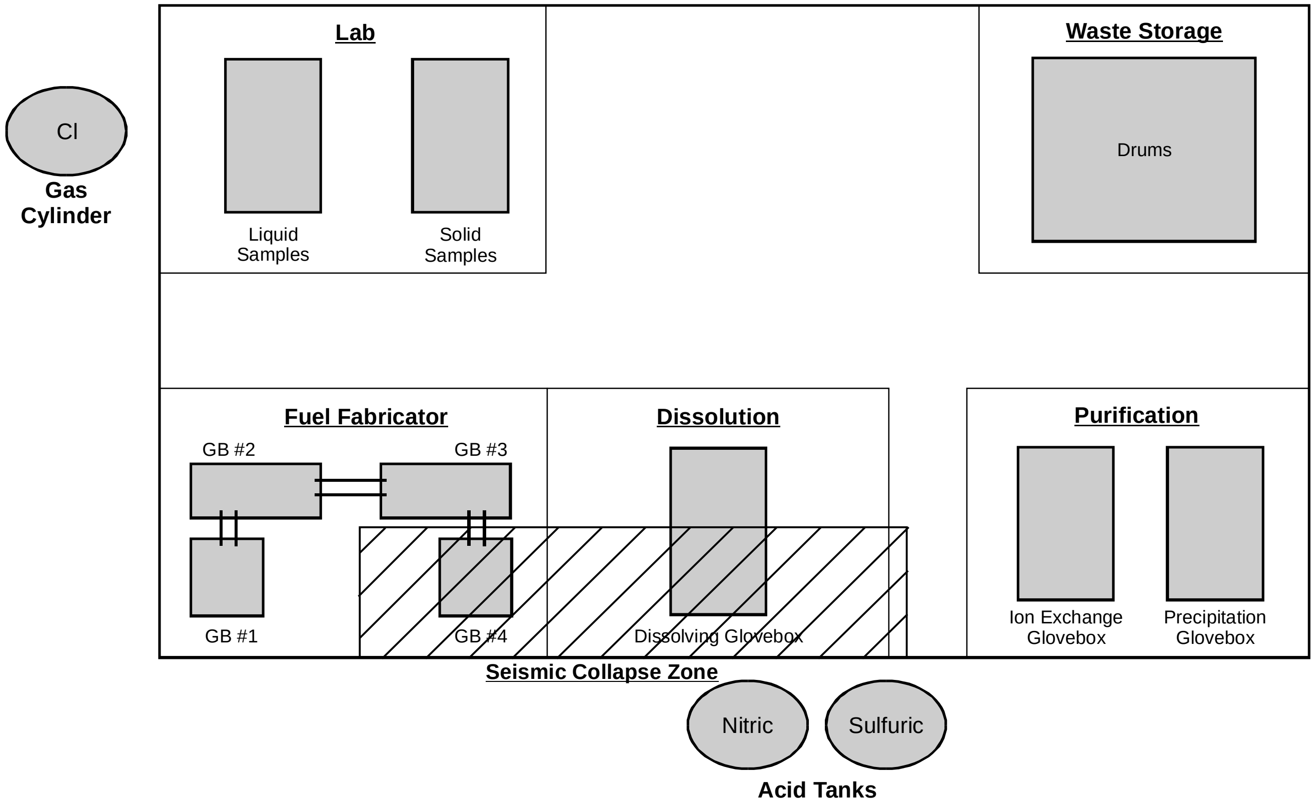

Figure 5-3. Seismic Collapse Zone.

Based on the batch operation discussions for this example in the MAR section, 3,000 g of material can be in the dissolution glovebox. Six thousand grams of powder from the precipitation operation can be in the fuel fabricator line, with 3,000 grams in the front end (i.e., glovebox #1), and 3,000 grams in the back end (gloveboxes #3 and #4).

At first glance, the largest source term of concern would occur if 3,000 g of powder is in glovebox #4, which is impacted by falling debris. A DR of 0.5 (3,000 of available 6,000 g) would be assigned to this material, with a DR of 0.5 for the powder in undamaged gloveboxes # 1 and #2. Moreover, it would be equally acceptable to use a DR of 1.0 with a MAR of 3,000 g for each of these locations.

But suppose by the time the material reaches glovebox #4 that it has been rendered into a ceramic state impervious to the stresses offered by the structural collapse. The ARF for the stress imposed upon ceramic components would be significantly less than the ARF for the stress imposed upon powder. It is conceivable that the bounding release scenario might now move the 3,000 grams of material from glovebox #4 to glovebox #3, where it would still be powder and experience the limited release from seismic shock. These are the types of considerations that come into play when generating source term estimates.

Another possible source of airborne material would be the seismic vibration experienced by surface contamination in all four gloveboxes. This material might contribute in a minor way for the first three gloveboxes as it could have a larger ARF (for smaller quantities) than bulk powder contained in cans or equipment. It could even prove the dominant source term from glovebox #4 if the ceramic fuel forms in question truly are undamaged in the post-seismic state. This drives home again the point that the source term analysis assesses multiple factors. While individual factors should not be unrealistically exaggerated, no potential contributor should be dismissed without consideration.

Moving to the issue of the dissolution glovebox, consider two cases. In the first, the spray chamber and acid storage tank are located at the south end of the glovebox in the collapse zone. Both should be considered structurally compromised in the aftermath of such an event. The question is what value to assign for what MAR? In this case, the ARF for liquids will exceed that for metal. The accident analysis should therefore assume a full dissolution run of four items has finished and the liquid tank contains 3,000 grams of material in solution. The DR for this MAR is 1.0.

The second case is one where the spray chamber and acid storage tank are located at the north end of the glovebox, outside of the collapse zone. This would initially lead to an assumed DR of zero. If, however, the piping that transfers liquid out of the glovebox passes through the collapse zone, some release is possible. If the pipe is one inch in diameter, and the affected length is ten feet, with an additional twenty feet in the next room over that might drain back to this new low point, a total of 4.6 liters might be available to spill. This yields a DR of 0.15 (4.6 liters out of 30). Likewise, if the acid storage tank survived, but seismic analysis indicated failure of a penetration on the tank at the 15-liter level, 15 liters could be assumed to spill from the tank and 15 liters remain, yielding a DR of 0.5.

As a final note, analysts should realize that the structural strength of the majority of the facility, and the seismic capacity of the gloveboxes, is an initial condition of analysis. That is why the hypothetical analysis discussed above focused on areas of potential facility damage. See discussions in Chapters 2 and 3 of this Handbook regarding initial conditions and protection as design features in the DSA and TSRs.

5.2.3 AIRBORNE RELEASE FRACTION AND RESPIRABLE FRACTION

5.2.3.1 OVERVIEW OF REQUIREMENTS, GUIDANCE, AND PRACTICES FOR DETERMINING ARF/RF

DOE-STD-3009-2014, Section 3.2.4.1, provides the following information/directions related to ARF and RF:

> The ARF is the coefficient used to estimate the amount of a radioactive material that can be suspended in air and made available for airborne transport under a specific set of induced physical stresses. The RF is the fraction of airborne radionuclide particles that can be transported through air and inhaled into the human respiratory system. The RF is commonly assumed to include particles of 10-μm Aerodynamic Equivalent Diameter and less. Bounding estimates, and in many cases median estimates, for radionuclide ARFs and RFs for a wide variety of MAR and release phenomena are presented in DOE-HDBK-3010. The bounding estimates shall be used unless a different value is provided in an applicable standard or is otherwise technically justified. In cases where direct shine may contribute significantly to dose, that contribution should be evaluated without the use of the RF, and without the use of the ARF if due to a spill release resulting in exposure to a pool. ARFs and RFs are selected based on physical conditions and stresses anticipated during accidents. DOE-HDBK-3010 defines bounding ARFs and RF mechanisms and airborne release rates based on physical context.

The ARF and RF are evaluated together except in circumstances where it is desired to know the total release of a given material, or when the RF is one, such as is the case with gases. Defining these two parameters generally presents the greatest difficulty in source term analysis. Historically, available information on the subject was extremely limited. As a result, whatever information could be found was used regardless of its true applicability. Little quality control was applied either: different ARFs were assigned by different analysts based on the same information, best guesses became quasi-facts with sufficient repetition, numbers were transposed in copying and passed down. In response to this state of affairs, the DOE set in motion a project to collect the available data on ARF/RFs for material at nonreactor nuclear facilities, test its application in real life circumstance, and attempt to define bounding values for various phenomena. This effort culminated in the development of DOE-HDBK-3010-94. The estimates from that document have since been reproduced in NUREG/CR-6410 and ANSI/ANS-5.10, *Airborne Release Fractions at Non-Reactor Nuclear Facilities*. Both of the documents cited were subject to significant peer review.

In the development of DOE-HDBK-3010-94, available experiments and other data were correlated with the major types of material forms present at materials handling facilities, as well as the normal accidents of concern for such facilities. The major types of material were considered to be: (1) gases, most specifically tritium; (2) liquid solutions, both organic and aqueous; (3) solids, including metals, bulk powders, aggregates, spent fuel and other special forms; and (4) surface contamination, whether in the form of holdup in processes, material entrained in waste, or soil contamination. The major types of accidents considered included spills, fires, explosions, seismically induced vibrations and impacts, and criticalities. The latter, while included in DOE-HDBK-3010-94, represent a special case whose potential MAR is directly defined by the physics of the phenomena itself.

The net result of correlating data to material and accidents was a general categorization of ARFs by four categories: (1) explosive, (2) thermal, (3) mechanical, and (4) aerodynamic entrainment (i.e., suspension in air or resuspension). Explosive stresses of interest are shock effects, blast effects, and venting effects associated with detonation (e.g., high explosive), deflagration (e.g., most gas explosions), and over-pressurization (e.g., heating confined material to rupture pressure). Thermal stresses include evaporation of liquids and combustion of organic liquids, combustion of solids and contaminated waste, and intense heating of noncombustible material. Mechanical stresses of concern include free-fall spill to impact, vibration/shock induced by events such as an earthquake, and impact or crushing of material and containers by falling debris. Aerodynamic entrainment relates to the special case of material freshly deposited on surfaces in the immediate aftermath of an accident or other releases as evaluated in DOE-HDBK-3010-94 Chapter 5, and for wind suspension from a bed of powders or aged contaminated soils as evaluated in the DOE-HDBK-3010 Chapter 4.

Along with ARF values, associated RFs were assigned whenever possible. The size distribution of accident generated aerosols is a particularly complex issue, as most experiments cannot be designed so as to capture a truly representative sample. The logistical requirements of sampling typically result in a skewed sample. Either a sample is obtained where the larger size particles have already deposited due to sampling at a distance or engineered features of the sampling device itself, or the size distribution is affected by the physical chaos of the event itself on in-close sampling equipment. Further, this most basic of problems does not even address detailed physics interaction problems, such as the attractive forces between particles (inter-particle attractive forces) or between particles and the surface (including the effect of surface roughness and the presence of other materials that increase the adhesion of the particles to the surface).

Table 5-1, taken from ANSI/ANS-5.10-1998 (R2013), *Airborne Release Fractions at Non-Reactor Nuclear Facilities*, Table A-1, "Bounding ARFs and Applicable Experimentally Measured RFs," presents a brief summary of ARF and RF values currently available. This table is an update to a similar summary Table 3-1, "Bounding ARFs and Applicable Experimentally Measured RFs," initially developed for

NUREG/CR-6410 in 1998. This is only a summary, and the discussion of ARF selection to follow is both brief and general in nature. ARF and RF values should be chosen using DOE-HDBK-3010-94, DOE-STD-5506-2007, NUREG/CR-6410, technical journal articles, from other approved DSA's for unique situations, or derived from physics/chemistry principles. The source of the values needs to be cited and technically justified for use. As stated in the quote above, alternate values to the DOE-HDBK-3010-94 bounding values may be technically justified. Qualitative engineering judgment should not be used as the sole basis for departing from DOE-HDBK-3010-94 bounding values, without substantial technical basis from data that can be appropriately extrapolated or used as an analogy − see Section 5.4.1 below.

An ARF value is selected on the basis of the scenario postulated, the type and level of stress presumed to impact the MAR, and the characteristics of the MAR. Both volatile and nonvolatile materials can be suspended. To suspend a stable material at rest, it is necessary to impact the material sufficiently to convert it to a dispersible form and to provide sufficient air flow to carry the suspended material into the local flow field. In the case of volatile materials, the physicochemical environment to convert the material to its gaseous form needs to be present. If the conversion is due to a chemical reaction, sufficient reactant needs to be available to convert all the affected MAR to its gaseous phase. If the quantity of reactant necessary for conversion is limited and only converts a portion of the volatile material to its gaseous phase, the fraction converted becomes the ARF. In the case of material in the gaseous phase, no RF can be assigned, since, all the material can be transported and inhaled as long as the material remains in the gaseous phase. Airborne reactions, however, can either convert some gaseous materials to solid particles (e.g., reaction of NO_2^- with NH_4^+ to produce NH_4NO_3), attach them to existing airborne particles (e.g., attachment of I_2), or result in adhesion to surfaces (e.g., I_2).

Table 5-1. Summary of Bounding ARF and RF Values.

(Extracted from American National Standard ANSI/ANS-5.10-1998 (R2013) with permission of the publisher, the American Nuclear Society; with addition of Clark, 2015, uranium thermal ARF/RFs**)**

NOTES:
The codes in the column titled "TSL" (Technical Support Level) indicate the following:
1 - supported by experimental data from more than one independent source of the stated range with experimental support for particle generation mechanism;
2 - experimental support over that stated range;
3 - single experimental datum or inferred from other studies.
In the "ARF (RF)" column, the value for the ARF is given in exponential form, and the value for the RF, where used , is given in decimal form, and in parentheses. If no RF is given, it is set to 1.0. Letters in square brackets ([a], [b]) refer to notes at the end of the Table A1 as presented in ANSI/ANS-5.10-1998 (R2013). Other minor formatting and editing changes were also made to the original Table A1, and any non-editorial changes to Table A1 are shown in *{italicized text}*. "DOE Handbook" refers to DOE-HDBK-3010-94.

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments
		Explosive Forces: Detonation		
Reactive Metal Implosion, Pu surrounded by and in intimate contact with high explosives (HE), HE:Pu ratio > 1 to 10, single point detonation	1E+0 (0.2)	2	Mensing et al., 1995, Shreve and Thomas, 1965	Calculated from airborne sampling data for operation "Roller Coaster" 1965 (experiments to determine the dispersal of nuclear materials by explosives).
Implosion, metal surrounded by and in intimate contact with high explosives (HE); HE:metal ratio >1 to 10, single point detonation	2E-1	3	ANSI/ANS-5.10-1998	Based on small scale experiments on the dispersal of metal hemisphere by explosives. Applicable to metals less reactive than Pu. Release of any Pu is estimated by ARF/RF values shown.
Metal or Solution – Explosion, metal or aqueous solution, high explosive in intimate contact with material, HE:material ratio 0.07 to <1	TNT Eq. [a]	2	DOE Handbook, Sections 3.2.2.1 and 4.2.2.1	
Powder – Explosion, High Explosives lying on surface, HE:powder ratio 1 to 100	ARF/RF = 0.2 x TNT Eq. [b]	2	DOE Handbook, Section 4.4.2.1	From soil lofted during field tests where HE (bare and as artillery shells) were placed directly on the soil surface.
HEPA Filters *{Shock pulse}*	2E-6	2	DOE Handbook, Section 5.4.2.1	Small pieces of glass fiber medium were dislodged from a few locations on the creases in the downwind region of the filter.

Stress/Material	ARF (RF)	TSL	Reference[*,#]	Comments
Explosive Forces: Deflagration				
Powder Unshielded, directly under or in blast volume of large explosion with high confinement pressure	1E+0 [c]	2	DOE Handbook, Section 4.4.2.2.1	
In containers or at a distance of meters from the blast volume, aerodynamic entrainment by accelerated gas velocities	5E-3 (0.3)	2	DOE Handbook, Section 4.4.2.2.2	
HEPA Filters *{Venting by pressurized gases}*	1E-2	2	DOE Handbook, Section 5.4.2.2	
Explosive Forces: Over-pressurization to Rupture				
Liquid, confined in vessel or container Slow buildup of pressure [d], vented above the surface level of liquid, failure <0.35 MPa_g	5E-5 (0.8)	2	DOE Handbook, Section 3.2.2.3.2.A	
Slow buildup of pressure, vented above the surface level of liquid, failure pressure >0.35 up to 3.5 MPa_g	2E-3 (1.0)		DOE Handbook, Section 3.2.2.3.2.A	
Rapid buildup of pressure, vented above the surface level of liquid	NVA [e]		DOE Handbook, Section 3.2.2.3.2.B	
Rapid buildup of pressure, vented below the surface level of liquid [f]	1E-4	2	DOE Handbook, Section 3.2.2.3.1	
Superheated liquids ("flashing spray"), <50 ^oC superheat	1E-2 (0.6)	2	DOE Handbook, Section 3.2.2.3.3.A	
Superheated liquids ("flashing spray"), 50 ^oC – 100 ^oC superheat	1E-1 (0.7)	2	Mishima et al., 1968, Borkowski et al., 1986, and Kataoka and Ishii, 1983, DOE Handbook, Section 3.2.2.3.3.4	
Powder Confined in vessel or container, release pressure < 0.17 Mpa_g (< 25 psig)	5E-3 (0.4)	2	DOE Handbook, Section 4.4.3.3.2	
Confined in vessel or container, release pressure > 0.17 < 3.5 Mpa_g (25–500 psig)	1E-1 (0.7)	2	DOE Handbook, Section 4.4.2.3.1	
Vitrified High Level Waste Canisters High pressure sufficient to dissolve the plug	3E-5	3	DOE Handbook, Section 4.3.1.1	Based on a measured value of 3.5E-4 of inventory as particles in the upper plenum of canister and ARF/RF of 1E-1/0.7.
Thermal Stress				
Volatile compounds	1E+0	1	Brereton et al., 1997	AP AC Spills Report.
Liquid, aqueous solutions Simmering, no visible bubbles	3E-5	2	DOE Handbook, Section 3.2.1.1	

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments
Boiling [g]	2E-3	1	Mishima et al., 1968, Borkowski et al., 1986, and Kataoka and Ishii, 1983, DOE Handbook, Section 3.2.1.3	
Liquid, organic combustible Volatile compounds	1E+0	2	DOE Handbook, Section 3.3.1, 3.3.7	
Non-volatile compounds, burns to self-extinguishment, no significant surface turbulence	1E-2	2	DOE Handbook, Sections 3.3.1, 3.3.7	
Non-volatile compounds, vigorous burning with surface turbulence, burns to self-extinguishment	3E-2	2	DOE Handbook, Sections 3.3.3, 3.3.4, 3.3.5, 3.3.7	
Non-volatile compounds, vigorous burning with surface turbulence, to complete dryness	1E-1	2	DOE Handbook, Sections 3.3.3, 3.3.7	
Burning of combustible liquid over air-dried residue from solution on porous, non-heat-conducting surface	5E-3 (0.4)	2	DOE Handbook, Sections 3.3.6, 3.3.7	
Burning of combustible liquid over air-dried residue from solution on heat-conducting surface	2E-1 (0.3)	2	DOE Handbook, Sections 3.3.6, 3.3.7	
Solid reactive metal				
Plutonium, < ignition temperature [h] of oxide formed	3E-5 (0.04)	2	DOE Handbook, Section 4.2.1.1.2	
Plutonium, > ignition temperature	5E-4 (0.5)	1	Mishima, 1966, 1967; Luna, 1994; Carter and Stewart, 1970; Eidson et. al., 1988; Eidson and Kanapilly, 1983, DOE Handbook, Section 4.2.1.1.3	
Plutonium, free-fall spill of molten metal into air, small fall distance	1E-2	2	Stewart, 1963, DOE Handbook Section 4.2.1.1.4	
Plutonium, small drops of molten metal violently dispersed that travel greater than 1 m in air	1E+0 (0.5)	1	Raabe et. al., 1978, Chatfield, 1969, DOE Handbook Section 4.2.1.1.5	
Uranium, less than ignition temperature [i], greater than 500 ˚C	1E-3	2	DOE Handbook, Section 4.2.1.2.1	
Ignitable forms of β-phase Uranium Alloys, greater than 500 °C	1E-3	2	DOE Handbook, Section 4.2.1.2.1	Elder and Tinkle (1980) and experiments using Staballoy DU penetrators.

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments
Ignitable forms of pure-Uranium and α-phase Uranium Alloys, greater than 500 °C	1E-4	2	Carter and Stewart (1970)	Discussion of Carter and Stewart Experiments in DOE Handbook Section 4.2.1.2.1 for Median ARF/RF value.
Non-ignitable forms (e.g., bulk/large pieces) of pure-Uranium and/or α-phase Uranium Alloys, below ignition temperature	1E-6	2	Clark (2015)	Note: Median ARF/RF rounded to nearest order of magnitude. From Table 5 in Clark (2015), 5E-7 is rounded up to 1E-6.
Non-ignitable forms (e.g., bulk/large pieces) of β-phase Uranium Alloys, below ignition temperature	1E-5	2	Clark (2015)	Note: From Table 5 in Clark (2015), arithmetic mean is rounded down to 1E-5, same as the geometric mean.
Non-ignitable forms (e.g., bulk/large pieces) of γ-phase Uranium Alloys, below ignition temperature	1E-7	2	Clark (2015)	Note: From Table 5 in Clark (2015), 5E-8 is rounded up to 1E-7.
Uranium, free-fall spill of molten metal greater than 1 m	1E-2	2	DOE Handbook, Section 4.2.1.2.2	
Uranium, explosive dispersal of thin sheets of metal	1E+0	2	DOE Handbook, Section 4.2.1.2.3	
Concrete				
Tritium (^{3}H) as water, > 20 ˚C to 200 ˚C	5E-1	2	DOE Handbook, Section 4.3.1.2	
Tritium (^{3}H) as water, > 200 ˚C to 600 ˚C	1E+0	2	DOE Handbook, Section 4.3.1.2	May also suspend radionuclides held in cement matrix if cement is decomposed and particles of CaO can be suspended.
Solid, powder				
Nonreactive [j], up to 1,000 ˚C, upflow around powder to 100 cm/s	6E-3 (0.01)	2	DOE Handbook, Section 4.4.1.1	
Reactive, plutonium compounds, up to 100 ˚C, upflow around powder to 100 cm/s: Plutonium fluoride	1E-3 (0.001)	2	DOE Handbook, Section 4.4.1.2	
Solid, Compounds				
Reactive, plutonium compounds, up to 100 ˚C, upflow around powder to 100 cm/s: Plutonium oxalate, nitrate	1E-2 (0.001)	2	DOE Handbook, Section 4.4.1.2	
Solid, contaminated combustible				
Packaged waste, burns to self-extinguishment	5E-4	2	DOE Handbook, Section 5.2.1.1	

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments
Loose cellulosic material, burns to self-extinguishment	1E-2	2	DOE Handbook, Section 5.2.1.2	
Loose polystyrene	1E-2	2	DOE Handbook, Section 5.2.1.4.3	
Loose, other plastics	5E-2	2	DOE Handbook, Section 5.2.1.4	
Light cellulosic material remaining suspended during complete combustion (i.e., ash)				
UO_2 preformed particle	4E-1	2	DOE Handbook, Section 5.2.1.3	
Contaminated with air-dried residues from solution	8E-2	2	DOE Handbook, Section 5.2.1.3	
Solid, contaminated HEPA filters passage of heated air up to 400 ˚C [k]	1E-4		DOE Handbook, Section 5.4.1	
Aerodynamic Entrainment/Resuspension [l]				
Homogeneous Deposit	ARR:			
Liquid, indoors, shallow pool on heterogeneous surface (e.g., stainless steel, glass, concrete), normal building ventilation flow/low airspeed (< 2 m/s, ~5 mph)	4E-7/hr	3	DOE Handbook, Section 3.2.4.5	
Liquid, indoors, as above, covered with substantial layer of debris or indoor static conditions	ARR: 4E-8/hr	3	DOE Handbook, Section 3.2.4.5	
Liquid, outdoors, large pool, up to 13.6 m/s (~30 mph)	ARR: 4E-6/hr	3	DOE Handbook, Section 3.2.4.5	
Powder, pile on heterogeneous surface (e.g., concrete, stainless steel, glass), normal building ventilation flow/slow airspeed (< 2 m/s, ~5 mph)	ARR: 4E-5/hr	3	DOE Handbook, Section 4.4.4.1	
Powder, indoors, as above covered with substantial layer of debris or indoor static conditions	ARR: 4E-6/hr	3	DOE Handbook, Section 4.4.4.1	
Powder, dispersed into flowing air, airspeed up to 9.1 m/s (20 mph)	[m]	2	DOE Handbook, Section 4.4.3.2	
Heterogeneous Deposit	ARR:			
Liquid, outdoors, absorbed on soil, no large standing pools of free liquid, up to 22.7 m/s (50 mph)	9E-5/hr	2	DOE Handbook, Section 3.2.4.4	
Powder, indoors, loose surface contamination [n], normal building ventilation flow, low airspeed (<2 m/s, 5 mph)	ARR: 4E-5/hr	3	DOE Handbook, Section 5.3.4	

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments
Powder, outdoors, due to the passage of vehicular traffic across or by loose powder on road, up to 22.7 m/s (50 mph)	ARR: 1E-2/ pass	2	DOE Handbook, Section 4.4.4.2	
Mechanical Stress [o]				
Free-Fall Spill				
Liquid, aqueous solution, spill distance < 3 m	2E-4 (0.5)	2	DOE Handbook, Section 3.2.3.1	
Liquid, slurry (<40 percent solids), spill distance < 3 m	5E-5 (0.8)	2	DOE Handbook, Section 3.2.3.2	
Liquid, viscous solution, spill distance < 3 m	7E-6 (0.8)	2	DOE Handbook, Section 3.2.3.3	
Liquid, spill distance > 3 m (see reference)			DOE Handbook, Section 3.2.3.1	
Powder, spill distance < 3 m	2E-3 (0.3)	1	Sutter et al., 1981, Ballinger et al., 1988, Plinke et al., 1991, Heitbrink et al. 1992, DOE Handbook, Section 4.4.3.1.2	
Powder, spill distance > 3 m (see reference)		2	DOE Handbook, Section 4.4.3.1.3	
Powder, shock impact due to falling debris	1E-2 (0.2)		DOE Handbook, Section 4.4.3.3.2	
Powder, dispersed into flowing air, to 9.1 m/s (20 mph) (see reference)			DOE Handbook, Section 4.4.3.2	
HEPA filter, object strikes encased [p] filter or encased filter impacts unyielding surface after fall	5E-4	3	DOE Handbook, Section 5.4.4.1	
HEPA filter, object strikes unencased filter or unencased filter impacts unyielding surface after fall	1E-2	3	DOE Handbook, Section 5.4.4.2	
Spent nuclear fuel				
Noble gases	5E-2	2	Soffer, 1993	
Iodine (I_2)	2.3E-3	3	Mishima, 1995	
Cesium vapor	2.5E-4	3	Mishima, 1995	
Fines	2.4E-4 (7E-5)	2	Mishima, 1995	
Crush/Impact				
{Vitrified} Glass	[q]	2	DOE Handbook, Section 4.3.3	
Aggregate	[r]	2	Owczarski and Mishima, 1996	

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments
Spent nuclear fuel				
noble gases	7E-2 [s]	2	Kent, et al., 1995	For the degree of fragmentation in experimental program.
iodine (I_2)	2E-3	2		
^{3}H (as HTO)	1E-2	2		
Ffuel	2E-3 (7E-5)	2		Bounding for energy density (crushing force) imparted to material in the range of 10 to 100 J/cm^3.
Encapsulated ceramic oxide pellets, particles generated but not released, impact velocities of steel to 188 mph, concrete to 99 mph, and soil to 550 mph	5E-3 (0.6) *{[t]}*	2	Mishima, 1995	
Shock/Vibration				
Loose surface contamination *{powder}* *{contaminated noncombustible materials}*	1E-3 (0.1) *{(1.0)}*	2	DOE Handbook, Section 4.4.3.3.1 *{Sections 5.2.3.2, 5.3.3.2.2}*	
{Bulk powder]	*{1E-3 (0.1)}*	*{2}*	*{DOE Handbook, Section 4.4.3.3.1}*	
{Loose surface contamination, substrate packaged in container such as pail or drum}	*{1E-3 (0.1)}*	*{2}*	*{DOE Handbook, Section 5.2.3.2}*	

[a] A very conservative assumption of mass airborne in respirable size range (10 μm AED) is equal to the TNT Equivalent calculated for the explosion.

[b] Particles in the respirable size range of initial inventory made airborne, provided that this value does not exceed the fraction of *{respirable}*particles in the size range in the source material.

[c] RF for these events cannot exceed the fraction of *{respirable}* particles in the source material.

[d] Absorption and equilibration of gases in liquids is a function of chemical composition of the solution, the surface area and depth of the liquid, and the volume of the gas. Equilibrium may take minutes to hours dependent upon conditions.

[e] NVA = No value currently available.

[f] Generation of RF liquid droplets can be greater than the values shown here that bound circular, knife-edge orifices of 0.125-in diameter and greater with upstream pressures up to 200 psig. The "worst case" for RF droplets of solutions is a crack 50 micrometers wide. The longer the length, the more liquid that can be vented for a given upstream pressure. This type of crack is not a common nor typical occurrence for faults in pipes or vessels, and, at higher pressure, would probably propagate into a wider, longer crack.

[g] Only applies to bubbly flow (distinct bubbles visible, <30 percent liquid in form of bubbles). Does not apply to churn turbulent nor chaotic boiling regimes.

[h] Ignition temperature for plutonium metal is a function of surface to mass ratio (S:M). At S:M of 100 cm^2/g, the measured ignition temperature for plutonium metal is in the range of 160 ºC. The ignition temperature rises rapidly after S:M 10 cm^2/g and ranges from 480 to 520 ºC for bulk pieces.

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments

[i] Like plutonium, the ignition temperature for uranium metal is a function of the Surface to Mass ratio (S:M). At S:M of 100 cm^2/g, the uranium ignition temperature is in the range of 200 ° C to 300 °C. Like plutonium it rises rapidly in the region of S:M 10 cm^2/g and reaches temperatures in excess of 700 °C or more. There is some doubt that bulk pieces of uranium can attain ignition conditions except for very special circumstances.

[j] Does not react chemically to change form under accident conditions postulated.

[k] Assumes HEPA filter medium (glass fiber) softens and melts at higher temperatures and thus retains particles accumulated on the fiber surfaces. *{This should not be taken as a presumption that filters will remain functional for prolonged exposure to temperatures up to 400 ˚C.}*

[l] In this part of the table (the next nine items), the second column is the Airborne Release Rate (ARR), rather than ARF and RF.

[m] ARF = 0.0134[U] + 0.00543, where U is local windspeed in m/s.

[n] Loose surface contamination that can be removed by swiping or by low air speeds such as blowing across the deposit.

[o] From here to the end of the table, the second column is again ARF (RF).

[p] Encased denotes a container that does not £ail due to impact of falling objects nor impact with unyielding surface after fall of the container.

[q] Formula for crush/impact forces on brittle solids is shown on pg. 4-52 of DOE-HDBK-3010-94. For vitrified HLW, the empirical correlation 2E-11[J/cm^2] shown is applicable. The user should be cautious in application of this formula since the value calculated is an energy density applied to the material. If the crush/impact force is applied to all the material, the energy density is simply the force/volume. If the crush/impact force is only applied to a portion of the object (e.g., the object impacts just a portion of the surface of the brittle material), the formula only applies to the volume being crushed.

[r] For aggregate materials such as cement and sandstone, the correlation factor for use in the formula on pg. 4-52 of DOE-HDBK-3010-94 is 3E-11.

Stress/Material	ARF (RF)	TSL	Reference*,#	Comments

[s] For spent nuclear fuel, the empirical correlation is found in the NRC Safeguards Report (Kent, et al., 1995)

{[t] Care should be taken in use of this value. It is based on extreme impact energies.}

* Original sources cited in Section A3 of ANSI/ANS-5.10-1998 for Table 5-1 above are as follows:

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Mishima, J., *Plutonium Release Studies* 1. *Release From the Ignited Metal,* BNWL-205, December 1965, Pacific Northwest Laboratory, Richland, WA.

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Stress/Material	ARF (RF)	TSL	Reference*,#	Comments

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Elder, J.C. and Tinkle, M.C. 1980. *Oxidation of Depleted Uranium Penetrators and Aerosol Dispersal at High Temperatures,* LA-8610-MS, Los Alamos National Laboratory, Los Alamos, NM.

In the case of liquids and solids, the material is either subdivided into droplets or particles, or, in the case of powders, is de-agglomerated. De-agglomeration of a powder at rest is not readily accomplished. This is especially true for stored powders, where the smaller particles have had time to settle into the interstices between larger particles. De-agglomeration/separation is difficult due to the small surface areas of small particles and the limited space for gas flow between them. Even in a heavier medium, such as a liquid, the application of sonic agitation for long periods (30 minutes or more) is necessary to restore a size distribution approximating the original distribution. All phenomena (including detonations with minimal stand-off distances) do not fragment small particles (<100 μm). Thus, the amount of particles in the respirable size range that can be suspended is limited by the amount of material of this size found in the original source powder. Thus, the amount of particles in the respirable size range that can be suspended is limited by the amount of material of this size found in the original source powder. See Section 4.4, Powders, of DOE-HDBK-3010-94 for further discussion of the difficulty of de-agglomerating powders.

Bulk solids and liquids require more energy to fracture the bonds that hold the form together. In the case of liquids, the material is drawn into a fine filament or sheet that breaks when the tensile strength of the material is exceeded. This can occur in many ways. If the liquid forms bubbles at the surface from boiling or the passage of a gas through the liquid, breakup of the bubbles generates fragments that can be suspended or result in secondary droplets when condensation of the liquid vapors. A mechanism that can form significant amounts of fine liquid droplets is a "flashing spray" that forms upon the venting to lower pressures of a liquid that is super-heated. The liquid initially forms a column approximately the shape of the opening. Then, bulk vaporization of the liquid (a significant fraction of the liquid is "flashed" into a vapor) within the column results in rapid subdivision of the remaining liquid. The greater the superheat, the smaller the diameter of the liquid droplets. In all cases of heated liquids, additional evaporation of the liquid occurs during airborne transport and, depending on the temperature, environmental factors, the distance traveled, and solute concentration, the droplet diameter decreases.

