DATE: May 5, 2003

FROM: STEPHEN M. SMITH, DIRECTOR
OFFICE OF MANAGEMENT COMMUNICATIONS, ME-43

TO: DIRECTIVES POINTS OF CONTACT

SUBJECT: DRAFT DOE G 421.1-X, *Accident Analysis Guidebook*

This is to notify you that the subject draft Guide has been posted in the "Draft" section of the Directives Portal for simultaneous use and coordination. The Guide provides an overview of the safety analysis process followed by discussions on how to approach characterizing the phenomena that may result in the airborne suspension of contained hazardous materials.

Comments on the Guide are due July 7, 2003. Comments should not be designated "major" or "suggested." They should simply be labeled as "comments." Because Guides provide nonmandatory, supplemental information about acceptable methods for implementing requirements, comments supplied will be considered advisory in nature.

The following procedures should be followed for the submission of comments:

Directives Points of Contact at Headquarters Elements: Submit one set of consolidated comments to the originator of the Guide: Richard Englehart, EH-53, Room 3087, Bldg. 270CC Germantown, facsimile (301) 903-6172; or INTERNET address: richard.englehart@hq.doe.gov.

Send an additional copy of comments to LaVerne Fuller, ME-43, Room 4B-172, Forrestal, facsimile: 202-586-1972, or to: laverne.fuller@hq.doe.gov.

Directives Points of Contact at Field Elements: will submit consolidated comments to their appropriate Lead Program Secretarial Office. If appropriate, the package submitted by Field Elements may include as an attachment, the comments provided by contractors.

Contractors will submit comments directly to their appropriate Field Elements.

Questions concerning the content of the Guide should be directed to Richard Englehart, (301) 903-3718. Questions on the directives system should be directed to LaVerne Fuller at (202) 586-1996.

Attachment

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NOT MEASUREMENT SENSITIVE

DOE G 421.1-X
XX-XX-03

ACCIDENT ANALYSIS GUIDEBOOK FOR INTERIM USE AND COMMENT

[This Guide describes suggested nonmandatory approaches for meeting requirements. Guides are not requirements documents and are not construed as requirements in any audit or appraisal for compliance with the parent Policy, Order, Notice, or Manual.]

U.S. DEPARTMENT OF ENERGY
Office of Environment, Safety and Health

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Office of Nuclear and Facility Safety Policy

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FOREWORD

The Safety Basis Requirements of the Nuclear Safety Management Rule, 10 CFR 830 Subpart B, requires the development of facility safety bases as part of DOE's overall authorization basis for operations. This requirement includes the performance of hazard and accident analyses. DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Safety Analysis Reports* (DOE 1994a), describes an overall method that integrates hazard and accident analysis to support proper definition of a safety basis. Integrated Safety Management (ISM) requires the analysis of hazards. Other DOE directives require the preparation of hazard and accident analyses, as well. Examples of these are: Emergency Preparedness, Environmental Impact Statements, and Fire Hazard Analyses. This Guide provides an overview of the safety analysis process followed by discussions on how to approach characterizing the phenomena that may result in the airborne suspension of contained hazardous materials. The basic flow path of accident analysis from problem formation to final dose estimation, including: theoretical modeling of accident phenomena, source term estimation, intrafacility transport, atmospheric transport and dispersion, and dose/exposure estimates are covered. Where possible, acceptable methods to quantify dominant parameters are cited.

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Chapter One
Introduction

1.1 Background

The Safety Basis Requirements of the Nuclear Safety Management Rule, 10 CFR 830 Subpart B, requires the development of facility safety bases as part of DOE's overall authorization basis for operations. This requirement includes the performance of hazard and accident analyses. DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Safety Analysis Reports* (DOE 1994a), describes an overall method that integrates hazard and accident analysis to support proper definition of a safety basis. DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities* (DOE 1994b), provides a technical basis for estimating radiological releases for both hazard and accident analysis. Other standards are available for other technical areas, such as those related to natural phenomena.

1.2 Purpose

This guidebook provides an overview of the safety analysis process followed by discussions on how to approach characterizing the phenomena that may result in the airborne suspension of contained hazardous materials. Where possible, acceptable methods to quantify dominant parameters are cited. It is important to emphasize that analysis methods and parameters discussed in this and other references, when used in a specific situation, must be fully justified as being appropriate for that situation. It is not sufficient to justify a method or parameter solely on the basis that it is contained in a reference or standard.

It should always be kept in mind that the minimum amount of analysis commensurate with a given need is best. For example, if potential consequences are well below levels of concern, very simple estimates with minimal, if any, refinement are appropriate. That is why DOE does not, in general, require a quantitative accident analysis for Hazard Category 3 facilities. Additionally, even when consequences might warrant more extensive work, analysis should not be driven by mere intellectual curiosity or a desire for unreasonable standards of perfection. Accident analysis is a tool to support decisionmaking, not a goal in and of itself.

This document is considered a work-in-progress, with the expectation that it will be revised periodically to incorporate lessons learned throughout the DOE complex. Section 1.3 below describes the intended content of this Guide, and the Table of Contents identifies the pending Sections as "Reserved." The full development of the Guide is being managed by the Office of Environment, Safety and Health, Office of Nuclear and Facility Safety Policy (301-903-3465).

1.3 Guidebook Outline

Chapters 2 through 5 will provide an overview of the safety analysis framework established by DOE in its orders and standards. Chapter 2 will summarize the overall safety analysis process related to safety analysis reports or Documented Safety Analyses (DSAs). Chapters 3 and 4 will provide amplification on the two major technical activities of that process—hazard and accident analysis. Chapter 5 will discuss other uses for accident analysis within the DOE complex.

Chapters 6 through 11 will follow the basic flow path of accident analysis from problem formation to final dose estimation: Chapter 6 will discuss theoretical modeling aspects of accident phenomena; Chapter 7 covers source term estimation; Chapter 8 provides methods for estimating in-facility transport; Chapter 9 will address environmental dispersion outside a facility; and Chapters 10 and 11 will cover pertinent issues in estimating the consequences of radiological and toxic chemical exposures, respectively. Chapter 12 will provide an overview of computer code verification and validation. The following appendixes (not included in this revision) will be provided as well:

A. Acronyms and Abbreviations
B. Glossary
C. Radiological Thresholds
D. Dose Conversion Factors (Federal Guidance Reports 11 and 12)

1.4 References

10 CFR 830. 2001. *Nuclear Safety Management*, U.S. Department of Energy, Federal Register, vol. 66, no. 7, January 10.

DOE (U.S. Department of Energy). 1993. *Natural Phenomena Hazards Performance Criteria Categorization Guidelines for Structures, Systems, and Components*, DOE-STD-1021-93, July; Change Notice No. 1, January 1996.

DOE (U.S. Department of Energy). 1994a. *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports*, DOE-STD-3009-94, July; Change Notice No.1, January 2000.

DOE (U.S. Department of Energy). 1994b. *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, vols. 1 and 2, DOE-HDBK-3010-94, December.

DOE (U.S. Department of Energy). 1994c. *Natural Phenomena Hazards Characterization Criteria*, DOE-STD-1022-94, March; Change Notice No. 1, January 1996.

DOE (U.S. Department of Energy). 1994d. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE-STD-1020-94, April; Change Notice No. 1, January 1996.

DOE (U.S. Department of Energy). 1995. *Natural Phenomena Hazards Assessment Criteria*, DOE-STD-1023-95, September; Change Notice No.1, January 1996.

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Chapter Seven
Source Term Analysis

7.1 Introduction

This chapter discusses development of source terms for accident analysis. The source term is the amount of hazardous material released from a given confinement volume under the stress posed by a hypothetical phenomenological event.

The chapter covers application of four of the five parameters comprising the five-factor formula presented in Figure 7-1 below: material at risk (MAR), damage ratio (DR), airborne release fraction (ARF), and respirable fraction (RF). These parameters are evaluated in terms of the stresses imposed by internal events, external events, and natural phenomena.

Examples of the type of thought processes, bounding assumptions, and overall methodological used in parameter determination are also provided. For additional reference, see Chapter 7.0, Application Examples, of DOE-HDBK-3010-94, which provides a large number of detailed examples.

In the development of facility safety bases, it is important that accident analyses be done on a conservative basis because safety measures intended to prevent or mitigate an accident need to be adequate to handle the full spectrum of potential accident magnitude. The factors of the five-factor formula are themselves dependent on individual parameters that have some distribution and uncertainties associated with them. While it is inappropriate to use bounding values of all the parameters involved in a factor, reasonably conservative values should be used in each. These parameters, where possible, should be supported by test data. Another consideration that needs to be recognized is uncertainties in accident models resulting from incomplete understanding of physical phenomena, modeling simplifications, and completeness of the modeling. It is important that analysts recognize that, at best, analysis results are an estimate, not absolute truth. These cautions apply also to the leakpath factor (the fifth factor in the five-factor formula), which is discussed in Chapter 8.

7.2 Calculating Source Terms

The amount of hazardous material released as a result of accident-imposed stresses is typically evaluated by a prescribed formula that considers the influence of five factors. **Figure 7–1**, reproduced from Chapter 4, displays those factors and their relationships. The basic concept as follows:

$$\text{MAR} \times \text{DR} \times \text{ARF} = \text{Initial Source Term (IST)}$$

$$\text{IST} \times \text{RF} = \text{Initial Resirable Source Term (IRST)}$$

$$\text{IST or IRST} \times \text{LPF} = \text{Building Source Term (BST)}$$

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 as either a gas or a respirable 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 MAR × DR , with the DR being expressed as a total fraction or material released or a leakage rate.

The RF identifies what fraction of the airborne aerosol can be inhaled and retained in the body. IRST is of major interest for nuclear material handling operations as, with the exception of MAR such as tritium gas, criticality 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 IRST are the same.

Chapter 8, Leakpath Factor Calculation, discusses the development of source terms that have been depleted due to filtration or deposition as the source term migrates through additional layers of confinement. Applying all relevant leakpath factors yields the amount of material released to the environment, sometimes called the BST as most handling operations occur inside fixed facilities. That is not however, true of some waste and environmental restoration activities, and subcategories such as glovebox source term, room source term, etc., are sometimes identified as well.

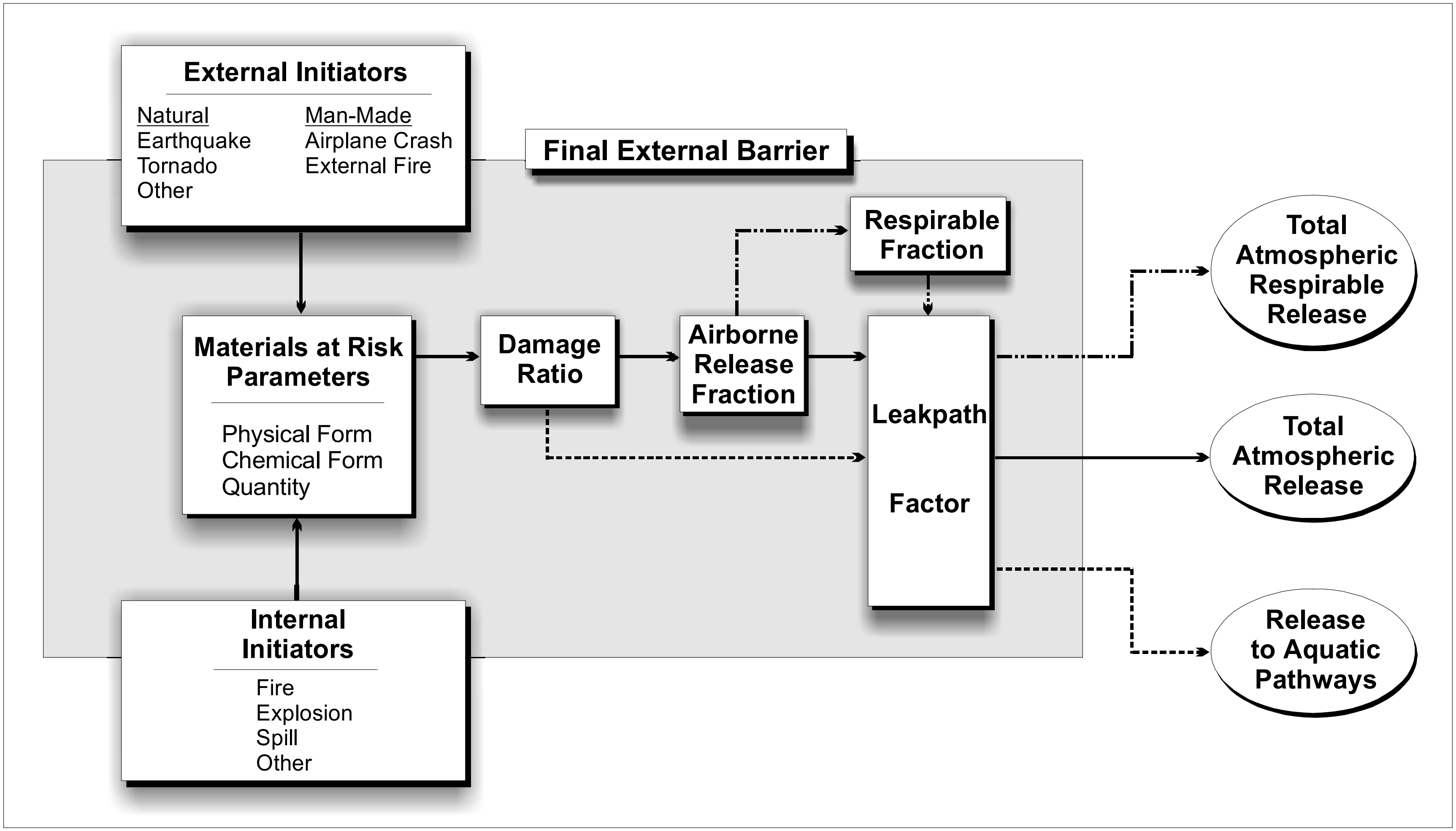

Figure 7–1 Five Factors Formula

7.2.1 Material-at-Risk (MAR)

DOE-HDBK-3010-94 defines MAR as "the amount of radioactive materials available to be acted upon by a given physical stress." The concept is considered equally applicable to hazardous chemicals.

The MAR value assigned should be consistent with the hazard identification performed for a given facility or operation. That is, the hazard identification used some basis to determine the maximum hazardous material accumulation reasonably foreseeable. The MAR should use that same basis. If it does not, absent a compelling explanation the basis for either the hazard identification or the MAR designation, or both, becomes suspect.

Specifying the amount of a given material reasonably foreseeable is typically 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 amount of material present can be precisely specified.

Administrative limits dominate the assignment of MAR values for radiological 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, storage containers, etc, in terms of batch sizes, process parameters, and criticality or other procedural limits. It is noted, however, that criticality limits are sometimes set at elevated values in comparison to actual operating quantities in order to minimize the chance of a violation. Where this is the case, the MAR is typically assigned a lower value as long as procedural limits exist.

Finally, statistical sampling or historical data are primarily used for waste-handling and environmental cleanup activities. While some waste-handling operations will have upper limits for a given storage vessel such as a drum, most of the vessels will hold far less than this amount, making its assumption in mass grossly conservative. Likewise, cleanup efforts, whether in the field or in facility as was the case with duct contamination remediation at Rocky Flats, the quantities involved cannot be precisely specified. A theoretical reconstruction based on historical data, measurement, sampling, or some combination of these three is required.

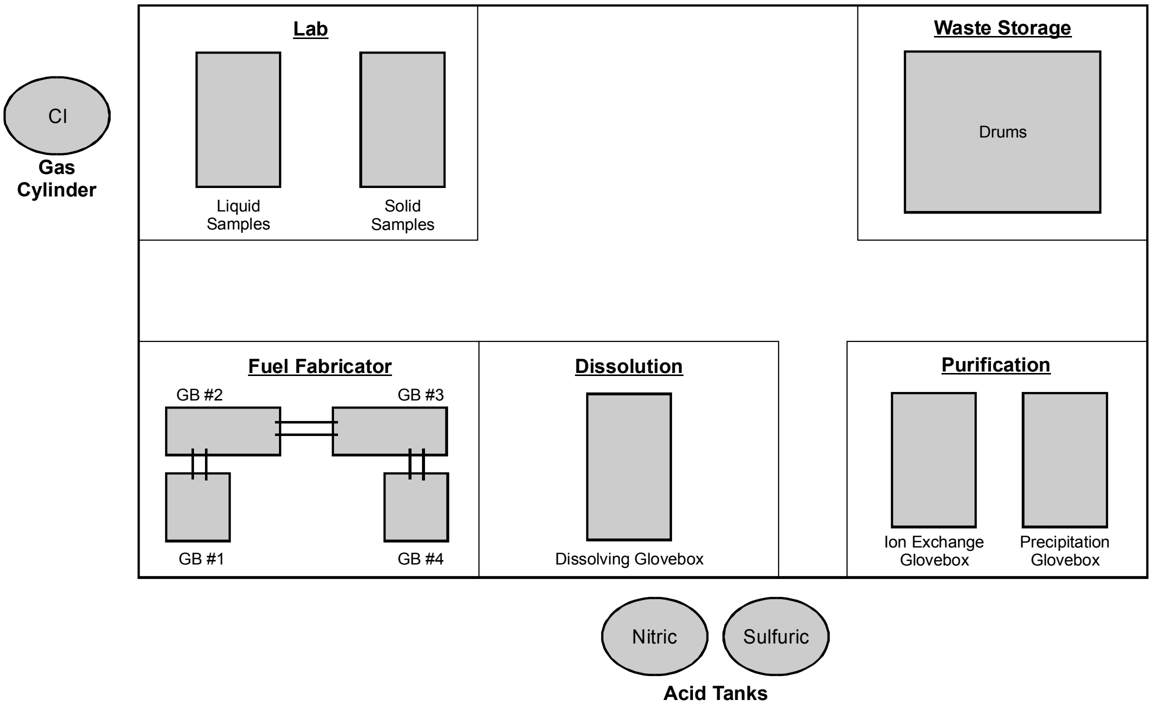

Figure 7–2 Example Facility

Examples

Figure 7–2 offers a simplified representation of a nuclear materials handling facility. 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 and nitric acid storage tanks. A MAR must be developed for each of these operations.

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

A. External Storage

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 become part of the basis based on the operating concentrations desired. If 32% by weight nitric acid and 15% sulfamic acid are what is supplied, these would be the values used to define density, given some faith in the reliability of the supplier and the operation's monitoring of process parameters. Absent either of the last two factors, the process safety management is too defective to support a useful analysis.

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

B. Dissolution

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:

$$Pu + 3NH_2SO_3H \rightarrow Pu^{+3} + 3NH_2SO_3^{-1} + 1.5H_2$$

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

C. Plutonium

Suppose criticality calculations have 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 suppose also that the same calculations allow only 1,300 g of solid plutonium and plutonium in solution in a flooded spray chamber. Clearly, this limit supercedes the larger value. But then suppose further that the actual pieces to be dissolved contain a maximum plutonium quantity of 750 g. While assigning a MAR of 3,000 g would bound the actual operation, under the circumstances it would introduce a needless factor of 4 conservatism. Indeed, to make bounding estimates intended to cover any number of operational errors a priority offers no clear stopping point. After all, if someone were willing to violate procedures to the level of cramming four shapes into the spray chamber, there is no obvious reason to consider the largest criticality limit a meaningful ceiling.

There is, however, an administrative burden placed on facility management by assigning a MAR of 750 g. If a campaign of unusual shapes ranging in quantity up to 1,000 g becomes necessary, and there is no way to split the shapes into two pieces, then the USQ process would have to be implemented. Therefore, a facility might arbitrarily assign a MAR of 1,000 g, 1,100 g, etc., to allow some flexibility. DOE has generally allowed this type of reasoning within reasonable bounds. In this example, one such bound would be the criticality limits. DOE would not allow a MAR greater than these limits, as the authorization basis would then implicitly presume their violation. Subtler judgments could come into play if criticality is not limiting, as can be the case with solid storage, particularly of uranium. Suppose a facility with a large site boundary had determined that their dispersion calculations showed a maximum offsite dose of 100 millirem for 1,000 g of metal in the spray chamber. Based on a local site boundary limit of 5 rem, a MAR of 50 kg is then back calculated. DOE has rejected such back calculations in principle as avoiding the entire issue of defense-in-depth by inherently assuming some level of release to be "acceptable." There is a larger issue, however, related to assigning MAR based on administrative limits in general. The MAR assigned should not be so unrealistically large as to, in essence, remove the oversight function from even major process changes. The DSA authorization basis is intended to work with the USQ process, not circumvent it.

D. Hydrogen

There is another potential material of concern identified by the stoichiometric equation for the dissolution reaction:

$$Pu + 3NH_2SO_3H \rightarrow Pu^{+3} + 3NH_2SO_3^{-1} + 1.5H_2$$

While not technically a MAR itself, assessment of the maximum amount of hydrogen potentially present depends on the plutonium MAR assigned. Given that the 30 liters of 15% sulfamic acid contain more than enough acid to dissolve a complete piece of plutonium metal, the metal value assigned based on administrative limits becomes the limiting reagent. Using a simplified molecular weight of 239 yields 3.1 moles of plutonium for 750 g. This in turn could yield up to 4.7 moles of hydrogen gas. Under standard conditions (22.4 liters/mole), this becomes 105 liters, or 3.7 cubic feet. Obviously, this entire quantity cannot be instantaneously generated and should not be assumed as such, but it does represent a theoretical upper limit.

In this particular case, the amount of hydrogen generated does not change drastically for reasonable variances in the plutonium MAR. This may not always be the case, however. When assigning MAR values, administrative limits can be based on collateral or byproduct considerations. Another example of this is Pu-238, an isotope for which heat-loading concerns can limit quantities where the type of operation could easily accommodate more material for another isotope.

F. 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. Suppose 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. To the degree individual accidents are sufficiently localized so as to affect only a subset of stations, however, the scenario-specific MAR would 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 (e.g., after incorporation into a ceramic matrix). The MAR would need to be defined by form and station in order to properly assess vulnerability.

Another factor in the assignment of a MAR value for this process could be the way it is operated. Suppose the process is a semibatch process run in campaigns. Three-thousand grams (the feed of four dissolving operations) may be entered into glovebox no. 1, and 3,000 more grams entered when the first batch has progressed to glovebox no. 3. After the completion of this second batch, the process is then shut down for accountability cleanup. If that is the case, then the overall MAR figure for the room decreases to 6 kg of plutonium oxide. Glovebox nos. 1 and 2 should also never hold more than 3 kg at any one time.

There are many potential case-specific subtleties in the assignment of MAR values. The important factor to remember is that the assessment is focused on a reasonably conservative amount of a given material, not the maximum amount that could be present if facility management exercises no control whatsoever over its operations. This does require, as noted previously, the existence of safety management programs such as procedures and training, which would serve to limit the potential for error.