Bulk solids of various categories have different physical characteristics. For brittle materials (e.g., glass-like materials, aggregate, composites), crush-impact forces (including shock waves from explosions) can result in fragmentation. The level of force and the material tensile/compressive strength are factors that influence the particle size distribution of the fragments formed. Materials that have elastic-plastic response to the application of forces (e.g., metals) require greater forces and are generally fragmented only by the pressures generated by the detonation of solid explosives in contact with the surface of the metal. Crush-impact forces generally result in deformation and tearing of metals; unless, the metal is embrittled.

One feature in particular of the data analysis is noted. ARF and RF values are assigned by physical context. That is, the physical context of the material determines the stress it experiences. For example, consider the case of powder spills. The bounding ARF/RF specified in DOE-HDBK-3010-94 (page 4-77) for plutonium oxide powder falling freely (< 3 m) through air is 6E-4. The bounding ARF/RF assigned if plutonium oxide falls inside a container is 1E-4. The difference is that the physics of release for the free-fall spill are driven by shear stress from air currents moving through the powder. That phenomenon physically does not exist inside a container. Release in the latter case is driven primarily by flexing of the container substrate upon impact with the ground, with some self-acting mitigation in the form of a powder's physical tendency to agglomerate. Therefore, if powder falls inside a can, acknowledging that point does not constitute improper crediting of a can in unmitigated analysis. For the perspective of DOE-HDBK-3010-94, the pedigree and capability of the can is irrelevant. The physical fact of it defines the stress being experienced by material. Further, it is not reasonable to assume personnel carry plutonium powder about cupped in their hands. In unmitigated analysis, however, if the can is not to be credited, it should assume to open upon impact with the ground and release the appropriate source term (i.e., can inventory * 1E-4, per DOE-HDBK-3010-94, page 4-85).

The treatment of TRU waste is another such example. The respirable release fraction for loosely strewn waste in a fire is 1E-2. But packaged waste, even in as primitive a form as plastic bags or pails, is assigned a respirable release fraction of 5E-4. The experimental data supports that distinction due to the physical fact that a clumped mass traps particles in a self-filtering effect.

5.2.3.2 EXAMPLES FOR DETERMINING ARF/RF

Given that it is not desired to use this document as a primary reference for selecting release fractions, the reader is referred to the extensive examples in Chapter 7 of DOE-HDBK-3010-94. Only a brief discussion is provided regarding one aspect of the example previously cited in Section 5.2.1.2 above. It is intended to demonstrate the basic thought process for ARF selection.

A. Case One

Consider the example facility of Figures 5–2 and 5–3, specifically the fuel fabrication line. Presume for the moment that the structural collapse depicted in Figure 5–3 does not occur and all four gloveboxes remain intact (i.e., upright in a largely undamaged state) during a seismic event. What stress is then being imposed on any powder contained in the glovebox?

The four main categories of potential stress are explosive, thermal, mechanical, and aerodynamic entrainment. No explosion or fire is postulated for this event. No debris impacts either the powder or its outer glovebox confinement. This could lead an analyst to dismiss mechanical impact as well, but that would be a mistake, because even intact gloveboxes will experience transitory movement of structural members and an associated seismic vibration. If the gloveboxes held only solid metal, such a stress would present no significant force. For the much more fragmented powders, however, that force is sufficient to produce a small amount of aerosolization.

Examining Table 5-1 for mechanical stresses indicates that an ARF and RF of 1E-3 and 0.1, respectively, are assigned for shock/vibration of bulk powders. Previous examinations of this case have indicated the maximum MAR is 6,000 g of plutonium oxide powder for all four gloveboxes. The initial source term would therefore be 6 g, and the initial respirable source term 0.6 g.

Given this 0.6 gram respirable release, could surface contamination produce a significant contribution? Table 5-1 indicates that the ARF and RF for shock/vibration of loose surface contamination is assigned an ARF and RF of 1E-3 and 1.0, respectively, thus yielding a combined ARF/RF one order of magnitude greater than that for bulk powder. For the purpose of discussion in this example, if significant contribution is defined as 10 percent of the 0.6 gram source term, then surface contamination would have to contribute 0.06 g of airborne material to be significant. Working backward with the ARF/RF of 1E-3 yields a required surface contamination MAR of 60 g. That is certainly possible given that historical surface contamination levels for representative gloveboxes can range up to 50 g. Using a value of 0.1 g/ft^2 for powder handling gloveboxes (from historical experience), and assuming each glovebox is 12 feet by 4 feet by 4 feet (with a factor of 1.3 applied for equipment inside the gloveboxes) yields a total MAR of 116 g for all four gloveboxes. It can be concluded, therefore, that surface contamination is a nontrivial contributor. Both of these approaches to determine the level of surface contamination (MAR) and potential airborne release, are appropriate application of DOE-HDBK-3010.

This last result points out another question that an analyst should always keep in mind: when is a result real, and when is it an artifact of analysis? Examining the specifics of DOE-HDBK-3010-94 indicates that the main reason the ARF/RF for surface contamination is assigned a higher value than for bulk powder is because no real confidence existed as to a generic size distribution for surface contamination residues. It is, in essence, simply a conservative assumption. DOE-HDBK-3010-94 contains multiple cautions against taking its bounding recommendations as absolute statements of reality, or as a starting point for extrapolating ever more extreme circumstances that could theoretically exacerbate the physics of release. Either of these approaches can quickly tumble over into analytical gamesmanship, defeating the cited purpose of DOE-HDBK-3010-94, which is “to provide information to support general bases for decision making.”

B. Case Two

Consider again the example facility of Figures 5-1 and 5-2, specifically the fuel fabrication line. Presume for the moment that the structural collapse depicted in Figure 5-3 does occur, but is sufficiently severe to collapse all four gloveboxes. What additional stresses are then being imposed on any powder contained in the glovebox?

Depending on how the powder is contained, and the nature and orientation of the debris impacting gloveboxes, it may not experience much in the way of additional stress. In the interests of conservatism, however, that is not presumed for the type of gloveboxes common in the DOE weapons complex. The collapse is instead broken down into the sequence of distinct events occurring. First, the glovebox is experiencing a fall of some kind, more so if it tips over than if it simply slumps downward, but the latter is considered equal to the former given that it is difficult to specify the exact nature of the collapse. Second, the glovebox is impacted by debris. Windows can break or contents can be spilled out of the glovebox. Either case raises the possibility of debris impacting powder.

For spill distances less than three meters, Table 5-1 specifies an ARF and RF of 2E-3 and 0.3, respectively, for the free-fall spill of powders. This circumstance is not, in fact, a free-fall spill, but the experimental data on free-fall spills is the closest equivalent available. Any conservatism involved in the use of this ARF/RF is simply accepted. Table 5-1 also lists an ARF and RF of 1E-2 and 0.2, respectively, for debris impacting powder. This might not be considered if the nature of the debris is small fragments or if the gloveboxes are shielded by slumping installations in the overhead. That will not be presumed to be the case. If the box contains loose powder that falls and is heavily impacted by debris, the cumulative ARF/RF could be as high as 6E-4 + 2E-3 = 2.6E-3.

Conversely, suppose all powder in the glovebox is held in cans or other metallic containers. The overall effect might then be characterized as two similar events. The can falls with the glovebox and is impacted by debris as it lands. As noted, DOE-HDBK-3010-94, the ARF/RF for shock impact and falling debris on confined bulk powder is 1E-4. The cumulative ARF/RF could therefore be as low as 1E-4 + 1E-4 = 2E-4. In this case, however, the idea of powder being outside of a container while in a glovebox is not an absurd construct similar to personnel carrying plutonium cupped in their hands outside of a glovebox. If the operation naturally lends itself to the powder being confined, that initial condition should be preserved in the TSR control set.

5.2.4 AIRBORNE RELEASE RATE

Sometimes ARFs are expressed as a function of time. The parameter is then identified as an airborne release rate (ARR). This is, in fact, the norm for chemical releases. Gas escaping from a damaged cylinder will leak at a rate of so many pounds per second. Liquids spilled into a bermed area or as a shallow pool dispersing to its limits will evaporate at a rate of pounds per minute, depending on the surface area of the pool, its temperature, and the specific physical properties of the liquid.

Radionuclides are treated in a more overall fashion, as noted in the examples of Section 5.2.3, Airborne Release Fractions and Respirable Fractions. Most radioactive material releases occur due to momentary chaotic stresses. Therefore, even when the release might occur over a minute or several minutes, the total quantity airborne is assumed to exit the facility at one moment in time. That is often the case even for an event such as a fire, which occurs over an interval of tens of minutes, sometimes even hours. In these cases, unlike with the leak rate of a gas of a given pressure or the evaporation of a pool of a given liquid, there is no simple physical principle from which to compute reasonable time dependence. The most common exceptions to this are solution criticalities (whose time for a complete set of pulses is part of the event definition) and aerodynamic entrainment, which is defined as a rate. Chemical releases are discussed further in Section 5.3.

<u>Example</u>

It is not unreasonable to assume that an event as severe as the earthquake assessed in the Case Two example from the previous section could result in cleanup activities being delayed for some period of time. Aerodynamic entrainment will suspend more material during that period. How should that release be estimated?

An assumption is that for long duration releases, DOE-STD-3009 limits the unmitigated consequence analysis to eight hours. Table 5-1 defines an ARR of 4E-6 per hour for “powder, indoors ... covered with substantial, layer of debris or indoor static conditions.” Using that value, the ARR for 6,000 g of spilled oxide powder would be 2.4E-2 g/hr, or a total of 0.2 g/8 hr. If this figure were trivial compared to the overall facility release, it could either be ignored or lumped in with the immediate release.

5.2.5 LEAKPATH FACTOR

The term “leak path” refers to the path taken by material released in a facility on its way to the outdoor atmosphere. Common leak paths of a building are air ventilation ducts, door gaps, and various building leaks. The “leakpath factor” (LPF) is the “fraction of the radionuclides in the aerosol transported through some confinement deposition of filtration mechanism” (DOE-HDBK-3010-94, page 1-6). The LPF used in the common five-factor formula is the total fraction of respirable airborne material released during the accident that escapes from the building to the environment. Once an aerosol is formed, it continuously depletes (in concentration) due to natural mechanisms such as gravitational settling and other lesser important mechanisms such as impaction, agglomeration (a subset of gravitational settling), diffusion to surfaces, and possibly mechanical filtration. The LPF is of interest because it has the potential for reducing the initial source term (IST) at the point of generation before it exits the facility, thus producing a much smaller release to the external environment.

The DSA analysis does not allow credit for a facility LPF for unmitigated analysis. Unmitigated analyses necessarily start with LPF of 1.0. For mitigated analysis, the LPF is dependent on the physical characteristics and configuration of the facility as it is estimated to exist under the postulated accident conditions.

Assignment of an LPF of 1.0 is the general practice for most low consequence facility DSAs. As accident consequences from bounding events increase into the rem range for the offsite public, LPF determinations become important and a process and strategy for estimation of a LPF < 1.0 generally becomes appropriate, such as crediting filtration or other natural depletion mechanisms. An active confinement ventilation system with filtration is the preferred mitigative control as required by DOE Order O 420.1C, and discussed further in DOE-STD-3009-2014, Section A.8, Hierarchy of Controls. However, sometimes a passive confinement strategy may be justified that credits other natural depletion mechanisms.

Other than for filtration systems, LPFs are functions of building ventilation, building leak-tightness, atmospheric conditions (e.g., wind speed), building pressurization by a fire, the length of the leakpath, floor area for deposition of particulates, and other factors. They are specific to the building and the location of the source within that building, and are specifically estimated for each scenario and building. Therefore, the effort in estimating the LPF is significant and the analyst should consider that there may be limited benefit for refinement of LPF below 1.0 for facilities with a small MAR.

Historically, some DSAs have been developed applying complicated in-facility transport analyses using the MELCOR or CONTAIN codes. [42] Egress doors being open during evacuation have been considered for both normal ventilation and loss of ventilation scenarios. Also, based on these types of computer code analyses, and/or hand calculations, DSAs have credited an in-facility transport LPF for loss of power concurrent with radioactive material release within the facility. Under such scenarios, doors open during evacuation and otherwise closed doors with some assumed leakage past the door seals have been considered. The adequacy of those LPF justifications has been determined based on facility-specific ventilation designs, specific circumstances and postulated accident environments; approved by the DOE Safety Basis Approval Authorities.

[42] These codes were not designed for modeling dozens of volumes. The uncertainty increases with the number of nodes and junctions.

Many LPF estimates are assumption-driven, can be challenging to defend, and should be carefully applied. Therefore, it is always important to remain cognizant of the inherent uncertainty in the LPF due to analytical variances in all of the parameters used in the assignment, which applies to both active and passive confinement strategies. As is the case with all safety analysis calculations, sufficient conservatism is factored into the overall determination by reasonably conservative assignment of the respective input parameters. Also, assumptions used in LPF analysis are required to be identified and evaluated so that the need for TSR controls can be decided for a facility-specific situation.

5.2.5.1 FILTRATION LPF

If a release passes through filtration before reaching the atmosphere, a conservative LPF assumption based on filter efficiency (i.e., LPF = 1 – efficiency) for the accident conditions being evaluated should be made. This is appropriate if active ventilation filters releases that do not breach primary confinement systems (e.g., gloveboxes). However, this does not represent a bounding LPF for energetic releases that breach primary confinement systems if active secondary confinement ventilation pressure differentials are not maintained during full building evacuations over several minutes. Moreover, the measured filter efficiency may not directly lead to the LPF determination if there are unfiltered leak pathways in the system or through building penetrations that need to be evaluated.

General guidance on HEPA filter design, installation, testing, and service life is provided in Chapters 3 and 8 of the DOE-HDBK-1169-2003. HEPA filters, by definition, have a minimum filtration efficiency of 99.97% for 0.3 µm particles (the most penetrating size). For accident analysis, DOE-HDBK-1169-2003 (page 2-31) states the following:

> Accident analysis typically assumes a first stage credit of 99.9 percent efficiency (DF of 10^3) for removal of plutonium aerosols. Second and subsequent stages typically assume an efficiency of 99.8 (DF of 5×10^2). [DF = Decontamination Factor] These assumed efficiencies are based on the premises that: (1) the HEPA filters have successfully been through the DOE Filter Test Facility (FTF) at Oak Ridge; (2) they are installed and in-place leak tested to at least 99.95 percent; (3) they are installed in a system built to the specifications of AG-1; and (4) are tested in accordance with national standards.

This assumption is predicated upon the filters in question having been leak tested upon installation and tested thereafter in accordance with national standards. The efficiencies assigned translate to LPF values of 1×10^{-3} for 99.9 percent and 2×10^{-3} for 99.8 percent. Thus, one stage of HEPA filtration has an LPF of 1×10^{-3}; two stages of HEPA filtration have an LPF of 2×10^{-6}. Assuming HEPA filter efficiency of 99.9% for the first HEPA filter stage and 99.8% for the second stage (in series) is appropriate if both HEPA filters are credited in the analysis to reduce consequences, and are designated and maintained as safety SSCs.

Section F.2.1.3 of NUREG/CR-6410 provides the following additional guidance regarding HEPA filter efficiencies to mitigate accidents:

> … HEPA filters must demonstrate a particle collection efficiency of >99.97 percent for 0.3-µm diameter particles and have a particle collection efficiency of >99.95 percent for similar sized particles in-situ (installed in the system). For accidents in which conditions at the HEPA filter are unchanged from normal operating conditions, use of the in-situ tested efficiency is recommended for analysis (Elder et al., 1986). If a series of HEPA filters is protected by pre-filters, sprinklers, and demisters, efficiencies of 99.9 percent for the first filter and 99.8 percent for all subsequent filters is recommended for accident analysis (Elder et al., 1986). If conditions are severe or the filters are

unprotected, efficiencies as low as 99 to 95 percent are recommended (USNRC 1978).

Even if tested after installation and periodically to meet industry standards, some DSA mitigated analyses have credited a smaller LPF (e.g., 0.01 or 0.1) since that was sufficient to reduce the unmitigated offsite and CW doses to low consequences (see Table 2-8, Consequence Thresholds. However), if unprotected, the filter may be breached by flame impingement, which will open up the leak path to near unity or it may be located remote from flame but be plugged by soot or other factors (as specified in DOE-HDBK-1169, Chapter 10); further discussion on this topic is found in Section 4.2.3.2 of this Handbook. Any modeling of LPF (e.g., through the use of computer codes such as MELCOR) will have to account conservatively for the damage to HEPA filters by fire conditions.

5.2.5.2 LPF MODELING

A more realistic estimation of the LPFs associated with complex pathways (e.g., rooms, corridors, stagnant supply and exhaust ducting) other than HEPA filtration also have the potential to significantly reduce release estimates for the DSA mitigated analysis (Ma, 2006). If the release passes through long passageways, cracks, or torturous routes before exiting to the atmosphere, fall-out and plate-out can be considered in determining LPF. It is possible to calculate how much material of a given size range will deposit out in the time it takes to navigate the available release paths. When multiple paths are present, LPFs may be specified individually for each path, or may be summed into one overall LPF. In more complex cases, each path normally is assigned its own LPF. As the LPF for aerosol particles depends on particle size, multiple LPFs may be assigned for various size ranges as well.

Determination of LPFs less than unity takes a variety of forms. Quantitative LPFs can be performed by hand calculations or by using a variety of computer codes, each dependent upon the complexity of the facility, the specific release parameters and the magnitude of unmitigated accident consequences. As would be expected, small LPFs require substantial justification, particularly if the LPF is the dominant parameter and necessary in the reduction of accident consequences below the safety classification guidelines discussed in Chapter 10.

Because of this strong dependency on the facility and phenomenology of the release, default LPF values are not recommended. There are several hand-calculation methods to calculate the parameters that go into developing a LPF. One method is NUREG/CR-6189, *A Simplified Model of Aerosol Removal by Natural Processes in Reactor Containments*, developed by Sandia National Laboratories for the NRC.

NUREG/CR-6410, Chapter 4, also provides guidance on calculating LPFs. It describes the phenomena that control transport through buildings. Such phenomena include ventilation and other flows of air, filters that remove particulates, and various effects such as gravitational settling, impaction on surfaces, thermophoresis. A portion of the introduction to that chapter is reproduced as follows:

> This chapter describes in-facility transport and deposition of gases, heavy gases, vapors, and particles, together with controlling parameters, basic aerosol physics, and airborne chemical reactions. The chapter emphasizes airborne particles, because such aerosols seem to predominate in accidents that might occur in fuel cycle facilities. The quantitative value that expresses the fraction of initially airborne material that successfully escapes the facility is called the Leakpath Factor (LPF). For particles, the LPF primarily depends on three parameters: the flow rate of the aerosol through the facility, the particle sizes, and the areas available for deposition of contaminants.
>
> The objective of this chapter is to provide the tools necessary for defining the fraction of accident generated airborne material that escapes the facility and, if desired, the concentrations of airborne material throughout the facility as well as the amount of initially airborne material that has deposited

within the facility.

This chapter continues the accident analysis process whereby the source term provided in Chapter 3 is carried through and out of the facility. The primary final output is the fraction (for particles, the RF) of the source term that escapes the facility, the LPF. Secondary outputs are the concentrations and amounts deposited in the facility of the initial source term. To obtain these outputs, Chapter 4 provides guidance to help the user: (1) identify the facility barriers that define the flow path of the airborne material in the facility; (2) quantify the driving forces moving material along the flow path; (3) quantify the flow rates along the path; (4) quantify the effects of any mitigating engineered safeguards (e.g., filters); (5) quantify the roles of deposition processes along the flow path; and (6) estimate facility concentrations during the movement of the airborne source term.

Computer codes can be used to support LPF calculation for the mitigated analysis. Computer code calculations should be considered for highly complex facility configurations where multiple release paths exist and the relative importance of the various leak paths is not obvious. The computer codes are also extremely beneficial in the cases of time-dependent phenomena (e.g., propagating fires) and when the contaminant transport processes are complex, such as is the case where wide particle size distributions and coupled transport and deposition (e.g., agglomeration) processes exist.

The DOE Central Registry Toolbox code, MELCOR (Methods for Estimation of Leakages and Consequences of Releases), has been applied for some DOE nonreactor nuclear facilities and DOE has established code guidance supporting its use. MELCOR is a fully-integrated, engineering-level computer code whose primary purpose is to model the progression of accidents in light water reactor nuclear power plants. Major uses of MELCOR for nonreactor facilities include estimation of confinement behavior due to radiological source terms under postulated accident conditions, and their sensitivities and uncertainties in a variety of applications, evaluation of LPFs, and survivability of fans, filters, and other engineering safety features. A conservative LPF analysis should be consistent with the guidance provided in *MELCOR Computer Code Application Guidance for Leak Path Factor in DSA Final Report* (DOE, 2004d) that has been issued identifying applicable regimes in accident analysis, default inputs, and special conditions for using the code.

5.3 CHEMICAL RELEASE SOURCE TERMS

The MAR is the bounding quantity of a toxic chemical or mixture of toxic chemicals that is available to be acted upon by a single or series of physical stresses or insults from a postulated accident. Toxic chemical source terms may be evaluated using DOE-HDBK-3010-94, if appropriate, for a non-reactive toxic chemical release phenomenology or non-volatile liquid.[43] These source terms include airborne particulates suspended from accident stresses on solids, as well as the particulates (i.e., aerosols) from the non-flashed portion of pressurized liquids, aerosols from heating of liquids or free-fall spills, and aerosols aerodynamically entrained over time; all using the five-factor formula. However, the burden of proof is on the analyst to establish whether the bounding value or formula presented in that reference is an accurate representation of the particular accident phenomenology. Additional guidance related to the application of DOE-HDBK-3010-94 for chemical source terms is provided in “Applicability of Airborne Release Fraction and Respirable Fraction Values to Particulate Toxic Chemical Material Releases at DOE Sites” (Laul et al., 2006).

An alternative to the five-factor formula to calculate toxic chemical liquid and gas release source terms is

[43] Liquid that does not readily evaporate at normal ambient temperature and pressure due to its very low vapor pressure.

the EPA 40 CFR Part 68 methodology for worst-case scenario development provided in EPA-550-B-99-009. Detailed guidance, in Chapter 3 of that reference, is generally an appropriate starting point for determining release rates and release quantities for a full spectrum of releases of toxic chemical gases and liquids. However, that EPA reference is silent with respect to releases of airborne particulates suspended from accident stresses on solids, and for non-volatile liquids where vapor pressures are very small or where vapor pressure data are not available. In most cases, an RF value less than 1.0 should not be applied for chemicals given that chemical particulates larger than respirable that have not deposited out of the plume at the CW or MOI location may pose a health risk. For example, a particulate needs only be inhalable to have a health impact, and skin absorption can play a role in a chemical's toxicity although it is not specifically addressed in the derivation of concentration guidelines.

ARFs and RFs, which are highly dependent on particle size distributions and evaporative effects on aerosols, are selected based on physical conditions and stresses anticipated during accidents. For calculating toxic chemical releases from gases and liquid evaporation, the above more current EPA methodology is preferred. However, if EPA methodology does not provide relevant guidance for the accident scenario, DOE-HDBK-3010-94 defines bounding ARF and RF mechanisms based on the physical context of the accident stress. These include phenomena affecting liquids and powders such as a free-fall spill, fire or heating of a substance, and shock or blast effects (e.g., overpressures) from an explosion or detonation. These energetic phenomenologies are described in more detail in Chapter 4 (Section 4.3, Explosion Analysis), and in Section 9.5, Toxic Chemical Release Phenomenology and Subsequent Atmospheric Transport and Diffusion.

Section 5.2.4 and Table 5-1 summarize airborne release rate recommendations from DOE-HDBK-3010-94 that are applicable to aerodynamic entrainment of radioactive materials as a function of time. Those recommendations may also be applicable to toxic chemical releases involving suspension of toxic chemical powders or aerosols from heating of liquids.

The toxic chemical source term calculation generally results in a constant (i.e., linear) release rate in units of mass per unit time, or total release quantity in units of mass coupled with a specified release duration in units of time. For pressurized gas and pressurized liquid releases or evaporation of volatile liquids, the release rate is non-linear, varying over time, as indicated in Section 9.5. If the toxic chemical source term is not calculated as a constant release rate over the accident duration for solids, or as a pool evaporation rate for liquids and gases, the total airborne release quantity should be divided by the release duration consistent with the postulated scenario assumptions, or by recommended conservative estimates from the aforementioned guidance documents that appropriately address non-linear release phenomenologies.

For the calculation of toxic chemical releases from a chemical process, if dilution is inherent in the release pathway, dilution effects may be incorporated into the analysis by determining the concentration of the chemicals in the total stream flow that includes the offgas generation and a carrier gas such as fresh air. This stream flow concentration at the exhaust stack discharge is used to establish the toxic chemical release rates to the atmosphere. The stack discharge rate accounts for dilution effects of a carrier gas in the exhaust path starting above the liquid surface of the chemical reactions and ending at the exhaust stack discharge location. This can be calculated as a volume of toxic chemicals generated per unit time, as adjusted by the density of the toxic chemicals mixed with the carrier gas at the point of release from the facility.

This type of analysis accounts for fresh air entrainment in the process ventilation system due to ambient air exchanges with the environment for the unmitigated analysis, or the active process ventilation system for the mitigated analysis. These quantities represent the source term of the toxic chemicals in units of mass per time (e.g., mg/s) that are input to the 95th percentile dispersion conditions as discussed in

Section 9.7, Toxic Chemical Atmospheric Transport and Diffusion Models, for the determination of concentrations and resulting consequences to the CW and MOI.

For the unmitigated analysis, this adjustment may consider the mixing volume of the toxic chemicals generated at the chemical process location, diluted with ambient air exchange as driven by the outside environment. The dilution of the toxic chemicals from the process generation location, which is a function of the volume of the release path and ambient air exchange with the outside environment, may be performed using methodologies discussed in Section 5.2.5. Accounting for in-facility dilution effects is not the same as a LPF; it is considered to be a phenomenological component of the source term determination. The analyst, with the assistance of a HVAC engineer and chemical engineer, can establish the ambient air exchange factor based on the specific design of the process and the ventilation system. Another factor that may affect the unmitigated analysis is the stoichiometry of toxic chemical generation that may rapidly decay with the limited amount of air available since active ventilation is not credited, that is, the source term release rate would be nonlinear. See Chapter 6 discussions regarding an unmitigated analysis crediting an effective stack height due to a passive physical feature (i.e., discharge from an elevated stack), and/or may credit buoyancy effects due to a conservative estimate of offgas temperature at the point of release to the environment. Both of these effects would result in improved atmospheric dispersion. The assumptions of no active ventilation and crediting of the release from a stack with plume buoyancy due to the high temperature of the offgas are consistent with unmitigated analysis guidance in DOE-STD-3009-2014.

For the mitigated analysis, the analyst may consider crediting active ventilation. The ventilation flow will dilute the toxic chemical releases before discharge to the atmosphere (i.e., the source term release rate), and it may also drive a momentum flux at that release point, as discussed in the plume rise discussion in Chapter 6. For a chemical process, the toxic chemical reaction rate may be linear or nonlinear. Therefore, the first 15-minute release rate may be the most bounding unmitigated estimate and could be affected by other factors such as combustion/reactant air supply. A conservative estimate for the 15-minute decay period could be made if the release rate drops rapidly.

To illustrate the above discussion, consider an example release of nitrous oxide (NO) from a chemical process in a vessel provided with 1,000 cfm of process ventilation (air as the carrier gas) that is discharged to the atmosphere. An unmitigated analysis does not credit depletion due to filtration and an offgas treatment system. To simplify the illustration, although many species may be generated in the vessel offgas that are in the form of gases or aqueous vapors, this example evaluates a single toxic chemical. The NO has a mass generation rate of 11.7 kg/hr (3,250 mg/s) that is one of the constituents in the stream that has a total mass flow rate of 1,700 kg/hr. Therefore, NO contributes approximately 0.7% to the mass release rate from the stack (without considering the effect of the ventilation flow which would not substantially add to the mass flow rate). The stream density (NO mixed with other constituents at the point of generation) is 0.366 kg/m^3. For this density, the volume NO flow is 19 cfm and the total gas flow of 1,700 kg/hr has a volume flow of 2,700 cfm. Further assume that the total gas flow is mixed prior to entering a stack with an air flow of 1,000 cfm. To credit dilution, the ratio of NO flow to total stream flow is used to adjust the NO mass generation rate (3,250 mg/s) in the vessel. If the total stream flow is composed only of NO, the fraction is one and the NO leaving the stack is 3,250 mg/s. When the total gas stream (NO + remaining offgas parameters) is credited, the fraction is 19 cfm / 2,700 cfm = 0.0069 and the diluted NO leaving the stack is 22.4 mg/s. Similarly when the air dilution of 1,000 cfm is credited, the fraction is 19 cfm / 3700 cfm = 0.0050 and the diluted NO leaving the stack is 16.4 mg/s.

5.4 APPROPRIATENESS OF SOURCE TERMS

The brief discussions and associated examples in Section 5.2 should serve to clarify that source term determination is not an exact science. Instead, it involves a reasonable definition of circumstance, which is then broken down into a sequence of oversimplified parameters. This limited representation of reality demands a certain degree of conservatism to overcome the uncertainties introduced by the simplification.

No source term can account for all of the parameters introduced by first engineering principles, and this process may be subject to abuse. As an example, consider a glovebox with plutonium-239 powder collapsed by a seismic event and associated falling debris. It is possible to define the event so as to eliminate any consideration of the ARF/RF of 2E-3 associated with debris impacting the powder even if the actual facility configuration does not support such an assumption. This can be done by making poor assumptions relative to shielding effects or the nature of the debris falling, or by probability arguments that are not defendable. This can be minimized by standardization, expert elicitation and independent review. DOE-HDBK-3010-94 was prepared to facilitate the development of some consensus among DOE oversight and facility operators regarding a conservative estimate of consequence potentials. That consensus is necessary to effectively implement integrated safety management by minimizing the subjectivity in source term assessment.

The basis for determining source term appropriateness is to use a combination of parameters on the upper end of any potential uncertainty. That does not mean an average value, or even a 95th percentile value, since meaningful informed statistical distributions cannot be generated for most of the accidents under consideration. Instead, it means that a general consensus exists on upper and lower bounds for the cumulative scenario definition and associated parameter specifications, which should yield a source term in excess of the actual event that is not excessively conservative.

5.4.1 ADEQUATE TECHNICAL BASIS TO DEPART FROM DEFAULT OR BOUNDING VALUES

Section 3.2.4 of DOE-STD-3009-2014 states:

> Calculations shall be made based on technically-justified input parameters and underlying assumptions such that the overall consequence calculation is conservative. Conservatism is assured by the selection of bounding accident scenarios, the use of a conservative analysis methodology, and the selection of source term and input parameters that are consistent with that methodology.
>
> For some input parameters, this section identifies default or bounding values that may be used without further justification. Unless otherwise stated for a particular input value, this section allows use of alternative values when supported by an adequate technical basis. When an input parameter used is not a default or bounding value, an acceptable technical basis of the value describes why the value selected is appropriate for the physical situation being analyzed, and references relevant data, analysis, or technical standards. The completeness and level of detail in the technical basis should increase as the parameters depart from default or bounding values.

Additional guidance to develop an adequate technical basis that departs from default or bounding values is the focus of this subsection. There are two fundamental reasons for departing from default or bounding values:

1. It may be expedient to use clearly bounding and conservative values to demonstrate that no controls are necessary, which will result in a simplified analysis; and

2. Default values for a specific site may be too conservative leading to unnecessary burdensome controls.

For expediency, the analyst may perform a consequence calculation by simply using clearly bounding assumptions along with bounding and/or default input parameters provided in DOE-STD-3009-2014, DOE-HDBK-3010-94, or other sources such as NUREG/CR-6410, because the values to be used are easily identified and readily defended as bounding and conservative. The dispersion analysis Option 2 discussed in Section 6.10 of DOE-STD-3009-2014 is an example using this approach. If such a consequence calculation shows that no controls need to be SC or SS, then no refined or more complicated calculation is needed to classify controls. However, this approach generally results in an overestimate of consequences and likelihoods, sometimes by orders of magnitude. If this very conservative calculation yields consequences that exceed thresholds for control classification, a more refined analysis is performed unless implementing and protecting the controls derived from the simplistic analysis has a small impact on schedule and cost, especially lifecycle cost.

As calculations are refined, conservatism in the analysis is reduced, with appropriate technical justification, but no further than the point where either: (1) individual input parameters and underlying assumptions are less conservative than a best estimate (i.e., mean value) of their expected values during the accident scenario; or (2) the overall result of the consequence calculation is not conservative. Option 3 in Section 6.10 is an example using this approach to refine calculations after the required approvals are obtained.

Another example would include testing model results against a large and varied experimental database which includes data points measured under bounding circumstances. The analyst would then show, for every measured data point, whether the overall result of the model was bounding of the measured data point. The model inputs would have to be “fair and reasonable” in that the input parameters used while testing the model would have to be applicable to the conditions of each experimental data point. For example, it would not be reasonable to input a bounding temperature or flow rate into the model if the bounding temperature or flow rate is not representative of the measured data point used to test the model. This type of model-data test could be used to demonstrate overall conservatism of a modeling strategy.

Three requirements in DOE-STD-3009-2014 are important to providing assurance that consequence calculations are conservative for plausible accident scenarios, NPH events, and external man made events:

1. MAR values used in hazard and accident analysis shall be consistent with the values noted in hazard identification/evaluation, and shall be bounding with respect to each accident being evaluated.[7] [Section 3.2.4.1]

   [7] For facilities that provide retrieval, handling, storage or processing of TRU waste containers, a bounding MAR may be determined in accordance with DOE-STD-5506-2007.

2. Radiological consequences are presented as a TED based on integrated committed dose to all target organs, accounting for direct exposures as well as a 50-yr commitment. [Section 3.2.4.2]

3. While the three options allow for alternative methods to calculate the χ/Q values, all three options shall evaluate the dose at the MOI using either a 95th percentile for a directionally independent method or a 99.5th percentile for a directionally dependent. Conservatism of the X/Q value is ensured by using 95th or 99.5th percentile site-specific meteorology. All other values in the X/Q analysis do not need to be bounding to ensure a conservative result; past analyses have shown that piling up a number of conservative assumptions can lead to results representing a higher percentile above the 95th or 99.5th. This is also true for the overall accident consequence evaluation if all the other input values were selected at their maximum measured or theoretical values, hence, the reason for establishing the original bounding or default values in DOE-HDBK-3010-94 and DOE-STD-3009. [Section 3.2.4.2]

When default values are too conservative, resulting in unnecessary controls for unrealistic scenarios, input parameters can be adjusted if there is sufficient technical justification to show that the new parameters are still bounding. The rationale could be based on new representative experimental data on release fractions, or based on evaluation of the experimental data used to recommend bounding ARFs/RFs in DOE-HDBK-3010-94. For example, a bounding value for a free-fall spill of powders is based on a drop at a 3-m height. Typical glovebox operations in nonreactor nuclear facilities requiring manual operations could be evaluated based on a 1-m fall height for either a spill within the glovebox, or a seismic-induced toppling of the glovebox[44] based on the experimental data that provided the basis for the 3-m spill. Considerations should include the following factors:

- Representativeness of the data to the accident scenario being evaluated;
- Statistical completeness of the data (e.g., based only on a few samples?);
- Pedigree of the data; and
- Available data on particle sizes within the application domain of the calculation.

Regarding representativeness of the data, consider whether the data is applicable to the conditions of the bounding design basis accident being analyzed. Examples include drop height, explosion energy, fire severity, and other environmental considerations.

As a matter of practice, detailed statistical analyses are not necessary, nor expected. A review of the experimental data and what percentile ranking the selected alternate value is may provide some insights for the decision. However, DOE-HDBK-3010-94, Section 1.3, provides cautions regarding interpretations of the experimental data and that the experimental data should not be used as a basis for an ARF statistical distribution.

In some instances, the data available to support selection of input parameters are not prototypic of the situation being analyzed, or there is large uncertainty. Hence, sound technical judgment is essential in selecting appropriate input values, considering the range of possible values given the physical and chemical conditions involved with the accident scenario and the relevant uncertainty. Although some degree of subjective engineering judgment may be necessary, the rationale needs to have a technical basis and not just opinions. Expert elicitation is essential to the success of this process.

The completeness and level of detail of the rationale used in technically justifying individual input parameters increases as the parameters approach more realistic values. The methodology used in

[44] Other release mechanisms are also applicable as discussed in the DOE-HDBK-3010-94, Chapter 7.0, Application Examples.

selection of input parameters and analysis should not lead to unrealistic accident scenarios and concomitant consequence estimates, nor an overall realistic estimate of consequences that may be appropriate for a comprehensive probabilistic risk assessment (PRA). An example of an approach previously justified in a DSA is related to a facility-wide seismic evaluation where median ARF/RF values were applied for a large facility with MAR in many locations that would be acted upon by a common stressor such as a spill. Applying the bounding ARF/RFs with the maximum MAR and DRs would have resulted in an overly conservative estimate due to compounding conservatisms that could have resulted in unnecessary SS controls and potential physical upgrading of the structure and equipment to meet current seismic standards. The burden is on the safety analyst to justify that the overall consequence estimates will be sufficiently conservative for the purpose of determining the need for safety SSC or SACs. The following quote from DOE-STD-3009-94 CN3 (Section 3.4.2.X.2) should be kept in mind: “The degree of conservatism believed to be present in the calculation needs to be consistent with the Evaluation Guideline definition.” As alternate values depart from the bounding or default values, at some point the calculation will not meet the original intent of the Evaluation Guideline based on a conservative analysis.

It is plausible to discern if there is a lesser or greater degree of conservatism in a calculation, but it will always be difficult and require judgment to determine the adequate level of conservatism. Another consideration regarding conservatism is from DOE-HDBK-3010-94 Section 7.3.6.2, Release Estimation,” that states:

> In the examples in this handbook, DRs are typically bounded by assuming a value of 1.0 for the sake of simplicity. The above discussion indicates how conservative such a bound can be. It is important not to lose sight of the fact that the phenomena being examined are generally unlikely to highly unlikely. By the time a maximum MAR has been assumed, the DR has been maximized as 1.0, the bounding ARFs and RFs of this document have been applied, no leakpath is accounted for, and 95% or greater meteorology has been used for dispersion, the answer obtained is extreme. Objectivity must be retained in the evaluation process so that a rote conception does not distract available resources from areas where greater real gains in safety can be made. As previously cautioned in this handbook, answers obtained are only as good as the decisions they lead to.

6 ATMOSPHERIC DISPERSION

6.1 INTRODUCTION

Radiological and/or chemically hazardous materials released into the environment can be transported to potential receptors through air and water pathways. This chapter discusses the mechanisms of atmospheric transport and diffusion, collectively referred to as *dispersion*, of such pollutants. Chapter 8 discusses the consequences of exposure to radioactive materials and Chapter 9 discusses dispersion principles specific to chemical releases (such as dense gas dispersion).

The basic equation for the calculation of radiological inhalation dose to a downwind receptor is:

$$Dose\ (rem) = ST \times \chi/Q \times BR \times DCF \qquad \textbf{Equation 6-1}$$

where

ST = source term (Ci), as discussed in Chapter 5

χ/Q = atmospheric dispersion factor (s/m^3), discussed below

BR = breathing rate (m^3/s), and

DCF = dose conversion factor (rem/Ci)

This chapter and Chapter 8 address the recommended approach to evaluating the terms in the above equation. This discussion is intended to be a practical guide and thus discusses these topics only to the extent needed to support a given topic in order to calculate potential consequences to receptors downwind for the DSA accident analysis. Only atmospheric (airborne) dispersion is addressed in this chapter, as DOE-STD-3009 excludes waterborne pathways from consideration in a DSA, except when the water pathway could significantly contribute to the overall radiological consequences. However, Chapter 7 does provide some guidance on aquatic dispersion principles with respect to infrequent releases of radioactive materials into water bodies. That chapter also briefly addresses groundwater transport.

For in-depth background on atmospheric dispersion, consult these references:

- *Workbook of Atmospheric Dispersion Estimates, An Introduction to Dispersion Modeling* (Turner, 1994), which is based on *Meteorology and Atomic Energy (*Slade, 1968);
- *Atmospheric Science and Power Production* (Randerson, 1984);
- *Atmospheric Diffusion, Study of the Dispersion of Windborne Material from Industrial and Other Sources* (Pasquill and Smith, 1983);
- *Radiological Assessment: A Textbook on Environmental Dose Analysis* (NRC, 1983);
- *Radiological Risk Assessment and Environmental Analysis* (Till and Grogan, 2008); and
- DOE Central Registry "Toolbox Code"[45] guidance documents listed in the Chapter 11, *References*.

In addition, *Directory of Atmospheric Transport and Diffusion Models, Equipment, and Projects*, is an excellent background source for 64 dispersion models (OFCM, 1998).

6.2 KEY RECEPTORS

The concentrations of pollutants at selected downwind distances are estimated in order to calculate the consequences to hypothetical receptors. DOE-STD-3009-2014 identifies two generic receptors[46] to be considered in accident analyses involving atmospheric dispersion, the CW and the MOI.

<u>CW</u>: A hypothetical worker located at a distance of 100 m from a facility (building perimeter) or estimated release point, defined to allow dose comparison with numerical criteria for selection of Safety Significant (SS) controls described in Chapter 2. The CW may be located at a farther distance if an elevated or buoyant radioactive plume causes a higher exposure beyond the 100 m distance. For ground level releases, DOE-STD-3009-2014, Section 3.2.4.2, specifies the CW χ/Q value as 3.5E-03 s/m^3 (based on NSRD-2015-01, Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for Department of Energy Nuclear Facilities [DOE/ONS, 2015]).[47] For situations

[45] "Toolbox code" is a term used to identify software qualified to be listed in the DOE Safety Software Central Registry (http://energy.gov/ehss/safety-software-quality-assurance-central-registry) that is used primarily for DOE safety analyses. The toolbox codes for atmospheric dispersion are discussed later in this section.

[46] A third generic receptor, the facility worker (FW), is also considered in the DSA hazard evaluation. The FW is a worker within a facility boundary and located less than 100 m from the release point. Atmospheric dispersion is not considered for this worker.

[47] DOE-STD-3009-2014 Section 3.2.4.2 does not specify the CW χ/Q value for elevated or buoyant releases. It does allow a value other than 3.5E-03 s/m^3, if technically justified. See Section 6.13 for more discussion and methods to calculate an alternative value and for a justification of the 3.5E-03 s/m^3 value.

where a release is from a facility significantly smaller than that assumed in the default parameter (i.e., a 10-meter tall by 36-meter wide building), or if a building is not present, the default χ/Q value may not provide a conservative estimate of dispersion.

MOI: A hypothetical individual representing the public, defined to allow dose comparison with an EG for selection of SC controls described in Chapter 2. The MOI is located at the point of maximum exposure on the DOE site boundary of the facility in question for a ground level release, or at some farther distance if an elevated or buoyant radioactive plume produces a higher exposure (elevated release) beyond the site boundary. Although this definition is specifically for radiological exposures, it can be extended to toxic chemical exposures as well for selection of SS controls as described in Chapter 10, Hazard Control Selection and Classification.

Per DOE-STD-3009, "the DOE site boundary is a geographic boundary within which public access is controlled and activities are governed by DOE and its contractors, and not by local authorities. A public road or waterway traversing a DOE site is considered to be within the DOE site boundary if DOE or the site contractor has the capability to control, when necessary, the road or waterway during accident or emergency conditions."

Radiological exposure is treated differently than exposure to toxic chemical emissions. For radiological exposures, the total time-integrated effective dose (primarily due to inhalation dose) is normally of interest because it is bounding for most radionuclide releases. To be conservative, the receptor is assumed to remain in the plume centerline during the entire period of plume passage, although evaluations for mitigated analysis may consider engineered safety features and emergency management dose-reduction measures (evacuation, sheltering) for the CW. For toxic chemical exposures, on the other hand, a TWA, or peak concentration during some exposure period (such as 15 minutes) is normally of greatest interest. This is addressed further in Chapter 9.

6.3 METEOROLOGICAL PARAMETERS AFFECTING DISPERSION

Once released into the atmosphere, radiological and toxic chemical emissions are transported in the direction of the wind and diffused by atmospheric turbulence[48] in the horizontal and vertical planes. This atmospheric turbulence consists of random, chaotic air motion in the form of countless whirling eddies. These eddies have a great range of size, from millimeters to tens or even hundreds of meters in diameter, with the smaller eddies being embedded within the larger ones (Richardson, 1927). When a plume of radiological or toxic chemical material is released into the atmosphere, the smaller eddies cause the material to diffuse within the plume, while the larger ones cause the plume to meander, mostly in the horizontal plane. These turbulent eddies are formed by surface frictional effects (mechanical turbulence) and by vertical gradients in both the velocity and the temperature of the air (mechanical turbulence and buoyancy), as discussed below.

A puff or plume that is released at the ground level grows vertically due to vertical diffusion. It reflects vertically from the ground surface and from the top of the mixed layer, which act as vertical boundaries. This is discussed more fully below.

Figure 6-1 displays the atmospheric and terrestrial processes determining the ultimate fate of a radionuclide or chemical pollutant after it is released to the environment. These highly complex

[48] Molecular diffusion is much slower than turbulent diffusion in dispersing materials, and much smaller in scale, and thus may be ignored.

interactions of physical phenomena with underlying topography and foliar populations are extremely difficult to describe mathematically. In order to approximate the effects of such phenomena, a Gaussian plume model has found wide application.

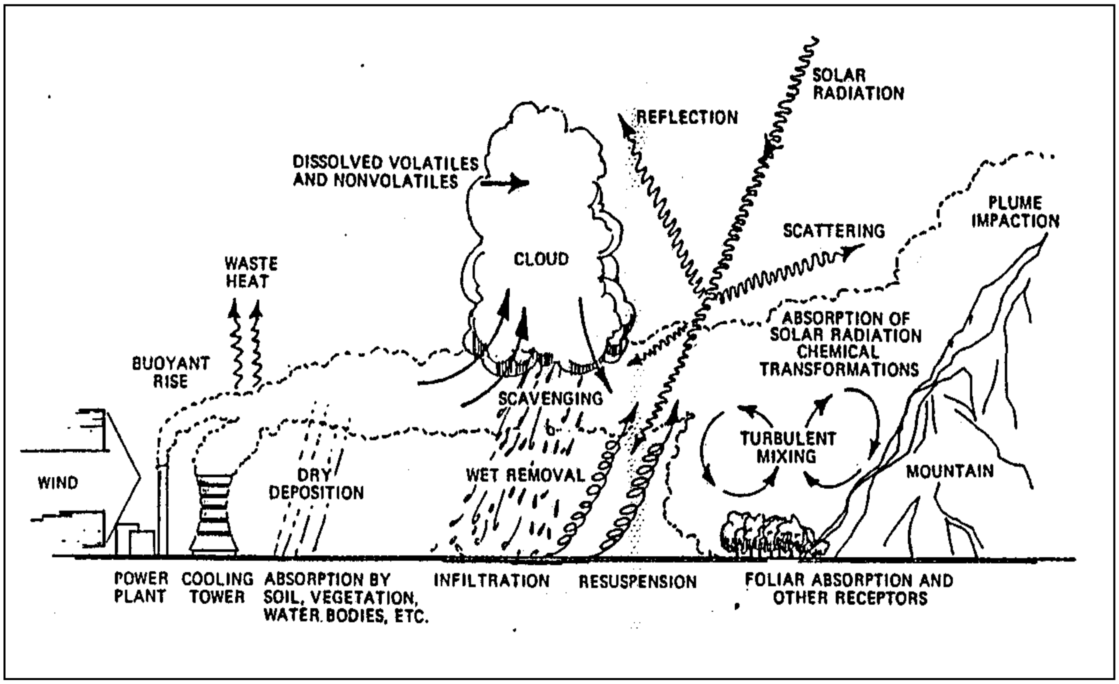

Figure 6-1. Atmospheric and terrestrial processes involved in determining the ultimate fate of a radionuclide or chemical pollutant.

The meteorological parameters affecting dispersion are discussed in the following subsections.

6.3.1 WIND SPEED, WIND DIRECTION, AND WIND DIRECTION STANDARD DEVIATIONS

Wind velocity is a vector quantity, having both magnitude and direction. Its magnitude is the wind speed. Variations in both magnitude and direction are important in dispersion.

6.3.1.1 WIND SPEED

The wind speed at the height of the release determines the travel time to reach a given downwind receptor and the amount of *initial* dilution from the point of release. The greater the wind speed, the more "stretched out" the plume will be and the more surrounding air will be mixed in. It is also a factor in determining the magnitude of atmospheric stability, which is discussed below. Mechanical turbulence is generated in the air when adjacent parcels of air move at different velocities, either at different speeds or in different directions; this is termed wind shear. Thus, a change in wind speed with height above the ground, or a variation in wind direction at different heights above the ground, causes mechanical turbulence. Mechanical turbulence is also generated when air interacts with some fixed object, such as the ground, described by roughness length, or with a building, described by aerodynamic effects (wake, cavity).

Short-lived radionuclides may decay appreciably if the transport time of the puff or plume to a receptor is long. The horizontal wind speed used in Gaussian models is based on the average wind speed over a selected time, usually fifteen minutes or one hour. Gaussian models are very conservative under light wind speed conditions (<1 m/s) since such conditions are too variable to be accurately approximated by a steady-state code. See Section 6.5.4.

6.3.1.2 WIND DIRECTION

The horizontal wind direction at the height of the release determines the initial direction of transport. The horizontal wind direction used in Gaussian modeling is the average, or first moment, of a series of "instantaneous" wind direction measurements. In meteorology, wind direction has traditionally been defined as the direction *from which* the wind blows, which is of interest to weather forecasters. However, most computer models for dispersion and consequence applications use wind direction to mean the direction *toward which* the wind blows. For example, a SE wind (as termed by meteorologists) will transport the plume to the NW. For a steady-state straight-line Gaussian model, once a plume segment is released, its direction of transport typically remains the same in time and space, as do the wind speed, turbulence intensities, and release rate. The MACCS2 code allows different segments to move in different directions.

6.3.1.3 WIND DIRECTION STANDARD DEVIATIONS

Atmospheric turbulence is directly related to the variability of the instantaneous wind speed and direction. This variability is normally expressed in terms of the standard deviation of a series of "instantaneous" wind direction measurements over a selected observation period, normally 15 minutes. The standard deviation, or second moment, of the horizontal wind direction (σ_θ) is commonly used to type atmospheric turbulence into stability classes. Some DOE sites also include the standard deviation of the vertical wind component (σ_φ) to type atmospheric turbulence, as discussed further in Section 6.4.2.2.

6.3.2 WIND SPEED PROFILE WITH HEIGHT

Wind speed varies with height in the Planetary Boundary Layer (PBL). It is often characterized with an equation known as the wind profile power law, which is a relationship between the wind speed at one height, and wind speed at another height. Winds generally increase with height as the frictional effects of the Earth's surface decrease as the distance from the surface increases. When the frictional effects of the surface are no longer felt, the upper boundary of the PBL, and bottom of the free atmosphere, is reached and the winds are termed geostrophic.

The wind profile of the PBL is generally logarithmic in nature (see PNNL-14584) and is best approximated using the logarithmic wind profile equation that accounts for surface roughness and atmospheric stability. However, the wind profile power law relationship is often used as a substitute for the logarithmic wind profile when surface roughness or stability information is available. Figure 6-2 presents a simplified representation of the logarithmic wind profile in the PBL, showing how wind speed increases with the height above the ground due to the reduction in the ground's frictional effect with height above the ground level.

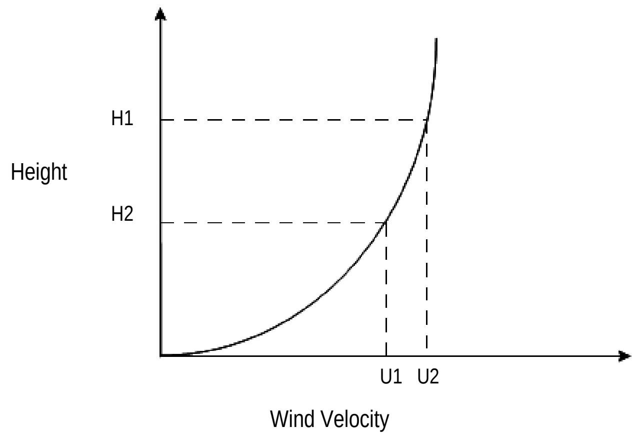

Figure 6-2. Logarithmic Wind Profile.

The wind profile power law relationship is described by:

$$u/u_r = (z/z_r)^\alpha \quad \textbf{Equation 6-2}$$

where

u = wind speed (m/s) at height z (m);

u_r = known wind speed at a reference height z_r; and,

α = empirically derived coefficient that is dependent upon stability of the atmosphere. For neutral stability conditions and a rural environment, α is approximately 1/7, or 0.143. For urban environments it is somewhat larger (EPA, 2000).

6.3.3 MIXING LAYER HEIGHT

For an evaluation of χ/Q that includes reflections from the ground and the top of the mixing layer, knowledge of the height of the top of the mixing layer at the site is required. Mixing height is the height above which relatively vigorous vertical mixing essentially stops; the layer from the ground to mixing height (mixing depth) is where vigorous vertical mixing occurs. Low mixing heights are related to a meteorological circumstance where air is generally stagnant with very little vertical motion and where radiological and toxic chemical emissions are usually trapped in a narrow layer near the ground surface. Under very stable conditions (F or G stability), the temperature inversion that is common to this stability class is typical of a low mixing height. Correspondingly, high mixing heights allow vigorous vertical mixing within a deep layer of the atmosphere and accordingly a good dispersion capacity.

Mixing heights can be used to estimate how far plumes rise in the vertical. The actual rise of a plume, however, considers complex interactions between atmospheric stability, wind shear, and heat release rate, density differences between the plume and ambient air, and radiant heat loss. Accordingly, an estimate of mixing height provides only an initial estimate of plume height, but with respect to DSAs, it is sufficient.

Mixing height varies throughout the day and throughout the seasons, since it is directly related to the amount of insolation that reaches the ground level. Mixing heights are usually lowest late at night or early morning and highest during mid- to late-afternoon. Average morning mixing heights range from

300 m to over 900 m above ground level (EPA Publication No. AP-101) for many locations in the United States. The highest morning mixing heights occur in coastal areas that are influenced by moist marine air and cloudiness that inhibit radiation cooling at night. Average afternoon mixing heights are higher than morning mixing heights and vary from less than 600 m to over 1400 m above ground level. The lowest afternoon mixing heights occur during winter and along coastal locations. Mixing heights vary considerably between locations and from day to day. *Smoke Dispersion Prediction Systems* (Ferguson, 2001) generated detailed maps and statistics of mixing heights in the United States that can be useful to the analyst.

The actual magnitude of the mixing heights can be obtained from Rawinsonde balloon soundings or from remote sensing techniques, such as sound detection and ranging (SODAR) and light detection and ranging (LIDAR). These remote sensing systems are becoming more commonly used at DOE sites and provide real-time data on the vertical structure of the atmosphere; whereas Rawinsonde data are discrete and specific to the time of each balloon release; usually at 12-hour intervals and perhaps at distances far from the DOE site. In the absence of such data, regional tables can be consulted, such as those in *Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution throughout the Contiguous United States* (EPA Publication No. AP-101). Each DOE site needs to technically justify its selection of mixing layer height in a dispersion modeling protocol (see Section 6.11).

6.3.4 VERTICAL TEMPERATURE PROFILES

Atmospheric turbulence can also be produced by temperature gradients, especially vertical temperature gradients. The pressure of the atmosphere decreases with height. Therefore, when a parcel of air is displaced vertically, it will expand if rising or contract if sinking to adjust its pressure to that of the surrounding atmosphere. The expansion or contraction is accompanied by an adiabatic (no gain or loss of heat) temperature change. Accordingly, as a parcel rises, it cools. If the surrounding air is warmer, the parcel will be heavier than its surroundings and sink back toward its original position until it reaches equilibrium. On the other hand, if the surrounding air is cooler, the parcel will be lighter and continue to move upward and its vertical motion is enhanced. Similarly, if the air parcel sinks, it warms up as it contracts. If the surrounding air is cooler, the parcel will be lighter and rise back toward its original position until it reaches equilibrium. However, if the surrounding air is warmer, the parcel will be heavier and continue to sink. Thus, turbulence is suppressed if the temperature profile of the air, termed the lapse rate, is less than adiabatic (subadiabatic), and enhanced if greater than adiabatic (superadiabatic). The dry adiabatic lapse rate near ground is about -9.8 °C/km (-5.4 °F/1,000 feet), while the moist adiabatic lapse rate, which depends on temperature, is about -5.8 °C/km (-3.2 °F/1,000 feet); the difference is due to heat required to overcome latent heat of the moisture in the air parcel (Wallace and Hobbs, 1977).

The atmospheric layer near the ground is termed the mixed layer, as this is where atmospheric turbulence is most common. During daylight, the ground heats up, warming the air near the surface through convective eddy transport. The lapse rate near the surface thus becomes superadiabatic and positive buoyancy forces enhance any existing mechanical turbulence caused by ground roughness or wind shear. At night, the ground cools due to release of long-wave radiation, causing the air near the surface to cool, and the lapse rate becomes subadiabatic and frequently inverted, suppressing much of the existing mechanical turbulence. At greater heights, a few hundred to a few thousand meters in altitude, the lapse rate may change. It is common for a turbulent lower atmosphere to be capped by a lapse rate that is subadiabatic so that turbulent eddies rising from below are suppressed. Vertical plume expansion is thus limited, reflecting off the top of the mixed layer, as well as off of the ground.

6.3.5 PRECIPITATION

With regard to precipitation scavenging (rainout, snowout, hailout), the rate of precipitation is needed as an input to models that address this atmospheric phenomenon. Rainout can cause major local deposition of radionuclides leading to radioactive "hot spots" at locations that receive rainfall. However, DOE-STD-3009-2014 does not require, nor does modeling code guidance recommend, the consideration of precipitation scavenging in DSAs. If the analyst wants to include wet deposition, a dispersion modeling protocol should be developed and approved as discussed in Section 6.11 below.

6.3.6 TEMPERATURE AND RELATIVE HUMIDITY

Temperature and relative humidity are not important parameters with respect to the calculation of radiological consequences. However, it is quite important with respect to calculation consequences from toxic chemical releases, which is addressed in Section 9.6.

6.4 GAUSSIAN PLUME MODEL FOR NEUTRALLY BUOYANT PLUMES

6.4.1 BASIC GAUSSIAN EQUATIONS

If pollutants are neutrally buoyant, as in the release of trace amounts of very fine particulates or gases, plume dispersion approximates a Gaussian distribution in both the crosswind (lateral) and vertical directions. As the plume moves downwind, it gets progressively larger and less concentrated. The Gaussian approximation of atmospheric dispersion assumes that as a plume is transported downwind, its horizontal expansion is essentially unlimited[49]. Vertical expansion is limited by the earth's surface and aloft under inversion conditions. The downward expansion of the plume stops at the ground, while upward expansion may be stopped if there is a stable layer (a "cap") at the top of the mixed layer. This cap acts as a lid to rising "thermals" of air, thus restricting the range and magnitude of vertical turbulence. The plume is often considered to "reflect" off both the ground and the top of the mixed layer, causing the *vertical* profile to become increasingly uniform as the plume proceeds downwind. For low level mixing heights, multiple reflections can occur from the ground and lid, especially for far-field receptors.

[49] Horizontal, or lateral, plume expansion may be somewhat limited by physical barriers, such as buildings and topographic obstacles, but these are normally treated as special cases. Vertical plume expansion is enhanced by these barriers but can also be limited by mixing depth.

Figure 6-3 (Turner, 1994) illustrates the general shape of a Gaussian plume as released from a stack. The coordinate system used in Gaussian equations is shown, in which *x* is defined as the downwind direction, *y* is the horizontal cross-wind direction, *z* is vertical direction, and *h* is the height of release. The height of the plume after release, or effective stack height, is *H*.[50]

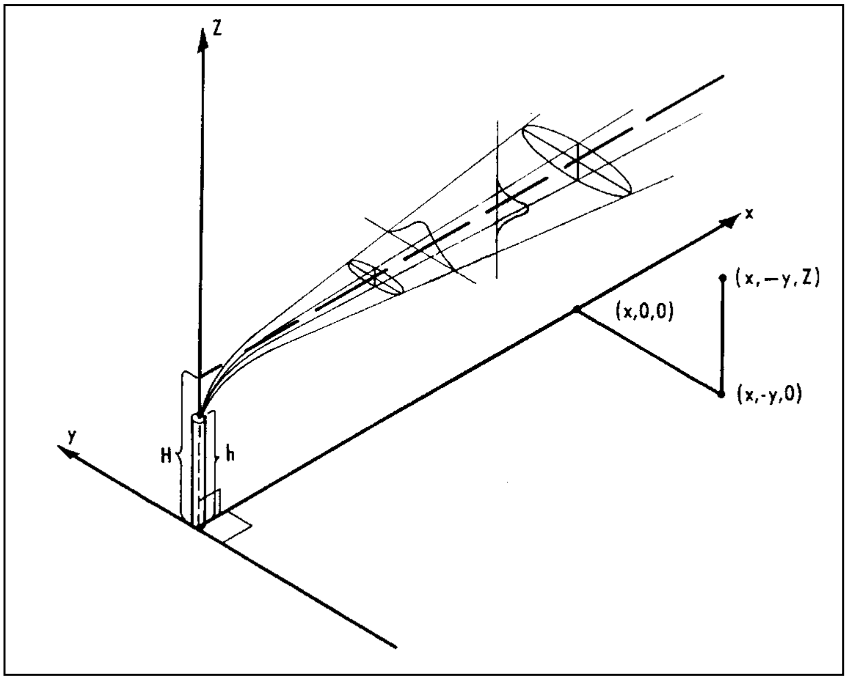

Figure 6-3. Coordinate System of Gaussian Plume.

The amount of atmospheric dispersion is usually expressed in terms of normalized concentration, or χ/Q, where:

χ = the concentration of the radionuclides or toxic chemical in air at some downwind (*x, y, z*) location; this can be either the instantaneous concentration (e.g., Bq/m^3 or mg/m^3) or the time-integrated concentration (e.g., Bq-s/m^3 or mg-s/m^3), and

Q = the constant rate of radionuclide or toxic chemical release (e.g., Bq/s or g/s), if χ is taken to be the instantaneous concentration, or total source strength (e.g., Bq or g), if χ is taken to be the time-integrated concentration.

The units of χ/Q are s/m^3 whether the instantaneous or time-integrated releases are considered or whether radioactive or toxic chemical releases are being evaluated. Thus, χ/Q is the concentration of the radionuclides or toxic chemical in air at the receptor per unit source rate, or time-integrated concentration per unit source release. The actual concentration of the radionuclides or toxic chemical in air (χ) at the receptor is thus the product of χ/Q and the rate of release of the radionuclides or toxic chemical (Q), as determined by the source term calculations from Chapter 5, Chapter 8, and Section 9.5 of this Handbook.

[50] The symbol "H" in this figure is shown as "h" in the remainder of this chapter.

When accounting for reflection off the ground, but not constrained by the top of the mixed layer, the Gaussian plume model (Slade, 1968) is expressed as:

$$\frac{\chi(x,y,z,h)}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} e^{-y^2/2\sigma_y^2} \left[e^{-(z-h)^2/2\sigma_z^2} + e^{-(z+h)^2/2\sigma_z^2} \right]$$ **Equation 6-3**

where

x = downwind distance of the receptor from the point of release (m),

y = horizontal cross wind distance of the receptor from the centerline of the plume (m),

z = distance of the receptor above the ground (m),

h = height of the plume centerline above the ground (m) (same as H in Figure 6-3),

σ_y = standard deviation of the horizontal Gaussian distribution (m) (converted from the "half width" of a rectangular cross-section of a plume),

σ_z = standard deviation of the vertical Gaussian distribution (m) (converted from the "half thickness" or "half depth" of a rectangular cross-section of a plume),

u = wind speed at a representative height (m/s).

With respect to ground-level releases, the analysis usually begins with the wind speed measured at a height of 10-m, which is the lowest standard height for measuring wind speed (NRC, 2007). The standard measurement height is the measurement level of winds at First-Order National Weather Service stations and the lowest level of measurement at most DOE sites and commercial nuclear facilities. The 2π in this equation is implicit in a Gaussian distribution, in which the lateral (y) and vertical (z) components each contribute $(2\pi)^{1/2}$. Physically, the wind speed, u, represents the initial dilution of the plume caused by the "stretching out" of the plume when it is released into clean air moving about the release. Note that the downwind distance (x) does not appear explicitly in this equation. The x dependence is implicit, as the σ_y and σ_z are functions of x only, for a given stability class. The choice of what wind speed is input into Equation 6-3 for ground-level releases is discussed further in Section 6.5, Characterization of Meteorological and Site Data.

The bracketed term in Eq. 6-3 defines the vertical distribution. If the radionuclides or toxic chemicals are reflected from the ground and from the top of the mixed layer, this term is to be modified. This is done mathematically by adding multiple mirror source terms. The bracketed term in Eq. 6-3 thus is replaced with:

$$\left[e^{-(z-h)^2/2\sigma_z^2} + e^{-(z+h)^2/2\sigma_z^2} + \sum_{n=1}^{N} \left(e^{-(z-h-2nL)^2/2\sigma_z^2} + e^{-(z+h-2nL)^2/2\sigma_z^2} + e^{-(z-h+2nL)^2/2\sigma_z^2} + e^{-(z+h+2nL)^2/2\sigma_z^2} \right) \right]$$ **Equation 6-4**

The term before the summation in Eq. 6-4 is the ground reflection component since perfect reflection is assumed. The series of terms after the summation represent multiple reflections from the top of the mixed layer and the ground. L represents the height of the top of the mixed layer and the summation is over the number (N) of reflections to be considered. The contribution of the summation term is a function of distance from the source and mixing height. This contribution is generally minor, especially for distances close to the source and for larger values of L. The higher-order terms contribute progressively less and the series is normally terminated after only a few terms. For example, in the MACCS code (NUREG/CR-

4691), the series is terminated at $N = 5$. As the plume travels and spreads, Equation 6-4 will eventually result in a plume that is fully mixed vertically, between the ground and height L. In order to simplify the computations, several codes switch from using an equation like 6-3 to using an expression that assumes a vertically mixed plume. Detailed information on this transition for the codes that perform it are available in the documentation for each code.

For a ground-level release ($h = 0$) when the receptor is at ground level ($z = 0$) (general assumption), the first two exponential terms become equivalent as each of the z-h terms is equal to 1. In this case, the “2” in the denominator of Eq. 6-3 cancels out with the “2” in the numerator, if the summation term is ignored, as is often done in hand calculations and in some software codes.

The maximum concentration occurs on the plume centerline ($y = 0$). Thus, if the summation term is ignored, the Gaussian equation simplifies to:

$$\frac{\chi(x, y=0, z=0, h=0)}{Q} = \frac{1}{\pi u \sigma_y \sigma_z}$$ **Equation 6-5**

If the summation term had not been ignored, the numerator in the above expression would have been greater than one. The numerator in the above expression is slightly greater than one because of the contribution of the summation term. Eq. 6-5, which is now only a function of downwind distance of the receptor, is often used in hand calculations for the CW and MOI, as plume centerline represents a conservative value.

6.4.2 GAUSSIAN PLUME WIDTHS AND DEPTHS

The horizontal and vertical spread of pollutants within a Gaussian plume is a function of the diffusion parameters, σ_y and σ_z, respectively. As representations of plume boundary spread, σ_y and σ_z are often referred to as the “half width” and “half thickness,” respectively.