G. Waste Storage

The waste storage area provides temporary storage capacity for up to thirty 55-gallon drums of transuranic waste. The drum limit for disposal is 30 curies plutonium equivalent (PE-Ci). Based the fact that no drums from this facility have ever approached that level, the facility has an internal limit of 10 PE-Ci. 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 4.2 PE-Ci, the 50th percentile loading is 0.2 PE-Ci, and the average loading is 1.4 PE-Ci.

Based on a maximum content of 30 drums, the MAR can range from a minimum of 6 PE-Ci (based on 50th percentile loading) to a maximum of 900 PE-Ci (based on disposal limit). That considerable range requires some common sense parsing. This is a case where the use of statistical sampling or historical data would be appropriate, if data are sufficient to support it. Even the 95th percentile drum loading is a factor of two less than local facility limit, and the average loading is a factor of seven less. The typical approach for this type of situation is to assume either the local limit of 10 PE-Ci or the 95th percentile drum loading of 4.2 PE-Ci. This provides a for a bounding case and allows consideration as to whether or not there is a significant margin of safety in reducing individual drum limits where practical. But as more drums become involved in a scenario, the majority are considered to be loaded to average levels. This again requires tracking in the future to verify that statistical averages do not increase significantly, but it is considered overly conservative to presume all drums are loaded to levels that in reality they are not. The drums are not storage vessels that are typically refilled to capacity with a given material, but rather repositories for an uncertain amount of entrained material whose estimated quantity is a function of statistical nondestructive assay in the first place.

The use of statistical sampling and historical data is common in cases of old waste storage or environmental restoration where detailed NDA records do not exist. One such example is the previously cited 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 NDA measurements of radiation levels along the length of the ductwork to arrive at workable estimates of material holdup quantities. It is important in such cases to be conservative, but again such conservatism should not try to protect itself from criticism by estimating unrealistically large quantities potentially crippling to any assessment process.

7.2.2 Damage Ratio (DR)

DOE-HDBK-3010-94 defines DR as "the fraction of MAR impacted by the actual accident-generated conditions under evaluation." It also notes that 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 typically even consider material in other rooms, as by definition such material is not at risk, and thus not part of the MAR. A purist can point out, however, that the material in other rooms is MAR with a DR of zero.

The second case is a seismic event that shakes the entire facility and topples various weak gloveboxes throughout the facility. In this case, analyses typically identify material in every room as MAR, specifying DRs over the range of zero 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 must 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.

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 reengineered to eliminate or minimize that possibility. If vitrified glass, or even hardened cement, waste is co-located in a room with an ion exchange glovebox, these can be quickly eliminated as MAR 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 can estimate whether or not temperatures necessary for combustion of bulk metal will occur for an extended period of time. Blast calculations 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.

Examples
A. Explosion

Figure 7–3 represents a room with multiple gloveboxes. The MAR for each of the eight glovebox lines in the room is as follows:

Glovebox Line	Material at Risk
A	2 kg powder in cans
B	1 kg powder in cans
C	2 kg bulk metal
D	2 kg powder in cans
E	1 kg powder in cans
F	0.5 kg metal samples 0.1 kg powder samples 0.05 kg hydride powder samples
G	2 kg bulk metal (west end) 12 kg powder in cans in a stainless steel vault (east end)
H	1 kg liquid in several waste bottles

The dot between glovebox lines D, F, and G represents, in TNT equivalent, the effective location of a vapor cloud explosion due to leakage from a small supply bottle offset from glovebox F. The inner dotted line represents a calculated overpressure of 8 psi, at which gloveboxes would be expected to suffer major structural damage. The outer solid line represents a calculated overpressure of roughly 2 psi, for which the damage expected might be gloveports blown out, possible window dislodgment, etc., but with the glovebox framework itself remaining largely intact. Presuming that a major sustained fire in the aftermath of this event is not plausible, what would be the appropriate damage ratios to assign?

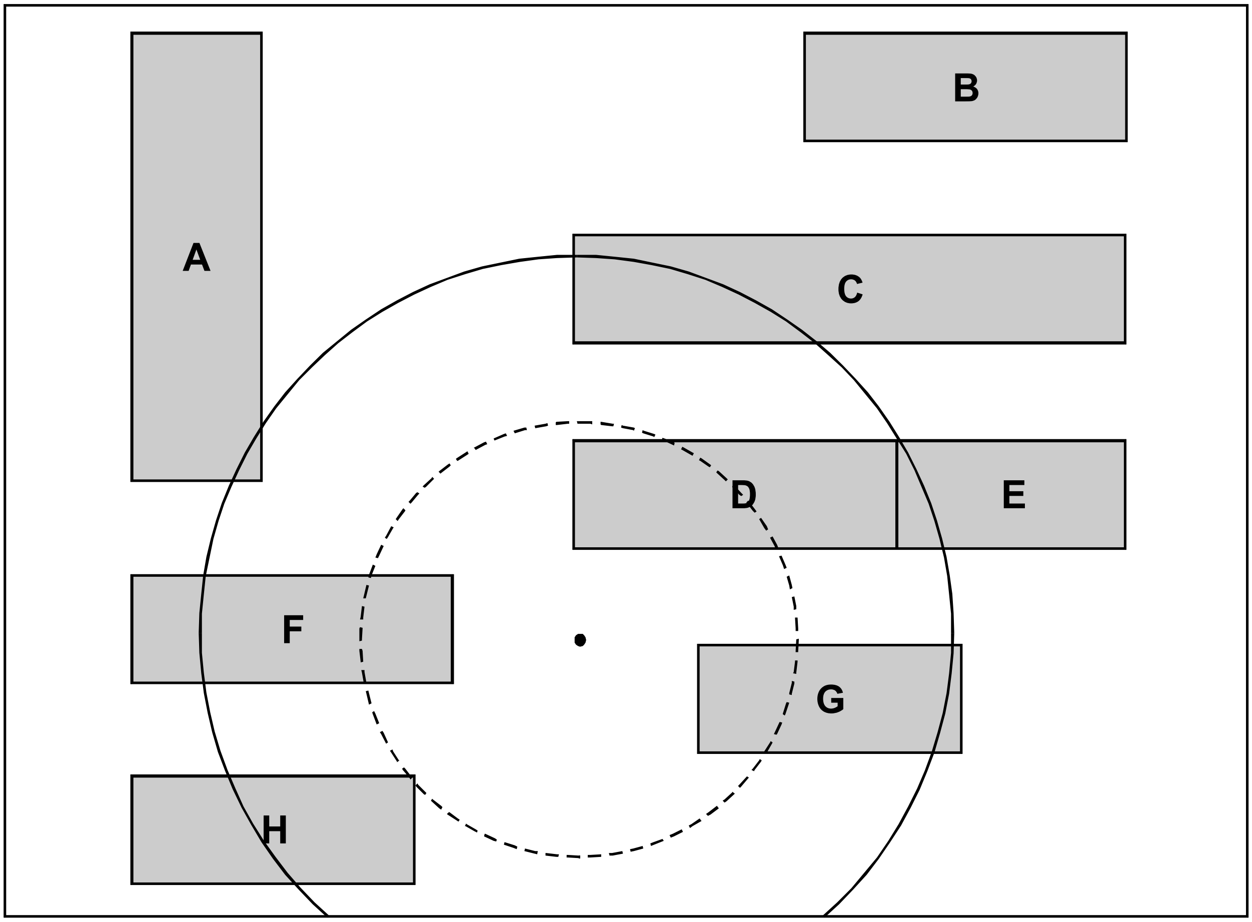

Figure 7–3 Explosion Example

Given that the essential physical stress is a brief, violent pressure pulse with an associated airflow, the simplest approach would be to assign DR values solely by form. Such logic would say powder and liquids are vulnerable and metal is not. This would yield a DR of one for 18.2 kg of powder and 1.0 kg of liquid, with a DR of zero for 4.5 kg of metal. The problem with such an approach is that it does not take into account the actual geometry of the event. Gloveboxes A and B, for example, will be subjected to little, if any, real stress regardless of what material they contain. Glovebox D, and at least a portion of glovebox G, however, may be substantially totaled. And while the far end of glovebox G contains 12 kg of powder, this particular accumulation has an additional layer of protection in the form of a stainless steel storage vault. Clearly, these specifics matter in terms of potential material release.

Looking at the specifics of the scenario, gloveboxes A and B would be assigned DR values of zero since their MAR remains shielded by intact gloveboxes. The same principle would apply to glovebox C as well, given that bulk metal will not be affected by the dissipated force doing limited damage to the glovebox. One possible exception, however, would be if the bulk metal were heavily corroded on its outer surfaces with a loose oxide. Depending on the materials locations vis-à-vis any glovebox damage, a small release could be generated. But even if that were the case, this nuance might be ignored if releases elsewhere in the room dwarfed its contribution. If it were included, the DR could be defined in one of two ways. Suppose 3 g out of the 2 kg existed as loose oxide. The first method would assign a DR of 1.5E-3 based on that ratio. The second method would simply redefine the MAR as 3 g of powder with an associated DR of one.

Gloveboxes D and E are obviously vulnerable. The powder contained in these two gloveboxes would be assigned a DR of one. But it would still be inappropriate to combine the two into one value, as the greater distance from the blast associated with glovebox E may yield a smaller ARF for this material.

Glovebox F contains three different types of material. Metallic solid samples, already contained in glass and plastic vials, will be largely unaffected. Absent a large fire after the event, they would typically be assigned a DR of zero (assigning an extremely low ARF would serve the same function). Powder samples would be assigned a DR of one, as would the hydride powder samples. It would again be inappropriate to combine these two materials as the hydrides are unstable and could have an ARF at least an order of magnitude greater than oxide.

The bulk metal in glovebox G is unlikely to produce a significant release, and almost certainly in comparison to the release from powders. In addition to the heavy corrosion issue previously mentioned for glovebox C, however, the portion of glovebox G holding the metal is in the major damage zone, where shrapnel impact is a possible concern as well. Therefore, even though no major release were anticipated, a DR of one for the metal would be assigned at least until detailed ARF assessment has been performed. The powder on the opposite end of this glovebox, however, is a different matter. It is not in the major damage zone, and is contained in cans within a robust vault shielded from shrapnel by intervening equipment. Some calculation of force/impact vis-à-vis vault structural strength would be necessary to support a DR of zero, but that is likely to be the final estimate.

The last glovebox, glovebox H, contains liquid in waste bottles. These could be knocked over or punctured. A DR of one would therefore be assigned pending ARF estimation.

The initial DRs estimated for this scenario are:

Glovebox Line	Material at Risk	DR
A	2 kg powder in cans	0
B	1 kg powder in cans	0
C	2 kg bulk metal	0
D	2 kg powder in cans	1
E	1 kg powder in cans	1
F	0.5 kg metal samples	0
	0.2 kg powder samples	1
	0.05 kg hydride powder samples	1
G	2 kg bulk metal (west end)	1*
	12 kg powder in cans in a stainless steel vault (east end)	0*
H	1 kg liquid in several waste bottles	1

*pending detailed assessment

Two final notes are offered on this example. First, it is not intended to imply that all DRs will be one or zero. This is a simplified case. A variant that could yield a DR between zero and one would occur if the outer wall of the powder vault in glovebox G was relatively flimsy and subjected to shrapnel. If the 12 kg of powder were segregated into six separate three-by-two internal enclosures, only those on the side facing the explosion might be impacted. In that case, the three enclosures on that side could be impacted, while the three on the opposite side would not. This would yield a DR of 0.5.

This example also did not include any residual contamination concerns. If the gloveboxes were heavily contaminated, historical wipe down data and assay measurements would offer estimates of surface contamination quantities and whether that contamination was fixed or loose. Given that kilogram quantities of power are being affected to begin with, this material may not increase the source term by much, but it is potentially accountable. Other issues of this kind can arise if there is holdup in the ventilation ducting overhead or in a given piece of equipment, such a s a furnace where molten material has splattered over many years. In such cases, the DR would again be derived from estimating the area subject to major blast effects.

B. Earthquake

Figure 7–4 is a reproduction of Figure 7–2 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.

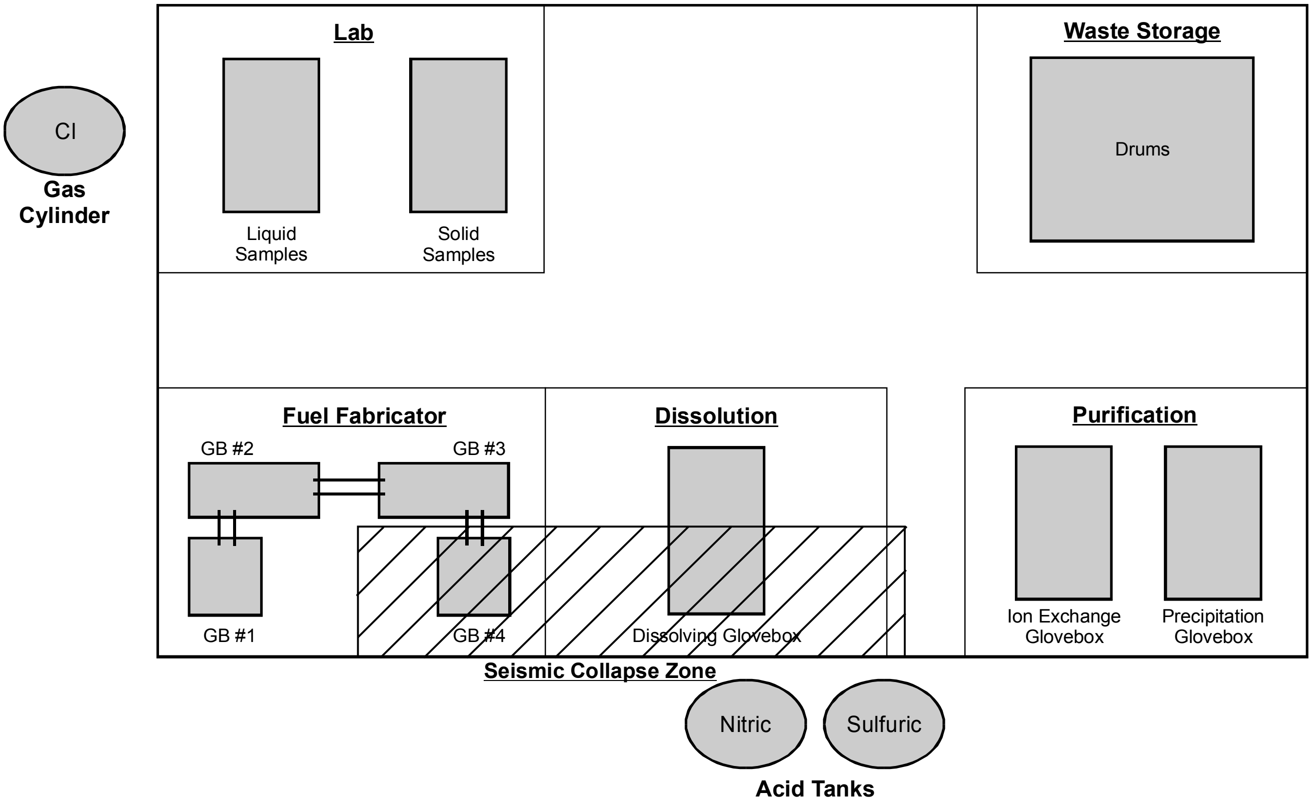

Figure 7–4 Seismic Collapse Zone

Recall that, at most, 6,000 g of powder can be in the entire line: 3,000 g in the first two gloveboxes and 3,000 g in the last two gloveboxes. At first glance, the largest source term of concern would be that from the 3,000 g of powder in glovebox no. 4, which is impacted by falling debris. A DR of 0.5 (3,000 of 6,000 g) would be assigned to this material, with an equal DR of 0.5 for the powder in undamaged gloveboxes. The two are kept distinct as the multiple stresses experienced by material in the crushed glovebox will yield release in excess of the single effect of seismic vibration in the intact gloveboxes. The leakpath factor for the crushed glovebox will also be one as opposed to a smaller value for intact gloveboxes.

But suppose by the time the material reaches glovebox no. 4 it has been rendered into a ceramic state impervious to those stresses offered by the structural collapse. The damage ratio for glovebox no. 4 would then be zero, and a bounding release estimate for this process would have to focus elsewhere. The 3,000 g previously assumed to be in glovebox no. 4 would be reassigned to glovebox no. 3, so that 6,000 g of powder experience seismic vibration with a DR of one. Another possible source of airborne material would then 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 contribute more significantly with regard to glovebox no. 4 due to the fact that this glovebox will now have an LPF of one. This drives home again the point that the source term analysis assesses multiple factors. No potential contributor should be dismissed based on one parameter alone.

Consider two cases for the dissolution glovebox. In the first, the spray chamber and acid storage tank are located at the south end of the glovebox in the collapse zone. Both must be considered structurally compromised in the aftermath of such an event. The question is what value to assign for what MAR? By procedure, one can have 750 g of plutonium metal in the chamber at the start of a cycle, 750 g of plutonium in solution at the end of a run, or some combination of both yielding a maximum plutonium quantity of 750 g. In terms of time of exposure, the latter is most likely given that it is assumed the seismic event occurs while the process is running. It is the differences in ARF, however, that answer this question. Metal is not significantly impacted by shock or impact from a fall; liquid is, or at least much more so than metal. Accordingly, a MAR of 750 g of plutonium in liquid form would be assigned a DR of one.

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.

One final facet of source term analysis demonstrated by this example is its fundamentally limited value. Yes, it provides useful information. But in terms of expending resources, a recommendation to repair the structural weak point causing the collapse is more productive than continued exacting analysis of exactly what the total release estimate could be. Likewise, if something as basic as a weak flange has been identified, a simple fix, if implemented, is preferred to sophisticated freeboard and atmospheric siphoning calculations that could yield a DR of 0.47 or 0.56 as opposed to 0.5. Source term analysis is a tool, not the product desired in and of itself.

7.2.3 Airborne Release Fraction (ARF) and Respirable Fraction (RF)

DOE-HDBK-3010-94 defines ARF as “the coefficient used to estimate the amount of radioactive material that can be suspended in air and made available for airborne transport under a specific set of induced physical stresses. “ RF is defined as “the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system and is commonly assumed to include particles 10 microns Aerodynamic Equivalent Diameter (AED) and less.” Particles greater than 10 microns AED are less likely to be transported into the lung, and thus are not as effective in imparting radiation dose to the body.

The ARF and RF are typically 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, data were extrapolated beyond any reasonable limit of accuracy, numbers were transposed in copying and passed down, etc. In response to this state of affairs, the DOE set in motion a project to collect the available data on airborne release fractions 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, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities* (DOE, 10/94). The estimates from that document have since been reproduced in NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook* (NRC, 3/98) and ANSI/ANS Standard 5.10, *Airborne Release Fractions at NonReactor Nuclear Facilities* (ANSI/ANS, 5/98).

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: explosive, thermal, mechanical, and aerodynamic entrainment (i.e., 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 overpressurization (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 release. Such material is especially vulnerable to wind forces resuspending it in the air in a way material that has settled for a lengthy period is not. In the latter case, the available data indicates the bounding values assigned for DOE-HDBK-3010-94 would be excessive, potentially by orders of magnitude.

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 (e.g., fire) 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 7-1 presents a brief summary of ARF and RF values currently available. It is emphasized that this is only a summary, and the discussion of ARF selection to follow is both brief and general in nature. Analysts unfamiliar with the details of DOE-HDBK-3010-94 should not attempt to apply ARF and RF values using this chapter as a reference.

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 suspendible 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 must be present. If the conversion is due to a chemical reaction, sufficient reactant must 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 MH_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 7-1. Summary of Bounding ARF and RF Values

Stress/Material	ARF (RF)	TSL	Reference
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
Implosion, metal surrounded by and in intimate contact with high explosives (HE); HE:metal ratio >1 to 10, single point detonation	2E-1	3	Boughton, unpublished
Metal or Solution – Explosion, metal or aqueous solution, high explosive in intimate contact with material, HE:material ratio 0.07 to <1	TNT Eq.[1]	2	DOE 1994, Sections 3.2.2.1 and 4.2.2.1
Powder – Explosion, High Explosives lying on surface, HE:powder ratio 1 to 100	ARF x RF = 0.2[2] x TNT Eq.	2	DOE 1994, Section 4.4.2.1
HEPA Filters – Shock pulse	2E-6	2	DOE 1994, Section 5.4.2.1
Explosive Forces: Deflagration			
Powder Unshielded, directly under or in blast volume of large explosion with high confinement pressure	1E+0[3]	2	DOE 1994, 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 1994, Section 4.4.2.2.2
HEPA Filters – Venting by pressurized gases	1E-2	2	DOE 1994, Section 5.4.2.2
Explosive Forces: Overpressurization to Rupture			
Liquid, confined in vessel or container Slow buildup of pressure[4], vented above the surface level of liquid, failure <0.35 MPa$_g$	5E-5 (0.8)	2	DOE 1994, 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 1994, Section 3.2.2.3.2.A
Rapid buildup of pressure, vented above the surface level of liquid	NVA[5]		DOE 1994, Section 3.2.2.3.2.B
Rapid buildup of pressure, vented below the surface level of liquid[6]	1E-4	2	DOE 1994, Section 3.2.2.3.1

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

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

[3] RF for these events cannot exceed the fraction of respirible particles in the source material.

[4] 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 ot hours dependent upon conditions.

[5] NVA = No value currently available.

[6] Generation of Respirable Fraction 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 Respirable Fraction droplets of solutions is a crack 50 micrometers wide. The longer the length, the

Stress/Material	**ARF (RF)**	**TSL**	**Reference**
Superheated liquids ("flashing spray"), <50 °C superheat	1E-2 (0.6)	2	DOE 1994, Section 3.2.2.3.3.A
Superheated liquids ("flashing spray"), 50 °C – 100 °C superheat	1E-1 (0.7)	2	Mishima et al. 1968, Borkowski et al. 1986, and Kataoka and Ishii 1983, DOE 1994, 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 1994, 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 1994, Section 4.4.2.3.1
Vitrified High Level Waste Canisters – High pressure sufficient to dissolve the plug	3E-5	3	DOE 1994, Section 4.3.1.1
Thermal Stress			
Volatile compounds	1E+0	1	Brereton et al. 1995
Liquid, aqueous solutions Simmering, no visible bubbles	3E-5	2	DOE 1994, Section 3.2.1.1
Boiling[7]	2E-3	1	Mishima et al. 1968, Borkowski et al. 1986, and Kataoka and Ishii 1983, DOE 1994, Section 3.2.1.3
Liquid, organic combustible Volatile compounds	1E+0	2	DOE 1994, Section 3.3.1, 3.3.7
Nonvolatile compounds, burns to self-extinguishment, no significant surface turbulence	1E-2	2	DOE 1994, Sections 3.3.1, 3.3.7
Nonvolatile compounds, vigorous burning with surface turbulence, burns to self-extinguishment	3E-2	2	DOE 1994, Sections 3.3.3, 3.3.4, 3.3.5, 3.3.7
Nonvolatile compounds, vigorous burning with surface turbulence, to complete dryness	1E-1	2	DOE 1994, 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 1994, 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 1994, Sections 3.3.6, 3.3.7
Solid reactive metal Plutonium, < ignition temperature[8]	3E-5 (0.04)	2	DOE 1994, Section 4.2.1.1.2

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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 nor vessels, and, at higher pressure, would probably propagate into a wider, longer crack.

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

Stress/Material	ARF (RF)	TSL	Reference
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 1994, Section 4.2.1.1.3
Plutonium, free-fall spill of molten metal into air, small fall distance	1E-2	2	Stewart 1963, DOE 1994 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 1994 Section 4.2.1.1.5
Uranium, less than ignition temperature[9], greater than 500 ^{o}C	1E-3	2	DOE 1994, Section 4.2.1.2.1
Uranium, free-fall spill of molten metal greater than 1 m	1E-2	2	DOE 1994, Section 4.2.1.2.2
Uranium, explosive dispersal of thin sheets of metal	1E+0	2	DOE 1994, Section 4.2.1.2.3
Concrete			
Tritium (^{3}H) as water, > 20 ^{o}C to 200 ^{o}C	5E-1	2	DOE 1994, Section 4.3.1.2
Tritium (^{3}H) as water, > 200 ^{o}C to 600 ^{o}C	1E+0	2	DOE 1994, Section 4.3.1.2
Solid, powder			
Nonreactive[10], up to 1,000 ^{o}C, upflow around powder to 100 cm/s	6E-3 (0.01)	2	DOE 1994, Section 4.4.1.1
Reactive, plutonium compounds, up to 100 ^{o}C, upflow around powder to 100 cm/s			
Plutonium fluoride	1E-3 (0.001)	2	DOE 1994, Section 4.4.1.2
Plutonium oxalate, nitrate	1E-2 (0.001)	2	DOE 1994, Section 4.4.1.2
Solid, contaminated combustible			
Packaged waste, burns to self-extinguishment	5E-4	2	DOE 1994, Section 5.2.1.1
Loose cellulosic material, burns to self-extinguishment	1E-2	2	DOE 1994, Section 5.2.1.2
Loose polystyrene	1E-2	2	DOE 1994, Section 5.2.1.4.3
Loose, other plastics	5E-2	2	DOE 1994, Section 5.2.1.4
Light cellulosic material remaining suspended during complete combustion (i.e., ash)			
UO_2 powder	4E-1	2	DOE 1994, Section 5.2.1.3
Air-dried solution residues	8E-2	2	DOE 1994, Section 5.2.1.3

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[8] Ignition temperature for plutonium metal is a function of surface to mass ratio (S:M). At S:M of 100 cm2/g, the measured ignition temperature for plutonium metal is in the range of 160 ^{o}C. The ignition temperature rises rapidly after S:M 10 cm2/g and ranges from 480 to 520 ^{o}C for bulk pieces.

[9] 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^{o} to 300^{o} C. Like plutonium it rises rapidly in the region of S:M 10 cm^{2}/g and reaches temperatures in excess of 700^{o} C or more. There is some doubt that bulk pieces of uranium can atain ignition conditions except for very special circumstances.

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

Stress/Material	ARF (RF)	TSL	Reference
Solid, contaminated HEPA filters - passage of heated air up to 400 °C[11]	1E-4		DOE 1994, Section 5.4.1
Aerodynamic Entrainment/Resuspension (treated as a release rate)			
Homogeneous Deposit 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 1994, Section 3.2.4.5
Liquid, indoors, as above, covered with substantial layer of debris or indoor static conditions	4E-8/hr	3	DOE 1994, Section 3.2.4.5
Liquid, outdoors, large pool, up to 13.6 m/s (~30 mph)	4E-6/hr	3	DOE 1994, 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)	4E-5/hr	3	DOE 1994, Section 4.4.4.1
Powder, indoors, as above covered with substantial layer of debris or indoor static conditions	4E-6/hr	3	DOE 1994, Section 4.4.4.1
Powder, dispersed into flowing air, airspeed up to 9.1 m/s (20 mph)	[12]	2	DOE 1994, Section 4.4.3.2
Heterogeneous Deposit 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 1994, Section 3.2.4.4
Powder, indoors, loose surface contamination[13], normal building ventilation flow, low airspeed (<2 m/s, 5 mph)	4E-5/hr	3	DOE 1994, Section 5.3.4
Powder, outdoors, due to the passage of vehicular traffic across or by loose powder on road, up to 22.7 m/s (50 mph)	1E-2/pass	2	DOE 1994, Section 4.4.4.2
Mechanical Stress			
Free-Fall Spill Liquid, aqueous solution, spill distance < 3 m	2E-4 (0.5)	2	DOE 1994, Section 3.2.3.1
Liquid, slurry (<40% solids), spill distance < 3 m	5E-5 (0.8)	2	DOE 1994, Section 3.2.3.2
Liquid, viscous solution, spill distance < 3 m	7E-6 (0.8)	2	DOE 1994, Section 3.2.3.3
Liquid, spill distance > 3 m (see reference)			DOE 1994, Section 3.2.3.1

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[11] 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 preseumption that filters will remain functional for prolonged exposure to temperatures up to 400°C.

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

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

Stress/Material	ARF (RF)	TSL	Reference
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 1994, Section 4.4.3.1.2
Powder, spill distance > 3 m (see reference)		2	DOE 1994, Section 4.4.3.1.3
Powder, shock impact due to falling debris	1E-2 (0.2)		DOE 1994, Section 4.4.3.3.2
Powder, dispersed into flowing air, to 9.1 m/s (20 mph) (see reference)			DOE 1994, Section 4.4.3.2
HEPA filter, object strikes encased filter or encased filter impacts unyielding surface after fall	5E-4	3	DOE 1994, Section 5.4.4.1
HEPA filter, object strikes unencased filter or unencased filter impacts unyielding surface after fall	1E-2	3	DOE 1994, Section 5.4.4.2
Spent nuclear fuel			
Noble gases	5E-2	2	Soffer
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
Shock/Vibration			
Loose surface contamination	1E-3	2	DOE 1994, Sections 5.2.3.2, 5.3.3.2.2
Loose surface contamination, substrate packaged in container such as pail or drum	1E-3 (0.1)	2	DOE 1994, Section 5.2.3.2
Bulk powder	1E-3 (0.1)	2	DOE 1994, Section 4.4.3.3.1
Crush/Impact			
Vitrified glass	[14]	2	DOE 1994, Section 4.3.3
Aggregate	[15]	2	Owczarski and Mishima, 1996
Spent nuclear fuel			
Noble gases	7E-2	2	Kent et al. 1995 (NRC safeguards report)
Iodine (I_2)	2E-3	2	
^{3}H (as HTO)	1E-2	2	
Fuel	2E-3 (7E-5)	2	
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[16] (0.6)	2	Mishima 1995

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[14] 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 objec t with mass and density only impacts a portion of the surface of the brittle material), the formula only applies to the volume being crushed.

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

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

In the case of liquids and solids, the material must either be subdivided into droplets or particles, or, in the case of powders, be deagglomerated. Deagglomeration 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. Deagglomeration/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.

Bulk solids and liquids require more energy to fracture the bonds that hold the form together. In the case of liquids, the material must be 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. Material that have elastic-plastic response to the application of forces (e.g., metal) 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.

Examples

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 regarding one aspect of the example previously cited in Section 7.2.1, Material at Risk, is provided. It is intended to demonstrate the basic thought process for ARF selection.

A. Case One

Consider the example facility of Figures 7–2 and 7–4, specifically the fuel fabrication line. Presume for the moment that the structural collapse depicted in Figure 7–4 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 7-1 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. These releases would occur within the glovebox, so that significant depletion will occur even before release to the general room. An additional leakpath from confinement inside the glovebox might also be warranted if the powder were held in tightly sealed cans or equipment, but that possibility would have to be assessed based on all the workstations available in each of the four gloveboxes.

Within the context of this 0.6 gram respirable release, could surface contamination produce a significant contribution? Table 7-1 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 ARFxRF one order of magnitude greater than that for bulk powder. If significant contribution is defined as 10% of the 0.6 gram source term, then surface contamination would have to contribute 0.06 g of airborne material. Working backward with the ARFxRF would yield 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 standard value of 0.1 g/ft^2 for powder handling gloveboxes, 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, which would not have been the case if the ARFxRF for the main powder MAR and surface contamination had been more equal.

This last result points out another question that a good analyst should always keep in mind: when is a result real, and when is it an artifice of analysis? Examining the specifics of DOE-HDBK-3010-94 indicates that the main reason the ARFxRF 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 7–2 and 7–4, specifically the fuel fabrication line. Presume for the moment that the structural collapse depicted in Figure 7–4 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 typically 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 cases raises the possibility of debris impacting powder.

For spill distances less than three meters, Table 7-1 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 ARFxRF are simply accepted. Table 7-1 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.

The two effects identified in the preceding paragraph are treated as additive, along with the original effect of seismic vibration assessed in Case One. The three ARFxRF values of 1E-4, 6E-4, and 2E-3 are summed to a total value of 2.7E-3. This is a factor of twenty-seven increase over the release from seismic vibration alone, with that increase being dominated by the effect of debris impacting powder.

7.2.4 Airborne Release Rate (ARR)

Sometimes airborne release fractions 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 characteristics of the liquid.

Radionuclides are typically treated in a more overall fashion, as noted in the examples of Section 7.2.3, 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 a reasonable time dependence. Even when the release is assumed to occur over some interval for atmospheric calculations, the total source term is simply divided by a general estimate of that time (e.g., 30 minutes, 1 hour). 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.

Example

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?

A typical assumption is that twenty-four hours pass before, at a minimum, some type of covering can be placed over the spilled material. Table 7-1 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 0.6 g/24 hr. If this figure were trivial compared to the overall facility release, it could either be ignored or lumped in with the immediate release.

7.3 Appropriateness of Source Terms

The brief discussions and associated examples in Section 7.2 should serve to make it clear that source term determination is not an exacting science. 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 degree of conservatism to prevent simplification from becoming obvious inaccuracy.

No source term can account all the parameters in play from first principles. The process is therefore inherently subject to abuse. Consider again the case of the glovebox collapsed by a seismic event and its 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 powder even if the actual facility configuration does not support such an assumption. This can be done by making misleading claims about shielding effects or the nature of the debris falling, or by stringing together contrived probability arguments. It is equally possible to insist that a triangular shaped piece of debris falls at just the right angle to impale a can of powder with maximum force, generating large pressurization releases. Both of these positions are acting in bad faith.

DOE-HDBK-3010-94 was prepared to facilitate the development of some consensus among DOE oversight and facility operators regarding reasonable consequence potentials. That consensus is necessary to effectively implement integrated safety management. Using the inescapable subjectivity in source term assessment to claim there are no significant consequence potentials for a given operation undermines the whole purpose of safety analysis. But using that same subjectivity to postulate ever more unreasonable combinations of circumstance simply because they are imaginable is equally damaging. It turns safety analysis into a game that facility management will fairly come to view as a pointless burden.

The basis for determining source term appropriateness is general, not specific. The combination of parameters used should simply be on the upper end of any potential uncertainty. That does not mean an average value, but it does not mean a 95th percentile value either, particularly since meaningful statistical distributions cannot be generated for most of the accidents under consideration. It means that a general consensus exists on upper and lower bounds for the cumulative scenario definition and associated parameter specifications. That consensus should yield a source term in excess of what would probably be seen if the event actually happened, but should not irresponsibly inflate that source term.

DOE-STD-3009 safety analysis methodology calls for a limited subset of accidents that bound the envelop of accident conditions to which an operation or process could be subjected to be carried forward to unmitigated accident analysis for the purpose of comparison to the Evaluation Guideline for safety SSC classification. The objective of this is to assure that the safety provisions intended to prevent or mitigate a family of related accident scenarios are adequate for the full range of challenges. If all the factors in an accident dose assessment were to be selected at an absolute bounding value of available data, the resulting dose calculation could be excessively conservative to the point that it would not meaningful. However, it is intended that reasonably conservative values of each parameter be used in analyses.

7.4 References

ANSI/ANS. 1998. *Airborne Release Fractions at Non-Reactor Nuclear Facilities*, ANSI/ANS-5.10, May.

DOE. 1994. *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities,* DOE-HDBK-3010-94, vols. 1 and 2, December.

NRC. 1998. *Nuclear Fuel Cycle Facility Accident Analysis Handbook,* NUREG/CR-6410, March.

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Chapter Eight
Leakpath Factor Calculation

8.1 Introduction

This chapter presents methods for calculating losses that might occur in the transport of material from its point of release in a facility to the outdoors. These losses are captured in the leakpath factor (LPF) of the five-factor formula previously defined in this guidebook.

8.2 Summary Definitions

The term "leakpath" refers to the path taken by material released in a facility on its way to the outdoors. The leakpath 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.

Aerosol particle LPFs are often dismissed in a bounding way as either equal to one—no transport losses—or due entirely to retention in HEPA filters, for which a value of the LPF is readily at hand. Chemical losses in leakpaths are usually not even considered. But a more realistic estimation of the LPFs associated with complex pathways has the potential to reduce release estimates by orders-of-magnitude.

There are numerous potential leakpaths from a facility. If the released material is a liquid, that liquid may flow through gaps under doors or reach the outdoors through drains. Its vapors may leave the facility through its ventilation system. If it is solid, workers may inadvertently carry it out of the facility, perhaps as powder contamination on clothing. If it is airborne as gas or aerosol[1], it can escape the facility through the facility ventilation system or building penetrations such as doors, windows, or gaps. For most DOE facilities, the airborne release is of primary concern, and common airborne release paths are the ones emphasized in this guidebook.

The LPF is the ratio of the total amount of material finally released from the facility, sometimes called the Building Source term (BST) to the IST. It represents the fraction of material released as initial source term that escapes to the environment. If multiple barriers are involved, leakpaths may be specified individually for each, or may be summed into one overall LPF. In more complex cases where material is divided among multiple release paths, each path will typically be 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.

As regards that last point, it is important to remember that a respirable fraction (RF) is already included in the five-factor formula to reduce the IST to those particles less than 10 microns aerodynamic equivalent diameter. If only respirable particles are of concern, as they are for evaluating the health effects from airborne exposure to alpha emitting radioactive material such as uranium and plutonium, the calculational basis assigned to the LPF can reasonably be taken as

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[1] An aerosol is a colloidal system of carrier gas and solid or liquid particulate fine enough to stay suspended for some time.

that for a representative respirable particle. If, however, the full range of airborne particle sizes is of concern, LPF must be evaluated discretely for each particle size class as the deposition rates will increase by orders of magnitude for the larger particles.

8.3 Typical Leakpaths at DOE Facilities

There are a number of characteristic features of DOE facilities that lend themselves to categorizing leakpaths. Such categorization is useful in that it points to an opportunity for common approaches to evaluating LPFs across the DOE complex.

8.3.1 Once-Through, Filtered[2] Ventilation System

The simplest leakpath to evaluate is that for a functioning once-through ventilation system. Such systems filter all exhaust to the outdoors through a common path. A once-through system is typically used to ventilate gloveboxes or downdraft tables where operations on exposed hazardous materials take place. Particulate losses in this leakpath are dominated by retention in the filter. The LPF for aerosol particles can therefore be taken to be that associated with the filter alone. Thus, $LPF = (1-\varepsilon)$, where ε is the overall filtration efficiency of the installed system[3], not just of the individual filter elements. For example, a given filter may have a very high efficiency, but if it is installed in a damaged or decrepit system, physical leakage past the filter housings may dramatically decrease system effectiveness. Another special case exists when an event with truly severe physical phenomena, such as a fire or explosion, occurs. If significant temperature or pressure pulse effects are transmitted to the filters, they may exceed the filters' design capability. In that case, the efficiency will be degraded, possibly all the way to zero.

For gaseous releases, a physical filtration mechanism of the type discussed above is normally considered to be of no use. Absent some other specialized system, the LPF will be one. In special cases, however, chemical reactivity with surface materials may yield a smaller LPF.

8.3.2 Recirculating, Filtered Ventilation System

Recirculating ventilation systems are also often used. In these, most of the room air is recirculated through HEPA filters, while a fraction is exhausted to the outdoors (through additional HEPA filters) to allow for fresh air make-up. Only the fraction exhausted from the facility reaches the outdoors and thus defines the leakpath. The recirculation stream acts as an in-facility air cleaning system and as such affects the amount of material available to enter the external leakpath. It is not, however, a leakpath itself. When ventilation is operable, the LPF for aerosol particles is again essentially the filter system efficiency in the facility exit path, which is simply challenged by less material.

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[2] HEPA filters are the most common type in use, and all that are allowed in many applications. Other filters are bag filters, scrubbers, zeolite columns and so on. Their treatment is conceptually the same.

[3] It is customary to credit only those HEPA filter banks that are routinely tested and maintained.

8.3.3 Glovebox Lines

Glovebox lines are equivalent to once-through HEPA-filtered ventilation systems. They are called out here to emphasize their vulnerability to accidental upset. Many accident-initiating events are postulated to occur in gloveboxes. The subsequent accident progression may compromise the gloves or plastic windows, in which case material can leak out into the room housing the glovebox. Room exhaust typically goes to a separate filtration system that must be accounted for with its own LPF, which includes the LPF from the glovebox itself.

8.3.4 Facilities Without Forced Ventilation

Material processing facilities are not designed without forced ventilation and will be in this state only if ventilation has temporarily failed. The only facilities without forced ventilation as a component of normal operations will typically be old facilities of limited occupancy and perhaps some specialized facilities. These will not be directly handling dispersible material. They will be doing research on “safe” forms or storing material having its own independent confinement.

Facilities that have HEPA filtered ventilation systems are relatively airtight by design. When the fans are not operating, the accident leakpaths to the outdoors are designed penetrations such as exhaust lines and doors, possibly accompanied by ill defined additions through breaches in exterior walls or the roof. The air exchange rate in an ambient facility is driven by pressure gradients induced by thermal/elevation differences (ventilation exhaust stacks), wind pressure and temperature differences. It is possible to estimate reasonable upper bounds on these drivers, but it requires relatively sophisticated methods to estimate reasonable, bounding LPFs for the various leakpaths, and indeed, to determine which of the potential leakpaths apply. Such methods are discussed in Section 8.5, *Methods for Estimating* LPF*s*.

Facilities that were not designed to contain material by means such as HEPA filtration, let alone facilities without overall forced ventilation systems, are relatively leaky. Using the methods in Section 8.5, it may be possible to obtain some reduction in the release for a physically robust building with limited penetrations, but in many cases the LPF will default to a value of one.

8.4 Factors That Affect the LPF

The basic driver determining the LPF is the nature of the leakpath itself. The two principle factors that affect the LPF are flow definition and physical attenuation mechanisms, such as inertial settling and filtration. For releases where a threshold concentration is of concern as opposed to the overall dose intake, as is often the case for hazardous chemicals, dilution can be a more significant factor than attenuation.

8.4.1 Flow Definition

A simple case is that for which leakage from the building occurs through an operating, filtered, forced air ventilation system. In that case, the transport of hazardous material that is released in a moderately energetic event will occur through a well-defined leakpath—the ventilation system—and the LPF will essentially be that of the filter system. This example is illustrated by the schematic of a simple facility in **Figure 8–1** below.

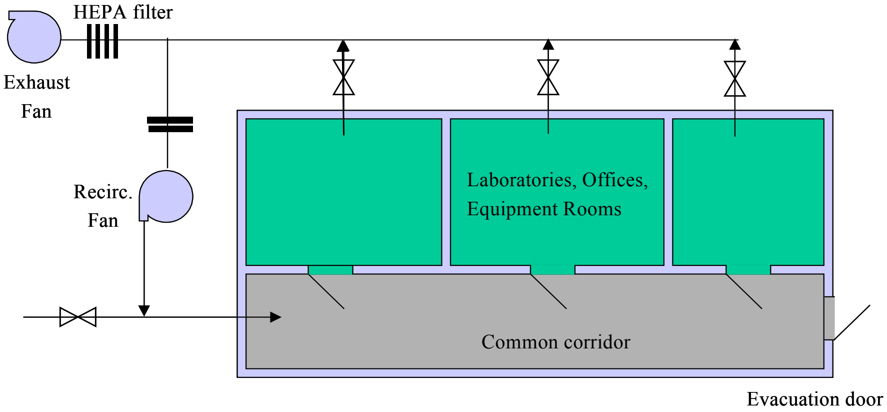

Figure 8–1 Example Leakpath in Ventilated Facility

If, however, an energetic event occurs in that facility, say, a larger fire that releases hazardous material, then the leakpath may be less well defined and, in fact, may be a function of time. This example is illustrated in **Figure 8–2**.

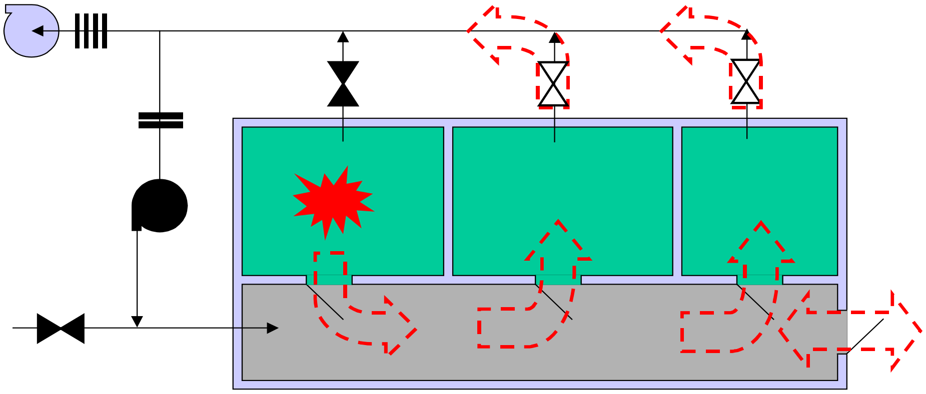

Figure 8–2 Example Leakpath in Ventilated Facility with Energetic Event

In that figure the event is indicated by the starburst in the first room on the left. The exhaust damper in that room closes (solid color) in response to heat from a fire, as does the intake damper to the facility. The recirculation fan shuts down, but the exhaust fan continues to exhaust the rooms not directly implicated. The potential flow (leak) paths are indicated by the dashed arrows.

A sufficiently energetic fire will heat the surrounding air enough to generate expansion flow that may exceed the capacity of the exhaust system. Under that condition, there will be a net, unfiltered, flow through the exterior doors of the building. The leakpath will then consist of two parallel strings. For less energetic events the leak will occur through the ventilation system as before. The difference is, of course, crucial to determining the BST. Note, also, that the flow path may be a function of time during the source period. That is, the path may include flow through the exterior door early in the event but revert to flow solely through the exhaust system as the fire burns past the point of peak heating and air in the facility begins to cool.