The most widely used sets of dispersion parameters are known as the Pasquill-Gifford curves (Pasquill, 1961; Gifford, 1961). These parameters have a varied basis. At shorter distances, some of the sigma-z parameters are based on the results of field experiments known as Project Prairie Grass that were performed on flat fields in Nebraska (Barad, 1958). Gifford adapted the original work by Pasquill and published the curves in graphical form (Gifford, 1961). The curves can also be found in NRC Regulatory Guide 1.145, and are shown in Figure 6-4. They are found in *Workbook of Atmospheric Dispersion Estimates, An Introduction to Dispersion Modeling* (Turner, 1994), Slade (1968), and Randerson (1984). These curves became known as the Pasquill-Gifford (P-G) dispersion curves[51], and the set of parameters represented by them are the P-G dispersion parameters. In Figure 6-4, the curves beyond 1,000 m are dashed because of lower confidence in those curves at the longer distances; Pasquill described some of the curves beyond 1,000 m as being speculative extrapolations. For distances less than about 50 m, these dispersion parameters did not provide a good fit to the observations. Moreover, building wake effects further complicated near-field dispersion. This situation led to a lower confidence in curves below 100 m, which is why the curves begin at 100-m. This limitation was a factor that influenced the choice of the selected distance for evaluating the exposure to a CW as 100-m. NUREG-1140 provides some insight into the decision to not use conventional Gaussian models at distances within 100 m.

[51]These curves are sometimes also referred to as the Pasquill-Gifford-Turner (P-G-T) curves, given their publication by Turner in a workbook initially developed in 1970 for the EPA (current version is the 2nd edition, Turner 1994).

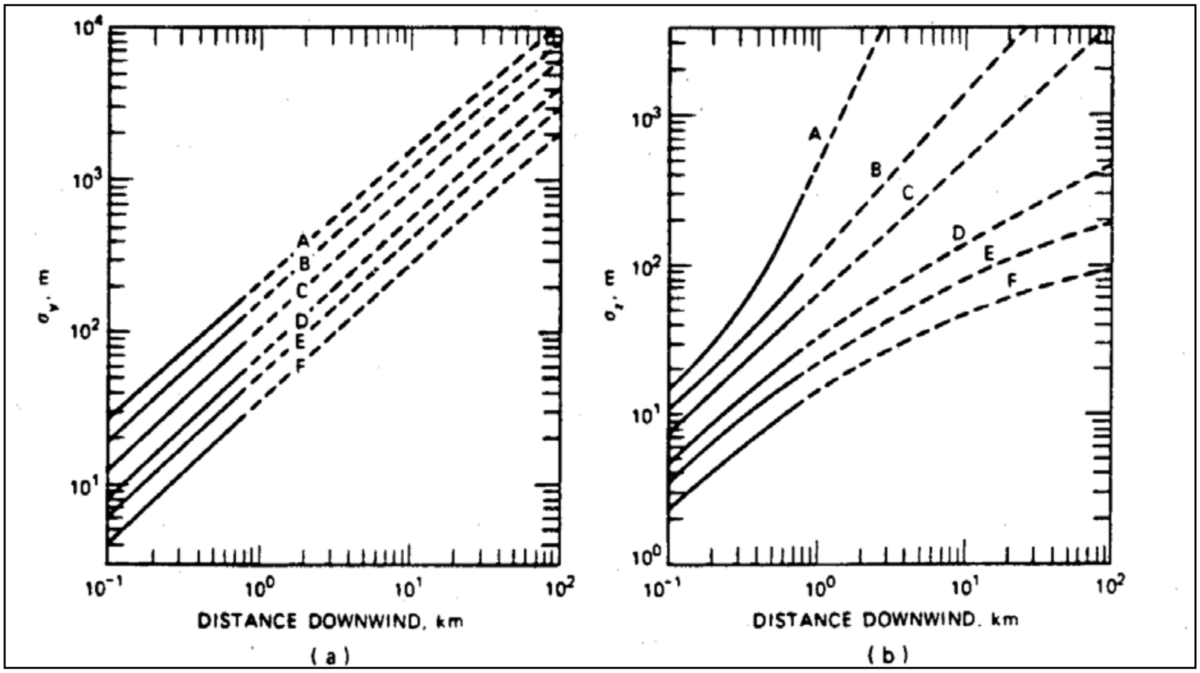

Figure 6-4. Variations of Horizontal and Vertical Plume Dimensions with Distance. The curve labels refer to atmospheric stability classes.

6.4.2.1 ATMOSPHERIC STABILITY CLASSES

Because atmospheric dispersion is so complex and turbulence is so random and chaotic, mathematical descriptions of atmospheric phenomena are, in most cases, developed from empirical data. One method defines distinct atmospheric stability classes and associates a magnitude of lateral and vertical diffusion with each stability class as a function of downwind distance only. Although these computations provide only a rough approximation to reality, they have proven extremely useful and are still in use, although treatments that are more accurate are available. The most common measurements employed in typing stability class are wind direction variability and vertical temperature gradients. The wind direction variability provides the best approximation of the mechanical turbulence component and the vertical temperature gradient provides the best approximation of the buoyancy component. The following subsections provide some definitions associated with stability class and the methods to type it in order to approximate the turbulence intensities that drive atmospheric diffusion. Schemes like that shown in Figure 6-4 are then used with the stability class to determine σ_y, and σ_z as a function of downwind distance. As seen in Figure 6-4, the σ_y, and σ_z curves are represented in graphical form. For computational purposes, there is a need for curve-fits, of which several have been developed. This is discussed further in Section 6.4.2.4.

The rate at which turbulence diffuses radioactive and toxic chemical releases depends upon the stability of the atmosphere. Seven distinct stability classes, namely, the Pasquill-Gifford-Turner (P-G-T) classes, have been defined. These classes, with their relationship to measured temperature gradient, and the conditions of occurrence, are defined below. The P-G curves use six stability classes (i.e., Classes A through F), although some schemes for assigning stability class use a seventh stability class (i.e., Class G). Therefore, from the results of the Project Prairie Grass atmospheric tracer tests, Pasquill and Gifford developed an atmospheric dispersion stability class scheme that is still used today, which is similar to Table II in Pasquill (1961).

- **A**: Extremely Unstable (strong superadiabatic). Normally occurs during bright sunshine with relatively low wind speed (< 3 m/s).
- **B**: Moderately Unstable (moderate superadiabatic). Normally occurs during conditions that range from bright sunshine, with wind speeds in the 3 to 5 m/s range, to dim sunshine, with wind speeds < 2 m/s.
- **C**: Slightly Unstable (slight superadiabatic). Normally occurs during conditions that range from bright sunshine with wind speeds in the 5 to 6 m/s range, to dim sunshine with wind speed in the 2 to 3 m/s range.
- **D**: Neutral (adiabatic). Normally occurs with moderate to dim sunshine, cloudy conditions, and at night, with wind speeds > 3 m/s. It also occurs with very strong wind speeds on either sunny or cloudy days. It usually is the most frequent of the stability classes.
- **E**: Slightly Stable (slight subadiabatic with or without inversion). Normally occurs at night or early morning with some cloud cover and with wind speeds in 2 to 5 m/s range.
- **F**: Moderately Stable (moderate subadiabatic with inversion). Normally occurs at night or early morning with little cloud cover and with relatively low wind speeds (< 3 m/s).
- **G**: Extremely Stable (strong subadiabatic with inversion)[52]. Normally occurs at night or early morning with very light to nearly zero wind speed (calm wind conditions).

The G stability class, as well as the F stability class, is associated with inversion breakup fumigation conditions, occurring in early morning, in which an elevated plume is rapidly forced to the ground. Due to the stable conditions (slow lateral and vertical diffusion) and the low wind speed (slow dilution), the plume concentrations from an elevated release are rapidly brought to the ground can be high. Fumigation represents the worst case scenario for near-field immersion doses associated with elevated releases.

Unstable conditions result in rapid-spreading lateral and vertical diffusion of pollutants (wide plumes), whereas stable conditions result in slow-spreading lateral and vertical diffusion (narrow plumes).

Although Class A stability is not rare, it is not as common as Classes B through F. Class D is the most common stability class because of the large number of combinations of meteorological conditions that can result in Class D stability. For example, high-wind conditions and/or cloudy conditions during the day or at night are normally Class D. During periods of extended rainfall and overcast conditions, as many as 100 consecutive hours of Class D stability have been recorded. Classes E and F most commonly occur at night. Class G is less common and it is often ignored in computer models based on the Gaussian equations.

6.4.2.2 METHODS OF CALCULATING STABILITY CLASSES

Many schemes have been proposed for determining stability class from measured meteorological parameters. The conditions listed above are dependent on wind speed and amount of incoming solar radiation, the latter a function of opaque cloud cover. These stability class definitions are not practical for many DOE sites because the amount of opaque cloud cover is a visually observed condition and not normally recorded by automated weather instrumentation. In addition, opaque cloud cover is somewhat

[52] The NRC uses class G in licensing all civilian nuclear power plants. In the RSAC code used at Idaho National Laboratory, an additional class, referred to as “class F fumigation”, is introduced. It is similar to class G but in the RSAC code is distinct from class G. Hotspot and GENII both include class G stability.

subjective, varying from observer to observer. Alternative methods have therefore been developed based on measured data.

Several methods exist to convert measured or observed meteorological data into atmospheric stability class data. Two methods are recommended given their regulatory support by the NRC and U.S. Environmental Protection Agency (EPA) and their use across DOE sites based on available meteorological data. Note that the NRC guidance for stability classification extends the original P-G scheme by subdividing P-G class F to create a seventh stability class (class G) for extremely stable condition. In contrast, the EPA guidance combines classes F and G into a single class F. The implications for atmospheric transport and diffusion modeling are addressed below.

The method that is prescribed by the NRC for supporting licensing of nuclear power plants makes use of measurements of vertical temperature difference (ΔT_z) to determine atmospheric stability as shown in Table 6-1 (NRC Regulatory Guide 1.145). In this method, ΔT_z is expressed in terms of the vertical temperature difference over a 100-meter layer of the atmosphere (termed ΔT_{100m}), with the lowest measurement 10-m above the ground. ΔT_{100m} is determined by doubling the difference in temperature measurements over a 50-meter layer at 60 m and 10 m, which are common temperature measurement heights at DOE sites, or by normalizing the difference to a 100-meter depth if the lower height is not 10m.

Table 6-1. Classification of Atmospheric Stability Based on Vertical Temperature Difference.

Stability Classification	Stability Class	Ambient Temperature Change with Height (°C/100 m)
Extremely unstable	A	$\Delta T_{100m} \leq -1.9$
Moderately unstable	B	$-1.9 < \Delta T_{100m} \leq -1.7$
Slightly unstable	C	$-1.7 < \Delta T_{100m} \leq -1.5$
Neutral	D	$-1.5 < \Delta T_{100m} \leq -0.5$
Slightly stable	E	$-0.5 < \Delta T_{100m} \leq 1.5$
Moderately stable	F	$1.5 < \Delta T_{100m} \leq 4.0$
Extremely stable	G	$\Delta T_{100m} > 4.0$

Example: If the temperature at 10 m was 10°C and at 60 m it was 9.5°C, the temperature difference would be -0.5°C/50 m (ΔT_{100m} = -1.0°C/100 m); a stability Class D.

DOE site meteorologists have observed that turbulence typing based on PBL temperature gradients tend to produce a distribution of stability categories that is more skewed toward the strongly stable (F and G) and strongly unstable (A and B) categories; especially if the upper measurement level is much lower than 60 m.

A method recommended by EPA calculates the stability in a two-step process based on turbulence measurements. The first step makes an initial estimate and the second makes a correction to the initial estimate. The initial categorization is based on the standard deviation of wind direction fluctuation in the azimuth (horizontal) plane (σ_θ) as shown in Table 6-2 (EPA-450/4-87-013).

Table 6-2. Initial Estimates of Stability Class, EPA Method.

Stability Class	Standard Deviation of Wind Direction, σ_θ
A	$22.5° \leq \sigma_\theta$
B	$17.5° \leq \sigma_\theta < 22.5°$
C	$12.5° \leq \sigma_\theta < 17.5°$
D	$7.5° \leq \sigma_\theta < 12.5°$
E	$3.8° \leq \sigma_\theta < 7.5°$
F	$\sigma_\theta < 3.8°$

The final categorization is then made by combining this initial estimate with the wind speed and time of day, specifically whether it is "day" or "night", as shown in Table 6-3. "Day" is defined here as being the period between one hour after sunrise and one hour before sunset. The remainder of the time is defined as "night."[53] The measurement height of the standard deviation of wind direction should be at the 10-m level.

[53] For some DOE sites that are located nearby large bodies of water and subject to sea breezes and lake breezes (such as Brookhaven National Laboratory, Argonne National Laboratory), it may be necessary to adjust the definition of "day" to account for the later onset of more stable conditions during morning and afternoon lake breeze and sea breeze conditions.

Table 6-3. Final Estimates of Stability Class, EPA Method.

Time of Day	Initial P-G Stability Class Estimate	Wind Speed Range, WS (m/s)	Final P-G Stability Class
Daytime	A	WS < 3	A
		3 ≤ WS < 4	B
		4 ≤ WS < 6	C
		6 ≤ WS	D
	B	WS < 4	B
		4 ≤ WS < 6	C
		6 ≤ WS	D
	C	WS < 6	C
		6 ≤ WS	D
	D, E, or F	ANY WS	D
Nighttime	A	WS < 2.9	F
		2.9 ≤ WS < 3.6	E
		3.6 ≤ WS	D
	B	WS < 2.4	F
		2.4 ≤ WS < 3.0	E
		3.0 ≤ WS	D
	C	WS < 2.4	E
		2.4 ≤ WS	D
	D	ANY	D
	E	WS < 5.0	E
		5.0 ≤ WS	D
	F	WS < 3.0	F
		3.0 ≤ WS < 5.0	E
		5.0 ≤ WS	D

Example: If the value of σ_θ was measured to be 3.0° azimuth, the initial classification would be Class F. Then if the wind speed was measured to be 4.0 m/s and it was nighttime, the final stability class would be Class E.

6.4.2.3 ADDITIONAL STABILITY CLASSIFICATION TECHNIQUES

Two additional methodologies are occasionally used: (1) the σ_E-σ_A method; and, (2) the SRDT method.

The σ_E-σ_A Classification Method is based on the direct measurement using three-dimensional mechanical or sonic anemometers of either the horizontal wind fluctuation, or azimuth angle (σ_A) or vertical wind fluctuation, or elevation angle (σ_E). The initial estimates for both the σ_E and σ_A methods, based on the standard deviation of turbulence measurements are shown in Table 6-4, EPA-454/R-99-005, *Meteorological Monitoring Guidance for Regulatory Modeling Applications* (EPA, 2000).

Table 6-4. Initial Estimates of Stability Class Based on Elevation Angle and Azimuth Angle Turbulence Measurements (EPA-454/R-99-005).

P-G Stability Class	Standard Deviation of Horizontal Wind Fluctuation (σ_E)	Standard Deviation of Vertical Wind Fluctuation (σ_A)
A	$11.5° \leq \sigma_E$	$22.5° \leq \sigma_A$
B	$10.0° \leq \sigma_E < 11.5°$	$17.5° \leq \sigma_A < 22.5°$
C	$7.8° \leq \sigma_E < 10.0°$	$12.5° \leq \sigma_A < 17.5°$
D	$5.0° \leq \sigma_E < 7.8°$	$7.5° \leq \sigma_A < 12.5°$
E	$2.4° \leq \sigma_E < 5.0°$	$3.8° \leq \sigma_A < 7.5°$
F	$\sigma_E < 2.4°$	$\sigma_A < 3.8°$

In addition, EPA-454/R-99-005 recommends two possible additional adjustments to the σ_E-σ_A method since the turbulence typing criteria are based on measurements at the standard height (Z) of 10 m and for locations with a terrain roughness length (z_o) of 15 cm. For sites with rougher terrain and/or measurement heights different from 10 m, the category boundaries should be adjusted by wind speed measurement height and terrain roughness factors:

$$\text{Measurement Height Adjustment Factor} = (Z/10)^p \qquad \textbf{Equation 6-6}$$

The exponent p is a function of P-G stability class and has different values for the σ_E and σ_A methods as shown in Table 6-5.

Table 6-5. Measurement Height Adjustment Factor for σ_E and σ_A Methods as a Function of Stability Class.

P-G Stability Class	σ_E Method p-value	σ_A Method p-value
A	0.02	-0.06
B	0.04	-0.15
C	0.01	-0.17
D	-0.14	-0.23
E	-0.31	-0.38

$$\text{Roughness Adjustment Factor} = (z_0/15)^{0.2} \qquad \textbf{Equation 6-7}$$

The SRDT Method involves the use of total solar radiation and surface wind speed data during the day to determine atmospheric stability. During the night, ΔT_z data and surface wind speed data are used (EPA-454/R-99-005). In this method, the wind speed is measured at or near the 10-m level or adjusted to this reference height. The SRDT method is outlined in Table 6-6 (EPA-454/R-99-005).

Table 6-6. Classification of Atmospheric Stability Based on SRDT Method.

	DAYTIME			
Wind Speed (m/s)	**Solar Radiation (W/m²)**			
	≥ 925	925 - 675	675 - 175	< 175
< 2	A	A	B	D
2 - 3	A	B	C	D
3 - 5	B	B	C	D
5 - 6	C	C	D	D
≥ 6	C	D	D	D
	NIGHTTIME			
Wind Speed (m/s)	**Vertical Temperature Gradient**			
	< 0		≥ 0	
< 2.0	E		F	
2.0 - 2.5	D		E	
≥ 2.5	D		D	

6.4.2.4 METHODS OF CALCULATING PLUME WIDTH AND PLUME THICKNESS

Once the stability class has been determined for a given weather condition, the plume widths and depths (σ_y and σ_z) are estimated in order to calculate χ/Q. This is needed for each hour of the year for five years or more, to be compliant with DOE-STD-3009-2014. Depending on completeness of the data record, consecutive years of recent meteorological data is preferred (EPA, 2000). Data is also needed for selected distances from the point of release, out to the MOI, or beyond if the plume is lofted. The calculational method is chosen depending on distance and terrain roughness.

> Example: If the stability class is determined to be Class E, and the Tadmor-Gur method is chosen, the values of σ_y and σ_z at 1,000 m would be calculated from $\sigma = a\,x^b$, where $a_y = 0.1046$, $b_y = 0.9031$, $a_z = 0.4$, and $b_z = 0.6021$. This gives $\sigma_y = 0.1046 \times 1000^{0.9031} = 53.6$ m and $\sigma_z = 0.4 \times 1000^{0.6021} = 25.6$ m. The width (σ_y) is then adjusted by the plume meander factor and the depth (σ_z) by the surface roughness factor. For a one hour plume duration and a 10-minute time base, the plume meander factor would be $(60 \text{ min}/10 \text{ min})^{0.2} = 1.43$, yielding $\sigma_y = 76.7$ m. For a surface roughness of 100 cm (such as in a forested region), the roughness factor would be 2.02, yielding $\sigma_z = 51.7$ m.

Calculations such as in this example, are performed within the various dispersion codes, such as MACCS2 (discussed in Section 6.9.1). They can also be calculated manually using a spreadsheet but this is normally done only for spot checking and scoping calculations.

Numerous methods of calculating plume dimensions for the different stability classes have been developed over the past 60 years. Many of these schemes attempt to determine the magnitude of atmospheric dispersion by relating σ_y and σ_z to stability classes, based on curve fitting of data that were taken during tracer experiments over flat grassland (Barad, 1958), and downwind distance.
One commonly used curve-fitting method is that of *Analytical Expressions for the Vertical and Lateral Dispersion Coefficients in Atmospheric Diffusion* (Tadmor and Gur, 1969), in which each σ value is expressed as a power law:

$$\sigma = a\,x^{b} \qquad \textbf{Equation 6-8}$$

where *a* and *b* are empirical constants, given in Table 6-7 (a_y and b_y for horizontal, and a_z and b_z for vertical), as used in the MACCS2 code, with the Tadmor-Gur typographical errors corrected (see Dobbins, 1979); the units of *x* and σ are in meters. There are two sets of vertical diffusion values as they depend on distance from the source.[54]

Example: For stability class D and a distance of 1 km (1000 m), the Tadmor-Gur formulation gives $\sigma_y = 0.1474 \times 1000^{0.9031} = 75.5$ m and $\sigma_z = 0.3 \times 1000^{0.6532-} = 27.3$ m.

A power law expression, when graphed on logarithmic coordinates, appears to be linear. Examination of the Pasquill-Gifford curves reveals that σ_y can be described by a power law, but σ_z cannot. Tadmor and Gur attempted to address this difficulty by performing different power law fits over different ranges of distance. It should be noted that Tadmor and Gur did not specify constants that are appropriate at distances less than 500 m. However, Eimutis and Konicek (1972) determined that a curve-fit with better fidelity to the Pasquill-Gifford σ_z can be achieved with a third fitted constant.

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[54] In some formulations, a third empirical constant, *c*, is added (as in Eq. 6-9) but in MACCS2, the *c* term of σ_z has been set to zero for mathematical convenience, which has required an adjustment to the values of *a* and *b*.

Table 6-7. Fitting Constants for σ_y and σ_z from Tadmor and Gur.

Stability Class	σ_y		σ_z (0.5 to 5 km)		σ_z (5 to 50 km)	
	a_y	b_y	a_z	b_z	a_z	b_z
A	0.3658	0.9031	2.5E-04	2.1250	NA*	NA*
B	0.2751	0.9031	1.9E-03	1.6021	NA*	NA*
C	0.2089	0.9031	0.2	0.8543	0.5742	0.7160
D	0.1474	0.9031	0.3	0.6532	0.9605	0.5409
E	0.1046	0.9031	0.4	0.6021	2.1250	0.3979
F	0.0722	0.9031	0.2	0.6020	2.1820	0.3310

* NA - Not available. Power-law constants for stability class C are applied, per recommendation of the MACCS2 code developer (DOE, 2004a).

Eimutis and Konicek adopted three sets of power-law expressions to cover three downwind distance regimes: (i) < 100 m, (ii) 100 m to 1000 m, and (iii) > 1000 m (Eimutis and Konicek, 1972). This parameterization is widely used in NRC dispersion models.

$$\sigma_j = a_j \cdot x^{b_j} + c_j$$ **Equation 6-9**

For $j = y$ (horizontal), $b_y = 0.9031$ and $c_y = 0$. The other constants a_j, b_j, and c_j are given in Table 6-8; a_z, b_z, and c_z are with respect to the vertical. Note that in the Table 6-8, typographical errors in Eimutis and Konicek have been corrected.

Table 6-8. Fitting Constants for σ_y and σ_z (from Eimutis and Konicek, 1972).

		ATMOSPHERIC STABILITY CLASS						
	Distance	**A**	**B**	**C**	**D**	**E**	**F**	**G**
a_y	all	0.3658	0.2751	0.2089	0.1471	0.1046	0.0722	0.0481
a_z	< 100 m	0.192	0.156	0.116	0.079	0.063	0.053	0.032
	100 to 1000 m	0.00066	0.0382	0.113	0.222	0.211	0.086	0.052
	>1000 m	0.00024	0.055	0.113	1.26	6.73	18.05	10.83
b_z	< 100 m	0.936	0.922	0.905	0.881	0.871	0.814	0.814
	100 to 1000 m	1.941	1.149	0.911	0.725	0.678	0.74	0.74
	>1000 m	2.094	1.098	0.911	0.516	0.305	0.18	0.18
c_z	< 100 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	100 to 1000 m	9.27	3.3	0.0	-1.7	-1.3	-0.35	-0.21
	>1000 m	-9.6	2.0	0.0	-13.0	-34.0	-48.6	-29.2

Example: For stability class D and a distance of 1000 m, the Eimutis-Konicek formulation gives $\sigma_y = 0.1471 \times 1000^{0.9031} = 75.5$ m and $\sigma_z = 0.222 \times 1000^{0.725} - 1.7 = 31.5$ m.

In addition to the Pasquill-Gifford curves, there are two other sources of atmospheric dispersion parameters available in some DOE Toolbox codes from *Diffusion Estimates for Small Emissions* (Briggs, 1973; as updated in Griffiths, 1994): (1) Briggs open-country curves; and,(2) Briggs urban curves. Just like the Pasquill-Gifford curves, the open-country curves are applicable to rural conditions. The Briggs urban curves are based on additional data from an atmospheric dispersion experiment in St. Louis (Hanna, 1982). In the Briggs expressions each σ is expressed as:

$$\sigma = a\, x\, (1 + bx)^{c}$$ **Equation 6-10**

where *a*, *b*, and *c* are constants, given in Table 6-9. Note that the Briggs-urban curves are not correct for rough rural conditions because of the lack of urban thermal effects on the scale of a large city.

Example: For stability class D, open country, and a distance of 1000 m, the Briggs formulation gives
$\sigma_y = 0.08 \times 1000 \times (1 + 0.0001\times1000)^{½} = 76.3$ m; and,
$\sigma_z = 0.06 \times 1000 \times (1 + 0.0015\times1000)^{½} = 37.9$ m.

Table 6-9. Fitting Constants for σ_y and σ_z from Briggs.

Curve Fitting Constant	ATMOSPHERIC STABILITY CLASS					
	A	**B**	**C**	**D**	**E**	**F**
	Open-Country Conditions					
a_y	0.22	0.16	0.11	0.08	0.06	0.04
a_z	0.20	0.12	0.08	0.06	0.03	0.016
b_y	0.0001	0.0001	0.0001	0.0001	0.00001	0.0001
b_z	0	0	0.0002	0.0015	0.0003	0.0003
c_y	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
c_z	1	1	-0.5	-0.5	-1	-1
	Urban Conditions					
a_y	0.32	0.32	0.22	0.16	0.11	0.11
a_z	0.24	0.24	0.20	0.14	0.08	0.08
b_y	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
b_z	0.001	0.001	0	0.0003	0.0015	0.0015
c_y	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
c_z	0.5	0.5	1	-0.5	-0.5	-0.5

Note: An incorrect b_z value of 0.00015 has been presented in many references in the literature for the stability classes E and F urban dispersion parameter equations, based on conversion of half-widths and half-depths of a rectangular plume with uniform concentration in the original Briggs, 1973 reference to lateral and vertical standard deviations of the Gaussian plume. Table 6-9 shows the correct value, 0.0015, as reported in Griffiths, 1994.

The Tadmor-Gur and Briggs Open-Country formulations give results that are nearly the same for some distance ranges and stability classes. However, they may differ by a factor of two or more for other distance ranges and stability classes. The fitting constants given in the above tables, and in other Gaussian models, are based on fitting curves to observational data of plumes released over flat grassland.

Pacific Northwest National Laboratory (PNNL) evaluated the various sets of dispersion parameters available with MACCS2 and GENII2 for rural terrain (Napier et al., 2011). Even though the evaluation was performed for Savannah River Site (SRS) morphology, the general conclusions summarized below are expected to be applicable to other DOE sites.

1. The Tadmor and Gur formulation is not recommended for distances less than 500 m. If deposition is included, the results may be invalid, even for receptors beyond 500 m.
2. Except for the Tadmor and Gur set of χ/Q results for less than 500 m, the other parameterizations yield χ/Q results that are essentially indistinguishable in the distances of interest (500 m to about 11 km) at the SRS site.
3. The χ/Q results from the Briggs Open-Country parameterization begin to diverge from the χ/Q results using the various P-G parameterizations at distances of about 10 km.
4. Beyond 10 km, the Briggs Open-Country χ/Q results are conservative and even more so for E and F stability classes (see Figure A-3 of Napier et al., 2011). The Briggs parameterization is universally available with the radiological dispersion toolbox codes and the only available option with the HotSpot code, and,
5. The χ/Q results from P-G parameterizations agree with one another out to the plotted distance of 30 km (see Figure A-3 of Napier et al., 2011).

It is not surprising that the χ/Q results from the P-G parameterizations agree with one another (except for Tadmor and Gur results for less than 500 m) for the entire range of distances given their common origin of the P-G curves and the Project Prairie Grass tracer data. Moreover, the divergence of the Briggs χ/Q results at distances beyond about 10 km should not invalidate its use at these large distances. The divergence seems to simply reflect the empirical foundation of a larger data set that includes data out to 10 km, compared to 1 km for the P-G data set.

Because the Briggs open-country dispersion parameters are partially based on elevated release data acquired at BNL, consideration may be given to using these for atmospheric dispersion modeling of stack releases. The SRS AXAIR code (AXAIR, 1986) uses the Briggs expressions for σ_z, since these expressions were considered more appropriate for stack releases that were common at SRS at the time of its development (Simpkins, 1994; Napier et al., 2011). Another example is the RISKIND code (Yuan, 1993), designed for potential radiological consequences from transport of spent nuclear fuel. It uses the Eimutis and Konicek dispersion parameters if the effective release height is less than or equal to 30 m and the Briggs dispersion parameters for higher elevated releases.

To more accurately predict atmospheric dispersion for specific conditions that differ from those represented by the P-G and Briggs open country parameterizations, adjustment factors have been developed to capture enhanced plume spread acting independently in a single direction, such as horizontally for plume meander and vertically for mechanical turbulence caused by surface roughness. These adjustment factors are discussed in Sections 6.8.1 and 6.8.2. Additionally, wakes caused by aerodynamic effects of the building introduce enhanced dispersion in the horizontal and vertical directions. Building wake dispersion and related modeling approaches are discussed in more detail in Section 6.8.3.

If the nature of radiological and toxic chemical releases makes them neutrally buoyant, as in the release of trace amounts of very fine particulates or of gases that have a molecular weight similar to that of air (28.97 g/mole), plume dispersion approximates a Gaussian distribution in both the crosswind (lateral) and vertical directions.

For continuous releases, the magnitude of the downwind diffusion (σ_x) is negligible in comparison with the speed of the wind. However, if the release is of short duration (a puff) the mean wind speed only acts as a transport agent and the turbulent diffusion in the downwind direction becomes meaningful.

Accordingly, a puff release is described by Gaussian equations in all three dimensions whereas a continuous release is described by Gaussian equations in two dimensions (width and thickness) and a length determined by wind speed and release duration. For a puff release, it is assumed that $\sigma_x=\sigma_y$.

For stability class G, NRC Regulatory Guide 1.145, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants,* recommends using a σ_y value that is 2/3 that of stability class F and a σ_z value that is 3/5 that of stability class F. With plume meander and building wake effects this NRC guidance recommends correction factors to σ_y for classes D – G, especially for low wind speeds. For example, for Class G the correction factor varies from a factor of six for wind speeds less than 2 m/s, down to a factor of one (no correction) for wind speeds of 6 m/s and above.

6.5 CHARACTERIZATION OF METEOROLOGICAL AND SITE DATA

The application domain that atmospheric dispersion codes approximate establishes the types of meteorological data needed to drive such codes. The choice of code that the analyst uses to solve a particular application may be limited by the availability and fidelity of meteorological data. This subsection gives a brief discussion of various meteorological data sets often used as input to atmospheric dispersion codes.

DOE-STD-3009-2014, Section 3.2.4.2 provides three options for selecting atmospheric dispersion methodology and the resulting χ/Q and gives the following guidance for development of meteorological data:

> In the case of Option 1, follow the meteorological data guidance within NRC Regulatory Guide 1.23 Revision 1, Meteorological Monitoring Programs for Nuclear Power Plants. For Options 2 and 3, the guidance in both Regulatory Guide 1.23 and in EPA-454/R-99-005, Meteorological Monitoring Guidance for Regulatory Modeling Applications, are acceptable means of generating the meteorological data upon which atmospheric dispersion is to be based. These two guidance documents should be evaluated for their applicability to the site or facility being evaluated. In the development of the meteorological database for Option 3, the impact of local surface roughness on the data may have to be considered.

DOE-STD-3009-2014, Section 3.2.4.2 also provides the following guidance for determination of the Offsite χ/Q, as follows:

> Regarding Option 2, DOE-approved, code-specific guidance for each toolbox code should be consulted. This is especially true with respect to developing χ/Q values using atmospheric dispersion models. Many of these toolbox codes allow for setting a specific parameter within the calculations. These parameter choices may either use the conservative parameters and options established in this section (Option 2) or reflect site-specific conditions to more accurately represent the accident scenario (Option 3). The parameter choices presented for use in Option 2 are given to provide a simple method for determining an appropriate χ/Q value, and the level of overall conservatism established is not reflective of what is required via the other acceptable options.

For codes that do not contain fixed values or calculate the parameters internally, DOE-STD-3009-2014 requires the following parameters be used for ensuring conservative calculation of offsite doses in accordance with Option 2:

- Non-buoyant, ground level, point source release;
- Plume centerline concentrations for calculation of dose consequences;
- Rural dispersion coefficients;
- A deposition velocity of 0.1 cm/sec for unfiltered release of particles (1-10 μm AED), 0.01 cm/sec for filtered particles, or 0 cm/sec for tritium and noble gases;
- A surface roughness of 3 cm;
- A minimum wind speed of 1 m/s;
- Plume meander may be used, consistent with the accident release duration and the appropriate code guidance; and
- Building wake factors should not be credited in the plume dispersion, outside of those already incorporated into plume meander.

The purpose of the required parameters for Option 2 is to produce conservative χ/Q values. Codes that use values more conservative than the required parameter values are acceptable. For example, if a dispersion code uses a minimum wind speed of 0.5 m/s rather than 1.0 m/s, this would result in a χ/Q value that is more conservative than if 1.0 m/s were used. Also, "Codes that do not contain fixed values or calculate the parameters internally" should be interpreted to mean codes that allow for the input of parameters that are less conservative to be set to values provided. Some dispersion codes allow for the adjustment of parameters, such as deposition velocity or surface roughness, to values less than the required parameter values.

The wind speed in meteorological data files is generally assumed to correspond to a reference height of 10 m and represents conditions at a height of 10 m and below. The various toolbox models treat the wind speed variability differently, as follows:

- Meteorological data read into the MACCS2 radiological dispersion software are assumed to correspond to a reference height of 10 m. MACCS2 does not adjust the wind speed used in the Gaussian plume equation for the height of release.[55] Thus, wind speed data in the meteorological data files are input directly into Gaussian plume model equation. The use of the 10-m wind speed is conservative in the calculation of the χ/Q value for an elevated release;

- Meteorological data read into the GENII radiological dispersion software are assumed to correspond to a reference height of 10 m. Wind speed data in the meteorological data files are input directly into the Gaussian plume model equation for release heights of less than 12 m. For releases of higher elevation, the wind profile power law is used to upwardly adjust the wind speed;

- The user specifies the reference height for the meteorological data with HotSpot. With HotSpot designed to read meteorological data files that are formatted for MACCS2, the reference height is 10 m. HotSpot adjusts the wind speed for any release height that differs from the reference height. For release heights of 2 m or less, the wind speed is calculated from the wind profile power law using a 2-m height. The user can disable the wind speed adjustment by specifying a reference height of 2 m for the meteorological data (Homann, 2010). This allows HotSpot to model a ground-level release using the wind speed data directly from the meteorological data files in a way consistent with MACCS2 and GENII (Homann, 2010).