This example illustrates the considerable complexity involved in defining leakpaths in even a moderately complex facility, particularly for transient energetic events and for events that involve time dependent responses of engineered safety features, such as the fire dampers illustrated above. For such cases, a realistically bounding analysis requires the use of computer models that can predict the thermodynamics of energetic events and the flow patterns they might engender or influence in the facility – that is, the thermal-hydraulics of flow throughout the facility.

8.4.2 Attenuation

Attenuation mechanisms in leakpaths extract material from the exhaust stream by deposition on surfaces in the leakpath. For particles, these mechanisms are those that transport particles to a surface through its associated boundary layer. Once a particle makes contact with the surface it will adhere and tend to stay adhered, particularly for particles in the respirable size range. For gases and vapors, the main attenuation mechanisms are sorption and reaction.

8.4.2.1 Particles

Particles are solid or liquid aerosol particles that by the definition of an aerosol remain suspended in air for some time after being released. Most of the particles of interest to DOE facilities are solid. Liquid droplets will tend to evaporate and reduce their solutes or suspensions to solid particles.

Particles that transport with the airflow are small enough to tend to stick to surfaces with which they come into contact, independently of their chemical or geometric characteristics. In this they distinctly differ from individual molecules, which may simply reflect from the surfaces they encounter. On the other hand, while molecules readily transport across streamlines, aerosol particles tend to follow them and thus to avoid surfaces. Smaller particles have higher diffusivities than larger ones and traverse streamlines by Brownian motion; larger particles have higher inertia and traverse streamlines because of their inertial lag. Particle attenuation in the leakpath is therefore a function of particle size and density; it is not usually a function of particle chemical composition or whether or not the particle is radioactive.

Since particle attenuation in a leakpath is a strong function of particle size, it follows that the leakpath may alter the size distribution of the initial source term, resulting in a different size distribution for the building source term. Sophisticated LPF calculations can simulate this effect. Simpler hand calculations will need to make conservative assumptions. For leakpaths with significant attenuation (LPF< < 1), only the least attenuated particles will escape to the environment. Essentially all of these can be assumed to be respirable.

8.4.2.1.1 Inertia, Including Settling

Aerosol particles, by definition, move slowly enough relative to their suspending medium (air) that the modified Stoke's equation for the aerodynamic drag on a particle (Fuchs-89) applies. Thus

$$F_D = 3\pi\kappa\eta d_p u / C(d_p) \tag{8-1}$$

where

F_D = drag force on the particle
η = viscosity of air
d_p = particle Stokes diameter, or sphere having the same volume as the actual particle
u = particle velocity relative to the surrounding air
κ = particle dynamic shape factor, a ratio of the fall velocity of a spherical particle of the same volume to the velocity of the actual particle, and is typically taken to be 3/2
$C(d_p)$ = Cunningham slip correction factor

The Cunningham slip correction factor reduces the drag on a particle 1 µm in diameter by less than 20 percent and rapidly converges on unity for larger particles. Given the large uncertainties attending much of the LPF analysis, and the fact that the bulk of the respirable aerosol mass will be associated with particles larger than 1 µm, this factor will be ignored in the following.

Aerosol relaxation times relative to a change in force are short and it is sufficient to consider the steady state only. Then, by Newton's 2nd Law, the forces on a particle cancel and

$$\frac{\pi\rho_p d_p{}^3}{6} a = 3\pi\kappa\eta d_p u \tag{8-2}$$

where the as yet undefined variables are

ρ_p = particle density
a = acceleration due to force field, such as the gravitational or centrifugal field.

Combining these two equations gives

$$u = \frac{a\rho_p d_p^2}{18\kappa\eta}. \tag{8-3}$$

The group $\frac{\rho_p d_p^2}{\kappa}$ is the square of the aerodynamic diameter[4], d_{ae}. The aerodynamic diameter is, by definition, the diameter of a sphere of unit density with terminal velocity equal to that of the

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[4] The aerodynamic diameter is also referred to as the aerodynamic equivalent diameter, or AED.

particle in question, and u is an expression of the particle's inertial behavior. The quantity $\tau = \dfrac{\rho_p d_p^2}{18\kappa\eta}$ is the relaxation time of the particle and in its non-dimensional form is the Stokes number $St = \tau v/L$. L is a characteristic dimension of the problem, and v is the characteristic velocity of the flow such that $u = a\tau$.

Capture of particles on surfaces due to inertia is called impaction. The efficiency of such capture is often correlated with the particle's Stokes number, and such correlations can be found in standard aerosol text books (e.g., Friedlander-77). For particles of finite extent, capture may also occur because of geometric interception (the center of mass of the particle follows the streamline and its extremities may therefore make contact with a surface even if the particle stays with the streamline). For such particles the correlations also depend on the dimensionless interception number, $R = d_p/L$, where L is a characteristic length – say the diameter of the intercepting fiber in a nested fiber filter bed.

Capture on a surface due to the particle's mass in the gravitational field is called settling or sedimentation. The settling velocity is given above and can be evaluated for characteristic aerosol particle sizes. This is done in **Table 8-1** below, using the typical values: $g = 981$ cm/s^2 and $\eta = 1.84 \times 10^{-4}$ g/cm-s (air at room temperature). Also shown is the particle's relaxation time in reference to impaction. The table cuts off at $d_{ae} = 10$ µm, the upper bound on what is by convention taken as the respirable particle range (ANSI-98).

The small settling velocities exhibited in Table 8-1 make clear that respirable aerosol particles remain suspended in air for a long time. Indeed, for most high volumetric flow leakpaths, flow is sufficiently turbulent to keep respirable particles in suspension as long as they don't enter the stagnant boundary layer that exists in the immediate vicinity of surfaces. Outside that boundary layer, they can be assumed completely mixed in the two cross-flow directions. With this assumption, one can write down the mass balance for a flow path:

$$\frac{dC}{dx} = -\frac{uY}{Q}C \tag{8-4}$$

where:

C = concentration of aerosol
Q = volumetric gas flow rate in the flow path
Y = cross flow dimension of the deposition area.

Equation 8-4 has the solution

$$C = C_i e^{-\frac{uYx}{Q}} = C_i e^{-\alpha}, \tag{8-5}$$

Table 8-1 Settling Velocities as a Function of Particle Aerodynamic Diameter. The Dynamic Shape Factor is Assumed to be Unity.

Particle Aerodynamic Diameter (μm)	Particle Relaxation Time (s)	Settling Velocity (cm/s)
0.1	3.0E-8	3.0E-5
0.5	7.5E-7	7.4E-4
1.0	3.0E-6	3.0E-3
2.0	1.2E-5	1.2E-2
3.0	2.7E-5	2.7E-2
4.0	4.8E-5	4.7E-2
5.0	7.5E-5	7.4E-2
6.0	1.1E-4	0.11
7.0	1.5E-4	0.15
8.0	1.9E-4	0.19
9.0	2.4E-4	0.23
10.0	3.0E-4	0.30

where C_i is the aerosol concentration at the beginning of leakpath and $\alpha = - uYx/Q$. The LPF is then simply given by

$$LPF = \frac{QC}{QC_i} = \frac{C}{C_i} = e^{-\alpha}. \tag{8-6}$$

Other formulations may be found for low flow situations, i.e., where air flow velocities are sufficiently small such that diffusion is appreciable as a mechanism for mass transfer.

Example Calculation

It is instructive to evaluate this expression for a representative leakpath in the case that particle settling is the only significant deposition mechanism. Assume the leakpath consists of a corridor that is 200 ft long, 30 ft wide, and 10 ft high. Also assume that it is ventilated with an air exchange rate of 12 per hour. With ventilation off, the air exchange rate is assumed to be just one per hour, the same as that of a reasonably air-tight house (Engelmann 1990).

As this particular leakpath will be used multiple times for illustrating the effect of various attenuation mechanisms, its major characteristics are provided:

Length (l) = 60.96 m
Width (w) = 9.144 m
Height (h) = 3.048 m
Volume (V) = 1,699 m^3
Cross Flow Area (A_c) = 27.871 m^2
Hydraulic Diameter (d_H) = $4A_c/(2l+2w) = 4.572$ m

For 12 air exchanges per hour

Volumetric Flow Rate (Q) = $5.663\ \mathrm{m^3/s}$
Average Velocity (v) = 0.2032 m/s
Reynolds Number (Re) = $\nu d_H/\nu = 59{,}250$

ν is the kinematic viscosity of air, which is $0.1568\ \mathrm{cm^2/s}$ at room temperature.

For 1 air exchange per hour

Q = $0.4719\ \mathrm{m^3/s}$
v = 0.01693 m/s
Re = $4{,}937$

When deposition occurs only to the floor, such as it does for settling, Y (Equation 8-5) is w = 9.144 m. When deposition occurs equally to all surfaces, such as it does for diffusion, $Y = 2(w+h) = 24.384$ m.

Using the appropriate values from this set in Equations 8-5 and 8-6, along with Equation 8-1 for the settling velocity of spherical particles ($a = g$ and $\kappa = 1$), or equivalently, Table 8-1, one can plot aerosol particle concentration as a function of distance along the leakpath with particle aerodynamic diameter as parameter. This is done in **Figure 8–3**.

Alternatively, one can look at the value of LPF at the end of the 200-ft leakpath and make the ventilation flow rate variable, keeping the aerosol particle size as parameter. This is done in **Figure 8–4**.

These two figures illustrate how sensitively the LPF is to aerosol particle size. By the end of the 200 ft leakpath, as much as 25 percent of the10 μm particles will have settled out, even for ventilation rates providing 12 air exchanges per hour – the highest rate for some plutonium process rooms. For rates a tenth of that, 95 percent of these particles will have deposited by settling. On the other hand, for 2 μm particles the picture is quite different. At the high flow rate, only 1 percent of the 2 μm will have deposited by the end of the leakpath. At the low flow rate, that number is still only 12 percent. **Table 8-2** summarizes these observations in terms of the linear ventilation velocities, v.

Table 8-2 LPFs for 200-ft Corridor

d_{ae} (μm)	v = 2 cm/s	v = 20 cm/s
2	0.88	0.99
10	0.05	0.75

In addition to settling, particle inertia can lead to deposition by impaction on flow obstructions, such as air cleaning devices, protrusions into the flow path, bends in the flow and by ejection from turbulent flow. Generally these mechanisms become significant only at high flow rates. They are also very specific to the geometry of the flow path / obstruction and usually not worth pursuing for routine DOE safety analyses.

The efficiency of the impaction mechanism is characterized by the Stokes number for the particle and flow field. As an example, for flow around a circular cylinder transverse to the flow, the impaction efficiency is 50 percent when the Stokes number has a value of about 3, based on empirical data as well as theory (Friedlander-77). Here the Stokes number is defined in terms of the gas flow velocity far from the cylinder and the radius of the cylinder.

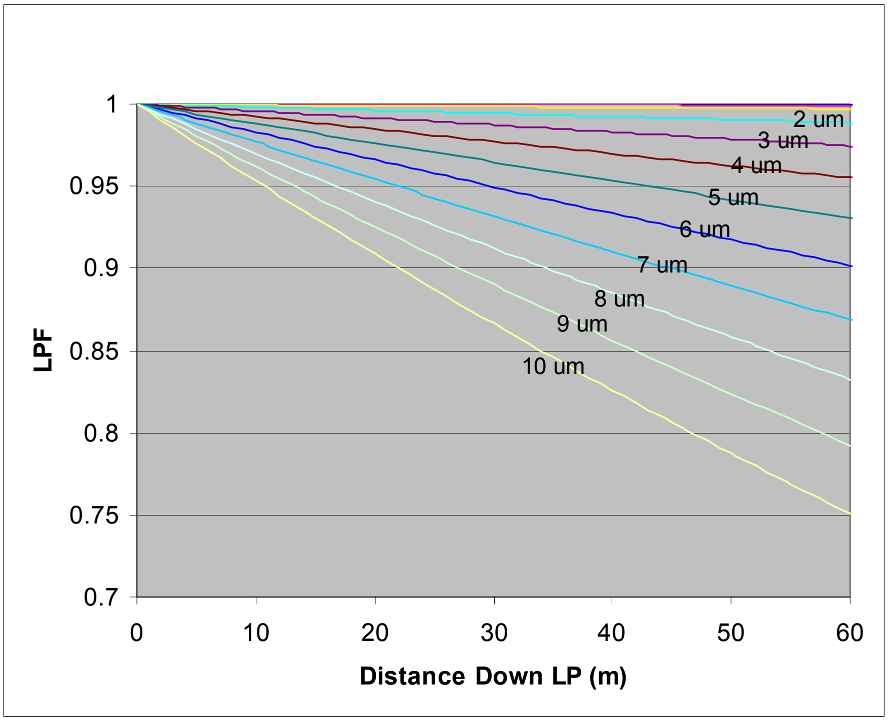

Figure 8–3 Leakpath Factor for a Ventilated Corridor for Indicated Aerodynamic Particle Diameters (12 Air Exchanges per Hour)

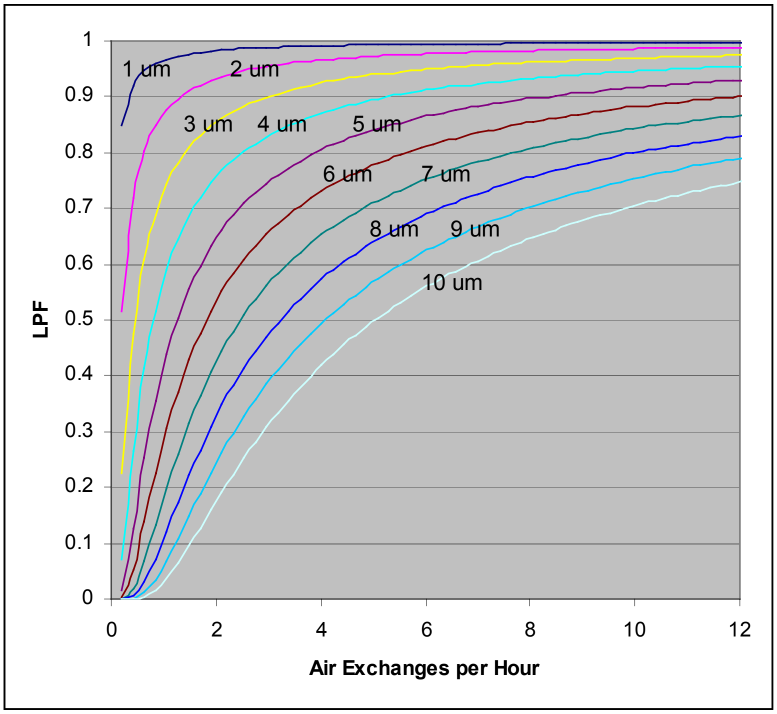

Figure 8–4 Leakpath Factor for a 200-ft Ventilated Corridor for Indicated Aerodynamic Particle Diameters

As an example, calculate the Stokes number for a 10 μm aerodynamic diameter particle in the flow field about a 1 cm cylinder that is transverse to the flow. From Table 8-1, the relaxation time, τ, for the particle is 3.0E-4 s. Assume the flow is 1 m/s. Then

$$St = \tau v/L = 3\text{E-}4\ \text{s} \times 1\ \text{m/s} / 10^{-2}\ \text{m} = 0.03,$$

for which the impaction efficiency is essentially zero. HEPA filters (Section 8.4.2.1.5, *Filters*) consist essentially of beds of cylinders (fibers). They are efficient at capturing particles by impaction because their fibers are very thin (less than 10 μm) and there are many of them in the flow path through the filter. The collection efficiency of a single HEPA filter fiber at design flow is typically only around one percent.

8.4.2.1.2 Diffusion

Aerosol particles also migrate across the flow streamlines by both Brownian (molecular) and turbulent diffusion. The latter is the major mechanism for bulk mixing. It is so effective, even for apparently stagnant containments, that aerosol behavior models usually assume an aerosol to be well mixed – as did the example for gravitational settling in a Section 8.4.2.1.1, *Inertia, Including Settling*.

The turbulence associated with the low air velocities in most leakpaths of interest does not generate the small-scale turbulent eddies that can traverse the stagnant boundary layer at solid surfaces. At high flow rates a particle's turbulence induced trajectory can propel it across this layer, but for the expected flow rates in the leakpaths of interest here, this mechanism is ineffective and overpowered by Brownian diffusion.

Aerosol diffusion behavior follows the standard convective diffusion equation (Brodkey-67):

$$v \cdot \nabla C = D_p \nabla^2 C, \tag{8-7}$$

where the (Brownian) diffusivity, D_p, is now, however, given by the Einstein relation (Fuchs-89)

$$D_p = \frac{kT}{F_D} = \frac{kT}{3\pi\kappa\eta d_p}. \tag{8-8}$$

Here k = Boltzmann's constant, T is the absolute temperature, and v is the convection velocity.

The diffusion flux to a surface is just

$$N_p = -D_p \nabla C = D_p \frac{C}{\delta_p} \tag{8-9}$$

where it is assumed that particles that reach the surface will stick ($C = 0$ at the surface), and where δ_p is the particle concentration boundary layer thickness.

D_p/δ_p is the diffusion deposition velocity and can be directly compared to the settling velocity for particles of various sizes. This is done below for the idealized example leakpath of Section 8.4.2.1.1*, Inertia, Including Settling.*

Example Calculation

Start with the same corridor (200 ft ×30 ft ×10 ft) used in the previous example. Instead of the 12 air exchanges per hour that were assumed before, one exchange per hour is assumed to be representative of ambient ventilation (forced ventilation off).

Using the values

$$\begin{aligned} \eta &= 1.84 \times 10^{-4} \text{ g/cm-s} \\ T &= 300 \text{ K} \\ \kappa &= 1 \text{ (-)} \\ k &= 1.38 \times 10^{-16} \text{ erg/K,} \end{aligned}$$

$D_p = 2.387 \times 10^{-7}/d_p$, for the particle diameter d_p, in μm and D_p in cm^2/s. Hence $u = D_p/\delta_p = 2.39 \times 10^{-7}/d_p\delta_p$, d_p in μm and u in cm/s.

From Equation 8-5, it is seen that the decay of concentration due to diffusion or settling is governed by the exponential argument, $\alpha = -\frac{uYL}{Q}$, where u refers to the corresponding deposition velocities and Y is 9.144 m for settling and 24.384 m for diffusion. L is the length of the corridor, 60.96 m. $T = 300$ K. In quiescent containments, $\delta_p \sim 0.1$ mm has proven to reasonably fit theory to experiment (Jordan-74), and that value is used. Note that settling is characterized by the aerodynamic diameter, while diffusion is independent of the particle's inertia (density) and depends on its geometric diameter. The two diameters are the same if the particle's density is taken as 1 g /cm^3. The dynamic shape factor is also again assigned as $\kappa = 1$.

The LPF for this example is given by Equation 8-6 and evaluated in **Figure 8–5** for settling and diffusion separately as a function of the particle diameter. It is immediately obvious from this figure that Brownian diffusion plays a negligible role for particles with diameter greater than 0.1 μm, at least in the example leakpath, even for long residence times. The mass of material released to the outdoors will be predominantly associated with the larger particles transported through the leakpath.

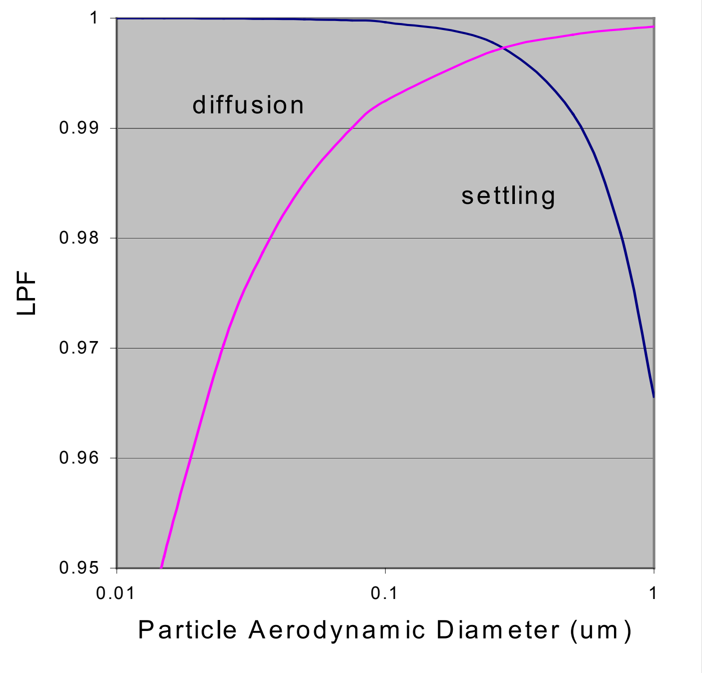

Figure 8–5 Comparison of the Contributions of Settling and Diffusion to the LPF of a 200-ft Leakpath as a Function of Particle Size (δ_p = 0.1 mm. One Air Exchange per Hour)

From Figure 8–4, these can be several micrometers in (aerodynamic) diameter, and from Figure 8–5, particles of this size do not diffuse to any extent.[5] Note that in the example particles with diameter around 0.3 µm are most likely to penetrate the leakpath. Particles both larger and smaller than these are more likely to be deposited. It is exactly this phenomenon that dictates the maximum penetrating size for HEPA filters to be between 0.1 and 0.3 µm. Similarly, this is the reason why particles of this size most probably penetrate to the alveoli of the lungs.

8.4.2.1.3 Thermophoresis

Phoresis is the term used to describe the motion of particles in a non-uniform field or carrier. When that motion is due to a temperature gradient in the carrier, it is called thermophoresis. Generally, thermophoresis may provide a deposition mechanism when the gas containing aerosols is hot relative to the inside surfaces of a leakpath. Such conditions may occur when, for example, hot gases associated with a fire are sucked into ventilation ducting.

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[5] Most accidents that generate airborne particles do so by fractionation of bulk material (solid or liquid) or dispersion of powders. In these cases, the airborne particles will have aerodynamic diameters that range beyond 10 µm. Only for vapors that nucleate is a situation in which Brownian diffusion dominates conceivable.

Thermophoresis is a complex phenomenon that is not completely described by current theories. For particles at the upper end of the respirable range, those of most interest because they are associated with the bulk of the mass, Epstein's expression (Davies-66) for the deposition velocity

$$u = -\frac{2k_g\sigma}{2k_g + k_p}\left(\frac{k_g}{P}\right)\nabla T \tag{8-10}$$

is recommended, provided $k_p/k_g \leq 10$. In this expression

k_g = thermal conductivity of the gas
k_p = thermal conductivity of the particle gradient at the location of the particle
σ ≈ 0.2, dimensionless constant of the theory
P = gas pressure.

Note that the deposition velocity, *u*, is independent of particle size.

The temperature gradient that is of interest to deposition is that at the deposition surface. It can be expressed in terms of the heat transfer coefficient, *h*, by equating the two expressions for the heat flux to the surface (Holman-76):

$$k_g\nabla T = h(T_w - T_g) \tag{8-11}$$

with T_w the deposition surface temperature and T_g the bulk gas temperature. Plugging this expression into Equation 8-10 gives

$$u = \frac{0.4k_g}{2k_g + k_p}\left(\frac{h}{P}\right)\left(T_w - T_g\right). \tag{8-12}$$

Example Calculation

Assume the particle is an oxide with $k_p \approx 1$ W/m·K. Air has a thermal conductivity of about 0.026 W/m·K at room temperature. A rule of thumb is that the heat transfer coefficient for freely convecting air typically lies between 5 - 25 W/m^{2}K (Holman-76). For the example leakpath (200 ft ×30 ft ×10 ft), the heat transfer coefficient is estimated using typical correlations from the literature. Assuming turbulent pipe flow, a suitable the heat transfer correlation is (Holman-76):

$$Nu = 0.023Re^{0.83}Pr^{0.33} \tag{8-13}$$

Where

Nu = Nusselt number: $Nu = hL/k_g$
Pr = Prandl number: $Pr = \nu/\alpha$.

Using the parameter values developed in the previous section for 12 air exchanges per hour, as well as $Pr = 0.7$ for air at room temperature, $Nu = 187$. The appropriate length, L, is the hydraulic diameter, also calculated in the previous section: $L = d_h = 4.57$ m. With these values, $h = 1$ W/m^{2}K, somewhat below the expected value. This value will be used in the following calculation of the deposition velocity.

Define $\Delta T = T_w - T_g$. The pressure of the atmosphere is roughly 10^5 N/m^2. Then

$$u = 9.9 \times 10^{-6} \Delta T \text{ cm/s.} \tag{8-14}$$

Comparing this expression to the settling velocity of a 1 μm aerodynamic diameter particle (Table 8-1), namely $3.0\text{x}10^{-3}$ cm/s, shows that the temperature difference must be $\Delta T = 303$ K or greater for the thermophoretic deposition velocity to equal that of gravity in the example leakpath. In fact, however, all the surfaces of the corridor play a role in thermophoretic deposition, while only the floor does for settling. When this is taken into account, one can see that a temperature difference of 114 K yields a thermophoretic deposition rate equal to that of gravity for a 1 μm particle.

A temperature difference of 114 K, along with the assumed heat transfer coefficient of 1 W/m^2·K, implies a heat flux to the wall surfaces of $1 \times 114 = 114$ W/m^2. For the example leakpath this heat flux leads to a power loss of

$$114 \text{ W/m}^2 \times 200 \text{ ft } (0.3048 \text{ m/ft}) \times 2(30\text{ft} + 10 \text{ ft}) (0.3048 \text{ m/ft}) = 0.17 \text{ MW.}$$

This is the power generated by a modest fire. A fire ten times this size, losing 10 percent of its power by conduction in the assumed leakpath is quite conceivable for accident conditions. Thermophoresis, unlike Brownian diffusion (treated above), may, therefore, compete with settling as an attenuation mechanism in the leakpath.

8.4.2.1.4 Fire Suppression System (sprays)

Water sprays might be expected to effectively reduce the aerosol concentration in a room – the same way rain appears to washout the dust in the atmosphere. In fact, washout of respirable aerosol particles by typical fire suppression sprays is an inefficient mechanism and requires residence time in the spray volume to accomplish any significant mitigation. This mechanism is typically ignored, an omission considered one of the conservatisms of analysis.

8.4.2.1.5 Filters

The filters (or particulate control/collection devices in general) of primary concern are High Efficiency Particulate Air (HEPA) filters. These are commonly made of pleated glass fiber mats that have been stabilized with a binder and treated with a water repellant. HEPA filers are characterized by a particle collection efficiency of 99.97 percent for 0.3 μm (geometric diameter) aerosol particles at their design flow rate.

The particle collection efficiency of a HEPA filter is a function of particle size. HEPA filters are least efficient for particles between 0.1 µm to 0.3 µm under standard design flow conditions. For particles either much smaller or much larger than this, they are much more efficient than the 99.97 percent design criterion (see Figure 8–5, which presents an example of the competing mechanisms determining sizes of maximum penetration)[6]. A filter stage in the filter plenum of the ventilation system of a DOE facility is periodically tested to efficiencies on the order of 99.95 percent. Such tests are intended primarily to identify leakage at the seal of the fiber medium against the frame of the individual filter element and of the elements against the support frame of the filter stage. On rare occasions, they may even identify punctures in the filter medium itself.

For safety analysis purposes, a realistic filtration efficiency for a filter bank that is not compromised by the postulated accident is its tested efficiency at the end of its life, i.e., prior to filter element replacement. That efficiency will be site specific and is likely to be somewhat less than 99.95 percent. The historical efficiencies assumed in DOE safety analyses and many Environmental Impact Statements have typically been 99.9 percent or 99.8 percent, with both values used at times—one for the first stage of filters and the other for subsequent stages. This distinction was based on discussions in the DOE's *Nuclear Air Cleaning Handbook* (DOE 1998). In all likelihood, there is no need for two distinct values used in combination, but the practice does have precedent.

Since HEPA filters involve capture mechanisms functioning on a statistical basis as opposed to simple straining for size, each stage of HEPA filtration is considered as effective at removing particles as any other. That is, passing through one HEPA filter gives a particle no better chance of passing through a second. If E is the filtration efficiency, then the penetration, P, is given by $P = 1 - E$, which defines the fraction of the material reaching the filter that is transmitted through it. For n filter stages in series (in a filter plenum), the bounding overall penetration, $P_t = P_1 \times P_2 \ldots\ldots \times P_n = P^n$. Note that P_t is the LPF of the filter plenum as a whole.

In the above, it is tacitly assumed that the filter efficiency determined from in situ testing of a filter stage is independent of particle size. While this is not true for the filter medium itself, it holds approximately for the tested efficiency of the filter stage as a whole since the test identifies leaks, whose penetration is relatively insensitive to particle size. In addition, filters at the end of a long ventilation duct tend to see a very narrow distribution of aerosol particle sizes, as might be expected from the arguments presented in conjunction with Figure 8–5.

If HEPA filters are exposed to an accident environment, their collection efficiency may deteriorate. Where such deterioration is significant, it should be taken into account. A general summary of what is known about HEPA filter performance under compromising conditions is found in a review article by Bergman (Bergman-94). For the safety analyst, there are two concerns in particular: (1) how is the mechanical integrity of the filter (its ability to survive a

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[6] Actually, modern HEPA filters have been shown to have a maximum penetration particle diameter of 0.15 µm, and an efficiency for that size of 99.9 percent (Bergman - 94). However, the fraction of the respirable mass associated with this diameter is negligible and continuing the widespread use 99.97 percent is adequate.

given pressure-drop or force) affected by the accident environment, and (2) how is the filtration efficiency of the filter (presuming it remains intact) affected by the accident environment?

Table 8-3 gives the lowest values of the pressure drop across a standard HEPA filter for which stuctural filter failure has been observed in experiment as a function of various accident environments. It is conservative to assume LPF (filter) = 1 if the analysis shows that the relevant ΔP threshold is exceeded.

Table 8-4 gives the influence of accident environments on the filtration efficiency of an intact filter element. That is, even if environmental conditions are below the structural failure thresholds, they may, nevertheless, compromise the collection efficiency of the filter. This should be taken into account in assigning a LPF to the filter. Note however that in general the LPF, or filter penetration, remains low as long as the filter remains structurally sound. The values in the table are for particles with diameter near the maximum penetration size.

NUREG/CR-6410 (NRC 1998) summarizes the findings of Bergman, et al. for HEPA filters and those of Moore et al. (1984) for other particulate collection devices found in DOE nuclear fuel cycle and weapons facilities.

Example Calculation

A HEPA filter plenum consists of four stages in series, each stage consisting, in turn, of 12 filter elements in parallel. The last three stages are tested yearly and have passed the 99.95 percent efficiency criterion. The first stage is never tested. The accident environment does not stress the filters beyond design basis. What is a conservative LPF for the plenum?

Since the first stage is never tested there is no basis for assigning an efficiency to that stage, it is conservatively assigned an $E = 0$. This may, in fact, be a gross conservatism. The other three stages have $E = 0.9995$, or $P = 5\text{E-}4$. Hence, $P_t = (5\text{E-}4)^3 = 1.25\text{E-}10$, or, equivalently, the plenum LPF = 1.25E-10. If E were set instead at an arbitrary standard value such as 0.001, the resulting LPF would be 1E-9. In practical terms, the exact values obtained for such small LPFs are meaningless. They serve simply to indicate that the release is not an issue of concern if it is directed to a properly maintained and tested HEPA filter plenum. This does, not, however, mean that any level of release within a facility is acceptable so long as it is filtered before external release.

8.4.2.2 Gases and Vapors

Gases and vapors behave very differently from aerosol particles. For one, they are not characterized by their size, but rather by their reaction with surfaces. Their molecular diffusivities are so large that their transport to leakpath surfaces by molecular diffusion is rapid, in contrast to the slow molecular diffusion of aerosol particles. And while aerosol particles generally adhere to the surfaces they contact, gases and vapors often do not. When they do, it is by the three mechanisms discussed below.

Table 8-3 Threshold Values for Differential Pressure Required to Structurally Damage the Standard HEPA Filter (Bergman-94)

Parameter	ΔP, inches W.G.
Baseline – new filter, normal conditions	37
Age – older than 15 years	13
Radiation – 6×10^7 Rad	18
Chemical – HNO_3, HF	37 – 0 (a)
Temperature	
< 200 C	37
200 – 300 C	
10 minutes	33
1 hour	30
10 hours	22
300 – 400 C	15
400 – 500 C	10
Moisture	
wet filter (relative humidity > 95%)	10
dry filter, previously wet	22
Pressure Pulse from explosion	29

(a) depending on length of exposure

Table 8-4 Effect of Environmental Parameters on Aerosol Particle Penetration through a HEPA Filter Element (Bergman-94)

Parameter	Filter Penetration, P = LPF
Baseline, new filter, normal conditions	3×10^{-4}
HF Corrosion (1,500 ppm-h)	1.3×10^{-3} or greater, depending on exposure time
Temperature	
< 200 C	3×10^{-4}
200 C – 300 C	1.3×10^{-3}
300 C – 350 C	4.3×10^{-3}
350 C – 500 C	3.03×10^{-2}
Particle Deposits	
Solids	1.5×10^{-4}
Liquids	$3.9 \times 10^{-4} \times \Delta P_w/\Delta P_d$ (a)
Air Flow (or Pulse)	$3.7 \times 10^{-6} (Q/400)^{2.58}$ (b)

(a) $\Delta P_w/\Delta P_d$ is the ratio of the pressure drop across the filter element when wetted to that when dry.
(b) Q is the flow rate in cfm.

8.4.2.2.1 Adsorption on Facility and Particle Surfaces

Gases and vapors may physically adsorb on structural or aerosol surfaces. Their capacity for doing so is small, however, and this will, in general, be a minor contributor to attenuation in the leakpath. Reactive gases and vapors may also sorb chemically, in which case their capacity to do so may be very large. If a gas or vapor reacts with a surface in the leakpath, then the molar flux to that surface can be written as
(Geankoplis-72):

$$N_A = \left(\frac{1}{k^{'}} + \frac{1}{k_c} \right)^{-1} C_A , \tag{8-15}$$

where it is assumed the reaction rate of species A with the surface is first order in the concentration of A and,

N_A = molar flux[7] of species A to surface
$k^{'}$ = chemical reaction velocity between species A and the surface, defined by molar flux $N_A = k^{'} C_A|_{\text{surface}}$
k_c = mass transport coefficient for species A transporting to the surface
C_A = molar concentration of C_A away from surface (the bulk space is well- mixed).

Note that if the reaction is fast ($k^{'} / k_c >> 1$), deposition is mass-transfer limited. On the other hand, if $k^{'} / k_c << 1$, deposition is reaction-rate limited and mass transfer can be ignored when calculating the LPF.

k_c can be found from standard correlations of the Sherwood number, Sh, defined (for low concentrations of A) as $Sh = k_c L/D_A$, with L a characteristic length and D_A the diffusivity of species A in the gas. These correlations are usually expressed as functions of the Reynolds number, Re, and the Schmidt number, $Sc = \nu/D_A$. When specific mass transfer correlations are not available, the heat-mass transfer analogy may be invoked by replacing the Prandl number ($Pr = \nu/\alpha$, α is the thermal diffusivity) in the relevant heat transfer correlation by the Schmidt number.

For large rooms with ill-defined flow, it may be necessary to approximate the mass transfer coefficient by expression $k_c = D/\delta_c$, where δ_c is the diffusion boundary layer thickness. This is related to the momentum boundary layer thickness, δ, by $\delta = Sc^{1/3} \delta_c$ (Geankoplis-72).

Example Calculation

The example leakpath of Section 8.4.2.1.1, *Inertia, Including Settling* is used again. It is a 200 ft corridor of cross-section 30 ft by 10 ft, with a ventilation air flow resulting in 12 exchanges per

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[7] Note that Equation 8-15 can also be valid with a mass flux, m_a instead of the molar flux, as long as C_a is interpreted as the mass concentration.

hour. Presume the material of concern is a gas (or vapor) that reacts instantly with the interior surfaces of the leakpath, i.e., $k' \to \infty$. Two approaches to finding the mass flux to the interior surfaces are illustrated.

One approach is based on the observation that at the surface, the mass flux is $N_A = D_A \nabla C_A|_{\text{surface}}$, which can be written as $N_A = D_A/\delta_c\,(C_A - C_A|_{\text{surface}})$, or $N_A = (D_A/\delta_c)\,C_A$, since $C_A|_{\text{surface}}$ must be zero because of the assumed fast reaction at the surface. Thus $k_c = D_A/\delta_c$, and one need only find D_A and δ_c. For this example, take a typical $D_A = 0.1$ cm^2/s. For an actual case, the D_A specific to the material of concern can be found in reference books such as Perry's Chemical Engineers' Handbook (Perry-84) or Bird et al. (Bird-60), or calculated from first principles.

In Section 8.4.2.1.3, *Thermophoresis*, the heat transfer coefficient was calculated to be $h = 1.06$ W/m^{2}K. Since $h\Delta T = k_g \nabla T = k/\delta_T \Delta T$, δ_T can be found to be $\delta_T = 0.026$ W/mK / 1.06 W/m^{2}K = 2.6 cm. Then, using the analogies

$$\delta = S_c^{1/3}\delta_c \text{ and } \delta = P_r^{1/3}\delta_{T,} \tag{8-16}$$

yields

$$\delta_c = (Pr/Sc)^{1/3}\delta_T, \tag{8-17}$$

which gives the desired boundary layer thickness once Pr and Sc are known. Having previously used Pr = 0.708 for air at 300 K allows calculation of Sc = ν/D_A
= 0.16 cm^2/s / 0.1 cm^2/s = 1.6. Thus $\delta_c = 2.0$ cm.

Using these values gives $k_c' = 0.05$ cm/s.

The alternate approach is to calculate k_c' directly, using the Sherwood number correlation (Geankoplis-72):

$$Sh = 0.023Re^{0.83}Sc^{0.33} \tag{8-18}$$

This correlation immediately gives $Sh = 245.7$, and, since $Sh = k_c' d_H/D_p$, $k_c' = 245.7$ (0.1 cm^2/s) / 257.2 cm = 0.096 cm/s – roughly twice as large as the value found from the heat – mass transfer analogy. The difference must be viewed as an illustration of the uncertainty in the calculations. Using the smaller value as conservative, gives a LPF for a chemical that is highly reactive with the structural surfaces of the example leakpath of 0.78. In other words, despite its high reaction rate with structural surfaces in the leakpath, much of the chemical escapes through the leakpath to the outdoors.

If particles are present in large number, they may provide competitive reaction surfaces and potentially reduce the LPF. That is, ignoring their presence may not be conservative. Treating both particles and structures is a complex problem best left to specialized computer codes.

8.4.2.2.2 Phase Change

Vapors, unlike gases, can, by definition, undergo a phase change in the leakpath, that is, they may condense on structural or aerosol surfaces, or they may evaporate from them. The most likely event is that an accident generates vapor from a heated pool and that the vapor subsequently condenses in the leakpath.

For hand calculations, it is reasonable to assume saturated air in the leakpath. A more refined calculation would apply the adsorption model of the previous section, Section 8.4.2.2.1, *Adsorption on Facility and Particles Surfaces*. The boundary condition at the surface of a structure is then $C_A|_{\text{surface}} = C_A^{\text{sat}}$ = the saturation concentration of the material A of concern at the temperature of the leakpath surfaces. This condition is assumed to pertain throughout the gas phase, that is, $C_A = C_A^{\text{sat}}$, if the gas phase can, in fact, saturate – the source is large enough. The source to the outdoors is then just $C_A^{\text{sat}}Q$, where Q is the volumetric flow along the leakpath. The LPF is this number divided by the source rate. If $C_A^{\text{sat}}Q$ exceeds the source rate of A, the LPF = 1.

Very small aerosol particles present in the leakpath may provide nucleation sites for supersaturated vapors, and thus a mechanism for transporting vapors out of the leakpath and reducing the associated LPF. This phenomenon is complex and its analysis is best left to specialized codes.

8.4.2.2.3 Chemical Reaction

Some systems are specifically engineered to trap gases and vapors by chemical reaction. A simple example of this is a packed bed scrubber designed to remove acid fumes from an exhaust stream by passing them up through a downflow of some reactive liquid. Where this is the case, there is generally either some process flow information from which to derive an efficiency of capture, or a specific design efficiency.

8.4.3 Dilution

A leakpath may affect the BST in ways other than attenuation of the source term through some type of deposition. There may be holdup in stagnant sections of the path, advection of clean air that dilutes the material released to the outdoors, or the creation of multiple, physically separated releases to the outdoors. In each of these cases, the health consequences to the public from the accident may be decreased. That is because chemical consequences are often determined by short-term maximum concentrations at the receptor point. Both advection of clean air into the release stream and multiple release locations in the facility envelope directly affect that concentration. Radiological consequences calculations are based on the time integrated concentration, or dose, and are therefore not sensitive to standard dilution. They can, however, be affected by distribution of source locations, since this affects the downwind time history of the concentration at a fixed location. Mixing with advected clean air also affects the residence time of the released material, and therefore the release duration. If the duration of the release is long enough, wind direction is likely to change during the release period and the concentration, and thus dose, to the receptor will be reduced.

Typically, the consequence to the public of a release in a facility is estimated by applying an atmospheric transport calculation to the building source term or BST, represented as a single point release. In such a calculation, no account is taken of the possibility that the source term may have been diluted on its path through the facility to the building release point. But suppose there is a constant source of airborne material of concern, for a given source period, in an interior room that is ventilated directly to the outdoors. The source may be due to the evaporation of a pool, a gas escaping its confinement, or any other mechanism that can be approximately characterized by a constant release rate until the material is exhausted or the source is cut off in some other fashion.

The concentration of the material of concern in the room (and exhaust) can be found from a simple mass balance:

$$V\frac{dC}{dt} = S - QC, \text{ or } \frac{dC}{dt} = \frac{S}{V} - \lambda C \qquad (8\text{-}19)$$

where

C = concentration of material of concern in room (and exhaust) (g/m^3)
Q = volumetric ventilation rate (m^3/s)
S = room source rate of the material of concern (g/s)
V = volume of room (m^3)

And

λ = Q/V is the room air exchange rate.

The solution to this equation, for $C = 0$ at $t = 0$ is

$$C = \frac{S}{Q}(1 - e^{-\lambda t}) \text{ for } t \leq t_s \qquad (8\text{-}20)$$

and t_s = time at which the source ends and

$$C = C_s e^{-\lambda(t - t_s)} \text{ for } t > t_s . \qquad (8\text{-}21)$$

Here

$C_s = \frac{S}{Q}(1 - e^{-\lambda t_s})$, the concentration at the time the source ends,

and is the maximum concentration achieved in the room.

Given this time dependent concentration in the exhaust, the source term, S_0, to the outdoors is just

$$S_0 = QC \tag{8-22}$$

or

$$S_0 = S(1 - e^{-\lambda t}) \text{ for } t \le t_s \tag{8-23}$$

and

$$S_0 = QC_s e^{-\lambda(t - t_s)} \text{ for } t > t_s. \tag{8-24}$$

Indoor mixing has, therefore, transformed the constant indoor source to a time dependent source term to the outdoors. Over the duration of the indoor source, the average building source term is

$$\langle S_0 \rangle = \frac{1}{t_s}\int_0^{t_s} S_0 dt = S\left[1 - \frac{1}{\lambda t_s}\left(1 - e^{-\lambda t_s}\right)\right]. \tag{8-25}$$

Note that if t_s is large relative to the room air exchange time, $1/\lambda$, the average source term to the outdoors, during the source period, is essentially just *S*. For example, when the source lasts for 20 min and the air exchange rate for the facility is 12 per hour, as is typical for ventilation rates in plutonium facilities, $\lambda t_s = 4$ and $<S_0> = 0.75S$. The difference between $<S_0>$ and *S* is, of course, made up by the continued release from the facility after the source has ceased (mass is conserved).

If the indoor source term is essentially instantaneous, it can be treated as an initial concentration equal to the total released mass, *M*, divided by the volume of the room, *V*. The initial concentration, C_i, is, then,

$$C_i = \frac{M}{V}, \tag{8-26}$$

and the source term to the outdoors is

$$S_0 = QC_i e^{-\lambda t} = Q\frac{M}{V}e^{-\lambda t} = \lambda M e^{-\lambda t} \tag{8-27}$$

or

$$\langle S_0 \rangle = \lambda \frac{M}{t_e}\int_0^{t_e} e^{-\lambda t} dt = \frac{\lambda M}{\lambda t_e}\left(1 - e^{-\lambda t_e}\right) = \frac{QC_i}{\lambda t_e}\left(1 - e^{-\lambda t_e}\right). \tag{8-28}$$

Indoor mixing, therefore, transforms both an instantaneous and a constant source term to an exponentially decaying building source term after the source has ceased.

Example Calculation

Assume a relatively "leaky" facility with ventilation off. Such a facility might have an air exchange rate of 0.3/h (Engelmann-90). Assume a constant source of 20-min duration. Then $\lambda t_s = 0.3/60 \times 20 = 0.1$, and

$$\langle S_0 \rangle = S\left[1 - \frac{1}{0.1}\left(1 - e^{-0.1}\right)\right] = 0.05S \qquad (8\text{-}29)$$

The 20-min average building source term is thus just 5 percent of the initial source term.

The short-term average concentration at the receptor, a frequently used measure for chemical health effects, is proportional to the short-term average building source term and is therefore also reduced to just 5 percent of the concentration that would have been calculated had indoor mixing not been taken into account.