[55] The algorithm in MACCS2 for determining the plume rise of a buoyant release does make use of wind speed correction with height, but this is the only place where MACCS2 accounts for wind speed variability with height.

6.5.1 PERSISTENCE

The simplest models assume that constant weather conditions prevail during the accident duration, whether unfavorable conditions or typical conditions. DOE-STD-3009-2014, Section 3.2.4.2 states that if representative meteorological data are not available, stability Class F and 1.0 m/s wind speed may be used for unfavorable radiological dispersion consistent with NRC's and DOE's long-standing practice as this approximates the 95th percentile atmospheric dispersion condition. For perspective, Class D stability and 4.5 m/s wind speed are used for "typical" conditions.

The choice of wind speed depends on the guidance document being followed. For sites in valleys where a high frequency of low wind speeds occur (such as Y-12), Class F stability and wind speeds less than 1.0 m/s may possibly apply. For many simple models, a meteorological data couplet of wind speed and stability class and the distance to the receptor are the only inputs that are needed, as the release rate and atmospheric conditions are time-invariant in Gaussian models. [56]

6.5.2 JOINT FREQUENCY DISTRIBUTION (JFD)

The JFD required by many atmospheric dispersion codes is the joint distribution of wind speed according to wind direction and stability class. The JFD is organized into a matrix that gives the percent of the time of each condition for specified numbers of wind speed groups and stability class for each of the 16 wind direction sectors (N, NNE, NE, … NNW).

This distribution is based on an extended period of meteorological observations, five or more years if available, in order to establish temporal representativeness since there are climate variations. DOE-STD-3009-2014, Section 3.2.4.2 requires that "For the calculation of offsite doses, five years of representative, recent meteorological data shall be used as input to the dispersion model", and within the past 10 years is considered to be "recent" as used in this context. The larger number of years smooths out the decadal climatic variations. Temporal representativeness simply means that the data base is sufficiently large to have captured a reasonable number of climatic anomalies such that an additional year of data will not substantively affect radiological and toxic chemical consequence calculations.

The wind speed data are sorted into bins, such as 0 - 1 m/s, 1 - 2 m/s, 2 - 4 m/s, as shown in Table 1 of ANSI/ANS-3.11-2015, *Determining Meteorological Information for Nuclear Facilities*. Since calm wind speeds cannot be used in a Gaussian plume model, the calms are redistributed into the lowest wind speed class based on the frequency of wind directions in the lowest two wind speed classes. The choice of bins may be dictated by the code but for some codes (such as GENII) the user chooses the number of wind speed bins and the ranges of these bins. These would depend upon the wind conditions at the DOE site. The number of frequency bins in this matrix can reach several hundred. For example, if six stability classes (A–F) and six wind speed bins are chosen, the total number of frequencies would be $6 \times 6 \times 16 = 576$. However, not all bins will be populated as stronger winds cannot simultaneously occur with Class A and Class F stability class conditions.

A utility computer program is usually needed to generate a JFD, especially if several years of hourly observations are being used. When a JFD matrix is being generated, the definition of wind direction used in the code should be kept in mind. In meteorology, wind direction has traditionally been defined as the direction from which the wind blows, which is of interest to weather forecasters. However, most

[56] An exception is that for the MACCS2 code, although a Gaussian model, the release is broken into one-hour segments. Each segment is calculated using the stability class and wind velocity at the time the segment is released.

computer models for atmospheric dispersion and consequence applications, such as those in the DOE Central Registry, use wind direction to mean the direction toward which the wind blows. The downwind (transport) direction is always 180 degrees out of phase with the direction that a meteorologist uses. Thus, the analyst should be aware the wind direction-sector orientation of the particular code being applied.

6.5.3 FULL DATA SET SAMPLING

An alternative to a JFD matrix that is used by MACCS2 and HotSpot is to use the data from all 8760 hours in a year, rather than discrete JFD matrix entries, to achieve the maximum temporal representativeness and therefore highest accuracy in calculating the overall site 95th percentile consequences or the sector-dependent 99.5th percentile consequences.

6.5.4 TREATMENT OF CALM AND VARIABLE WINDS

Industry practice for treatment of calm winds is that wind speeds that are below the threshold wind speed of the mechanical or sonic anemometer are generally set equal to the rated threshold wind speed or wind direction of a mechanical or sonic anemometer, whichever is lower. The threshold wind speed of a mechanical anemometer and wind direction mechanical vane is generally 1.0 mph (0.5 m/s). Sonic anemometers have somewhat lower threshold wind speed and wind direction capabilities and thus can measure even lower wind speeds; inferring wind speed from differences in the speed of sound and generally have a threshold wind speed of 0.6 mph (0.3 m/s).

However, the capability to monitor wind speed to extremely low levels is not the only consideration relative to the treatment of calm wind speeds in plume modeling, as the application domain limitations of the steady-state Gaussian plume model needs to also be taken into account.

- ANSI/ANS-3.11-2015, *Determining Meteorological Information at Nuclear Facilities*, defines a calm as, “any wind speed below the starting threshold of the wind speed or direction sensor; or any wind speed below that which is appropriate for input into plume models, whichever is greater. In the US, a calm wind is defined as any speed less than 1 mph” (0.5 m/s).
- EPA-454/R-99-005, *Meteorological Monitoring Guidance for Regulatory Modeling Applications*, Section 6.2.3 defines calm as “when the wind speed is below the starting threshold of the anemometer or vane, whichever is greater,” but also states that, “…for site-specific monitoring … a calm occurs when the wind speed is below 0.5 m/s”. EPA then recommends “to avoid unrealistically high concentration estimates at low wind speeds (below the values used in validations of these models - about 1 m/s) EPA recommends that wind speeds less than 1 m/s be reset to 1 m/s for use in steady-state dispersion models.”

The *Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for DOE Facilities* (DOE/ONS, 2015), cautions on the limitations of steady-state Gaussian dispersion modeling, as this type of model has the tendency to overpredict concentrations at the lower end of a range of conservative wind speeds; especially calm wind speeds. This is illustrated in Figure 6-5, which shows the ratios of normalized concentrations (χ/Q) predicted in wakes to observed concentration normalized to actual release rate as a function of wind speed. If the errors in the predicted values were associated with the wake, they would increase with wind speed. The authors observed that the overprediction (ratio >1.0 of the ordinate) is largest and more numerous at very low speeds and decreases with increasing wind speed, which indicates that the problem is underestimation of atmospheric dispersion in low wind speeds by a Gaussian model. The authors concluded that their original premise that the enhanced dispersion was due to building wakes was incorrect. Instead, the apparent enhanced dispersion noted in the vicinity of buildings at low wind speeds in wake dispersion experiments is caused by underestimation of dispersion by the basic dispersion algorithms rather than by increased turbulence in the vicinity of buildings.

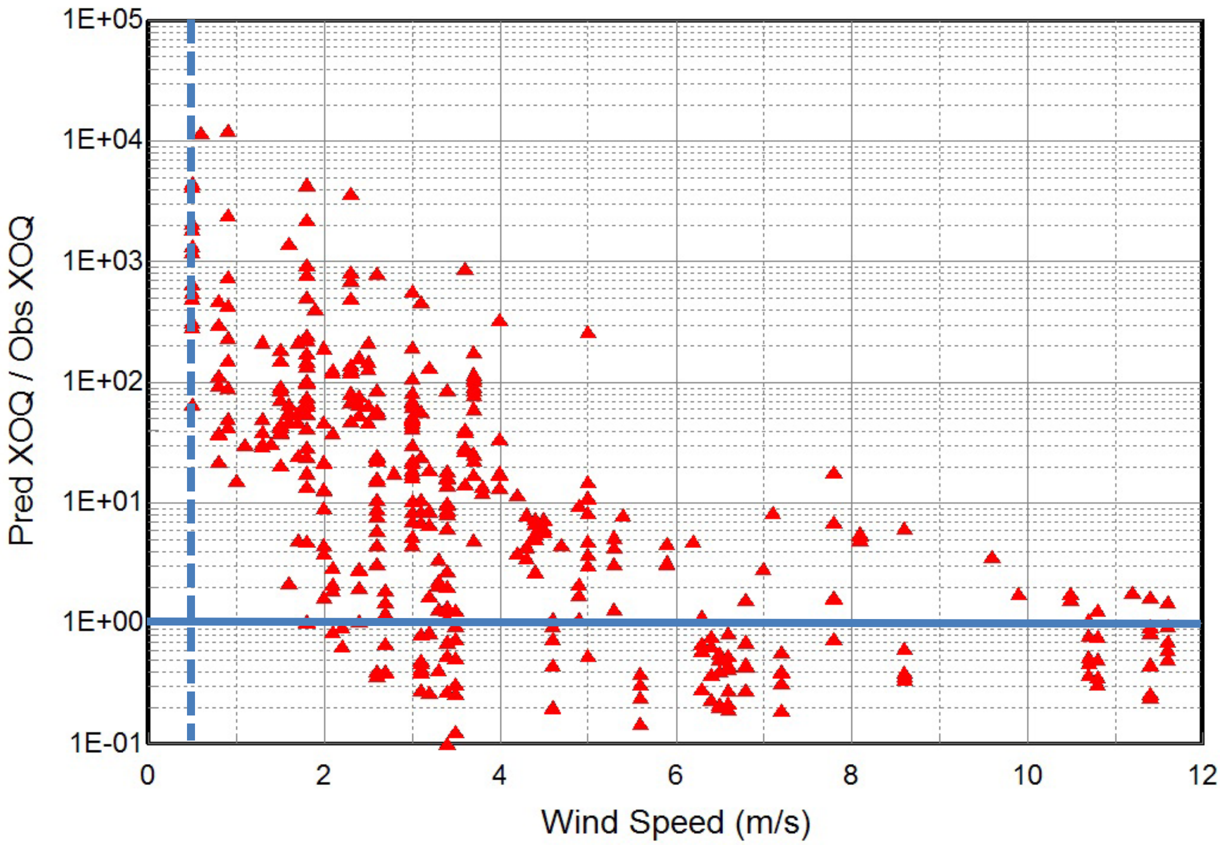

Figure 6-5. Ratios of predicted concentrations in wakes by a model without wake correction to observed concentrations as a function of wind speed (based on McGuire et al., 2007). (Ratios above solid line (Predicted/Observed = 1E+00) are over-predicting the concentration.)

Accordingly, Option 2 of DOE-STD-3009-2014, Section 3.2.4.2, specifies a minimum wind speed of 1.0 m/s (2.2 mph) relative to atmospheric dispersion modeling. This is consistent with generating the site meteorological data using the above EPA recommendation. Setting the calm wind speed to the anemometer threshold is consistent with the NRC Regulatory Guide 1.145 which relies on the NRC Regulatory Guide 1.23 Revision 1. Either method for generating the site meteorological data (EPA-454/R-99-005 or NRC Regulatory Guide 1.23 Revision 1) is acceptable as earlier described.

If a site's conditions have a high incidence of low wind speeds, the site may want to consider other atmospheric dispersion modeling approaches that addresses this condition, or the site should justify that applying Option 2 of DOE-STD-3009-2014 will produce a conservative result when applying the minimum 1.0 m/s (0.5 m/s) wind speed.

Unrealistically high estimates of χ/Q can be calculated under calm wind conditions, a result of the placement of wind speed in the denominator of the Gaussian plume model equation. EPA recommends that wind speeds less than 1.0 m/s be reset to 1.0 m/s for use in steady-state dispersion, and cautions against overly conservative model predictions with wind speeds less than 1.0 m/s (EPA-454/R-99-005).

DOE-STD-3009-2014 requires the use of 1.0 m/s as the minimum wind speed when using one of the Central Registry toolbox codes. MACCS2 substitutes a value of 0.5 m/s for the wind speed whenever it reads a wind speed value of less than 0.5 m/s from a meteorological data file, but this is allowed by DOE-STD-3009-2014 as the 0.5 m/s is a fixed part of the code, and it produces more conservative results than if 1.0 m/s is used. GENII allows the user to set threshold value through the input for the maximum wind speed for calms. Hotspot considers wind speeds down to 0.1 m/s and also considers a G Stability class. However, the analyst should set calm wind speeds to 0.5 m/sec unless there is sufficient justification to reducing it to a lower value.

6.6 METEOROLOGICAL DATA ADEQUACY FOR SAFETY ANALYSIS

The results from atmospheric dispersion codes can be no better than the input data and the conditions under which it is applied. Meteorological data used for consequence assessment needs to meet applicable DOE O 414.1D, Chg.1 quality assurance requirements. The meteorological program manager at the DOE site is responsible for developing quality-assured data. Meteorological data quality assurance programs are based on guidance in DOE-STD-1216-2015 and ANSI/ANS-3.11-2015. Section 5.12 of DOE-STD-1216-2015 states that guidance in quality assurance related to meteorological measurements and meteorological data processing may also be found in ANSI/ANS-3.2-1994 (R1999), *Administrative Controls and Quality Assurance for the Operational Phase of Nuclear Power Plants*. Moreover, Section 7.5 of ANSI/ANS-3.11-2015 also references ANSI/ANS-3.2-1994 (R1999), which presents the general quality assurance criteria for nuclear facilities with respect to meteorological data.

The accuracy of the codes is also limited by the approximations inherent in the models, with results being more reliable nearby the release point than farther away, within the application's domain. Inaccuracies in the meteorological data tend to amplify uncertainty with increasing transport distance. No matter how effective the meteorological monitoring system is, it is common that yearly data sets may have at least some hours of missing data. Some codes (e.g., MACCS2) require an uninterrupted data set. In order to address this issue, data substitution techniques in ANSI/ANS-3.11-2015 should be employed to complete the data set. For other codes that use JFD data as input, uninterrupted data is not required.

Generally, data need to be input with the full accuracy of the measurements and rounding should be only performed on the final results. Even the most comprehensive atmospheric dispersion codes in use today will likely be uncertain by a factor of two or more, even relatively close to the release point for flat terrain topography; DOE-STD-5506-2007 estimates a factor of four uncertainty. Therefore, one-digit accuracy, or at most two digits, is all that should be reported in the analyst's results, except perhaps for purposes of comparisons of similar results. Since there are so many uncertainties in the input data streams and within the models, the following phrase gives some perspective: "The mantissa is meaningless, while the exponent is everything."

The minimal set of meteorological data needed to run an atmospheric dispersion code that requires observational data would be at least one year of wind speed, wind direction, and an indicator of stability class. However, one year of data may not prove to be very temporally representative, as notable climatic anomalies frequently occur on as little as an annual basis (El Niño, La Niña), and decadal climatic anomalies have been noted.

NRC Regulatory Guide 1.194, *Atmospheric Relative Concentrations for Control Room Radiological Habitability Assessments at Nuclear Power Plants*, indicates that the size of the data set used in assessments should be sufficiently large such that it is representative of long-term meteorological trends at the site in question. In this Regulatory Guide, the NRC staff considered 5 years of hourly observations to be representative of long-term trends at most sites. However, the Guide also states "With sufficient justification of its representativeness; however, the minimum meteorological data set is one complete year, including all four seasons, of hourly observations."

A basic rule of thumb is to use at least five years of meteorological data to ensure that temporal representativeness would not be compromised. If a larger data base is available, it should be used, even if the resulting atmospheric dispersion estimates change from prior analyses. Moreover, DOE-STD-3009-2014 Section 3.2.4.2 requires that recent five years of data be used and requires either the directionally independent 95th or directionally dependent 99.5th percentile value. If five years of data are not available, justification for using a shorter period needs to be provided. A reanalysis should be performed every ten years, as the average of meteorological parameters change relatively slowly over time even under climate change conditions.

If onsite meteorological data is unavailable, meteorological data from a nearby weather station can be substituted provided the terrain at that site is similar and the data is spatially representative. Guidance on data substitution is provided in ANSI/ANS-3.11-2015.

6.7 TYPICAL AND UNFAVORABLE DISPERSION CONDITIONS

In calculating plume concentrations, or consequences to the receptor, both "typical" and "unfavorable" dispersion conditions are of special interest in accident analyses for ground-based releases. "Typical" would not be used to establish safety SSCs in a DSA but it is useful for Safety Goal comparison, if over the DOE EG as discussed in Chapter 10, *Hazard Control Selection and Classification*.

> Typical Dispersion Conditions: The median (50th percentile), the mean (average), or the mode (peak) of a distribution could all be considered as representative of "typical." However, the median is the most meaningful for plume dispersion, for several reasons. It is not heavily influenced by outliers (abnormally small or large values), as is the mean. For a bimodal distribution, which is common to dispersion, the mean may fall between the peaks (modes) of the distribution and thus be comparatively infrequent, which could not be considered "typical." The median could also be atypical in this sense but it, at least, has a relevant meaning. In addition, if mode were chosen as "typical", a bimodal distribution could give two valid choices if the peaks are nearly as large.

> Unfavorable Dispersion Conditions: This is normally taken to be the overall site 95th percentile dispersion of the full meteorological data set for at least one year, for which the consequences are smaller 95% of the time and larger 5% of the time. Other dispersion conditions are sometimes used for "unfavorable", such as "worst case", "near-worst case", or specific constant-weather conditions, such as Class F stability and 1.0 m/s wind speed. Near-worst-case conditions, which are most likely G stability class and nearly calm winds are extremely rare and would be overly conservative for most applications. True "worst case" is a single value, that is, the maximum value, obtained only once in the period of interest.

For elevated releases, the above rules of thumb would not apply as they would depend on the release height. Also, the amount of atmospheric dispersion corresponding to 50th or 95th percentile weather depends upon the nature of the release. If the release is a trace constituent, it can be treated with a Gaussian plume or puff model, depending upon the duration of the release. If it is a dense or heavy gas (discussed in Section 9.5.4), it is treated with a heavy-gas model that both limits vertical dispersion due to slumping, while simultaneously entraining ambient air through the sides of the plume. The amount of dispersion for the 50th or 95th percentile conditions would likely be different for a heavy gas model.

For whatever model is used, some rules-of-thumb can be established for non-lofted plumes, and these may be useful for "sanity checks" of results. Such rules-of-thumb at most sites would likely be similar to the following:

95th percentile χ/Q value is about ten times larger than the median χ/Q value for any distance;

50th percentile (median) χ/Q values for ground-level releases are similar to those of Class D and 4.5 m/s wind speed;

95th percentile χ/Q values for ground-level releases are similar to those of stability Class F and 1.0 to 1.5 m/s wind speed; and,

95th percentile χ/Q values at ground level for elevated releases are similar to those of stability Class A and
4.5 m/s wind speed.[57]

For lofted plumes, no such rules-of-thumb are possible as ratios of 95th percentile χ/Q to median, or some constant meteorological condition, χ/Q values vary with distance and the amount of lofting.

High-wind speed scenarios [such as sustained wind speeds of 45 m/s (100 mph)] are also of interest to the analyst. This is about 10 times greater than the wind speed that corresponds to the median χ/Q. High winds are always associated with Stability Class D, which is also the stability class associated with the median weather conditions and represents a well-mixed atmosphere. Because the value of χ/Q varies inversely as the wind speed (see Eq. 6-3), the high-wind speed χ/Q will therefore be about 10% of the median χ/Q. As a rule-of-thumb, for scoping calculations, the analyst can divide the consequences (such as dose) from exposure to radiological or other hazardous materials for median weather conditions by 10 to find the corresponding consequences for high-wind speed scenarios.

Tornados have even greater wind speeds, sometimes exceeding 200 mph (89 m/s) for Enhanced Fujita Scale 5 tornadoes, and can cause a facility to collapse. Moreover, the rapid atmospheric pressure drop can cause other types of releases. This NPH could soon be followed by a lower wind speed that would result in larger dispersion parameters than during the tornado itself. If the tornado causes damage that releases the MAR almost instantaneously, that should be modeled as high-wind dispersion, but slower developing source terms may occur during the subsequent low-wind conditions which should be modeled separately, and the dose consequences summed for the two contributions. Section 6.12.1, *Dispersion Under a High-Wind or Tornado Event*, has a further discussion of high wind or tornado dispersion. In addition, scenarios for environmental restoration projects involving contaminated soil where the source term is based on EPA methods incorporating an assumed wind speed should be modeled with the same wind speed in the dispersion analysis (a sensitivity analysis of wind speed vs. dose consequence may be necessary to determine a conservative analysis to determine the need for safety controls).

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[57] For elevated releases, the worst case stability class is Class A, since σ_z is greatest for that stability class. In addition, fumigation conditions represent a special worst case for elevated releases where the elevated, poorly-dispersed plume is quickly brought down to ground level.

6.8 SPECIAL GAUSSIAN MODELING CONSIDERATIONS[58]

6.8.1 AVERAGING-TIME AND LARGE EDDY PLUME MEANDER

The diffusion magnitude expressions in the previous sections are relevant for short-duration plumes released over relatively smooth terrain. However, plumes tend to meander for two specific reasons: (1) when release duration is longer than some tens of minutes; and (2) under stable light wind conditions when embedded larger eddies can dominate a relatively calm atmosphere. Large eddies, which are present in a stable, stratified atmosphere, tend to become more dominant in this situation, and can augment the magnitude of lateral movement. Therefore, for a receptor that remains in the plume for some time, meandering effectively widens the plume and thus decreases χ/Q. This is accounted for in the Gaussian equation by multiplying the plume width (σ_y) by a plume meander factor.

Two treatments of meander are available as an option in one or more of the toolbox codes, and both involve adjustments to increase the magnitude of σ_y. One approach to plume meander is based on the influence of averaging time and is available as an option in the two radiological consequence toolbox codes, MACCS2 and HotSpot, and one toxic chemical consequence code, EPIcode. Figure 6-6 qualitatively shows how the plume boundaries of the time-averaged plume may differ from those associated from a typical snapshot of the instantaneous plume. The second approach is related to the embedded large-eddy effects that occur under very stable atmospheric conditions.

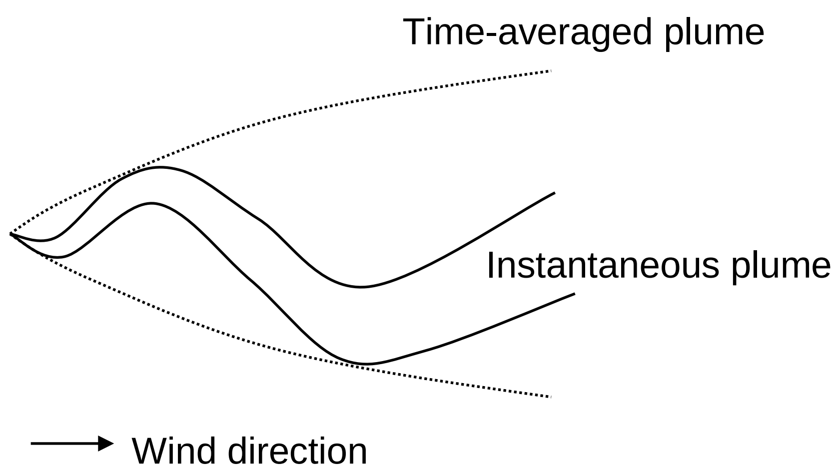

Figure 6-6. Time-Averaging Effect on Plume Boundaries.

The averaging time, also referred to as sampling time, over which the σ_y values were determined from experimental data, establishes the time base, usually on the order of minutes, for the horizontal and vertical diffusion parameters. A longer averaging time than the time base may be applied in the analysis of receptor exposure times for plumes with longer release durations, an option of the HotSpot code. The exposure time is assumed to equal the release duration in these analyses. A longer averaging time leads to greater widening of the plume boundaries. Embedded large eddies also causes movement of the plume centerline with time (the plume swings back and forth), another type of plume meander. The receptor on the time-averaged centerline location is only exposed intermittently to the concentration of the

58 Dense gas models are applicable to chemical releases and these types of models are described in Section 9.7.

instantaneous plume centerline due to this movement. As a result, the time-averaged centerline concentration is lower. These effects become even more pronounced with increasing averaging time.

The formulation for the plume meander factor[59] that is applied to σ_y based on the averaging-time concept is given by:

$$\textit{Averaging-time plume meander factor} = (\textit{release duration / time base})^n \quad \textbf{Equation 6-11}$$

The time base and exponent, *n*, are hard wired in EPIcode and HotSpot to values of 10 minutes and 0.2, respectively. MACCS2 and ALOHA allows the user to specify the time base and to input two different values of *n* to correspond to two different time ranges, the exponent is 0.2 for plume duration of one hour or less and 0.25 for a longer duration (DOE, 2004c, *ALOHA Computer Code Application Guidance for Documented Safety Analysis: Final Report*). The averaging-time plume meander factor is never allowed to be less than unity, and the experimental basis is limited to periods of no longer than 100 hours. The release duration can vary from a few minutes for a spill to several hours of a fire. For explosions, deflagrations, or other short-period releases, plume meander should not be applied.

The other type of plume meander is related to embedded large-eddy effects that occur especially under very stable conditions with very light wind speeds and that were observed from tracer studies first performed in the mid-1970s. After careful review of the results of the tracer studies, the NRC developed this plume meander factor and incorporated it in NRC Regulatory Guide 1.145 for atmospheric stability classes D, E, F, and G. The NRC also acknowledged it in several of their atmospheric dispersion models. This Regulatory Guide also recommends not using any meander factor for stability classes A, B, or C at any wind speeds. The NRC method is only applicable to the Pasquill-Gifford horizontal and vertical dispersion curves.

Plume meander is also implemented in several atmospheric dispersion models such as ARCON96, RASCAL, and Version 2.6 of MACCS2 (Napier et al., 2011). ARCON96 (NUREG-6631 Revision 1) and RASCAL increase both the horizontal and vertical diffusion magnitudes; especially under stable light-wind conditions. These two meander factor approaches should not be utilized at the same time.

The large-eddy plume meander factor is applied to augment σ_y and σ_z, but only for distances up to 800 m, where its effects are damped out. Beyond 800 m, σ_y values reflect the augmented spreading up to 800 m plus non-augmented spreading beyond 800 m. The large-eddy plume meander factor ranges between 1 (no meander) and 6. Figure 6-7, taken from NRC Regulatory Guide 1.145 Revision 1, graphically displays the magnitude of the meander factor as a function of downwind distance for stability classes D, E, F and G.

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[59] The plume meander factor is sometimes referred to as the plume expansion factor.

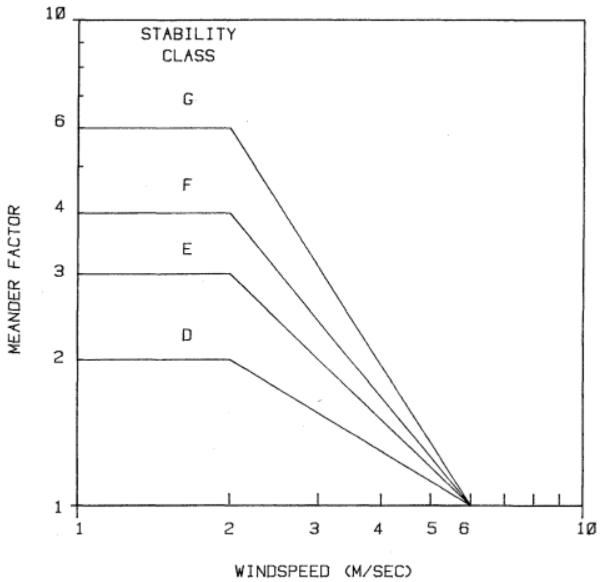

Figure 6-7. Correction factors for σ_y values by stability class (Figure 3, NRC Regulatory Guide 1.145)

The large-eddy plume meander factor actually increases for more stable conditions (from E to G stability class) and increases as wind speeds approach calm under the same stability class.[60] This dependency is exactly opposite to the aerodynamic building wake phenomenon that is very small under these light-wind very stable meteorological conditions, but increases significantly as the wind speeds increase and the stability class becomes neutral or slightly unstable. The faster the winds are that encounter the building, the stronger the flow separation becomes which yields a larger aerodynamic effect on the wind field.

6.8.2 MECHANICAL TURBULENCE DUE TO SURFACE ROUGHNESS

Mechanical turbulence is generated as wind flows over and around irregular obstacles (morphology) on the earth's surface. Such obstacles are both natural (topographic and vegetation) and anthropogenic (buildings and other structures). In general, the rougher the terrain underneath the atmosphere moving above it, the more mechanical turbulence is generated and consequently the better the diffusion. The rougher the surface, the larger the turbulent eddies formed, mainly in the vertical, and thus the greater vertical dispersion, as expressed by an enhancement of σ_z. The increase in σ_z is called the roughness factor and it cannot be less than unity. Because σ_z is increased, the plume-centerline χ/Q is proportionally reduced by the magnitude of the roughness factor.

Mechanical turbulence continually persists once it is generated. The atmospheric mechanical turbulence at a given location reflects the upwind development of the PBL and the contributing influence of upwind surface elements that can be several hundred meters or more away. The surface roughness length (z_0), discussed earlier, is a measure of the amount of mechanical mixing introduced by the surface roughness elements over a region. As an approximation, the roughness length is approximately one-tenth of the actual physical height of the surface roughness elements (Hanna and Britter, 2002). In determining z_0 for

[60] Meander factor values of one (no widening) are associated with wind speeds of 6 m/s or larger and atmospheric stability classes A, B, and C.

application to plume transport modeling, surface characterization should thus include both upwind, also known as “fetch,” and downwind regions with respect to the postulated release location.[61]

McElroy and Pooler first developed “urban” dispersion parameters in *St. Louis Dispersion Study* (1968).[62] As a rough rule of thumb, vertical dispersion is increased by one stability class for urban areas due to the additional mechanical turbulence generated by the buildings (for example, an atmospheric condition resulting in Class F stability in rural environments becomes Class E stability in urban environments). The concrete buildings also reradiate their heat at night resulting in local temperature increases, termed the urban heat island, and cause additional buoyancy turbulence.

The field conditions of the Project Prairie Grass upon which the P-G dispersion parameters were developed are characterized by a surface roughness length of 3 cm (Napier et al., 2011). To more accurately predict dispersion for specific conditions that differ from those represented by the P-G and Briggs open-country horizontal and vertical diffusion parameterizations, adjustment factors have been developed for σ_z to reflect the enhanced mechanical turbulence caused by surface roughness.[63] One commonly used formulation that has been recommended by the American Meteorological Society (AMS) is given below (Hanna et al., 1977).

$$\textit{Surface Roughness Factor} = (z_0/z_{ref})^{n} \, (z_0 \geq z_{ref}) \qquad \textbf{Equation 6-12}$$

where z_{ref} is the reference roughness length associated with the field experiments on which the σ_z curves are based. For a P-G σ_z, the reference surface roughness length is 3 cm[64]. This formulation under-predicts σ_z enhancements observed near rugged terrain (Hanna et al., 1977).

The exponent, *n*, of Eq. 6-12 varies between 0.1 and 0.25, with larger values associated with shorter distances and rougher surfaces (Hanna et al., 1977; Irwin, 1980). Comparing diffusion data for surface roughness lengths of 3 cm and 100 cm for distances up to a few kilometers, in *Atmospheric Dispersion Parameters in Gaussian Plume Modeling. Part II. Possible Requirements for Change in the Turner Workbook Values* (EPA-600/4-76-030b), Pasquill noted a roughness factor of approximately 2, which translates to an exponent value of 0.2. In providing guidance to SRS on dispersion analysis, the PNNL-led review team provided the recommendation that is reflected in Table 6-10 (Napier et al., 2011).

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[61] For example, both the release location and receptor (such as the CW at 100 m) may be in the same open area that may be characterized by a small value for z_o. If this area is relatively small (a few hundred meters in diameter) and is surrounded by a building complex or forest, it may be appropriate to factor in the surface elements in the surrounding region in the determination of z_o. This approach is being used at SRS.

[62] For a detailed description of this study, see Venkatram et al., “The Analysis of Data from an Urban Dispersion Experiment,” Atmospheric Environment 38: 3647–3659 (2004).

[63] Note that a surface roughness correction would not be applied with the use of the Briggs urban dispersion parameters because these parameters already reflect the surface roughness effect of large buildings in addition to the urban heat island influence at night. A roughness length of 0.6 cm was reported by Barad (1958), based on the Prairie Grass experiments.

[64] The reference roughness length for the Briggs open country set of dispersion parameters is complicated with the empirical basis that includes data other than that from Project Prairie Grass. Napier (2011) concluded that the P-G value of 3 cm is also applicable to the Briggs open country set of dispersion parameters given that χ/Q results using the Briggs dispersion parameters are essentially indistinguishable to those using P-G dispersion parameters at distances less than 10 km. Based on this reasoning, the 3-cm value for z_{ref} for applications for distances greater than 10 km would reflect a conservative perspective given that the χ/Q results based on the Briggs dispersion parameters are lower than those from the P-G dispersion parameters.

Specifically, a value of 0.2 is recommended for the exponent for distances up to 5 km, and a value of 0.1 for longer distances.

Table 6-10. Surface Roughness Adjustments Recommended PNNL-led Review Team.

Downwind Distance x (km)	**$0.1 < x \leq 5.0$**	**$x > 5.0$**
Roughness Factor Exponent	0.2	0.1
Roughness Factor (for z_o = 3 cm)	1.00	1.00
Roughness Factor (for z_o = 30 cm)	1.58	1.26
Roughness Factor (for z_o = 100 cm)	2.02	1.42

Various methods exist to estimate the surface roughness length. It may be appropriate to assign different values of z_0 for different regions of a site or for different receptor distances (such as the 100 m CW or site boundary distance) for the same postulated release from a given location.[65] It was noted above that the wind speed profile near the earth surface is influenced by roughness effects. This allows z_0 to also be estimated from wind profile observations, if available (Hanna and Britter, 2002).

Table 6-11. General Roughness Lengths for Various Terrain Types.

Terrain Description*	**z_0 (cm)**
Open sea, fetch at least 5 km	0.02
Mud flats, snow; no vegetation, no obstacles	0.5
Open flat terrain; grass, few isolated obstacles	3.0
Low crops; occasional large obstacles, $x/H > 20$	10.0
High crops; scattered obstacles, $15 < x/H < 20$	25.0
Parkland, bushes; numerous obstacles, $x/H \approx 10$	50.0
Regular large obstacle coverage (suburb, forest)	100.0
City center with high-rise and low-rise buildings	≥ 200.0

Note: x/H is ratio of downwind distance to obstacle height

Source: Wieringa, J. "Updating the Davenport Roughness Classification," *Journal of Wind Engineering and Industrial Aerodynamics*," Volume 41, Issue 1-3, October 1992, pp. 357-368.