If one assumes an instantaneous source, as for a rapid depressurization of a hazardous gas container, and again looks at the 20-min average source term, then by Equation 8-28,

$$\langle S_0 \rangle = \frac{\lambda M}{0.1}\left(1 - e^{-0.1}\right) = 0.95\lambda M = 0.95QC_i. \qquad (8\text{-}30)$$

which gives the building source term. This expression is used, in turn, in atmospheric dispersion calculations that determine the concentration of the chemical at the receptor. Equation 8-30 makes clear that the larger the volume into which the instantaneous release mixes, the lower the initial indoor concentration, C_i, and therefore the building source term and the concentration at the receptor.

8.5 Methods for Estimating LPFs

This section addresses three approaches to estimating LPFs in order of increasing sophistication. In application, the philosophy should be that of the graded approach: apply the simplest approach first. If that approach, in conjunction with the overall safety analysis, satisfies expectations on the facility being analyzed, such as those imposed by regulatory guidelines, then no further refinement of the LPF estimate is necessary. If expectations are not met, the next most sophisticated approach should be applied – and so on.

The three approaches are: utilization of default values, simple hand calculations, and sophisticated computer codes. They are addressed in turn below.

If the LPF calculation is motivated principally by the desire to calculate a building source term, then the graded approach can follow the suggestion of NUEG/CR-6410:

- If the MAR × DR × RRF is already small, temporarily skip this section, assign an LPF = 1, and see if the dose is acceptably small.
- If filters are intact and the ventilation system is functioning, apply the LPF of the filters and repeat the dose calculation, and see if the dose is acceptably small. (Be sure that the

accident event does not cause flow through an unfiltered path.) If not, proceed with the rest of the steps.

- If the power fails and the ventilation system becomes passive, then the flow path might involve other driving forces to move aerosols and gases. Accident- generated gases and heat (fires and explosions) and external wind pressure might become the principal movers of the airborne material. Here also the flows through leaky door cracks, other penetration, and accident-generated structure failure penetrations (earthquakes) become important. Thus one must, at this point, identify the driving forces and the flow paths of the airborne materials.

The emphasis in this section is on leakpaths for particles, which are of primary interest to nonreactor nuclear facilities in the DOE complex.

8.5.1 Default Values

The most bounding, and simplest default value for the LPF is, of course, LPF = 1. There are many instances, however, for which much smaller values of the LPF are reasonably conservative and appropriate as default values. Their use may often prove adequate, while the use of LPF = 1 may not. This section provides such default leakpath factors, or guidance for their ready determination (for aerosol particles only).

Leaky buildings, such as Butler buildings or tent structures such as those used in the DOE complex to house waste drums have an LPF ≈ 1. For buildings with HEPA filtered ventilation functioning, the dominant leakpath is the ventilation exhaust path. For it, the dominant contributor to the LPF is the HEPA filter system, consisting of one or more stages. For each periodically tested stage, the LPF should conservatively be derived from plant data on measured stage efficiencies at the end-of-life (i.e., prior to replacement). This will be somewhat less than the most stringent pass criterion used in testing – sometimes as high as 99.95 percent. For example, if a stage is assigned an efficiency of 99.9 percent, the appropriate default LPF is $1 - 0.999 = 10^{-3}$. If there are two such stages in series, the LPF is $10^{-3} \times 10^{-3} = 10^{-6}$, and so on.

If the ventilation system is not functioning, leaks are motivated by a pressure or thermal gradient across the building or by thermal expansion of the inside air due to events such as fires. Then the ventilation rate is a function of these drivers and the open area in the confinement envelope of the facility, whether doors, windows or the passive ventilation system itself. Correlations for estimating that flow are given in the next section. These are used here in a bounding sense to develop a family of LPF default values for passive facilities.

A 25 mph wind will dominate reasonably bounded temperature differences as a driver for ventilation flow. Using such a wind as the bounding driver, the bounding ventilation flow rate for a facility can be written in terms of the open area, A, as $Q = 0.84A$, where A is in ft^2 and Q is in m^3/ s. It will be shown in the next section that the LPF for a series of rooms in the leakpath can be simply calculated in a bounding way. That approach was used[8] to develop the following graphs of dose versus horizontal-up area, **Figures 8–6** through **8–10**. These graphs are used as follows.

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[8] Only settling of 2 µm AED particles is considered.

First the “leakiness” of the facility in question is estimated. For example, an 8 ft × 8 ft doorway that consists of twin doors with about an 1/8 inch gap on all sides provides an open area to the outdoors of $A = 0.4$ ft^2. This yields a Q of roughly 0.3 m^3/s. This value falls between those of Figures 8–7 and 8–8. To account for this fact, one could interpolate between the two figures or simply use the LPF obtained from Figure 8–8 ($Q = 0.5$ m^3/s) to bound the results.

Next, estimate the total horizontal-up surface area in the leakpath. This area will, at a minimum, encompass the total floor area. In areas with many internal structures, such as piping, gloveboxes, or furniture, the horizontal-up surface area is likely to be at least twice that of the floors alone. Using the total horizontal-up area, go to the appropriate figure (say Figure 8–8 in this case) and, using the curve labeled “1” for “single room in leakpath,” find the associated LPF. This is the desired default LPF.

This value of the LPF can be reduced if the leakpath consists of several distinct regions. In that case, the curve used for estimating the LPF is that whose assigned parameter value equals the number of such regions. Distinct regions of a leakpath are connected by flow constrictions, such as doors, in such a way that each region can be assumed to have its atmosphere convectively mixed before much of it is transported down the leakpath. Clearly a string of rooms or hallways connected by open or leaky closed doors satisfies this picture. If the regions determined in this manner are grossly different in size, they should be combined in such a way that all regions have roughly the same horizontal-up surface area. It is not necessary that such combination occur only between consecutive regions of the flow path.

For example, assume the leakpath has a total floor area of 500 m^2 and internal structures that raise the total horizontal-up area to 1,000 m^2. If the building is very airtight, then $A = 0.05$ ft^2 is a reasonable assumption. Equivalently, Q will be roughly 0.05 m^3/s. Figure 8–6 then applies. Picking the curve with parameter equal “1” to indicate no subdivision of the leakpath gives LPF = 0.3. But suppose the leakpath proceeds instead from a basement room[9] to a first floor room and then along a corridor to the relatively well sealed exit door. Curve “3” then applies, and if all three rooms have the same horizontal up-area, the LPF can be taken as LPF = 0.03, an order-of-magnitude less than that based on the assumption of a single, well mixed region. Two variant cases are considered as well: (1) if the basement were large enough to increase the average horizontal up area for each path to 1500 m^2, the leakpath would be reduced to 0.01; and (2) if the leakpath could be justifiably divided into five regions, Figure 8–6, Curve “5” would then apply, with an associated LPF reduction by yet another order-of-magnitude.

If the release of hazardous material is accompanied by a fire of any real size, the flow in the leakpath will be dominated by expansion of the air surrounding the fire. That expansion is proportional to the amount of heat released by the fire. A simple way of calculating an upper bound on the corresponding flow rate along the leakpath is provided in the next section and is used here. In a very bounding way, $Q = 2\ W$, where Q is in m^3/s and W is the power of the fire in MW. Fires are complex and the default LPFs that are calculated by this method are likely to be excessively conservative. For anything but a scoping calculation, the use of computer models such as MELCOR or CFAST is recommended.

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[9] Make-up air is assumed to be supplied by the (passive) ventilation system.

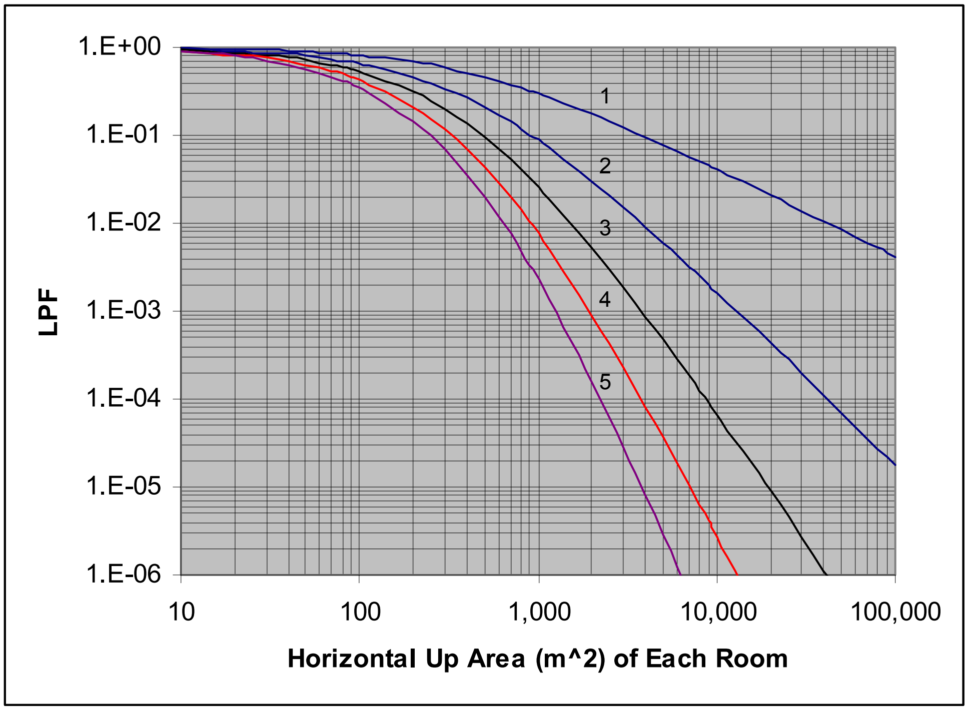

Figure 8–6 LPF for a Series of Rooms with Flow Rate *Q* = 0.05 m^3/s Parameter is the Number of Rooms in Series.

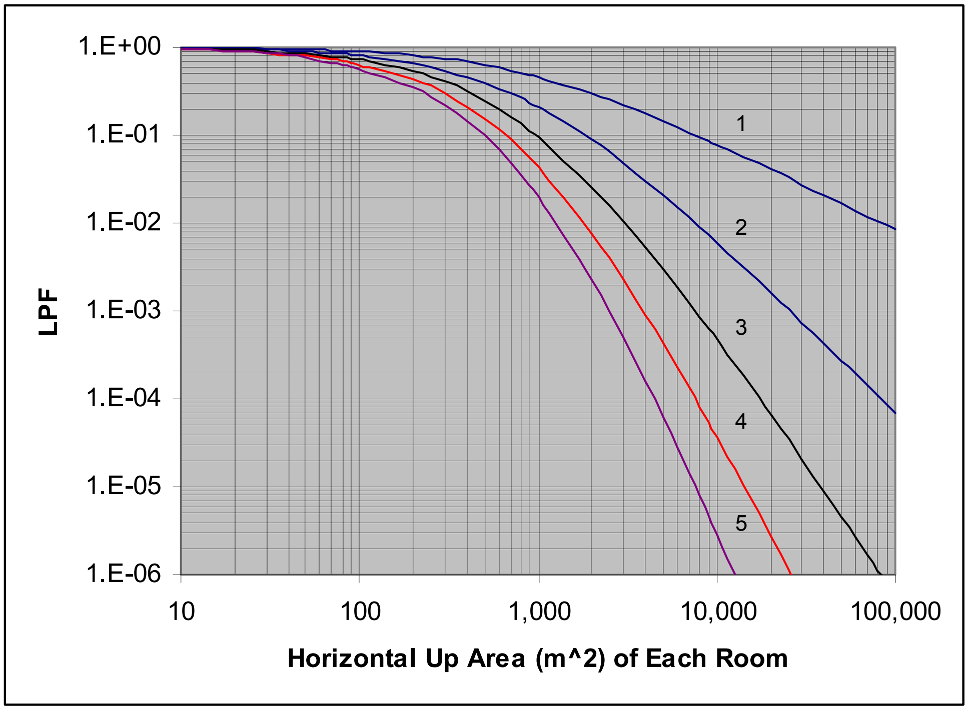

Figure 8–7 LPF for a Series of Rooms with Flow Rate *Q* = 0.1 m^3/s. Parameter is the Number of Rooms in Series

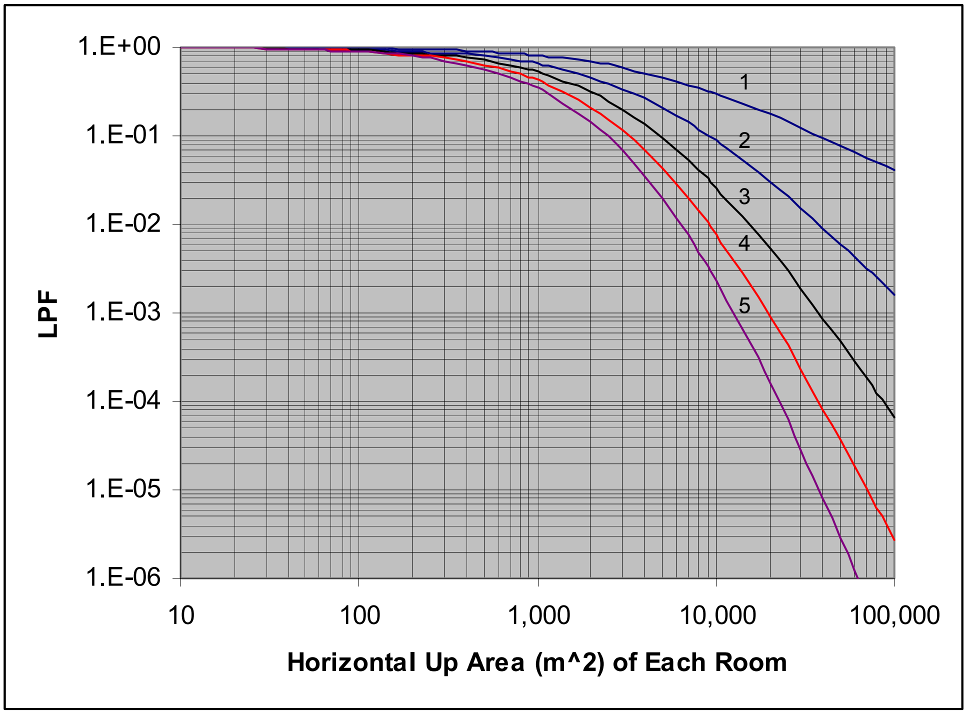

Figure 8–8 LPF for a Series of Rooms with Flow Rate *Q* = 0.5 m^3/s (Parameter is the Number of Rooms in Series)

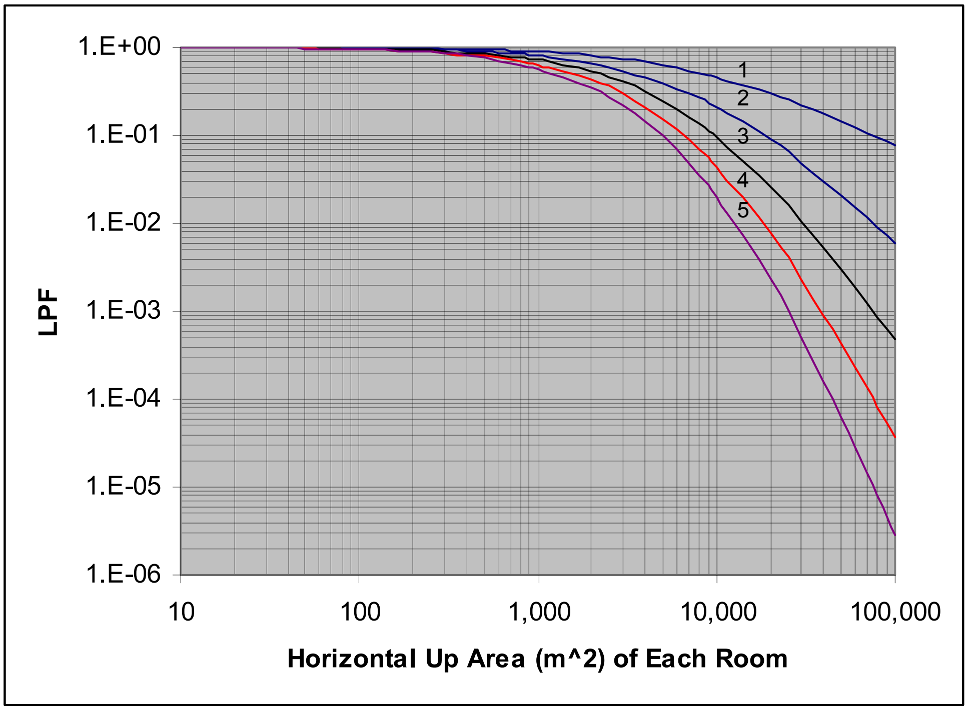

Figure 8–9 LPF for a Series of Rooms with Flow Rate *Q* = 1.0 m^3/s (Parameter is the Number of Rooms in Series)

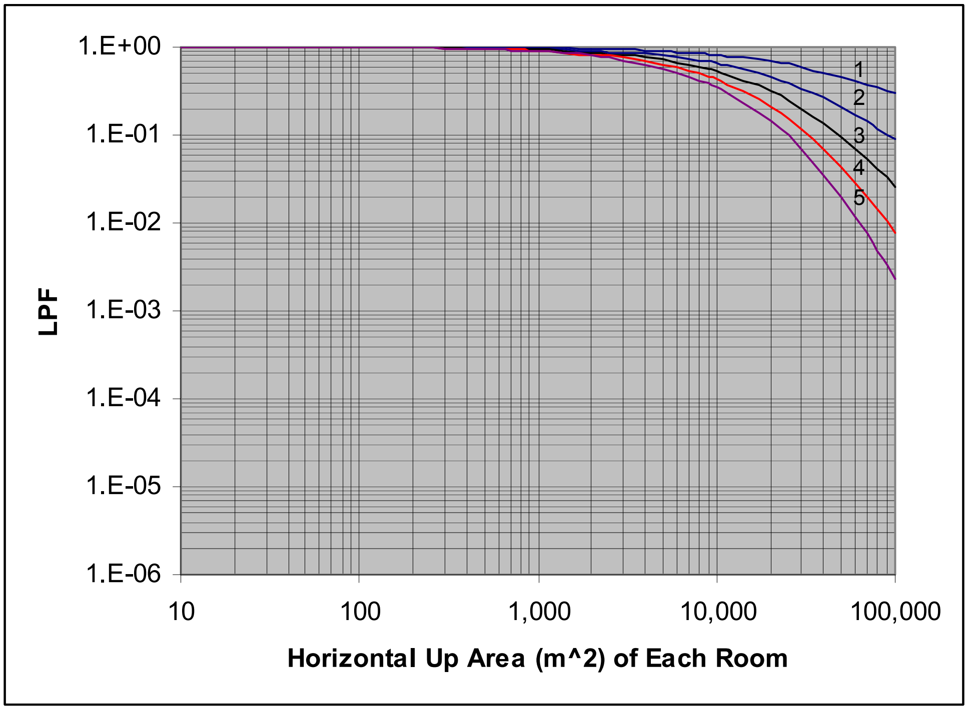

Figure 8–10 LPF for a Series of Rooms with Flow Rate $Q = 5.0$ m^3/s (Parameter is the Number of Rooms in Series)

8.5.2 Hand Calculation of the Leakpath Factor

The atmospheres of rooms with little directed flow tend to be relatively uniformly mixed. The mixing is driven by temperature gradients resulting from uneven heat flows to surfaces. Forced ventilation may disrupt such uniformity locally, but in general will enhance it, since it is designed to do just that. That is, the natural convection flow rate in the room exceeds that due to forced ventilation. The highest ventilation rates at DOE facilities provide 12 air exchanges per hour, or one every 5 min. Natural circulation time scales are of that same order of magnitude.

If a volume is well mixed, respirable aerosol particles mix with the flow, since their settling velocities are much less than the convection flow velocities (see Table 8-2). Their concentration can, therefore, be assumed uniform throughout the volume. Particles carried to the stagnant boundary layer adjacent to horizontal, upward facing surfaces will settle through it and adhere to the surface. Similar transport, due to other mechanisms, can occur at these and the other interior surfaces, but it was shown above that settling will in general dominate, and it will be focused on exclusively in the following. Ignoring other deposition mechanisms is conservative.

Given this description of deposition due to gravitational settling, one can find an expression for the LPF by drawing a mass balance on the species of interest, using the fluxes shown in **Figure 8–11**.

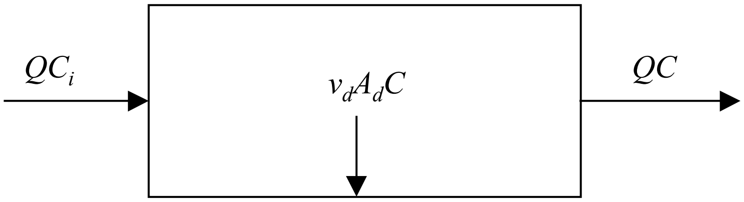

Figure 8–11 Mass Flows in Well-Mixed Control Volume

In Figure 8–11,

Q = convective volumetric air flow rate in and out of the volume
C_i = concentration of species entering volume
C = concentration of species in volume (and in flow out of it)
v_d = settling (deposition) velocity
A_d = surface area available for settling

At steady state, the mass flow rates must balance:

$$QC = QC_i - v_d A_d C \,. \tag{8-31}$$

Now the LPF is defined as the ratio of the material released from the volume to that entering it, so that

$$LPF = \left(\frac{QC}{QC_i}\right) = \frac{C}{C_i} = \frac{1}{1 + \frac{v_d A_d}{Q}} = \frac{1}{1+\alpha} \,. \tag{8-32}$$

where

$$\alpha = \frac{v_d A_d}{Q} = \frac{\tau}{\tau_d} \tag{8-33}$$

and

τ = V/Q is the average residence time of the room atmosphere,
τ_d = $V/v_d A_d$ is the characteristic particles settling time.

In the above, it is tacitly assumed that the aerosol of interest is monodisperse – that its particles all have the same size. What to do about polydisperse aerosols, aerosols composed of particles of a range of sizes, will be discussed later.

If the volume of interest is very long in relation to its cross dimensions, such as a long corridor or ventilation duct, for example, it is perhaps more accurate to assume that mixing occurs only in the cross flow direction. This case was treated in Section 8.4.2.1.1, *Inertia, Including Settling*, above, leading to Equation 8-5, which reduces to:

$$C = C_0 e^{-\frac{v_d A_d}{Q}}, \text{ so that } LPF = e^{-\frac{v_d A_d}{Q}} = e^{-\alpha}. \tag{8-34}$$

Note that for small α this expression is the same as that for a completely mixed volume.

These two expression for the LPF – one for a completely mixed volume, such as a laboratory, and one for a long corridor – form the basis of the LPF#l computer code that is treated in Chapter 4 of NUREG/CR-6410 (NRC-98).

It is now important to realize that while these expressions were derived for steady state conditions, including a constant source term, they in fact apply to any transient source term as well, provided the source goes to completion and the LPF is viewed as the integral LPF for the whole event. This is true because the transport and deposition history of each individual particle is independent of that of any other[10] and therefore does not depend on when the particle occupies the leakpath. Because this is true, it is possible to express the overall LPF of a series of laboratories and corridors or ducts as just the product of the LPFs of the individual components,

$$LPF = \prod_i LPF_i \,. \tag{8-35}$$

On the other hand, if the system consists of parallel flow paths, the overall leakpath factor is the sum of the individual leakpath factors weighted by the fraction, f_j, of the total flow passing through path j:

$$LPF = \sum_j f_j LPF_j \,. \tag{8-36}$$

Here the LPFs are based on the fractional flows associated with the individual paths – not the total flow out of the system. Also note that if what is desired of the LPF calculation is the time dependent, or the instantaneous concentration of the material of concern, as is needed for chemical consequence calculations, this model breaks down and cannot be used. In this case the LPF must be obtained by solving the appropriate differential equations numerically, that is, by using an appropriate computer code. Suitable computer codes for this task are listed later in this section.

Strictly speaking, the simple assumption of combining the components of leakpaths does not rigorously apply even when only the time integral of the concentration, or the dose, is of concern - as it is for determining the health consequences of a release of radioactive materials. In that case, the release may take place over a period that exceeds the assumed receptor exposure period, or the wind direction might have shifted during the release period and a time dependent

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[10] We do not consider agglomeration of particles - which would invalidate the contention.

LPF is needed. Ignoring these effects, as is done here and in the following is, however, conservative.

Similar expressions for the LPF could be developed for more complicated flow streams in multi-room facilities using the concepts discussed above. A common case in DOE facilities is that of recirculating flow through rooms subject to filtration.

8.5.2.1 Accounting for Particle Size Distributions

The LPF#1 code (NRC-98) calculates the LPF as discussed above for a distribution of particle sizes by discretizing that distribution and repeating the calculation for each size class. Doing this by hand would not be justified. Instead, consider the possibility of using just one characteristic particle size to do the calculation when the LPF of just the respirable fraction of the release is of primary concern, as it is, for example, for alpha emitting particles. Such an approximation may well be justified, considering the fact that the size distribution of finely dispersed source material is often not known at all.

A useful approach to accounting for size distributions when only the respirable fraction is of concern is explored by the LPF#1 code. Almost always a particle size distribution can be adequately represented as lognormal, that is, normal on the logarithm of the particle diameter. The (normalized) distribution of mass on diameter is then defined by just two parameters, for example, the mass median diameter, and the standard deviation, σ. It is useful in the following to use the aerodynamic equivalent diameter (AED) of a particle as a measure of its size. Then the mass median diameter is the aerodynamic mass median diameter, or the AMMD.

The respirable fraction (RF) of a distribution is the fraction of mass with AED less than 10 μm. For a lognormal distribution one can show that (AMMD in μm)

$$RF = \frac{1}{2}\left(1 + erf\left(\frac{\ln(10/AMMD)}{2^{1/2}\ln\sigma}\right)\right), \tag{8-37}$$

so that the distribution can as well be defined by RF and σ. This relationship is exhibited in **Figure 8–12**. It is perhaps more intuitive to estimate the RF of a given powder, say, than to arrive at its AMMD, particularly since the aerodynamic diameter is not in general the physical diameter. The standard deviation (σ) will also in general not be known, but it is known from experience that its value for powders that have not been size-classified is large (> 2) and it will be shown in the following that the LPF is surprisingly insensitive to its precise value.

It is now instructive to demonstrate the LPF for a typical control volume as a function of particle size distribution parameters. As mentioned above, this is best done with a simple computer code that repeats the evaluation of the expression for the LPF over the assumed particle size distribution. The results are given in **Table 8–5**. They were evaluated from the expression for the LPF of a well mixed volume, assumed again to be 30 ft × 30 ft × 10 ft, and an air exchange rate of 1 per hour (Q = 0.0708 m^3/s).

This table clearly shows that the variation in the LPF is minimal. An explanation for this fact can be found by looking at what the respirable tail of the lognormal distribution looks like. This is done in **Figure 8–13** for the parameter set used in Table 8–5. The tails are normalized to unit mass in the respirable fraction.

Table 8-5 LPFs for Single Mixed Volume as Function of Mass Distribution

RF	σ = 1.5	σ = 2.0	σ = 2.5
1%	0.380	0.416	0.447
10%	0.401	0.462	0.503

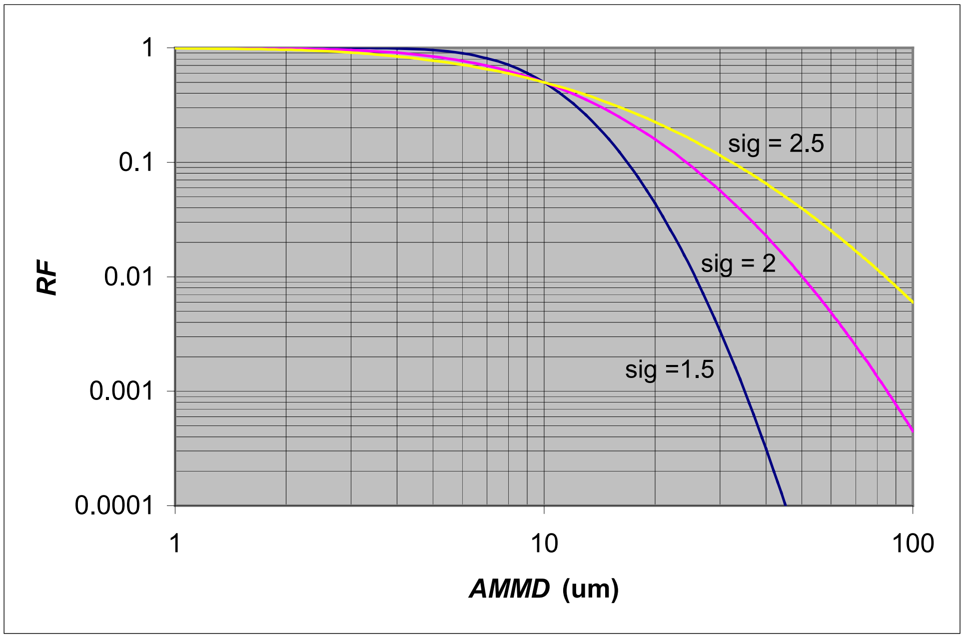

Figure 8–12 Respirable Fraction (RF) of a Lognormal Mass Distribution of a Given AMMD and σ (sig)

As expected, the more monodisperse the distribution (the smaller the σ), and the smaller the respirable fraction, the higher the relative fraction of particles near the 10 μm threshold. However, the differences are not dramatic. Note for example that the 10 percent curves for $\sigma = 2$ and $\sigma = 2.5$ are essentially identical, as are the calculated *RF*s for these distributions.

For the example problem, the LPF as a function of particle size is shown in **Figure 8–14**. One can see that picking a representative particle aerodynamic diameter of 5.5 μm for a monodisperse calculation of the LPF yields roughly (and conservatively) the values of the LPFs calculated for the range of polydisperse aerosols considered above.

This observation holds for the particular sample problem – a single, well-mixed volume. One might ask if the single particle size approximation remains adequate under other conditions – for example, if the leakpath consists of a string of such volumes. This is explored in **Figure 8–15**, which gives the LPF as a function of the number of (identical) well mixed volumes, calculated accurately for the indicated polydisperse aerosol and in approximation with a single particle diameter.

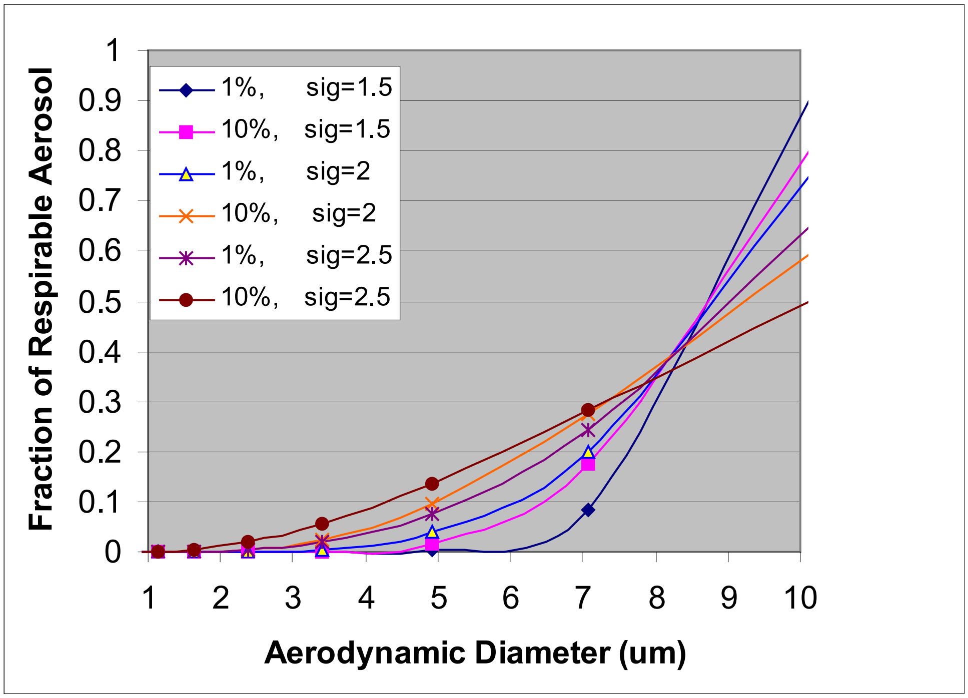

Figure 8–13 Respirable Tail of Lognormal Mass Distributions with Given RF and σ

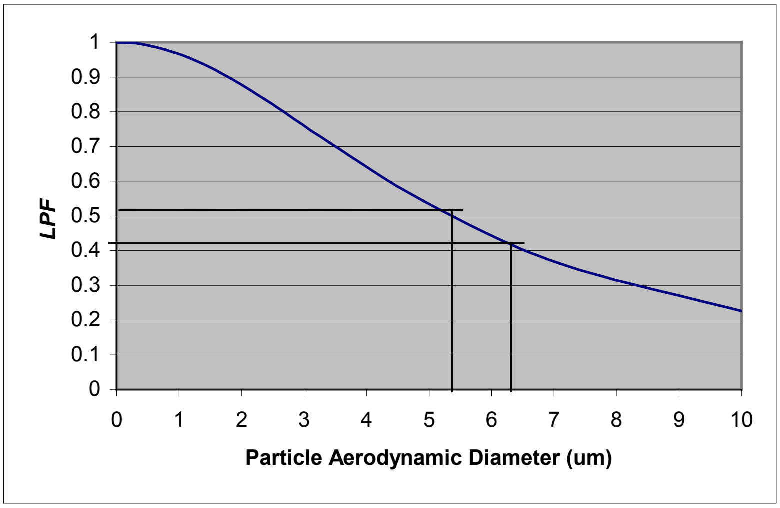

Figure 8–14 LPF for Sample Volume as a Function of Particle Size

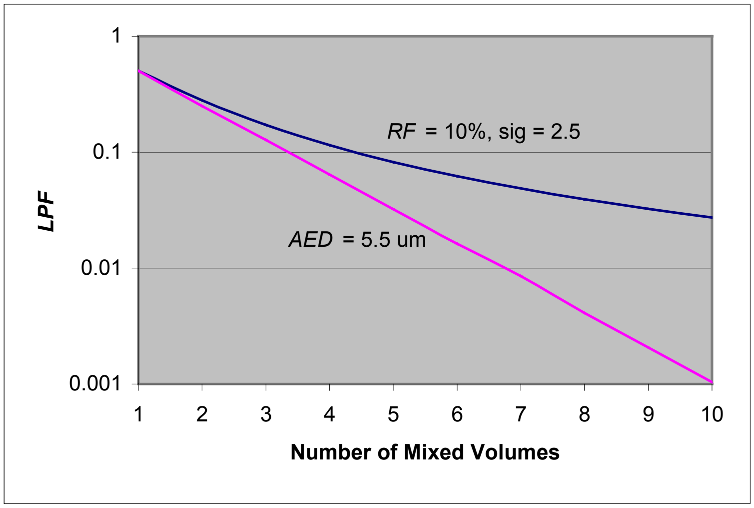

Figure 8–15 LPF as a Function of the Number of Volumes in the Leakpath

Note that the divergence is appreciable only for leakpaths consisting of five or more volumes. Note also that, as expected, the use of a single particle size that correctly characterizes the LPF of a single volume is increasingly non-conservative as the number of volumes in the leakpath string increases. This is due to the fact that each volume in turn preferentially filters the larger particles and that subsequent volumes therefore "see" smaller particles than did the previous volume.

For this example, the LPF for the lognormal distribution characterized by RF = 10 percent and σ = 2.5 is 0.025 for all ten volumes in series. The LPF for all ten volumes and a monodisperse aerosol is

$$LPF = \left(1 + \frac{v_d A_d}{Q}\right)^{-10} = 0.025 \qquad (8\text{-}38)$$

which can be evaluated for v_d to be 0.0378 cm/s for the sample problem. By Table 8-1, this implies that the characteristic AED for the ten-volume case lies between 3 and 4 µm, instead of the 5.5 µm found for the single volume LPF. Choosing AED = 3 µm for the characteristic particle size for the LPF of the single volume case, would give LPF = 0.758 instead of the actual 0.503, a 50 percent error in the direction of greater conservatism.

This exercise suggests that the analyst might, as a preliminary estimate of the leakpath factor, use the simple hand calculation model, picking a conservative particle size, say 2 or 3 µm if the leakpath is complex. If the so determined factor results in an acceptable source term, no further refinement of the calculation is needed. If the source term is unacceptable, a better estimate of the LPF should be attempted. This will require the use of a computer code and research of available data or estimates of the size distribution associated with the airborne release.

8.5.2.2 Gases and Vapors

For gases and vapors, the relevant deposition mass flux is given by Equation 8-16 as

$$N_A M_A = \left(\frac{1}{k'} + \frac{1}{k_c} \right)^{-1} M_A C_A ,$$

where $M_A C_A = C$, the mass concentration used in

Equations 8-32 and 8-34. (M_A is the molecular weight of the substance in question). Hence

$$v_d = \left(\frac{1}{k'} + \frac{1}{k_c} \right)^{-1}$$

in those equations, and the LPF is calculated as before, using this value. A_d is, of course, now the area of all reactive surfaces, not just the horizontal up surface area used for particle settling in the previous examples.

8.5.2.3 Determining Flow Rates

When the facility is ventilated by a forced air ventilation system, and the ventilation system is on during the accident, flow will be dominated by that system, provided there is no internal pressurization of the facility due to a large fire, for example. The volumetric flow rate, Q, of the above equations is then just the ventilation flow in the flow path, and can be obtained from ventilation operation specifications.

If the ventilation system is not on during the accident, and the facility is not pressurized by internal events, ventilation will occur by "natural" effects such as wind pressure on the building, and temperature differences between the environment and inside the facility. Such ventilation is termed natural ventilation. Equations for estimating a building's ventilation rate can be found in the ASHRAE literature. A convenient summary is given in a Battelle report, (Battelle-98). Two important equations given in that report are, for wind pressure-driven flows:

$$Q = 88 C_v A v \tag{8-39}$$

where all terms use English units, and

Q = volumetric flow in $\mathrm{ft}^3/\mathrm{min}$
C_v = effectiveness of openings (unitless)
= 0.55 for perpendicular winds
= 0.30 for diagonal winds
A = free area of inlet openings in ft^2
v = wind velocity in ft/s,

For temperature differences between in- and outdoors:

$$Q = 60C_D A \left(2g\Delta H_{NPL} \left(\frac{T_i - T_0}{T} \right) \right)^{1/2} . \tag{8-40}$$

Here,

C_D = discharge coefficient of opening
= $0.40 + 0.0025(T_i - T_o)$

and

g = 32 ft/s^2
ΔH_{NPL} = height from midpoint of lower opening to neutral pressure level (ft)
T_i = indoor temperature (R)
T_o = outdoor temperature (R)
T = the larger of T_o and T_i.

If an internal fire pressurizes the facility, that pressurization may overpower the ventilation system and motivate hazardous material leakage to the outdoors. The correct modeling of such accidents is complex and in general requires the use of computer models. These can treat the flow balance and in particular the obviously transient nature of the phenomenon. As noted previously, simple expressions for the LPF, while independent of the time dependent behavior of the internal hazardous material source term, require steady flow rates.

It is nevertheless sometimes instructive and possible to make rough estimates of the LPF under fire conditions. A simple approach to calculating the flow rate begins with the assumption that a fire in a room will try to pressurize that room, but that the pressure will remain approximately constant by bleeding off excess air (the air expands and flows out of the room). This model will be used to develop an expression for *Q*.

The ideal gas law is (the symbols have the usual definitions)

$$PV = nRT = \rho V \frac{RT}{M} \tag{8-41}$$

and, for constant *P*, this gives

$$\frac{\Delta V}{\Delta t} = \frac{nR}{P} \frac{\Delta T}{\Delta t} \tag{8-42}$$

If the fire releases a quantity, Q_R, of heat and a fraction, γ, of that energy is absorbed by the surrounding air, then to air heats up according to

$$mc_p \Delta T = \gamma Q_R \tag{8-43}$$

where

m = mass of air in fire room
c_p = specific heat capacity of air at constant pressure.

If $W_R = Q_R/\Delta t$ = the thermal power of the fire, and $Q = \Delta V/\Delta t$ = air flow rate, then combining Equation 8-42 with Equation 8-43 gives

$$Q = \frac{\gamma W_R}{T\rho c_p}\text{, independently of the volume of the room.} \qquad (8\text{-}44)$$

The above expressions are useful for a first cut at determining a suitable flow rate in developing the LPF, in the spirit of a graded approach to the problem. A more sophisticated approach is given in NUREG/CR-6410, Section 4.4 *Definition of Driving Forces for Transport* (NRC-98). There is a point, however, at which the need for increased realism will demand the use of computer models – particularly when the driving force for the flow is time dependent.

Example Calculation

Assume a typical 1 Mw fire. γ is usually taken to be about 0.7. Then, using the standard values for air at sea level and T = 300 K:

ρ = 1.2 kg/m^3;
c_p = 1 kJ/kg K

Equation 8-44 gives

$$Q = \frac{0.7\times 10^6 J/s}{1.2 kg/m^3 \times 300K \times 10^3 J/kgK} = 1.94 m^3/s\,. \qquad (8\text{-}45)$$

8.5.3 Computer Code Calculations

The hand calculations that are illustrated above are bounding in the sense that they tend to overestimate the value of the LPF. They do so because of the large number of simplifying assumptions that are necessarily invoked to make the calculation tractable. Thus, for example, the illustrated hand calculations account only for settling and assume steady flow. There may be situations, however, where other deposition mechanisms and flows come into play. Transient flows, for example, may result from transient fires or they may occur as the result of dampers being actuated or barriers failing during the accident. The leakpaths may themselves be redirected during the course of the release. Leakpaths may contain recirculating flow loops that cannot easily be considered in hand calculations.

Application of an appropriate computer model is indicated if the simple hand calculation results in a LPF that is unacceptably high and indications are that a refinement of the calculation with more sophisticated computer models might yield the desired result. The following subsection identifies candidate codes and illustrates the application of one.

8.5.3.1 Available Computer Codes

There is a considerable number of codes that have been developed to track the transport of aerosol particles in enclosed spaces. Generally these derive from two areas of research. One of these areas is Nuclear Reactor Safety Analysis and, in particular, fission product transport in the primary and secondary systems of nuclear reactors. The other is that concerned with the indoor air quality of inhabited buildings. Fortunately, computer codes relevant to these two areas have recently been reviewed. The nuclear facility codes are reviewed in a report that contributes to a DOE sponsored accident analysis methodology study[11] (LANL-96); the indoor air quality codes were reviewed for the Department of Defense by Battelle Columbus (Battelle-98). The reader is referred to these two documents for guidance in selecting a suitable code for leakpath analysis. The following employs one of the codes that is recommended in the DOE study, the MELCOR code (Sandia-97), in demonstrating the application of computer codes to estimating LPFs.

8.5.3.2 Computer Code Examples

<u>Example 1</u>

The LPF for a simple example can be calculated by hand. The corresponding code calculation should give the same result. As a demonstration, calculate the LPF for a facility consisting of two rooms as illustrated below in **Figure 8–16**, by hand and with the MELCOR code. The IST is assumed to be the instantaneous spill of 1 g of material uniformly aerosolized in Room 1. Ventilation flow rate (assumed constant) and particle size[12] are parameterized. Relevant geometry is indicated in the figure. It is assumed that mixing of the aerosol in each room is rapid compared to the corresponding air exchange rate – i.e., that the aerosol can be assumed uniformly mixed in each room.

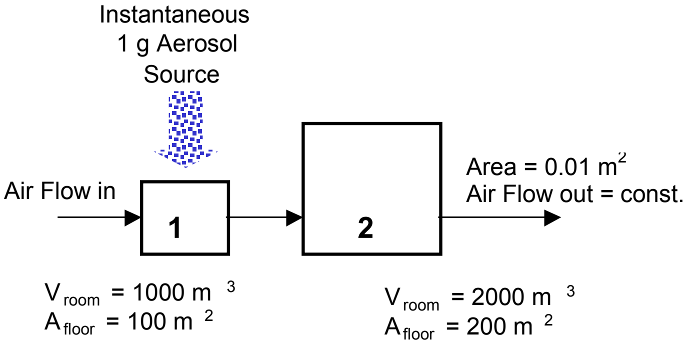

Figure 8–16 Two Volume Example Leakpath Problem

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[11] Accident Phenomenology and Consequence Analysis Methodology Assessment Program (APAC).

[12] Particle size in MELCOR is treated as uniform between bin boundaries that must be at least a factor of two apart.

Section 8.5.2 provides the analytical expressions needed to calculate the LPF for our example by hand. Applied to the example, they give:

$$LPF = \frac{1}{1+\alpha_1}\frac{1}{1+\alpha_2} = 10^{-6} v_d^2 \tau_1 \tau_2 \text{, since} \tag{8-46}$$

$$\alpha_1 = \frac{\tau_1}{\tau_d} = \frac{\tau_1}{V_1 / v_d A_{floor1}} = 10^{-3} v_d \tau_1 \text{, and} \tag{8-47}$$

$$\alpha_2 = \frac{\tau_2}{\tau_d} = \frac{\tau_2}{V_2 / v_d A_{floor2}} = 10^{-3} v_d \tau_2 . \tag{8-48}$$

As before, τ_i is the residence time, in seconds, of the flow in Volume i. v_d is the settling velocity, in cm/s, for the particle under consideration and can be taken from Table 8-1.