[65] One commonly-used method for estimating the surface roughness length is based on matching site observations with guidance tables, shown in Table 6-11. The current DOE Central Registry toolbox codes cannot accommodate more than one roughness factor.

The term “fetch” in Table 6-11 represents the roughness associated with the direction from which the wind is blowing (upwind), as the characteristics of the land covered by the wind in its path to the receptor will determine the ground roughness effects embedded in the air parcel.

An alternative approach is to use the EPA AERSURFACE software, which is based on input of 1992 National Land Cover Data (NLCD92) from the USGS (EPA-454/B-08-001). The NLCD92 data (http://landcover.usgs.gov/natllandcover.php) utilized by AERSURFACE consists of land cover data at spatial resolution of 30 meters, mapped using an Albers Conic Equal Area projection, and based on a 21-category morphology classification scheme, similar to what is shown in Table 6-11. AERSURFACE can be used to determine variations by sector, distance, and season, or an overall composite value.

MACCS2 and ALOHA allow the roughness factor to be entered as a user input that is used to scale σ_z. Historically, Eq. 6-12 has been used, due to its presence in MACCS2 software documentation (DOE, 2004a; NUREG/CR-4691 Vol. 2). None of the other DOE Central Registry radiological consequence codes allow for surface roughness adjustments to σ_z. The meteorological data file for GENII2, however, does include an input value for z_0, but it is not used to calculate a roughness factor. The z_0 value is an essential input for the deposition velocity calculation of GENII2.

Savannah River National Laboratory (SRNL) recently performed a study, *Roughness Lengths for the Savannah River Site* (Weber et al., 2012), where surface roughness was computed from H-Area meteorological tower 15-minute-averaged meteorological data measured at 61 m above the loblolly pine tree canopy using mechanical bivanes. Using the standard deviation of elevation angle and applying a simple formula based on tree canopy height, consistent estimates for roughness around the H-Area tower resulted in a mean value of surface roughness of 1.81 m. Application of this method for the 61-m level at D-Area meteorological tower and N-Area meteorological tower gave mean values of 1.71 m and 1.81 m, respectively. Since roughness results are azimuth dependent, as the fetch is different for each wind direction sector, the results were presented as averages over compass sectors spanning 22.5 degrees azimuth. These calculated values were compared to other methodologies that determine roughness. Additional data was obtained from a sonic anemometer at 61-m on the H-Area tower during a period of a few weeks in 2010 that supported the roughness calculations.

Based on the H-Area tower results, SRNL decided in 2012 to apply a surface roughness of 1.8 m in dispersion modeling applications, as discussed in the Executive Summary of the SRS surface length study (Weber, et al., 2012). This technique can be applied at all DOE sites to determine its site-specific surface roughness.

6.8.3 AERODYNAMIC EFFECTS OF BUILDINGS

The calculation of plume concentrations within the cavity and wake regions of even a simple block-like building is a very complex undertaking and generally requires Computational Fluid Dynamics (CFD) models to account for the all of the eddies generated by mechanical turbulence. A discussion of fluid dynamic principles required to solve this problem is beyond the scope of this Handbook.

Ground-level concentrations at some distance beyond the building, such as beyond five building heights, can be approximated. Another method available is to assign a virtual point source upwind of the building such that when this virtual plume reaches the building, the concentrations at the edges of the building are 10 percent of the centerline concentration.

As discussed earlier, building wake effects are most pronounced under windy conditions, whereas the plume meander effects are most pronounced under light wind conditions.

The Pasquill-Gifford and Briggs open-country dispersion parameters represent short-duration plumes released over relatively smooth and open terrain. When the terrain is marked by natural or anthropogenic obstacles, mechanical turbulence is generated as wind flows over and interacts with these obstacles. Surface roughness length was introduced earlier and formulations were summarized to adjust σ_z for the increased vertical dispersion from this source of mechanical turbulence. These formulations attempt to codify the collective influence of the full spectrum of surface elements that are predominantly along the line of plume transport[66]. As such, the surface roughness length concept is more applicable to long-range dispersion. In the vicinity of the radiological and toxic chemical releases, atmospheric dispersion is more likely to be dominated by the interaction of the plume with the wake and cavity regions of single building or a localized cluster of buildings. Releases from vents and small stacks can be entrained behind a building into its cavity due to the aerodynamic effect of the building on the wind field in which the release occurs.

The building wake dispersion models that are presented in this section make use of the standard dispersion parameters, σ_y and σ_z, plus application of additional factors to capture increased dispersion from the wake effects. In implementing these models, the analysts should generally make use of σ_y and σ_z values that are free from any other adjustments such as for plume meander or surface roughness effects.[67] The building wake dispersion models presented in this section are applicable to releases that are modeled as ground-level and non-buoyant and are based on the treatment of the atmosphere as an incompressible fluid, for mathematical simplicity.

Figure 6-8 depicts the cavity and wake zones[68] behind a sharp-edged building (Hosker, 1981).[69] The aerodynamic effect of this building exerts two influences on the release. The first influence is the entrainment of flow in the vicinity of the building into the cavity region behind the building. The second influence is the enhancement of lateral and vertical dispersion associated with the cavity and wake regions.

The calculation of plume concentrations within the cavity and wake regions of even a simple block-like building is very complex and beyond the capability of most models, perhaps with the exception of CFDs. However, the ground-level concentrations at some distance beyond the building, such as beyond five building heights, can be approximated. Several methods have been proposed. In one, Eq. 6-5 is modified to account for the cross-sectional building area, A:

$$\frac{\chi(x,y=0,z=0,h=0)}{Q} = \frac{1}{\pi(u\sigma_y\sigma_z + cA)} \qquad \textbf{Equation 6-13}$$

[66] The contributing influence of surface elements that are several hundred meters upwind of the release may be important for receptors that are a short distance away.
[67] The use of σ_z values that are adjusted for surface roughness for example, could involve the double-counting, to some extent, of the building's impact on diffusion. The analyst will need to technically justify any use of σ_y and σ_z values that already incorporate other adjustments in its atmospheric dispersion modeling protocol.
[68] The term wake is occasionally used in the published literature in reference to the cavity and wake zones, collectively.
[69] See also Hunt, J. C. R. et al., "Kinematical studies of the flows around free or surface mounted obstacles: (cont.)

where *c* is the building shape factor, usually taken to be 0.5, and *A* is the smallest cross-sectional area of the building between the source and receptor. Another method is to assign a virtual point source upwind of the building such that when this virtual plume reaches the building, the concentrations at the edges of the building are 10% of the centerline concentration. This corresponds to σ_y = width/4.3 and σ_z = height/2.15, a commonly applied option used with MACCS2. The distance to this virtual point source can then be back-calculated, using the existing wind speed and atmospheric stability class.

Both HotSpot and EPIcode codes allow for the specification of a vertical area source that can represent the initial dispersion (σ_{y0}, σ_{z0}) associated with cavity releases. The user inputs a horizontal dimension (L_H) and vertical dimension (L_V) to define the area source. From these input values, values of σ_{y0} and σ_{z0} are calculated, a virtual source location, upwind of the actual source is determined, and adjusted dispersion parameters calculated as discussed above for MACCS2.

The GENII2 software has two model options for building wake dispersion that are documented in the software design documents (*GENII Version 2 Software Design Document*, Napier et al., 2009).

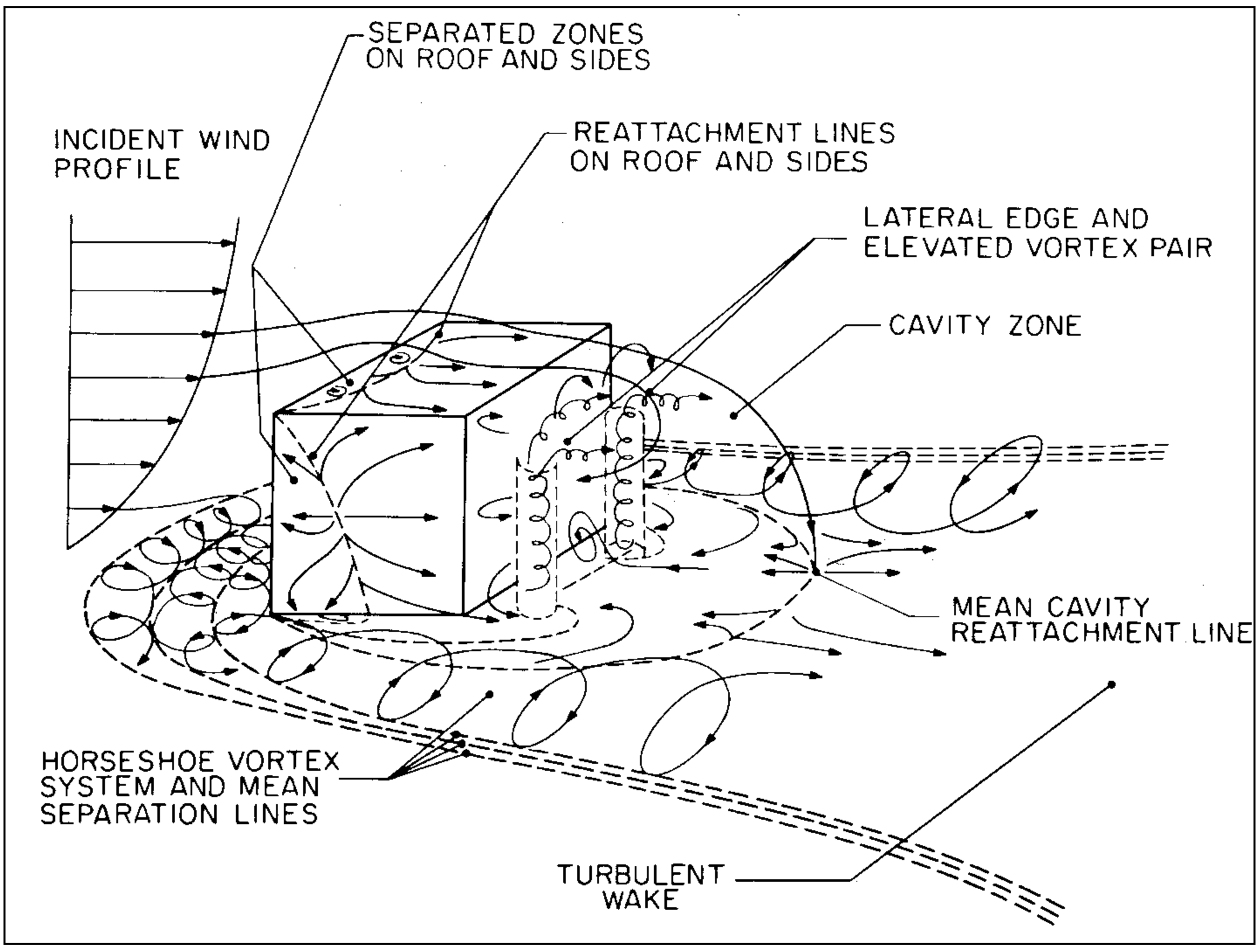

Figure 6-8. Schematic of Turbulent Air Flow around a Sharp-Edged Building.

(cont.) applying topology to flow visualization," J. Fluid Mech. 86, Part I, pp 179-200, 1978; Woo, H.G.C. et al., "Wind Tunnel Measurements in the Wakes of Structures," NASA CR-2806, NASA/Marshall Space Flight Center, Al, 1977.

6.8.4 PLUME MODIFICATIONS THROUGH DECAY, DAUGHTER IN-GROWTH, AND DEPOSITION PROCESSES

Atmospheric dilution and diffusion dominate the redistribution processes but they are not the only processes that affect the concentration distribution of a radioactive or toxic chemical material in a plume. With respect to radioactive materials, the concentration of a radioisotope of interest can decrease with time through a radioactive decay process, or can increase through the decay and in-growth of another daughter isotope.

Mass transfer processes in the atmosphere remove gases and particulates from the plume and can also reinsert particulates back into the atmosphere. The primary removal processes are dry deposition from gravitational settling and fallout, and wet deposition or precipitation scavenging from rain, snow, or hail. Reinsertion of deposited material back into the atmosphere to be transported to a new location is termed resuspension. These mass transfer processes are important in determining the ultimate fate of small respirable particulates, as well as ingestible particulates from radioactive compounds and chemically toxic materials.

The parameter Q represents the rate of release of material into the atmosphere. In the following discussion, the meaning of this parameter is extended to include other processes that change the radionuclide abundances and quantities of the material. These include decay and in-growth, removal of the material by dry and wet deposition processes, and resuspension of removed material. It may be noted that in some atmospheric dispersion models, the quantity χ/Q refers to only the atmospheric dispersion processes discussed earlier. Other models include the other processes discussed below. In NRC Regulatory Guide 1.111, *Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors*, NRC introduces the term depletedχ/Q, which is the concentration in the plume after dry deposition processes have removed, or depleted, some the material. NRC Regulatory Guide 1.111 also introduces the term D/Q, which is dry deposition. Accordingly, when using atmospheric dispersion models, note which definition is being used for χ/Q.

In-growth and decay of radioactive materials immediately occurs following their release into the atmosphere, regardless of the location of the material, whether within the plume, in materials that have fallen to the ground, or in materials that have been resuspended into the air. Decay refers to the loss of a given isotope through radioactive disintegration over time. In-growth refers to the build-up of one isotope by the decay of another, that is, it is the daughter product of the decay of this other isotope, termed the parent. The abundance of an isotope at any given time is a function of its decay rate as well as that of the parent isotope, if any, and the time since release.

For the initial atmospheric plume, not the resuspended plume, the time, t, is the transport time, that is, the distance (x) traveled divided by the average transport wind speed (u). For material deposited on the ground or for a resuspended plume, the time will be longer. The concentration of isotope, I, can be adjusted by multiplying the χ/Q by $A_i(t)/A_i(0)$ to account for the decay and in-growth of isotope i.[70] This is not of concern for long-lived, slowly decaying isotopes, such as Pu-239, but can be important for shorter-lived fission products from a criticality accident or from a reactor.

The rate of dry deposition is usually expressed in terms of a deposition “velocity” (V_d), a term having the units of velocity that expresses the rate of mass-transfer from the plume to the ground at the atmosphere-

[70] See Chapter 8 and Equation 8-4 for further discussion.

ground surface interface. The deposition "velocity" is defined as a deposition flux, ω_d (Bq m^{-2} s^{-1}) divided by the near surface air concentration, χ (Bq m^{-3}):

$$V_d = \omega_d (x, y) / \chi(x, y, 0) \quad \textbf{Equation 6-14}$$

The amount of material deposited on the ground at any particular location is the product of the deposition flux, ω_d, and the release duration. The dry deposition velocity is essentially a proportionality factor, and although it has the same units as a velocity, it is not a true velocity. With respect to Equation 6-14, the dry deposition velocity is evaluated at ground level. However, some codes apply a slightly higher elevation (e.g., GENII2; at height of one meter). A variety of mechanisms contribute to dry deposition. Gravitational settling is the dominant contributor for particles with diameters greater than or equal to 10 microns Activity Median Aerodynamic Diameter (AMAD).[71] For smaller-sized particles in the respirable range (<10 microns) other processes dominate, including turbulent diffusion, surface impaction, and Brownian diffusion. Values of V_d are a function of numerous meteorological variables (wind speed, atmospheric stability), impingement environment (terrain, land-use type, vegetation), and the particle size distribution and density of the particles. Generally, values for dry deposition velocity increase with increasing wind speeds, atmospheres that are more unstable, larger particle sizes, and terrain with higher surface roughness values. From various field experiments conducted over many years, dry deposition velocities are found to vary widely by several orders of magnitude, from 0.001 cm/s to 180 cm/s for particulates and from 0.002 cm/s to 26 cm/s for gases. Regardless of how V_d is determined, there are large uncertainties associated with it and there is currently no single accepted theoretical description of dry deposition that covers all common natural environments. However, parameterizations exist for many conditions of interest and are reasonably accurate for the conditions from which they were developed. Early dry deposition models are described in "*A Model for Predicting Dry Deposition of Particles and Gases to Environmental Surfaces*" (Sehmel and Hodgson, 1978), which were developed from wind tunnel experiments. The results of this model are consistent with a wide-range of historical deposition velocity measurements but did not take into account the effects of atmospheric stability or surface roughness from different land-use categories that were outside the scope of the aforementioned wind tunnel experiments. The default deposition velocity values originally recommended in the DOE Guidance Report for MACCS2 (DOE, 2004a) were based on the Sehmel and Hodgson model.

The current generation of atmospheric transport and diffusion models estimate the deposition velocity by analogy to electrical systems, where the deposition velocity is formulated as the inverse of the sum of resistances. GENII2 incorporates resistance-based deposition models. In these models the deposition velocity is calculated in time and 3-dimensional space because its value is dependent on time-varying atmospheric conditions and 3-dimensional variable surface characteristics.

A 2010 paper entitled "Development and Validation of a Size-resolved Particle Dry Deposition Scheme for Application in Aerosol Transport Models" presents more recent research in dry deposition modeling (original source: Petroff, A. and Zhang, L., 2010, Geosci. Model Dev., 3, 753-769, doi:10.5194/gmd-3-753-2010, as cited in Sugiyama et al., 2014). The research is constructed on the premise that while no single theoretical description of deposition processes exists that is valid for all land use types, deposition properties should be possible to parameterize over a wide range of natural environments based on available deposition velocity measurements. This model provides one of the most complete theoretical descriptions of deposition available and has been parameterized to match a large number of experimental data sets covering multiple surface types and land-use characteristics. This model has not yet been

[71] Activity Median Aerodynamic Diameter is the diameter of the particle for which half the activity is associated with particles larger than and half the activity associated with particles smaller than this size particle.

incorporated into any widely-used atmospheric dispersion models as it requires micrometeorological inputs that are not available from routine weather observations. However, it is used in one of the in-house atmospheric models at the National Atmospheric Release Advisory Center (NARAC). These models are summarized in Table 6-12.

The DOE Safety Software Central Registry includes atmospheric transport and diffusion models that either internally calculate deposition velocity using a formulation of a dry deposition model or that require the user to specify an appropriate value. For models like GENII2 that include a dry deposition model within the code, appropriate site-specific parameters (particle size distributions, particle density) should be specified that are representative of site-specific conditions. The analyst should follow the accompanying DOE guidance document for inputting site-specific parameters and follow the requirements in DOE-STD-3009-2014 for radiological consequences modeling.

Other atmospheric dispersion models, and DOE toolbox codes such as MACCS2 and HotSpot, require that deposition velocity be specified by the user. Guidance for specifying an appropriate value is contained within the software user's manual or within the accompanying DOE Guidance Documents (DOE, 2004a; 2004b; 2004c). For a more conservative simplistic analysis, it is recommended that a default deposition velocity value be specified. The latest guidance from DOE contained in DOE-STD-3009-2014 specifies a deposition velocity of 0.1 cm/s for unfiltered release of particles (1-10 µm AED), 0.01 cm/s for filtered particles, and 0 cm/s for tritium and noble gases. Although using 0.1 cm/s or using 0 cm/s will produce virtually the same results for close-in distances, a non-zero value acknowledges that particulate deposition is occurring. For DOE reservations with distant site boundaries, a 0.1 cm/s dry deposition velocity may significantly lower the dose at those distances. Also, note that the deposition velocity depends on particle size. For the 0.3-µm particle, the recommended deposition velocity is 0.01 cm/s (DOE HSS Safety Bulletin 2011-02).

When a more site-specific value is desired to refine the analysis, the analyst may calculate a site-specific value using an external dry deposition model (e.g. GENII2, CALPUFF, Petroff and Zhang), and then use the calculated value as an input parameter to the code. Site-specific values are desirable when the default value produces overly-conservative estimates of exposures. External models should be evaluated for appropriateness for the situation being modeled. External models can be used in one of two ways: 1) executing the model after applying appropriate SQA; or, 2) performing a hand calculation or spreadsheet using the deposition velocity model formulation. The specific model formulation can be obtained from the model's software design document or from the original published literature. The analyst should also follow the guidance specified in DOE-STD-3009-2014 for using site-specific methods and the atmospheric dispersion modeling protocol in Section 6.11.

Table 6-12. Summary of Deposition Velocity Models of Interest
(This table was reproduced from Sugiyama et al., 2014).

Model	***Aerodynamic Resistance r_a (s/m)***	***Quasi-laminar sublayer resistance r_b (s/m)***	***Surface Transfer Resistance r_c (s/m)***	***Settling velocity v_s (m/s)***	***Deposition velocity, v_d (m/s)***
Sehmel and Hodgson (1978)	$A = f(Sc, D_p, u_*, z_o, D_b)$			$\frac{(\rho_p - \rho_g) g D_P^2 C}{18\mu}$	$\frac{v_s}{1 - e^{-v_s / u_* e^A}}$
GENII/ RATCHET	$u(z_d) / u_*^2$	$6.5 / u_*$	100	$\frac{(\rho_p - \rho_g) g D_P^2 C}{18\mu}$	$\left(\frac{1}{r_a + r_b + r_t + r_a r_b v_s}\right) + v_s$
AERMOD/ CALPUFF	$u(z_d) / u_*^2$	$\frac{1}{u_*\left(Sc^{-2/3} + 10^{-3/St}\right)}$	-	$\frac{(\rho_p - \rho_g) g D_P^2 C}{18\mu}$	$\left(\frac{1}{r_a + r_b + r_a r_b v_s}\right) + v_s$
Petroff and Zhang (2010)	$A = f(Sc, D_p, z_o, LAI, u_*, L, D_b, d, T, h, ObstSize)$*			$\frac{\rho_p g D_P^2 C}{18\mu} + V_p$	$\left(\frac{1}{r_a + r_b}\right) + v_s$

u_*	= friction velocity (m/s)	D_p	= particle diameter (m)
v_s	= settling velocity (m/s)	Sc	= Schmidt number
z_o	= surface roughness length (m)	St	= Stokes number
d	= zero-displacement height (m)	LAI	= leaf area index (dimensionless)
h	= canopy height (m)	L	= Obukhov length scale (m)
μ	= dynamic viscosity of air	T	= ambient air temperature (K)
D_b	= Brownian diffusivity (m^2/s)	ObstSize	= characteristic obstacle size (m)

*The Petroff and Zhang model uses a complex formulation that depends upon the dominant land-use category, the Monin-Obukhov length, the surface friction velocity, the air temperature and the particle size distribution as inputs.

Per DOE-STD-3009-2014, wet deposition is not evaluated in DOE hazard and accident analyses, however, this topic is addressed here for completeness to include a discussion of this phenomenology. Wet deposition, or precipitation scavenging, is more difficult to parameterize than dry deposition, as it depends upon cloud physics parameters that vary in time and space that are usually unavailable to the analyst. Each type of precipitation (rain, snow, or hail), passing through the plume collects particulates by accretion and scavenges soluble gases. The rate of depletion by wet deposition, dQ/dt, is proportional to the amount of material in the plume (Q). Thus, the change of material in the plume (dQ/dt), can be represented in Equation 6-15.

$$dQ / dt = -\Lambda Q \qquad \textbf{Equation 6-15}$$

where Λ represents the washout coefficient (s^{-1}). The solution to Eq. 6-15 over a time interval Δt gives

$$Q / Q_0 = \exp(-\Lambda \Delta t) \qquad \textbf{Equation 6-16}$$

Q_0 represents the amount of material entering this interval and Q represents the amount leaving. The value of Δt depends on the transport wind speed and the distance interval being evaluated. As with dry deposition, Eq. 6-16 would be an adjustment factor to apply to χ/Q for wet deposition occurring in the distance interval Δx during time interval Δt.

The washout coefficient, Λ, is a function of the precipitation rate, the type of precipitation (rain, snow, hail), and the type of material being scavenged (particulate or gas). For particulates in rain, the washout coefficient can be approximated by a power law of the rainfall rate in Equation 6-17:

$$\Lambda = a\, I^{\,b} \qquad \textbf{Equation 6-17}$$

where I is the precipitation rate (mm/hr) and a and b are dimensionless empirical coefficients that depend upon the particle size distribution. For example, in the MACCS code (NUREG/CR-4691), the values used are $a = 9.5 \times 10^{-5}$ and $b = 0.8$. For gases, the washout coefficient depends upon the solubility of the effluent as well as the precipitation rate. Families of empirical curves have been developed for various rainfall rates to estimate the washout coefficient. This procedure is made more complex by the spatial variability of the rainfall. Frequently, rainfall rates vary significantly within a rainfall event, and different washout coefficients may need to be applied to various segments of the plume as it travels to the receptor. This is virtually impossible to do with a steady-state Gaussian model and would need to be addressed by 3-dimensional Lagrangian mass-consistent codes, which are briefly discussed in Section 9.7. The use of a Doppler radar system to provide spatial representations of precipitation rates can assist this calculation.

An accurate estimation of washout is needed in the near-field for elevated releases because of the efficiency of this removal process for both particulates and gases. As an example, during an unscheduled release from the Ginna Nuclear Plant in 1980, the *maximum* ground-surface concentrations of ^{131}I were measured just beyond the containment building in the snow. In addition, larger doses from the Fukushima Dai-Ichi release in 2011 were the result of wet deposition that occurred days after the release. Although accurate estimations of washout are needed, most computer models treat it in only a cursory manner, if at all.

Plume depletion accounts for the material removed by either or both of the deposition processes, and accordingly reduces, or depletes, the χ/Q value. Depletion of the plume by either dry or wet deposition processes also results in soil contamination. Contaminated soil can be subsequently resuspended as a new source term should the soil be dry coupled with windy atmospheric conditions. Resuspension is generally higher in urban regions due to increased anthropogenic activities.

Although resuspension processes can contribute to exposure to individuals, the acute effect is small and therefore DOE-STD-3009-2014 does not require its inclusion in a DSA analysis.

6.8.5 PRINCIPLES GOVERNING PLUME RISE AND DOWNWASH

Two physical processes can each propel a neutrally-buoyant plume vertically upward to a level higher than that of its initial release, an effect called plume rise. The first process is termed momentum plume rise, in which the vertical efflux velocity of the radiological or toxic chemical release propels the plume upward, further above its elevated emission point. The second process is termed buoyancy plume rise, which occurs if the temperature of the plume is warmer than that of the ambient air.

Accounting for stack-tip downwash of the plume is essential in either process. Downwash can occur under high wind-speed conditions, and it can also occur if the release is from a vent or small stack into the wake and cavity behind the building. A brief discussion follows on both of these plume rise processes that can be integrated into an atmospheric dispersion model to account for these effects. Most atmospheric dispersion models calculate both momentum rise and buoyancy rise and consider that the dominant one is the one giving the greater plume rise.

6.8.5.1 MOMENTUM PLUME RISE

The calculation of momentum plume rise requires knowledge of the vertical efflux speed and the horizontal wind speed at the point of release, and the diameter of the stack from which the effluent is released[72]; the smaller the stack diameter the greater the efflux speed for a given mass flux. As the plume is transported downwind and away from its source of momentum, the upward momentum is gradually dissipated and ultimately the wind bends the plume over into the horizontal plane. The amount of momentum plume rise is a function of the ratio of the vertical efflux speed to the wind speed. Any additional plume rise only occurs due to plume buoyancy effects.

For radioactive effluents that are released from free standing stacks whose design meet the EPA Good Engineering Practice (GEP) stack height criteria, the entire effluent escapes the influence of the facility structures. GEP stack height is defined as 1.5 times the height of the nearest facility structure plus either the height or width of that structure, whichever is larger.[73]

For releases from structures that meet GEP stack height criteria, and under neutral or unstable stability conditions (stability classes A – D), plume rise can be calculated from:

$$\Delta h = 1.44\, d\, (v_e / u)^{2/3}\, (x / d)^{1/3} - C \qquad \textbf{Equation 6-18}$$

where Δh is the amount of plume rise (m) above the release level, v_e is the efflux speed (m/s), u is the horizontal wind speed (m/s), x is the downwind distance (m), and d is the diameter of the stack (m). This equation shows the relationship between the two competing parameters, v_e, and u. C is the downwash correction factor and is set to zero if $v_e/u \geq 1.5$, or:

$$C = 3\,(1.5 - v_e / u)\, d \qquad \textbf{Equation 6-19}$$

if $0 < v_e/u < 1.5$. Under stable atmospheric conditions (E – G stability classes), the following two empirical equations are evaluated, and the smaller value is applied:

$$\Delta h = 4\,(F_m / S)^{1/4} \qquad \textbf{Equation 6-20}$$

and

$$\Delta h = 1.5\, S^{-1/6}\, (F_m / u)^{1/3} \qquad \textbf{Equation 6-21}$$

---

[72] Momentum plume rise equations do not apply to stacks that direct the plume horizontally or downward (“J” stacks).
[73] Note that 1.5 times height of building plus height of building equals 2.5 times height of building, which matches the NRC guidance. If the building is squat (wider than tall) “1.5 times height plus width” will exceed the “2.5 times height” rule.

where F_m is the momentum flux

$$F_m = v_e^2 (0.5\ d)^2 \qquad \textbf{Equation 6-22}$$

S is the stability parameter

$$S = (g / T)(d\Theta/dz) \qquad \textbf{Equation 6-23}$$

g is the acceleration of gravity (m/s^2), T is the ambient temperature (K), and $d\Theta/dz$ is the potential temperature lapse rate (K/m), which is the sum of the actual temperature lapse rate and the adiabatic lapse rate.

For plume rise from non-GEP stacks or building vents, empirical relationships from field studies were developed at the Millstone Nuclear Power Plant in 1978. The central result of this study is that there are two forces acting on the plume. The efflux velocity (v_e), which can be visualized as an escape velocity, and wind speed (u), which can be visualized as a capture velocity. Accordingly, the v_e/u ratio is the driving parameter. When $v_e/u > 5$, the vertically-directed momentum flux, which affects escape from the building, dominates the horizontally-directed wind speed, which affects capture in the building wake, and the release is treated as elevated. This means that although the release emanated from a short stack or a vent, it still will fully escape the aerodynamic effects of nearby buildings due to the high momentum flux coupled with low wind speed. The GEP stack height equations apply in this case. On the other end of the spectrum, when $v_e/u < 1$, the release is effectively ground-level and no plume rise occurs. Two intermediate cases were also developed from the field study. These are the partially entrained and the partially elevated cases and are expressed in terms of an entrainment coefficient, E_t, which is the fraction of the plume entrained into the wake and cavity behind the building. The remainder escapes entrainment.

Partially Entrained: For cases where $1.5 < v_e/u < 5$, a portion of the plume is entrained and the remainder of the plume remains elevated. An entrainment coefficient can be calculated for this case as follows:

$$E_t = 0.30 - 0.06\ v_e / u \qquad \textbf{Equation 6-24}$$

Partially Elevated: For cases where $1 \leq v_e/u \leq 1.5$, an entrainment coefficient can be calculated for this case as follows:

$$E_t = 2.58 - 1.58\ v_e / u \qquad \textbf{Equation 6-25}$$

In both of these cases, the elevated portion of the plume is subject to plume rise, while the entrained portion of the plume is down-washed to ground level.

6.8.5.2 BUOYANCY PLUME RISE

The calculation of buoyancy plume rise requires knowledge of the effluent temperature or the energy released in a fire or other energetic event and the ambient temperature at the point of release.[74] If the plume temperature is higher, positive (upward) buoyancy occurs, while for a relatively cold plume, negative buoyancy occurs. The stability class of the atmosphere also affects the buoyancy rise, at least initially. Unlike momentum rise, which may take only 30 to 40 seconds, buoyancy rise may continue for

[74] For indoor fires assume no plume rise, to be conservative. The plume will cool and plate out as it exits the facility, and as there is no way to accurately estimate the extent of cooling, assume there is no plume rise. An indoor air temperature may be used if there is a need to quantify the exit temperature.

many minutes due to its slower upward speed compared to momentum rise. The buoyancy rise can be calculated in two parts. The first is the initial rise and is dependent on the stability class. The second is the gradual rise and is independent of stability class. The larger of the two is then chosen as representative.

The initial plume rise is independent of distance downwind, but is dependent on stability class. For classes A – D, and buoyancy fluxes less than 55 m^4/s^3, the plume rise is given by (Briggs, 1975)

$$\Delta h = 21.425\, F_b^{\,3/4}\, u^{-1}$$ **Equation 6-26**

where F_b is the buoyancy flux. For fluxes greater than 55 m^4/s^3, the plume rise is given by

$$\Delta h = 38.71\, F^{\,3/5}\, u^{-1}$$ **Equation 6-27**

For classes E – G, the plume rise is given by

$$\Delta h = 2.6\, [F_b / (u\, S)]^{1/3}$$ **Equation 6-28**

except for calm conditions, for which it is appropriate to use

$$\Delta h = 4\, F_b^{1/4}\, S^{-3/8}$$ **Equation 6-29**

The gradual plume rise, which is independent of stability class, can be calculated from the empirical relation

$$\Delta h = 1.6\, F_b^{1/3}\, x^{2/3}\, u^{-1}$$ **Equation 6-30**

The buoyancy flux depends upon whether the release is from a stack or from a fire. For a stack release, the buoyancy flux is

$$F_b = g\, v_e\, d^2\, \Delta T / (4\, T_s)$$ **Equation 6-31**

Where, ΔT is the stack gas temperature (T_s) minus ambient temperature. For a fire it is given by

$$F_b = 8.79 \times 10^{-6}\, \Omega$$ **Equation 6-32**

where Ω is the rate of release of sensible heat (watts)[75]. Eq. 6-29 would let the plume rise indefinitely, so it is necessary to cap the plume rise. Several methods of capping the buoyancy rise have been used. One way of doing this is to terminate the use of Eq. 6-27 when one of the following three conditions occurs: (1) when Δh reaches $300\, F_b/u^3$ (Briggs, 1975); (2) when the plume centerline has reached the height of the top of the mixed layer; or (3), when one hour has elapsed since the plume release began.

6.8.6 PLUME IMPACTION

DOE sites that are located in mountainous terrain may need to address plume impaction of elevated releases, especially if a large rise in the topography is nearby (see Figure 6-1). With respect to this type of morphology, the analyst should screen any elevated releases that may have the potential for impaction

[75] The total energy released in a fire can be partitioned into various forms, such as sensible heat, radiant heat, and latent heat. Sensible heat gives rise to changes in temperature and density and thus it determines the buoyancy flux.

using the EPA code CTSCREEN. This code is a Gaussian plume dispersion model designed as a screening technique for plume impaction assessments in complex terrain. CTSCREEN is also a screening version of the CTDMPLUS model. This code and its user guide can be accessed at https://www.epa.gov/scram/air-quality-dispersion-modeling-screening-models.

6.9 DOE CENTRAL REGISTRY OF RADIOLOGICAL DISPERSION AND CONSEQUENCE ANALYSIS CODES

Since 2004, a collection of computer codes, including those for performing atmospheric dispersion and radiological or toxic chemical consequence analyses, have been designated as Toolbox codes in the DOE Safety Software Central Registry (CR) and managed by the DOE Office of Quality Assurance & Nuclear Safety Management Programs (AU-32). While these models have widespread use and have accumulated considerable levels of analyst understanding, they still warrant careful consideration in the preparation of inputs and assumptions to ensure that the resulting radiological and toxic chemical consequence outputs are technically defensible and consistent with expectations of the analysis, and that resulting safety control sets are adequate, robust and implementable. Accordingly, every Toolbox model needs to be independently evaluated according to the SQA principles in DOE O 414.1D, *Quality Assurance*, and additional useful guidance in DOE G 414.1-4, *Safety Software Guide for use with 10 CFR 830 Subpart A, Quality Assurance Requirements* (2010). Modeling techniques inherent in the toolbox software and guidance for their use, including input requirements, are discussed below. Note that model evaluation is not one of the 10 work activities to be considered per DOE O 414.1D, Attachment 4 nor is this topic discussed in DOE G 414.1-4A.

Of the eight toolbox codes that comprise the DOE Safety Software Central Registry (CR), three are applicable to radiological dispersion and consequence analysis applications (GENII, MACCS2, and HotSpot) and two are applicable to toxic chemical dispersion and consequence analysis applications (ALOHA and EPIcode). The other toolbox codes address fires (CFAST), in-facility transport (MELCOR) and biological uptake (IMBA). The three radiological dispersion computer models are listed in Table 6-13 along with their respective developing organization, toolbox version, the year designated for the DOE Safety Software Central Registry, and current version supported by their developer. Additional information on the DOE Safety Software Central Registry and individual atmospheric dispersion and consequence analysis computer models is available through the website http://energy.gov/ehss/safety-software-quality-assurance-central-registry.

Inclusion of a code into the DOE Safety Software CR provides DOE users the assurance that the SQA level is adequate for safety analysis applications along with implementation of applicable site-specific SQA requirements per the site's quality assurance program. These requirements might include site acceptance testing, user training, configuration control, and error reporting. In the case of a specific DOE Safety Software CR computer code, the gap analysis against SQA standards and requirements and the code guidance development process are specific to the version at the time the computer software was designated for the Central Registry. If a later version of the computer code is being considered for use, the DOE contractor is responsible for determining that the quality assurance level of that code version meets applicable DOE requirements.

Table 6-13. Computer Models in DOE Safety Software Central Registry for Radiological Consequence Analysis.
(Content shown is current as of publication date)

Computer Code	Lead /Developing Organization	Version/ Year Designated for the Toolbox	Current Version Supported by the Developer
GENII	Bruce Napier / Pacific Northwest National Laboratory	V1.485 / 2004 V2.10.1 / 2013	V2.10.1
HotSpot	Steve Homann / Lawrence Livermore National Laboratory	V2.07.1 / 2010	V3.01
MACCS2	Nate Bixler / Sandia National Laboratory	V1.13.1 / 2004	WinMACCS V3.7; MACCS2 V2.6.0

The codes in the CR were developed outside of DOE and in other Federal agencies (NOAA, NRC, or EPA)]. Access to the toolbox codes or their use is subject to agreements, conditions, and restrictions established by the code owners or Federal Agencies. The CR is currently managed by AU-32 within EHSS and the focus of AU-32 is to work with the code developers/owners to have the Toolbox codes updated (closing the gaps) and maintained following SQA provisions of applicable national consensus standards such as ANSI/ASME NQA-1-2008 which is the preferred standard cited in DOE O 414.1D for safety software.

In the preface to the DOE Central Registry, DOE states that the Chief Health, Safety and Security Officer (DOE/HS-1, which is currently the AU-1 organization) is responsible for managing the Safety Software Central Registry. However, the toolbox code owners are responsible for ensuring that the codes are maintained in accordance with established DOE O 414.1D requirements. and DOE G 414.1-4A provides additional SQA guidance.

As stated on the DOE/AU website, use of the CR toolbox codes is not mandatory. Of the three options given in DOE-STD-3009-2014, Section 3.2.4.2 for radiological dispersion analysis, only Option 2 requires the use of a toolbox code. However, using the toolbox codes offers a number of advantages to DOE and its contractors, which include:

- The evaluation performed provides valuable information on the code regarding application of SQA requirements;
- The evaluation generally extends beyond the DOE safety software quality assurance criteria to the review of the code's capability to properly perform safety basis calculations;
- The DOE-specific guidance documents identify limitations and vulnerabilities not readily found in other code documentation;
- Due to the established pedigree, quality assurance assessments of the toolbox code by the users (DOE personnel and site contractors) may be reduced in scope; and
- Increase of user base and experience across the DOE complex.

ALOHA, EPIcode, GENII, MELCOR, CFAST, and MACCS2 were the original six computer codes designated for the DOE Central Registry in 2003, and each code's SQA, gap analysis, and code usage guidance documents were published in 2004. The gap analyses for these six codes were completed before issuance of DOE O 414.1C, *Quality Assurance*, and the safety software guidance, DOE G 414.1-4[76]. The two documents provided a framework for the evolving DOE requirements for safety software. With the release of DOE O 414.1C and DOE G 414.1-4, and subsequently DOE O 414.1D the safety software requirements were more clearly identified (Attachment 4 to the respective Orders) and guidance for meeting the requirements provided.

HotSpot V2.07.1 was added to the CR in 2010 after a detailed SQA evaluation that determined that the adequacy of the HotSpot SQA program and associated documentation, with some modifications (gaps), that met the safety SQA requirements of the DOE O 414.1D. With the available SQA documentation, the necessity of a separate guidance document was not established. HotSpot has been recently upgraded to Version 3.01 and further revision to the code is underway following which the code developer intends to request a subsequent SQA evaluation by DOE/AU-33.

More detailed discussions of the capabilities of MACCS2, GENII, and HotSpot are given below. These cover available toolbox atmospheric transport and diffusion models for radiological analysis. The toolbox models for toxic chemical consequence analysis, ALOHA and EPIcode, are addressed in Section 9.7. Additional supported radiological consequence codes (e.g. RASCAL, NARAC, RSAC-8, HYRAD, ARCON96), which have had some use at various DOE sites, should be evaluated on a case-by-case basis as to their applicability to the safety analysis that is undertaken. Should the analyst select any of these other codes, an atmospheric dispersion modeling protocol (see Section 6.11) needs to be developed and approved by the DOE site office.

The three radiological toolbox codes listed in Table 6-13 are briefly discussed below. The toolbox version of these codes is available through the Radiation Safety Information Computational Center. Table 6-14 summarizes important features of the toolbox software and serves as a roadmap to the guidance given in this Handbook with respect to radiological consequence analysis.

[76] DOE O 414.1C, and its supporting Safety Software Guide, were issued 6-17-05.

Table 6-14. Summary Guidance on the Use of Computer Models in DOE Central Registry for Radiological Dispersion Analysis.

Model Feature	GENII	HotSpot	MACCS2	Guidance
Prescriptive Meteorology Capability	Not readily available as an option	User-defined wind speed and stability class can be input via one of the meteorological input modes	User-defined wind speed and stability class can be input via one of the meteorological input modes	Generally has been used for modeling dispersion for a high wind event. Another example is that stability class F and 1.0 m/s wind speed may be used when site-specific hourly meteorological data are not available.
Plume Transport with Hourly Meteorological Data	One continuous plume generated for each hour based on constant wind direction, wind speed and stability class	One continuous plume generated for each hour based on constant wind direction, wind speed and stability class	For each source term, one continuous plume generated for each hour with constant wind direction, but wind speed and stability class changing after each hour of transport; up to 4 plumes can be used to transport and disperse 4 distinct source terms	The GENII2, HotSpot and MACCS2 approaches are compliant with DOE-STD-3009-2014.
Years of Meteorological Data	Up to ten years in single code execution	Up to five years in single code execution	One year per code execution – mean value of 95th or 99.5th percentile χ/Q from all executions typically determined	Five years is recommended (DOE-STD-3009-2014, Section 3.2.4.2).
Percentile Output for a Given Distance Based on Statistical Sampling of Meteorological Data	95th percentile for each wind direction sector, considering only plumes traveling in the given sector	95th percentile from overall cumulative probability distribution from all directions combined	95th and 99.5th percentile from overall cumulative probability distribution from all directions combined	The approach of HotSpot/MACCS2 is conservative and accepted by DOE-STD-3009-2014 even though not fully compliant with NRC Regulatory Guide 1.145. Determining the maximum sector result from GENII2 is a conservative approach with respect to DOE-STD-3009-2014.

Model Feature	GENII	HotSpot	MACCS2	Guidance
Wind Speed Profile	i) Reference height for meteorological data is an input value in first line of meteorological input data file ii) Wind speed is adjusted for release heights that differ from reference height iii) Release heights less than 12 m are modeled using 10-m wind speed iv) Surface wind speed is used together with roughness length (z_0) input in meteorological data file for determining friction velocity (u_*)	i) Default reference height for meteorological data is 10 m, but the user may change it. ii) Wind speed is adjusted for release heights that differ from reference height.	i) Reference height for meteorological data is always 10 m ii) Wind speed is not adjusted for release heights that differ from reference height	The 10-m wind speed is recommended for ground level releases. For elevated releases above 10 m, adjustment of the wind speed is standard practice (HotSpot, GENII2); no adjustment is conservative (MACCS2).
Treatment of Calm Wind Speeds	User specifies minimum wind speed value (any wind speed values in meteorological data file less than minimum value is reset to minimum value)	Software resets any wind speed values in meteorological data file less than 0.1 m/s to 0.1 m/s	Software resets any wind speed values in meteorological data file less than 0.5 m/s to 0.5 m/s	Specifying a minimum wind speed of 1.0 m/s is recommended (DOE-STD-3009-2014, Section 3.2.4.2).
Dispersion Parameter Sets	• Eimutis and Konicek (NRC) • Pasquill-Gifford (EPA) • Briggs Open Country • Briggs Urban	• Briggs Open Country • Briggs Urban	• Tadmor-Gur • Briggs Open Country • Eimutis and Konicek (NRC) • Briggs Urban	Briggs Urban set not recommended. Tadmor-Gur not recommended for distances less than 500 m. The toolbox version of MACCS2 has a lookup table error which may limit which dispersion parameters can be used. See Section 6.4.2.

Model Feature	GENII	HotSpot	MACCS2	Guidance
G Stability Class	i) Modeled explicitly with Eimutis and Konicek (NRC) set of dispersion parameters ii) Modeled as F stability class for other sets of dispersion parameters	i) Vertical dispersion modeled as F stability class ii) Modeling of horizontal dispersion specified by user to be equivalent modeled as any stability class in range of A through F	Modeled as F stability class	Modeling G stability class as F stability class is recommended. Experiments have shown that plume meander under class G yields dispersion conditions that are no more conservative than under Class F.
Adjustment of horizontal dispersion parameter (σ_y) for plume meander	No adjustment currently modeled	Averaging time method	i) Averaging time method ii) NRC method	The averaging time method is recommended; no adjustment is conservative.
Adjustment of vertical dispersion parameter (σ_z) for surface roughness (z_o) effects	No adjustment (User enters z_o value in meteorological data file that is used to define the wind speed profile and calculate the deposition velocity)	No adjustment	User enters roughness adjustment factor	Equation 6-12 or either Equation 6-13 or 6-14 is recommended together with one of the methods discussed to determine z_o; no adjustment is conservative for ground-level non-buoyant releases.
Adjustment of initial values (at source) for σ_y and σ_z for building wake effects	User inputs building dimensions and software determines initial σ_y and σ_z values	User inputs building dimensions and software determines initial σ_y and σ_z values	User inputs initial values for σ_y and σ_z	Increased dispersion from building wake effects should only be used for ground-level releases. No other adjustments should be made to the dispersion parameters for plume meander or surface roughness effects. Ignoring building wake dispersion is generally more conservative. Option 2 in DOE-STD-3009-2014 does not allow for crediting of building wake factors.

Model Feature	GENII	HotSpot	MACCS2	Guidance
Effective Stack Height	User enters effective release height	User enters effective release height	User enters effective release height	The use of plume rise equations in Appendix E is recommended to determine effective release height taking into account stack-tip downwash and aerodynamic entrainment effects of buildings. Assuming ground release is generally more conservative.
Plume Buoyancy	Plume rise model from stack available as an option. Not recommended for fire-release modeling.	• Stack plume rise model • Pool-fire plume rise model (open field)	Plume rise model from stack available as an option.	The three models employ similar models for plume rise from a stack as long as the stack meets GEP criteria. The HotSpot pool fire model is only applicable with an open field release. When using MACCS2 to model fires, the guidance of this Handbook should be followed, including inputting the height of the tallest co-located structure to account for building entrainment that can inhibit plume rise. Ignoring buoyant plume rise is conservative.
Deposition Velocity for Respirable Source Term	Software determines value for each meteorological sample using other input data and algorithms in the model	User enters value	User enters value single value	The GENII2 deposition velocity model is approved for safety analysis. When GENII2 is not used for the dispersion and consequence analysis, the 95th percentile deposition velocity determined from the GENII2 output is recommended as input to either the MACCS2 or HotSpot software. Alternatively, the default value of 0.1 cm/s for an unfiltered release may be used.
Resuspension	Option available to user	Option available to user	Option available to user	Resuspension does not need to be modeled per DOE-STD-3009-2014 since that this atmospheric redistribution mechanism develops slowly; including this dose pathway is conservative.

Model Feature	GENII	HotSpot	MACCS2	Guidance
Radioactive Decay During Plume Transport	Option available to user	Option not available to user	Option available to user	Decay of radioactive isotopes in the plume is a function of the travel time and the half-life of each specific radionuclide that is present in the plume. In practice, this effect is appreciable with radioisotopes of half-life on the same order or shorter than the time to reach the receptor under consideration. For non-reactor facilities, inadvertent criticality event would be the primary accident type for which this factor is important.
Grid Spacing	User selection	User selection	User selection	Grid spacing can have an impact on the radiological dose calculations.
Mixing Height Treatment	Variable depending on data input	Seasonal, user input	Seasonal, user input	Mixing height represents the lid on vertical dispersion. Once the plume reaches the mixing lid, it reflects back to the ground.

6.9.1 MACCS2

The MELCOR Accident Consequence Code System (MACCS) code,[77] and its successor, MACCS2,[78] are based on a straight-line Gaussian plume model. MACCS was developed originally for the NRC, whereas MACCS2, an enhanced version, was developed to address DOE applications.

MACCS2 V 1.13.1 is a DOE toolbox code, and because it is a comprehensive and flexible code it is one of the most widely used codes in the DOE/NNSA complex. The MACCS2 package includes three primary enhancements: (1) a more flexible emergency response model; (2) an expanded library of radionuclides; and (3) a semi-dynamic food-chain uptake model. The new code features allow detailed evaluations of potential consequences to workers at nearby facilities on large DOE reservations and allow the user to assess the potential impacts of over 800 radionuclides that could not be considered with the earlier MACCS code.

MACCS2 requires significant user experience to set up input files which include:

- Range intervals;
- Population distribution;
- Weather scenario;[79]
- Release height, number, and duration of plumes;
- Radionuclides released;[80]
- Organ doses and health risks;
- Dose conversion factors;
- Evacuation timing and routes;
- Costs of decontamination and interdiction;
- Sensible heat;
- Radiation shielding parameters; and
- Deposition and resuspension.

WinMACCS V 3.10, a new version of MACCS2 with a Windows-based user interface, has been released, but has not yet (as of Handbook publication) been approved as a toolbox code (McFadden et al., 2007).

MACCS2 has also been successfully used in modeling the atmospheric dispersion and consequences of a plume of Pu-239 particulates resulting from an HE detonation, although it was not originally designed for that purpose.

DOE Safety Advisory 2009-05, *Errors in MACCS2 χ/Q Calculations*, describes a problem at large distances (greater than 2 km) with the lookup table with MACCS2 versions 1.13.1 and 2.4 (DOE Safety Advisory 2009-05; Napier et al., 2011) and it details an approach for avoiding the error. When using this approach, the results should be verified to ensure the error was adequately addressed. PNNL evaluated the Safety Advisory approach and found it to be insufficient at addressing the problem (Napier et al., 2011). This error has been fixed with MACCS2 Version 2.6. The PNNL team recommends the use of

[77] NUREG/CR-4691; NUREG/CR-6059.
[78] NUREG/CR-6613; NUREG/CR-6547.
[79] Constant weather, various variable-weather scenarios (such as using one year of hourly averages of wind speed and direction, stability class, precipitation), and type of weather sampling.
[80] Over 800 can be specified in MACCS2, an increase of over 500 from MACCS.

the power law approach (Tadmor and Gur dispersion parameters) that avoids this potential error when using MACCS2 for distances greater than 500 m (Napier et al., 2011).

The toolbox version of the code (MACCS2 V1.13.1) is not strictly compliant with DOE-STD-3009-94 CN3, Appendix A calculation requirements for determination of the overall site 95th percentile χ/Q. However, its results can be viewed as providing a reasonable approximation to this level of consequence, and can be used for the Option 2 χ/Q method from DOE-STD-3009-2014, Section 3.2.4.2. Historically, MACCS2 has been used to calculate the offsite 95th percentile χ/Q for DOE facilities despite the fact that the methodology used does not take into account variations in site boundary distances. As stated in DOE-EH-4.2.1.4:

> MACCS2 and MACCS do not comply fully with … [NRC Regulatory Guide 1.145 Position 3] methodology for determination of direction-independent 95th percentile dose to the offsite individual. It may be used to conservatively evaluate the 95th percentile direction-independent dose to receptors equidistant to the source.
>
> Given site-specific data, the 95th percentile consequence is determined from the distribution of meteorologically-based doses calculated for a postulated release to downwind receptors at the site boundary that would result in a dose that is exceeded 5% of the time. DOE-STD-3009 allows for variations in distance to the site boundary as a function of distance to be taken into consideration. Assuming the minimum distance to the site boundary applies in all directions is a conservative implementation that is easily supported by MACCS2 and that essentially makes the calculations sector independent.

6.9.2 GENII

The Hanford Environmental Radiation Dosimetry Software System, GENeration II (GENII), is also based on a straight-line Gaussian plume model. GENII V1.485 (Napier et al., 1988), which is a DOS-based toolbox code, is available from the Radiation Safety Information Computational Center as package CCC-601. A newer, Windows-based version, GENII V 2.10.1, with a user-friendly interface (FRAMES) has been evaluated and approved as a toolbox code.

The GENII code has been thoroughly documented and was developed under a stringent quality assurance program based on ANSI/ASME NQA-1-2008. It has been used in consequence calculations by safety analysts for many years.

GENII is a comprehensive and flexible code with a strong emphasis on environmental dispersion processes beyond those of atmospheric dispersion (aquatic dispersion, groundwater transport). (See Chapter 7.) To quote from the APAC Working Group 5 report (APAC/TEEL-5, 1998):

> GENII is a radiological assessment computer code system that estimates individual and collective doses to humans from the environmental transport of radionuclides in the atmospheric, surface water, and other environmental media, such as biotic transport and manual redistribution to the surface from buried waste. GENII is used for a variety of radiological assessments including 1) acute atmospheric releases, 2) chronic atmospheric releases, and 3) residual soil contamination.

GENII V 2.10.1 has extensive libraries of isotopes and associated dose conversion factors. It calculates doses from inhalation, ingestion, and external radiation (cloudshine and groundshine).

The required meteorological data to drive the code consists of JFDs of wind speed and stability class for each of the 16 wind directions, usually taken to be 22.5-degree azimuth compass directions, with the first one centered on north. The toolbox version of the code (GENII V 1.485) is not strictly compliant with DOE-STD-3009-94, CN3 Appendix A calculation requirements for determination of the overall site 95th percentile dose. However, its results can be viewed as providing a reasonable approximation to this level of consequence. Users should also recognize that the older version uses atmospheric dispersion models that do not account for plume depletion from wet and dry deposition phenomena or resuspension.

The GENII code also allows the user to specify radionuclide concentrations in the environmental media, as may be produced from another code or previous analysis. In this mode, GENII will calculate the corresponding radiological doses from various pathways.

6.9.3 HOTSPOT

The HotSpot Health Physics Codes, or HotSpot program, provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. The toolbox version of this code is Version 2.07.1 (Homann, 2010) and, as with the other two radiological consequence codes, is based on the Gaussian plume model. The user inputs a 95 percent meteorological condition[81] and selects various source term options and dose output options. The software is also used for safety analysis of facilities handling radioactive material. HotSpot atmospheric dispersion model codes are a first-order approximation of the radiation effects associated with the short-term (less than a few hours) atmospheric release of radioactive materials.

As is true for MACCS2, HotSpot is not strictly compliant with DOE-STD-3009-2014, and for the same reasons. HotSpot Version 3.0.1, has been released, but has not yet been approved as a toolbox code.

6.10 ATMOSPHERIC DISPERSION OPTIONS IN DOE-STD-3009-2014

Three options are given in DOE-STD-3009-2014 to evaluate atmospheric dispersion and the resulting χ/Q:

- Option 1: Follow a process based on NRC Regulatory Guide 1.145*;*
- Option 2: Use a DOE-approved toolbox code and apply the conservative parameters; or
- Option 3: Use site-specific methods and parameters as defined in a site/facility specific DOE-approved modeling protocol.

All three options evaluate the χ/Q at the MOI using either a 95th percentile for a “directionally independent” method or a 99.5th percentile for a “directionally dependent” method. NRC Regulatory Guide 1.145 defines how to derive the “95th percentile directionally independent” and the “99.5th percentile directionally dependent” χ/Q values. For each of these, the minimum distances to the site boundary in 45° azimuth-wide sectors centered on 16 directions (N, NNE, …) is to be derived and the χ/Q value for each hour during the year is to be calculated. The term “directionally independent” as used in

[81] Hotspot Version 2.07.1 and Version 3.01 can also work with hourly observations.

DOE STD-3009-2014 means that the determination of the overall site 95th percentile χ/Q is calculated by creating a cumulative probability distribution for all sectors combined based on all the meteorological annual data and using the actual site boundary distance for each sector, and choosing the 95th percentile value. The "99.5th percentile directionally dependent" value is found by creating a cumulative probability distribution for each sector using the actual site boundary distances, determining the 99.5th percentile value for each, and choosing the maximum value.

The value of χ/Q using Option 1 can be accomplished manually using a spreadsheet. Option 3 allows the use of software generated at the site if it follows a DOE site-approved atmospheric dispersion modeling protocol. For Option 2, one of the toolbox codes is to be used. It should be noted that the often-used MACCS2 software does not fully comply with NRC Regulatory Guide 1.145, as explained above, yet is accepted by DOE as the 95th percentile value for the closest point on the site boundary is conservative. POSTMAX V2.0 (Sartor, 2009), software developed at LANL, can be used to generate the 95th percentile value of χ/Q from the MACCS2 output that is compliant with NRC Regulatory Guide 1.145. POSTMAX2 has been subjected to SQA at LANL (Letellier and Ashbaugh, 2001) but it is not one of the toolbox codes, so therefore anyone using POSTMAX2 for a DSA will need to do their own SQA.

6.11 ATMOSPHERIC DISPERSION MODELING PROTOCOL

The following 15-step modeling protocol provides additional dispersion analysis guidance beyond that of Section A.7 of DOE-STD-3009-2014 and is applicable to both radiological and toxic chemical releases. This modeling protocol guidance addresses evaluation of the MOI receptor, as appropriate, for submittal to the DOE Safety Basis Approval Authority (SBAA) for approval prior to its application. Guidance for implementing the recommendations below can be found elsewhere in this chapter and in Chapter 8 regarding radiological dose estimation, or in Chapter 9 regarding toxic chemical consequences.

The 50-mile population dose calculation is included for situations where accidents cannot be prevented or mitigated to less than the 25-rem EG and a comparison to DOE Policy 420.1, *Department of Energy Nuclear Safety Policy*, may be required; or if necessary, for evaluation of beyond DBA/EBA accidents (Section 3.1) to provide a risk perspective of any "cliff edge" effects or insights for emergency planning.

The 100 m CW is not included in this modeling protocol since guidance has already been established in OE-3:2015-02, *Atmospheric Dispersion Parameter (χ/Q) for Calculation of Co-located Worker Dose.* Section 6.13 provides specific guidance for the CW χ/Q. Assumptions and inputs for the CW evaluation that are different from the MOI dispersion analysis are documented in the DSA Chapter 3 hazard evaluation methodology, or alternately, in the accident analysis methodology. The 15-step modeling protocol worksheet looks like this:

1. Identify dispersion model and version number chosen and the basis for its selection:
    a. Identify dispersion model and version number chosen, and indicate whether it is an approved version of a toolbox code available through the DOE CR.
    b. Describe the appropriateness of the modeling technique relative to the site-specific and facility-specific application and the basis for its selection.
    c. State whether the default values recommended in the DOE guidance document for the DOE Central Registry toolbox code will be used, or technically justify the use of alternate values.
    d. If a DOE CR toolbox code is not used, describe the SQA assessment has been performed, or will be performed on the selected code.

Note 1: Safety SQA requirements in DOE O 414.1D need to be met prior to using any code that is not in the DOE CR toolbox.

e. In lieu of selecting a DOE CR toolbox code or other industry-accepted code, the proposed dispersion analysis may be performed within a spreadsheet, if it is documented as an engineering calculation that complies with applicable site SQA requirements.

Note 2: DOE sites may choose any modeling approach it deems applicable to facility-specific phenomenology and site-specific atmospheric dispersion, as long as it is approved by the DOE SBAA prior to its application for the DSA accident analysis. The SBAA is expected to rely on subject matter experts experienced in dispersion analysis and/or an expert review panel for evaluating the selected modeling approach.

2. Specify the receptors to be evaluated:
   a. MOI
   b. Other sensitive receptors
   c. 50-mile population (when needed)

3. Describe site- and facility-specific elements:
   a. *Release height*: Indicate the height of the release above plant grade and determine whether it is sufficiently high to escape the aerodynamic effect of nearby buildings to become elevated.

      Note 3: If the release height is less than 2.5 times higher than nearby adjacent buildings, the release height should be set to zero (i.e., ground-level release).

      Note 4: If release is from a stack 2.5 (or more) times higher than nearby adjacent buildings, but the stack is not seismically-qualified, it should be treated as a ground-level release.

   b. *Terrain profile to determine potential interactions (plume impaction)*: If the release height is determined to be ground-level then terrain effects do not affect the analysis unless it is a dense gas release that may be gravity-fed into a nearby depression. For elevated releases, impaction of the plume on a downwind hill or mountain should be incorporated into the analysis. If a non-toolbox code has been selected to model the impact of terrain effects on atmospheric dispersion, describe the site's unique terrain profile.

   c. *Surface roughness data source (population, terrain)*: Identify the surface roughness or terrain type (i.e., urban, rural) applicable to the analysis for the site morphology and indicate how this affects the horizontal and vertical turbulence parameters. Provide a technical basis for the establishment of site roughness parameters inclusive of tree types, density, configuration, topography, building locations and types, and local land use.

      Note 5: Surface roughness considers both upwind (i.e., fetch) and downwind characteristics of the release point, and the value used for the MOI could be different from that for a 50-mile population dose calculation.

   d. *Population distribution within 50-mile radius*: For population dose calculations, determine the population in each of the annular sectors, the census year represented, and whether day-night population distributions are to be applied and the justification for their application.

      Note 6: Population doses are included in this Handbook since it may be of interest for special risk assessments to compare to the DOE Safety Goal in DOE P 420.1, Department of Energy Nuclear Safety Policy, and could be used to provide perspective should a facility have mitigated doses to the MOI that exceed the 25 rem EG.

e. *Site map with locations of receptors of interest*: Develop a map of the DOE site with DOE-controlled property line and MOI site distances for the 16 sectors, in conformance with NRC Regulatory Guide 1.145, and other relevant boundaries, inclusive of the Perimeter Intrusion and Detection Alarm System or other security physical control boundaries.

f. *Location of release points*: Develop a map that shows the location of all release points that are being analyzed, or describe whether the release is not associated with fixed locations (e.g., a release in a large outdoor waste staging area).

g. *Mixing Layer Height*: Select the appropriate mixing layer height and justify its selection.

4. Describe release characteristics:

a. *Initial plume dimensions*: Should the release become entrained in the wake and cavity of a nearby building, describe the method to calculate the initial horizontal and vertical plume dimensions, if treated as a virtual point source.

b. *Positive and negative buoyancy*: If plume buoyancy occurs due to sensible heat of the release, or its density, as in a hydrogen release, indicate its applicability to the analysis and the analytical technique to be employed to account for it. For heavy gas (dense gas) releases, determine if the release quantity, boiling of a cryogenic liquid, and/or density of the release, represented by the Bulk Richardson Number, would subject it to dense gas dispersion conditions and describe the analytical technique to be employed to account for it. See footnote 55 with respect to indoor fires.

c. *Elevated or ground-level release*: Based on the presence of a nearby or adjacent building, determine whether the release is elevated or down-washed to ground level. For elevated releases of gamma-emitting radionuclides, additional cloud shine dose calculations using an appropriate finite plume model may be necessary. Describe the finite plume model to be used.

d. *Aerodynamic influence of nearby buildings*: Establish the appropriate code to account for the aerodynamic effect of the buildings on the release.

e. *Energetic releases*: Identify the code to be used for each energetic release situation and the justification for its use. Releases from fires can be modeled with MACCS2 and Hotspot. For other energetic releases (e.g., detonations, deflagrations, delayed ignition, BLEVEs), codes other than MACCS2 or HotSpot that are better suited to assess release dynamics for energetic events may be employed if an effective release height calculation cannot be justified for input to an appropriate Gaussian model.

Note 7: ALOHA V 5.4.6 is a toolbox code that is designed to address detonations, delayed ignition, radiant heat from a fire, and a BLEVE.

5. Describe source term phenomenology and characterization, as applicable to any particular accident scenarios:

a. *Particulate and Pressurized Liquid Releases: Five-Factor Formula (MAR, DR, ARF, RF, LPF)*: Include a discussion whether the unmitigated and mitigated source terms, as determined by the DOE-HDBK-3010-94 methodology, warrant any special considerations for input to the dispersion analysis, or state why there are none.

Describe if the source term has any special physical release properties that may influence dispersion or consequence estimates. Indicate whether it will be modeled other than as a point source, not already addressed in the considerations above, or whether it will be modeled considering momentum from the discharge velocity, or as a buoyant release due to elevated discharge temperature of the release, fire, or explosion.

If credited in the mitigated analysis, identify LPF from building configurations and presence or absence of HEPA filters.

b. *Particulate and Pressurized Liquid Releases: Particle-Size Distribution*: Since particle size distribution spectra are very important for establishing RF, ARF, and deposition velocity, establish the applicable particle size distribution from DOE-HDBK-3010-94, supplemented by representative studies and experiments. If the particle size distribution is unknown, assume a conservative distribution from available data to bound the calculation.

c. *Pressurized and non-Pressurized Gaseous Releases: Release Period and Release Rate*: Determine gaseous release as a function of time for pressurized gaseous releases.

If gaseous release is constant and continuous establish a constant release rate as input to a peer-reviewed Gaussian plume model.

If release is for a brief period (i.e., less than a minute), establish a release quantity as input to a peer-reviewed Gaussian puff model.

d. *Pressurized Liquid and Gaseous Releases: Density with respect to ambient atmosphere*: Select appropriate code to address whether positive buoyancy or negative buoyancy is applicable.

Note 8: HPAC SCIPUFF has been used to address positively buoyant gases (e.g., hydrogen) and ALOHA, DEGADIS, SLAB and HPAC have been used to address negatively-buoyant gases (e.g., chlorine).

e. *Gaseous Releases: Reactivity on release to the atmosphere*: Effects of atmospheric chemistry should to be considered on releases that may undergo chemical transformation during transport to the MOI and population (e.g., uranium hexafluoride and anhydrous ammonia).

f. *Gaseous Releases: Fire scenario chemical transformation*: Oxidation of radionuclides or toxic chemicals in fires result in new substances, depending on temperature and availability of oxygen. Peer-reviewed literature should be consulted in the determination of the new substances to be evaluated.

Note 9: Seek assistance from a process chemical engineer or chemist to determine the new substances and their quantities to be evaluated.

g. *Pressurized Gaseous Releases*: Identify the size of the orifice and whether choked flow is applicable. Due to the nature of this type of release, it is non-linear and the release rate decreases with time.

Note 10: Consult technical literature for release rate characterization and if flow is choked by speed of sound limitation.

h. *Pressurized Liquid and Non-Pressurized Liquid Releases*: Determine the evaporation rate of the puddle using appropriate mass balance methodology. Unless release is confined in an impoundment basin, an unconfined puddle depth should be justified based on the surface type, or a depth of 1 cm may be assumed consistent with 40 CFR 68, *Chemical Accident Prevention Provisions,* guidance for a worst case spill (EPA-550-B-99-005).

Note 11: ALOHA V 5.4.6 has a useful mass-balance algorithm, or manual calculation methods presented in Appendix B can be applied.

i. *Pressurized Liquid Release*: Depending on the substance and the pressure and temperature that it is stored, the release will be in two phases. Immediate flashing results in a gaseous puff and a puddle. The puff should be evaluated with a Gaussian puff model and the subsequent puddle evaporation by a Gaussian plume model.

Note 12: HPAC and ALOHA Version 5.4.6 contain useful algorithms to determine flash-aerosol-puddle quantities. Manual calculation methods presented in Section 4.3 of this Handbook can also be applied.

j. *Sensible Heat from Fire*: Determine impacts of sensible heat from fire in terms of radiant heat impacts on human skin exposure and on facility integrity.

Note 13: ALOHA V 5.4.6 contains useful algorithms to determine radiant heat impacts of sensible heat.

k. *Deflagration*: Determine energetic release propagation rate. If slower than the speed of sound, a deflagration fireball results. Select the appropriate peer-reviewed code to establish impacts to workers, public, the environment, and SSC integrity.

Note 14: NASA fireball code (Dobranich et al., 1997) addresses this phenomenology and the analyst may wish to consult this report for guidance.

l. *Detonation*: Determine energetic release propagation rate. If faster than the speed of sound, a detonation occurs. Select the appropriate peer-reviewed code to establish impacts to workers, public, the environment, and SSC integrity.

Note 15: ALOHA V 5.4.6 contains useful algorithms to determine overpressures from detonations.

m. *Detonation (delayed ignition)*: Delayed ignition detonations may occur hours after release and depend on the mechanical turbulence generated by obstacles (trees, buildings) in its transport path.

Note 16: ALOHA V 5.4.6 contains useful algorithms to determine overpressures from delayed ignition detonations.

n. *BLEVE*: Determine whether a fire of a tanker or container can result in a BLEVE.

Note 17: ALOHA V 5.4.6 contains useful algorithms to determine overpressures from a BLEVE.

6. Describe meteorological data sources and assure its fidelity:

   a. *Onsite instrumented meteorological tower*: Indicate whether an onsite source of representative meteorological data is available and if so, indicate locations of meteorological towers on site map with release locations. The meteorological program should monitor wind speed, wind direction, and an indicator of atmospheric stability (e.g., temperature difference, sigma theta, sigma phi).

   b. *Heights of measurement*: Identify the heights of measurement for each of the meteorological parameters that will be used in the analysis. Ideally, wind speed and wind direction data are measured at the standard 10-meter height. If wind speed is measured at a non-standard height, wind speed power law height adjustments should be considered. The temperature difference minimum height should be at least 35 meters if the delta T method is used to determine stability class.

   c. *Certification of data quality*: Indicate whether the onsite meteorological data has been quality assured under the guidance of Section 7.4 of ANSI/ANS-3.11-2015. Provide a certification from the site meteorological program manager, or other organization accountable for the effective operation of the meteorological program.

d. *Pre-processing and averaging methodology*: Demonstrate that the raw meteorological data have been appropriately pre-processed and averaged to be applicable to the assessment.

e. *Missing data handling techniques*: Since all meteorological data bases have some gaps due to calibrations and instrument malfunctions and missing data needs to be addressed, demonstrate that the data base has appropriate missing data handling as part of its quality assurance program.

f. *Offsite representative meteorological source (e.g., National Weather Service)*: If quality-assured onsite meteorological data are not available, determine a surrogate data source nearby the site and demonstrate that it is spatially representative.

7. Describe meteorological data application to dispersion assessment:

   a. *Applicable meteorological parameters*: State which meteorological parameters will be used in the dispersion assessment.

   b. *Calm wind speed threshold and handling methodology*: Calm wind speed handling methodology is very important to consequence assessments since very light wind speeds are part of the 95% and 99.5% meteorology. Demonstrate that calm wind speeds are appropriately handled in the data base and are tied to the threshold wind speed limitations of the mechanical or sonic anemometry.

   c. *Turbulence typing methodology*: Choose the technique to type turbulence and demonstrate that the methodology selected is representative of the site's roughness and other site-specific and facility-specific characteristics.

   d. *Incorporation of surface roughness in turbulence typing*: Since surface roughness affects mechanical turbulence generation, the horizontal and vertical dispersion parameters should reflect this. Demonstrate whether the site should be characterized as a rural or urban site by profiling the site's roughness. Rough rural sites can be described using rural dispersion parameters with an applicable roughness correction but should never be classified as urban.

   e. *Wind speed power law height adjustments*: If wind speed and wind direction measurements are at any height except the standard of 10 meters, appropriate wind speed height adjustment techniques (e.g., power law) should be invoked. Power law exponents are a function of atmospheric stability class. Indicate which power law methodology is employed and justify why it is applicable to the site.

8. Select meteorological data period:

   a. *1-5 years*: At least 5 years of recent meteorological data are needed to demonstrate temporal representativeness. Depending on completeness of the data record, consecutive years of recent meteorological data are preferred (EPA, 2000). Identify the years of data that will be evaluated, and explain any anomalies, such as years being excluded if not able to be certified. If data base is shorter than 5 years, a representativeness demonstration is required to determine any uncertainties.

   b. *More than 5 years*: If meteorological data are available in this temporal range, use as much as are available. The larger the data base, the less likely a climatological "Black swan" is missed in the statistics.

9. Select appropriate atmospheric dispersion parameters:

Demonstrate that the dispersion parameters are applicable to site characteristics. The dispersion parameters can be taken from the following menu:

a. Pasquill-Turner-Gifford (rural terrain, hand scaling)

b. Briggs urban and rural

c. McElroy-Pooler (urban terrain)

d. Eimutis and Konicek curve fitting of the Pasquill-Turner-Gifford data

Note 18: Eimutis and Konicek are used in MACCS2. However, the analyst should be aware of the table lookup error in the toolbox version of the MACCS2 code.

e. Tadmor and Gur curve fitting of the Pasquill-Turner-Gifford curves

Note 19: Tadmor and Gur are used in MACCS2, but are not recommended for the MOI within 500 m of the release.

f. Other dispersion parameters resulting from special site atmospheric tracer studies and/or other peer-reviewed evaluations.

10. Select plume averaging time, if different from release duration, and demonstrate its applicability to selected horizontal and vertical dispersion parameters.

    a. If time-based meander factors are used, ensure that the time basis is consistent with the technical basis of the selected dispersion parameters (e.g., 3 minutes for P-G-T).

11. Describe release duration and exposure period:

    a. Demonstrate that the selected release duration range is applicable to the assessment.

    b. Use a peer-reviewed dispersion model appropriate for the scenario in question. For Gaussian models, use a *plume* code for releases longer than one minute, and for a period shorter than one minute, use a puff code or turn off any time-based meander corrections in a plume code. For energetic releases, use an appropriate codes other than MACCS2 or HotSpot that are better suited to assess release dynamics for energetic events, or justify use of an effective release height input to an appropriate Gaussian model.

12. Describe aerodynamic building effects:

    a. *NRC Regulatory Guide 1.145 technique***:** Demonstrate that this conservative plume downwash into the lee-side cavity is applicable to the assessment.

    b. *Other peer-reviewed technique***:** Identify other peer-reviewed techniques, such as discussed in Section 6.8.3 of this Handbook, and demonstrate that this other technique is applicable to the assessment.

13. Describe dry deposition and plume depletion:

    a. *Dry deposition technique*: Indicate whether the dispersion assessment will include dry deposition and provide justification for the site-specific methodology employed. Refer to LLNL-TR-654366, *Deposition Velocity Methods for DOE Site Safety Analysis* and "Detailed Technical Basis for Default Dry Deposition Values" in the DOE/HSS Safety Bulletin No. 2011-02 for guidance.

Note 20: For tritium dispersion modeling, an appropriate deposition velocity is 0 cm/sec. Deviation from this deposition velocity value needs to be justified.

b. *Plume depletion technique*: Indicate whether the dispersion assessment will include plume depletion and provide justification for the site-specific methodology employed.

14. Describe χ/Q statistics and determine applicability to the assessment.

    a. *Direction-Independent (overall site) 95-percentile*: Usual choice for conservative evaluations of the cumulative distribution of the annual meteorological data for all 16 sectors accounting for the distance to site boundary in each sector.

    b. *Direction-Dependent 99.5-percentile*: Acceptable alternative to the direction-independent 95^{th} percentile for conservative evaluations based on the maximum sector cumulative distribution determined using actual site boundary distances for each sector.

    c. *Other percentile*: Demonstrate applicability to the dispersion assessment of any other percentile than those above for use in realistic analysis of Beyond Design/Evaluation Basis Accidents, if that option will be used.

15. Provide a summary of the basis for the conclusion that the selection of the parameters and input values, as identified above, will provide an overall radiological dose or chemical exposure consequence that is bounding and conservative. Include a list of conservatisms below.

Note 21: Peer-reviewed models used in this protocol need to meet the SQA criteria in DOE O 414.1D and DOE G 414.1-4A.

6.12 NON-GAUSSIAN DISPERSION MODELING

6.12.1 DISPERSION UNDER EXTREME WIND OR TORNADO EVENT

Dispersion under extreme (high) wind or tornado event conditions warrants additional considerations with respect to consequence analysis. The analysis performed for an extreme-wind/tornado event condition; severe enough to challenge SSC integrity, should initially address the effect of the event, including its incidence and return period, causing the release. Site-specific data may be used to characterize the extreme meteorological conditions, using a Probabilistic Wind Hazard Analysis (PWHA). Guidance for developing a PWHA is identified in ANSI/ANS-2.3-2011 (R2016), DOE-STD-1020-2016, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, and DOE-HDBK-1220-2017, *Natural Phenomena Hazards Analysis and Design Handbook for DOE Facilities*. If the analysis determines releases are likely to occur after the initial storm impact, the assessment should incorporate the appropriate meteorological conditions.

Once the SSC failure is established, consequences from the unmitigated release through the breached barrier in a less-turbulent atmosphere following the event should be evaluated at locations that include the maximum exposure point and other locations of interest. The simultaneous assumption of an extreme wind or tornado accident scenario with minimal dispersion lends high confidence as to the conservatism of the final result.

Section B.3 of NRSD-2015-TD1 (2015) refers to a 1996 study by Weber and Hunter, *Estimating Dispersion from a Tornado Vortex and Mesocyclone (U)*, that provides a peer-reviewed technique to determine downwind concentrations from releases caused by extreme winds or tornado that removed a primary confinement barrier. In the specific scenario studied, the tornado damages the structure and draws the released substance into its vortex. This scenario is comparable to an accident characterized by an instantaneous release and a short exposure time. The study is illustrative of the considerations for the conditions resulting from a tornado that would first be assessed and calculated at the maximum exposure point. A second and longer-term phase would also be included to account for a secondary release, potentially without crediting the presence of a structure. The two receptors may be at different distances from the source of release.

Weber and Hunter (1996) indicated that atmospheric transport and diffusion of a release from the facility into the environment during a tornado can be modeled with a DBA dilution factor (*Ψ/Q*), designated for a specific class tornado and applied for the distance from the facility to the receptor. The *Ψ/Q* parameter (units of s/m^3) represents the time-integrated ground-level centerline air concentration normalized by the mass released, and is analogous to the *χ/Q* value that is calculated from the Gaussian plume equation for neutrally buoyant releases. The Fujita scale (F1 to F5) is commonly used to categorize tornadoes. For most DSAs, the tornado is assumed to be either F2 or F3. Figure 6-9 shows *Ψ/Q* values as a function of downwind distance for different mean translational speeds of an F2 tornado.

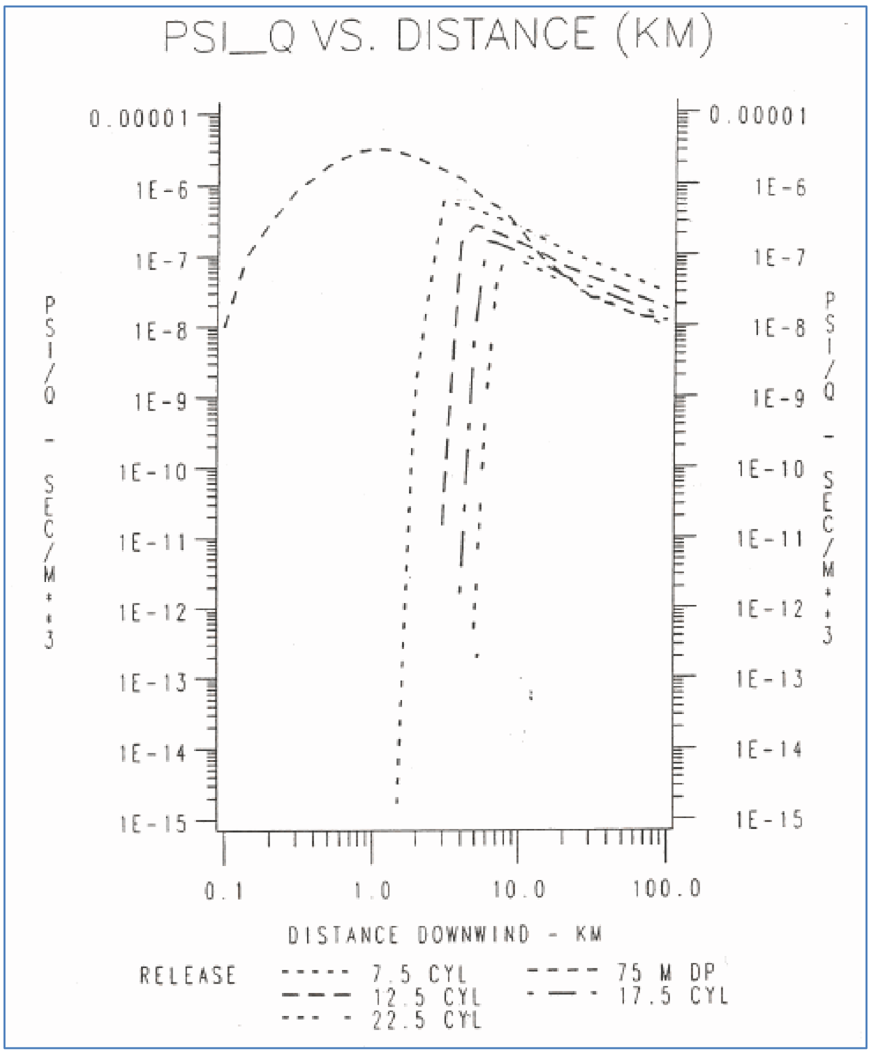

Figure 6-9. Maximum time-integrated ground-level centerline air concentration (s/m^3) versus downwind distance (km) for different mean translational speeds from 7.5 m/s to 22.5 m/s.[82]

The consequence analysis should select a maximum *Ψ/Q* for the assumed translational speed. For example, a translational speed of 7.5 m/s leads to a maximum air concentration at approximately three kilometers downwind. The product of the maximum *Ψ/Q* value and the release rate yields the ground level air concentration at the maximum exposure point and locations of interest.

6.12.2 FINITE PLUME EXTERNAL DOSE MODELING

Chapter 8 addresses radiological dose consequences, primarily from the inhalation pathway. However, depending on the mix of radionuclides, it is possible that inhalation doses may not be controlling, especially if an elevated radionuclide release has a higher proportion of strong gamma-emitting isotopes (such as Co-60, Xe-133, Cs-137). In this particular circumstance, the semi-infinite plume Gaussian model may not be sufficient for establishing radiological consequences and a finite plume external dose model may need to be applied. For an elevated plume, the concentration at the ground level and concomitant inhalation dose is zero, whereas, the dose from the gamma radiation of the overhead plume can be much greater than zero.

There are several codes available to calculate gamma shine doses, including *External Dose Conversion Factors From Finite Airborne Radioactive Plumes* (Momeni, 2001) and *Monte Carlo N-Particle Transport Code System* (MCNP, 1998), the latter a Monte Carlo transport code. With respect to the finite-cloud sector-average model (Hamawi, 1976), the long-term gamma-ray dose in the atmosphere from a sector-averaged plume may be expressed as a product of several factors multiplied by a sum of two attenuation integrals.

Since INL operates a reactor capable of releasing gamma-emitting fission products, it has included a finite plume model within its radiological consequence code, *RSAC-6 Radiological Safety Analysis Computer Program* (Schrader and Wenzel, 2001). The latest version of this code is RSAC-8. Although ORNL operates a high-flux irradiation reactor, it does not employ a finite plume code in its suite of dispersion models.

6.12.3 PLUMES FROM ENERGETIC EVENTS[83]

In the initial phase of an energetic event in air, a volume of gas is created that is hot and of high pressure. Because the gas is hot, it rises through its own buoyancy and by the overpressure of the event (see Section 4.3.1). This gas expands rapidly until it equilibrates with the atmospheric pressure. These initial processes determine the plume's initial dimensions and height. After it reaches equilibrium with the ambient atmosphere, conventional atmospheric diffusion processes act on this plume, carrying it downwind as it continues to expand through turbulent diffusion.

HotSpot V 2.07.01 (Homann, 2010), includes atmospheric dispersion models for a nuclear explosion, non-nuclear plutonium explosion, non-nuclear uranium explosion, fire, and tritium release. These models estimate the short-range (<10 km) downwind radiological impact following the release of radioactive

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[82] Downdraft speed is 10 m/s and height of the cylindrical mesocyclone is 3500 m (from Weber and Hunter, 1996). (fn. 82 cont.) CYL refers to the modeled cylindrical shape of the tornado and M DP refers to the results of another tornado modeling study, for comparison.)

[83] See Section 9.5 for additional discussion.

material resulting from a short-term release (<few hours), explosive release, or fuel fire event. The nuclear explosion program estimates the effects of a surface-burst nuclear weapon, which includes prompt effects (neutron and gamma, blast, and thermal).

Virtual source terms are used to model the initial atmospheric distribution of source material following an explosion and fire. The release is partitioned into 5 segments at varying heights up to the cloud top with upward virtual source terms as shown in Section 9 (*HotSpot Algorithms*) of the HotSpot V 2.07.1 User's Manual, reproduced in Figure 6-10. The cloud radius is equal to 0.2 cloud top.

The non-respirable release component is the fraction of the total quantity of material involved, available for dispersion into the atmosphere, which has a separate non-respirable deposition velocity default value of 8 cm/sec, and is used to determine ground shine, submersion, and plume depletion.

The non-respirable release component is the fraction of the total quantity of material involved, available for dispersion into the atmosphere, which has a separate non-respirable deposition velocity default value of 8 cm/sec, and is used to determine ground shine, submersion, and plume depletion.

Another code has been developed expressly for this purpose, the Explosive Release Atmospheric Dispersion (ERAD) code from SNL (Boughton and DeLaurentis, 1992). This code is a three-dimensional numerical simulation of particle dispersion in the atmosphere and includes cloud dynamics, buoyancy effects, and turbulent diffusion. It was designed to run on a small field-deployable computer. The details of this model are beyond the scope of this guidebook, but to summarize, it treats particle dispersion as a stochastic process that can be simulated with a Lagrangian Monte Carlo method. Comparisons with field tracer data (Roller Coaster) show reasonably good agreement between the model predictions and measurements.

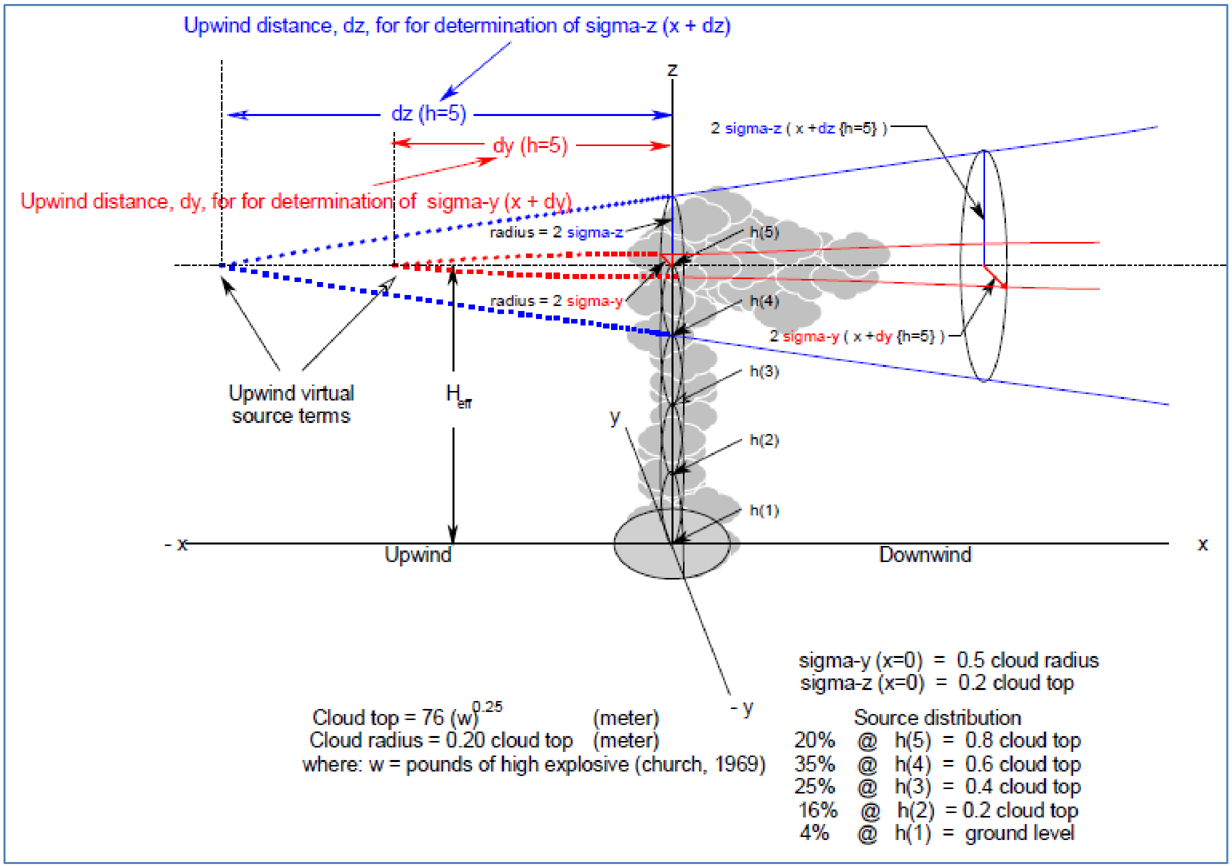

Figure 6-10. Virtual Source Terms used in HotSpot for Explosion or Fire.

ERAD is difficult to use, in that the required array of three-dimensional meteorological data cannot be easily obtained for code input, and the final consequence statistics cannot be easily derived. An alternative method was therefore derived that makes use of a dispersion and consequence code that is commonly used at DOE sites, namely, MACCS2 (see below). In this method, *Plutonium Explosive Dispersal Modeling Using the MACCS2 Computer Code* (Steele, 1998), equations are derived that give the cloud top height and the cloud radius as a function of time and amount of explosive used. Because the plume asymptotically approaches the "final" height and size, the expressions are evaluated at three minutes following the detonation, as the height and size are nearly the same then as their asymptotic values. This leads to two simple expressions. The cloud top height (*CTH*) is given by

$$CTH\ (m) = 75\ w^{1/4} \qquad \textbf{Equation 6-33}$$

where *w* is the weight of the explosive in pounds of TNT equivalent. The cloud radius (R) is

$$R\ (m) = 16\ w^{1/4} \qquad \textbf{Equation 6-34}$$

These expressions are found to match observations surprisingly well. For use in MACCS2, the initial height of the plume is set to $CTH - R$, and the initial cloud size is set to $\sigma_y = \sigma_z = R$. The resulting plume concentrations are found to match observations about as well as ERAD did. Note that the above discussion does not apply to indoor explosions.

6.13 CO-LOCATED WORKER DISPERSION FACTOR

As mentioned in, Section 6.2, *Key Receptors*, the CW is a hypothetical individual located at a distance of 100 meters from a facility (building perimeter) or estimated release point. Unmitigated CW dose calculations are used to evaluate whether SS controls are needed for protection of onsite workers. DOE-STD-3009-2014, Section 3.2.4.2 requires that:

> A χ/Q value of 3.5 x 10^{-3} sec/m^3 shall be used for ground-level release evaluation at the 100 meter receptor location unless an alternate onsite χ/Q value is justified. This value may not be appropriate for certain unique situations such as operations not conducted within a physical structure. When an alternate value is used, the DSA shall provide a technical basis supporting the need for the alternate value and the value selected.

The threshold for designation of SS controls is a 100 rem dose and the χ/Q value of 3.5 x10^{-3} s/m^3 is part of the unmitigated dose calculation for the 100-m CW receptor. New nuclear facilities or major modifications to existing facilities apply the χ/Q value specified in the Standard; however, there may be a limited number of situations where this value is not appropriate for the release conditions, and an alternate value may be more appropriate. NSRD-2015-TD01 and OE-3 were issued in 2015 to establish the regulatory basis of this χ/Q value. A discussion of this technical report and OE-3 follows.

6.13.1 TECHNICAL REPORT FOR CW X/Q VALUE

NSRD-2015-TD01 assesses the "default χ/Q value" and its technical and regulatory bases (DOE/ONS, 2015). The purpose of the technical report is to explore the sensitivities of the radiological χ/Q value, previously stated is conservative. The χ/Q value in Appendix A to DOE-STD-1189-2008 was based on NUREG-1140, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licensees*, that applied Gaussian plume dispersion methodology for a 95% conservative meteorological condition with a building size of 10 m × 36 m, and included other commonly utilized conservative assumptions (e.g., centerline concentrations).

Although the default χ/Q value was based on a number of conservative assumptions, the technical report determined that atmospheric dispersion calculations were most sensitive to variations in initial plume dimensions that were driven by the aerodynamic effects of the physical structure at the point of release. The technical report analyzed sensitivity studies using the radiological consequence codes MACCS2 and ARCON96 (NRC Regulatory Guide 1.194, *Atmospheric Relative Concentrations for Control Room Radiological Habitability Assessments at Nuclear Power Plants*), and the toxic chemical codes ALOHA and EPICode, to conclude that the default χ/Q value represents a conservative estimate of atmospheric dispersion for calculating both radiological and toxic chemical exposure of the CW, where the release is subject to aerodynamic effects from a facility building with a nominal cross-sectional area of 10 m × 36 m. However, the technical report also acknowledged that for uncommon situations where there is a radiological or toxic chemical release from a facility smaller than that assumed in the analysis (e.g., tank farm piping), where the enhanced turbulence from the aerodynamic effects of the facility on the wind field would be smaller, the default χ/Q value may not provide as conservative an estimate of atmospheric dispersion; specifically when benchmarking against Gaussian plume models such as MACCS2.

6.13.2 ALTERNATE X/Q VALUE JUSTIFICATION

DOE-STD-3009-2014, Section 3.2.4.2, allows the application of an alternate χ/Q value as long as the need for this alternate value is justified and its technical basis is documented in the DSA. Although limited, there are situations that may warrant the use of an alternate χ/Q value. As the Technical Report demonstrates, inherent to the default χ/Q value is the assumption that the release is from a nuclear facility with a building size of at least 10 m × 36 m. However, if the building size is smaller than 10 m × 36 m, or if there is no building structure at all, the default χ/Q value may no longer be as conservative and an alternate technique is justified.

Moreover, there may still be a need for using an alternate χ/Q value when the release is from a sufficiently large building. This situation may arise when updating a DSA that was based on DOE-STD-3009-94, CN3 or DOE-STD-3009-2014. DOE sites that already have existing CW values calculated in their DSA should consider the need for updating their analysis to the specified value in DOE-STD-3009-2014 and the impact that it has on control selection. If the updated analysis establishes that no change to SS designation occurs, or no new SSCs or SACs are identified, then the DSA justification documents the selected χ/Q value, and provides a rational that use of the alternate χ/Q value would not impact safety control selection.

When an alternate χ/Q value is used in situations where the default χ/Q value may not be appropriate, the DSA justification should be commensurate with the method of calculating the alternate χ/Q value. The following two subsections discuss hand-calculation and computer code methodologies for calculating a χ/Q value where the default value is demonstrated to not be appropriate.

6.13.2.1 HAND CALCULATIONS FOR A X/Q VALUE WHERE THE DEFAULT VALUE IS NOT APPROPRIATE

Attachment E of NSRD-2015-TD01 provides a simple approach for determining a χ/Q value in situations where the default χ/Q value is demonstrated to not be appropriate for a conservative unmitigated analysis. The approach applies the Gaussian plume equation methodology, basing the initial plume dimensions, σ_{yi} and σ_{zi}, on the actual building width and actual building height that the release emanates from, as shown in Eq. 6-35.

$$\frac{x}{Q}(x = 100, y = 0, z = 0, H = O) = \frac{1}{\pi\, U\left(\sigma_{yi}+\sigma_{y_{100}}\right)\left(\sigma_{zi}+\sigma_{z_{100}}\right)} \qquad \textbf{Equation 6-35}$$

Where:

- U = Wind speed diluting the plume (m/sec);
- σ_{y100} = Standard deviation of concentration in the horizontal direction from 100 m of plume travel (m);
- σ_{z100} = Standard deviation of concentration in the vertical direction from 100 m of plume travel (m);
- σ_{yi} = Standard deviation of concentration in the horizontal direction based on the aerodynamic effects of the building width (m); and,
- σ_{zi} = Standard deviation of concentration in the vertical direction based on the aerodynamic effects of the building height (m).

The initial plume dimensions can be calculated from Eq. 6-36.

$$\sigma_{yi} = W/4.3 \quad \text{and } \sigma_{zi} = H/2.15 \qquad \textbf{Equation 6-36}$$

Where:

W = shortest building width (m); and,
H = minimum building height (m).

The intent of this approach is to address the potential issue concerning releases emanating from locations that either do not have a physical structure or where the building is smaller than 10 m × 36 m. For releases from locations without any physical structure, Eq. 6-36 simply reverts to the ground-level release equation (Eq. 6-5) for a plume that has traveled 100 m with no horizontal and vertical plume expansion to account for the aerodynamic effects of a facility on the wind field. This simple hand calculation or spreadsheet calculation can be quickly executed without employing an atmospheric dispersion computer code, which is consistent with the original intent of establishing a default χ/Q value. Examples of how to use the equation are provided in Attachment E of NSRD-2015-TD01 for different structure dimensions and when no structure is nearby. Case 2 from Table E-1 of the technical report is replicated below for releases from locations without any physical structure assuming that the 95 percent meteorology is Stability Class F and 1 m/s wind speed.

<u>NSRD-2015-TD01 Table E-1 Case 2:</u> For stability class F at a distance of 100 m, the Eimutis-Konicek[84] curve fit algorithms give the following standard deviation of concentration in the horizontal and vertical directions without a building present.

$$\sigma_y = 0.0722 \times 100^{0.9031} = 4.62 \text{ m}$$

$$\sigma_z = 0.086 \times 100^{0.74} - 0.35 = 2.25 \text{ m}$$

$$\chi/Q = 1 / [\pi \times 1 \text{ m/s} \times 4.62 \text{ m} \times 2.25 \text{ m}] = 3.1 \times 10^{-2} \text{ s/m}^3$$

The above χ/Q value can be adjusted by for plume meander[85] due to longer release duration. The standard deviation of concentration in the horizontal direction (σ_y) is adjusted by the plume meander factor (e.g., for a two-hour plume duration and a 3-minute time base) the plume meander factor would be (120 min/3 min) $^{0.25}$ = 2.515, yielding σ_y = 11.62 m, and χ/Q = 1.2Ex10^{-2} s/m^3.

DOE-STD-3009-2014, Section 3.2.4.2 requires that the "DSA shall provide a technical basis supporting the need for the alternate value and the value selected." The DSA justification should explain the rationale why the default χ/Q value is not representative for the particular situation, or other rationale for not adopting the default value, and document how the σ_{yi} and σ_{zi} were calculated from structure dimensions that affect the wind field and the resultant χ/Q value used. If a release is affected by a nearby larger structure, the larger structure width and height should be used in the χ/Q calculation.

6.13.2.2 COMPUTER CODE MODELING FOR A X/Q VALUE WHERE THE DEFAULT VALUE IS NOT APPROPRIATE

The following guidance is provided for a conservative unmitigated analysis when site-specific modeling is performed to estimate CW consequences at 100 m. Use of any alternate dispersion methodologies or

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84 Eimutus-Konicek curve fit algorithms were selected since the Tadmor-Gur curve fit algorithms should not be used for distances within 500 m.

85 Other computer codes evaluate plume meander differently, for example, the ARCON96 plume meander is independent of release duration and represents meander caused by larger eddies that are present in the atmosphere under stable light wind conditions.

attributes discussed below needs to have a valid technical basis and should be discussed with and approved by the DOE SBAA. The process is similar to that of documenting the proposed methodology and input assumptions in a atmospheric dispersion modeling protocol, described in Section 6.11, *Atmospheric Dispersion Modeling Protocol*. If an MOI modeling protocol is being developed, it can be extended to include the CW for cases in which the default value is not appropriate.

Dispersion modeling inputs for unmitigated consequences for the 100 m CW is expected to generally be the same as for the offsite atmospheric dispersion and consequence analysis if using the same computer code, unless unique to the CW evaluation. Dispersion attributes for the CW unmitigated analysis are as follows, and where noted, may apply to the toxic chemical dispersion analysis.

1. Use a DOE Toolbox Code and input values consistent with its guidance document such as the DOE-EH-4.2.1-MACCS2-Code Guidance, *MACCS2 Computer Code Application Guidance for Documented Safety Analysis*.

   Note 1: Other site-specific developed computer codes or industry-recognized computer codes can be considered if they have undergone appropriate validation and verification in accordance with DOE O 414.1D SQA requirements and appropriate technical justification provided.

2. Worst case meteorological assumptions (i.e., overall site 95^{th} percentile or sector-dependent 99.5^{th} percentile) can be based on local site meteorological data per Section 6.10 of DOE-STD-3009-2014, for radiological and toxic chemical releases.

3. Surface roughness of 3 cm (rural) is assumed for radiological and toxic chemical releases, unless an alternate site-specific value can be technically justified by peer-reviewed studies per guidance in Section 6.8.2, Mechanical Turbulence Due to Surface Roughness.

4. Aerodynamic effects of the facility on the wind field cannot be credited unless shown to yield more conservative or bounding results.

5. Dry deposition velocities are selected consistent with the default values provided in Section 6.8.4, Plume Depletion through Decay, Daughter In-Growth, and Deposition Processes, unless a site-specific value can be technically justified by peer-reviewed studies.

6. Plume buoyancy may be included when modeling outdoor fires or for fires venting through a large breach in the facility provided that it is not credited in a non-conservative manner.

7. Dispersion parameters are applicable to site characteristics.

   Note 2: Tadmor-Gur dispersion parameters are not recommended for close-in distances, under 500 meters.

8. Release duration and plume meander are consistent with the MOI atmospheric dispersion analysis unless there is a valid reason to adopt other assumptions unique for the CW atmospheric dispersion analysis.