Figure 8–17 shows the results of the LPF calculations on the example system of Figure 8–16 as a function of residence time $(\tau_1 + \tau_2)$ for the whole system. The parameter on the curves is the aerodynamic diameter of the source particles. Note that, indeed, the code calculations closely match those done by hand for this simple system experiencing constant ventilation flow. Only the sedimentation attenuation mechanism was considered. Particle agglomeration is calculated in MELCOR but not in the hand calculations. The congruence of the corresponding curves justifies its neglect in this case in which particle concentrations are too low for agglomeration to play a role. The slight difference between the code and hand calculated curves for the smallest particle size (~ 1.5 µm) is due to the fact that the MELCOR properly evaluates the Cunningham slip correction factor, $C(d_p)$, of Equation 8-1, while the hand calculations of v_d (Table 8-1) dismisses this factor as negligible in comparison to the uncertainties introduced by other simplifying assumptions.

Example 2

A more realistic example is that illustrated in Section 8.4, *Factors that Affect Leakpaths*, Figures 8–1 and 8–2. The scenario depicted in those figures is as follows:

- A one MW fire occurs in the room farthest to the left in the two the figures.
- The fire lasts for 15 min.
- There is an instantaneous release of 1 g of respirable aerosol 10 min into fire.
- The aerosol particle size ranges between 1 and 2 µm.
- The fire damper closes in fire room at 5 min into fire and prior to aerosol release. Personnel evacuate the building, leaving all room doors and the corridor door to the outdoors open.

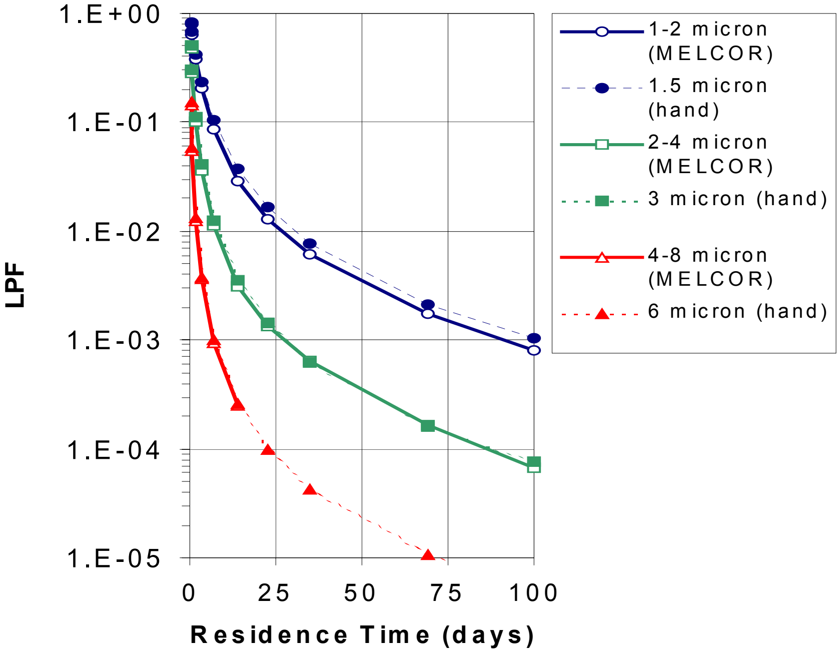

Figure 8–17 Comparison of Hand and Code Calculations for Example in Text

Assume the following facility parameters:

Rooms

30 ft × 30 ft × 16 ft, or 9.144 m × 9.144 m × 4.877 m

$$A_d = 83.61 \text{ m}^2$$
$$V = 407.8 \text{ m}^3$$

Corridor

90 ft × 10 ft × 16 ft, or 27.43 m × 3.048 m × 4.877 m

$$A_d = 83.61 \text{ m}^2$$
$$V = 407.8 \text{ m}^3$$

Fans

480 cfm = 0.2265 m^3/s through each room

HEPAs

one stage, 99.95 percent efficient.

From these, one can attempt to estimate the LPF by hand as in Example 1 above. This estimate will help in interpreting the MELCOR results below.

The first question might be: does the transient nature of the flow invalidate application of hand calculation models that are based on constant flow? The answer to that question can be estimated by looking at the characteristic times of the problem as follows.

The example calculation of Section 8.5.2, *Hand Calculation of the Leakpath Factor*, for flow due to fires, treats just this 1 MW case and gives a flow of 1.94 m^3/s, independent of the size of the room (Equation 8-45). Thus $Q = 1.94\ m^3/s$. Applying this flow rate to the fire room, gives a flow residence time for that room of $\tau = V/Q = 3.5$ min. According to the description of the problem, the aerosol is released instantly, 5 min before the fire ends. The residence time in the leakpath: fire room-corridor-outdoors is 2 × 3.5 = 7 min. This period is of the same order as the 5-min period left for fire induced flow. It is therefore reasonable to assume that a good portion of the IST makes it out of the facility before the flow ends – especially since the ventilation flow into the unaffected rooms from the corridor aids the flow out of the fire room and down the corridor.

Make the approximation that the fire induced flow in the leakpath continues at its average rate over the full extent of the fire: 1.94 m^3/s for 15 min, and assume that hand calculation models can be approximately applied. Application of the realistic MELCOR model will then confirm or deny this assumption, but either way, the hand calculations provides intuitive insight into the phenomenology involved.

Calculate the settling velocity for the 1 to 2 μm particles by assuming a characteristic aerodynamic diameter of 1.5 μm. Then, using Equation 8-3,

$$v_d = \frac{gd_{ae}^2}{18\eta} = \frac{981\times\left(1.5\times10^{-4}\right)^2}{18\times1.84\times10^{-4}} = 6.66\times10^{-3}\,cm/s\,.$$

From Equation 8-33,

$$\alpha = \frac{v_d A_d}{Q} = \frac{6.66\times10^{-4}\times83.61\times10^{4}}{1.94\times10^{6}} = 2.87\times10^{-3}$$

and the LPF for the fire room is $LPF = \frac{1}{1+\alpha} = 0.997$; that for the corridor is $LPF = e^{-\alpha} = 0.997$. The LPF for the leakpath fire room-corridor-outdoors is therefore LPF × LPF = 0.99. This LPF has been calculated assuming the fire induces the only flow in the facility, and that this flow is along the leakpath: fire to room to corridor to outdoors. In fact, the ventilation system in the other two rooms is assumed to operate and to pull flow out of the corridor through the open doorways. Some of the leak flow is therefore directed through the ventilation system and the HEPA filters (whose transmission of aerosol particles can be ignored relative to the direct losses through the exterior doorway).

The ventilation flow rate through each of the unaffected rooms is 0.2265 m^3/s, so that both rooms together provide a ventilation flow rate of 0.4530 m^3/s for the facility. This means that the net flow out of the exterior doorway is 1.94 – 0.453 = 1.49 m^3/s. Since without consideration of the ventilation system essentially all of the source aerosol transports to the outdoors, and since essentially none of the aerosol transmitted to the HEPA filters penetrates them, the overall facility LPF is LPF = 1.49/1.94 = 0.77.

The results of the MELCOR calculations of this scenario are shown in **Figures 8–18** through **8-20**. Figure 8–18 shows the disposition of the aerosol as a function of time. Note that the "deposited" mass is essentially the mass caught in the HEPA filters of the ventilation system. The figure shows that roughly 72 percent of the IST is transported to the outdoors – in remarkable agreement with the hand calculations. In contradistinction to the hand calculations, however, the code provides a time history of the aerosol material in the facility. It shows that the aerosol lingers for some 3 hr or so—much longer than was estimated by hand.

The distribution of airborne material by location in the facility as a function of time is provided in Figure 8–19. Figure 8–20 shows the distribution of deposited material as a function of time. Such time and location resolved information is not provided by hand calculations but could prove extremely useful for planning emergency response strategies, particularly in more complex facilities than the simple example shown here.

The Example 2 scenario is also interesting because there must be a threshold fire size below which the fire induced flow is overpowered by the ventilation system. For such fires the LPF would be just that or the HEPA filters, namely $1 - 0.9995 = 5 \times 10^{-4}$ (much less than the 0.72 calculated for the 1 MW fire). It takes a computer code to realistically calculate that threshold.

Example 3

In each of the previous examples, a dominant leakpath to the environment is easy to identify. Further, the characteristic flow rate along the leakpath can be calculated without major complications associated with expansion into large neighboring, dead-end volumes, or flow diversion through parallel leakpaths. Unfortunately, these ideal conditions rarely occur in practice. Rather, accident scenarios of interest for many facilities involve multiple simultaneous leakpaths to the environment, each characterized by different flow rates and contaminant removal properties. In some cases, contaminant release to the environment is strongly influenced by time-dependent characteristics of the accident scenario.

One method for dealing with such complex situations is to make simplifying assumptions (such as selecting a single 'conservative' leakpath) and apply the methods illustrated in Examples 1 and 2. An alternative, however, is to construct a computer model of the facility that represents all the possible leakpaths, their individual flow properties and contaminant removal mechanisms. A computer code such as MELCOR is designed specifically for that purpose. This example illustrates the major features of a MELCOR calculation of LPF for a facility with complex leakpaths.

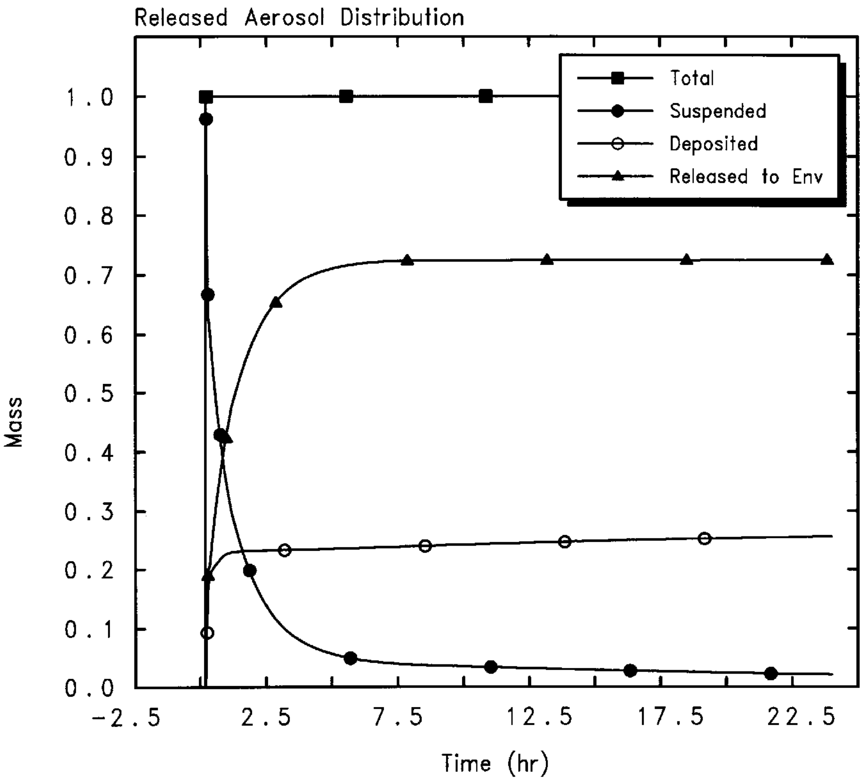

Figure 8–18 Example 2 - MELCOR Prediction of the Aerosol Distribution

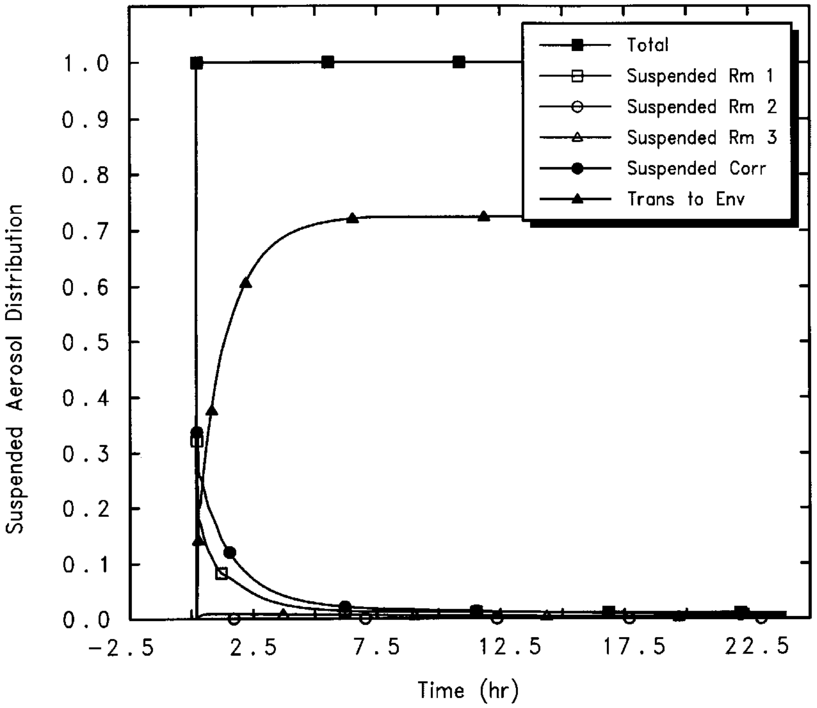

Figure 8–19 Example 2 - MELCOR Suspended Aerosol Distribution by Location

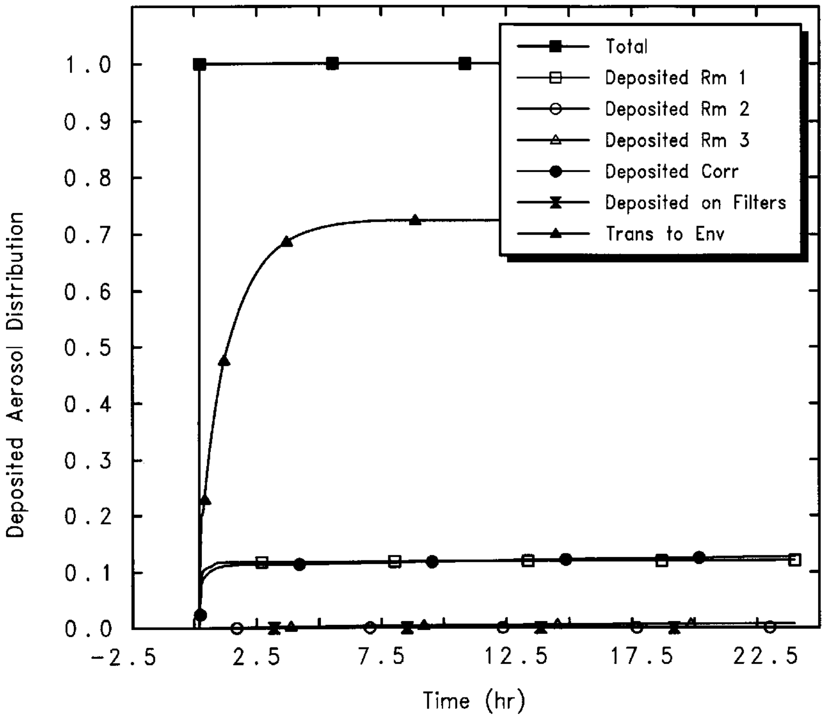

Figure 8–20 Example 2 - MELCOR Deposited Aerosol Distribution by Location

In this example, consider the accidental release and transport of plutonium aerosol within a nuclear material storage facility. The facility stores nuclear materials (metal and oxide) in air-cooled arrays located in a subterranean vault below the main floor of the facility. The main floor of the facility (which is the subject of this example) contains shipping/receiving docks, shipping container packing/unpacking areas, container inspection facilities, and office space. Each of these areas is accessed through a serpentine corridor that winds through center of the facility. Building emergency exit doors for the facility are located at each end of the corridor. Personnel entrance doors are located at the front of the facility and in the shipping/receiving area. An illustration of the main floor of the facility is shown in **Figure 8–21**.

A MELCOR model was developed for this facility, and was used to calculate LPF under a wide variety of postulated accident conditions (Shaffer-99). The MELCOR model consists of a network of control volumes, flow pathways, and structural surfaces. With a few exceptions (described below), each room of the facility is treated as a distinct control volume, and each doorway separating adjacent rooms is treated as a distinct flow path. The normal position of doors between adjacent rooms is reflected in the flow area specified for the associated flow path[13]. Corridors with long characteristic transport lengths are subdivided into a series of connected control volumes to represent the gradual migration of suspended material along their

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[13] The position of individual doors (or more properly, flow path areas) can be adjusted to investigate the importance of door position to LPF. If desired, control logic can be developed to change door positions during a simulated accident (for example) to simulate door opening, and subsequent closure following personnel evacuation.

length. Major building structures, such as walls, floors and ceilings are defined and linked to appropriate control volumes to account for heat transfer. These surfaces are also available for aerosol deposition according to their spatial orientation. For example, gravitational settling occurs onto upward-facing horizontal surfaces (i.e., floors), whereas deposition by diffusion can occur on all surfaces.

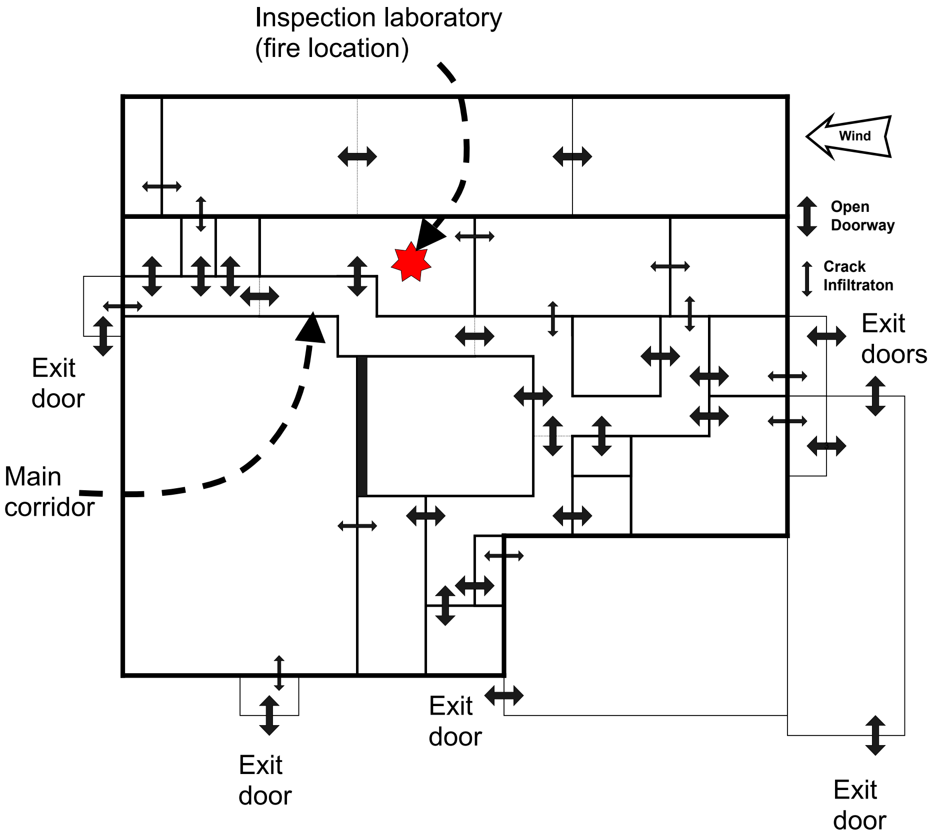

Figure 8–21 Floor Plan for the Main Floor of the Example Storage Facility

In addition to the control volume network simulating the movement of air and contaminants among various rooms in the facility, HVAC systems are represented in the MELCOR model. Key features of the HVAC model include exhaust and recirculation fans, inline HEPA filters, flow control dampers and flow distribution ductwork. HVAC ductwork and intake/exhaust registers are defined in a manner that preserves their actual elevation, thus allowing natural circulation flow through the system to be represented during postulated accident scenarios in which the ventilation fans do not operate.

The accident scenario examined here involves a fire in a container inspection laboratory near the center of the main floor of the facility (the location is marked in Figure 8–21). The fuel for the fire is assumed to be a quantity of ordinary combustibles based on an average loading of 1 lb/ft^2. The entire fuel load was assumed to burn at a steady rate 0.32 lb/s (or 2560 Btu/s) for the first 2,700 s of the accident, with a subsequent ramp to zero (i.e., the fire is completely extinguished) at 1 hr. The doorway connecting the laboratory to the facility's main corridor is assumed to be fully open. A sealed canister of PuO_2 powder is assumed to be engulfed by the fire, causing the internal pressure to rise above its burst point. Failure of the canister is assumed to occur 20 min after the onset of the fire, instantaneously releasing a fixed quantity of respirable PuO_2 aerosol.

One limitation of MELCOR for analyzing this type of accident scenario is that it does not contain models for calculating details of fire behavior[14]. In particular, the lumped parameter formulation of MELCOR prevents it from calculating the development and growth of a stratified hot gas layer at the ceiling of the affected room[15]. The code is also not designed to calculate the counter-current exchange of combustion gases through the open doorway into the corridor, thereby limiting its ability to properly calculate the rate at which carrier gases for airborne contaminants are expelled from the room. Other computer codes, such as CFAST [Peacock-91], are designed specifically to examine these thermal characteristics of room fires. However, like most fire codes, CFAST focuses only on fire phenomena; i.e., it does not calculate the transport of suspended contaminant material from the burning room. Consequently, a two-step approach is taken to address this example problem, using the CFAST and MELCOR computer codes. CFAST is first used to characterize the intra-room thermal environment generated by the fire; then MELCOR is used to calculate the transport and deposition of released plutonium aerosol throughout the facility.

Details of the CFAST model and calculation are not described here. Additional information on methods for room fire analysis is found elsewhere in this document. Results of the CFAST simulation of the room fire that are applied directly to the subsequent LPF calculation (using MELCOR) include:

- The neutral plane separating the hot gases expelled through the upper portion of the doorway and the fresh air entering the room at the bottom of the doorway is 2.8 ft above the floor.
- The rate at which fresh air is drawn into the burning laboratory = 3.4 lb/s.
- The maximum temperature of the thermal plume rising above the fire is 755°F.

Based on this information, the MELCOR model of the burning room is expanded to reproduce the thermal environment within the room, and the counter-current flow of gases into and out of the room. The expanded model of the affected laboratory and neighboring corridor is illustrated in **Figure 8–22**. The fire-induced flow field and temperature distribution within the laboratory is represented by network of 7 control volumes, which spatially separate the central fire column from neighboring (thermally stratified) portions of the room.

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[14] The same limitation applies to other codes commonly used for in-facility transport analysis, such as CONTAIN. The FIRAC and GASFLOW codes include models for fire behavior and particulate transport phenomena. However, FIRAC has been found to be difficult to operate [Battelle-96] and is no longer supported as an operating computer code. GASFLOW is a computational fluid dynamics (CFD) computer code recommended for use only when multi-dimensional flow effects are important [Spore-96].

[15] If the room is modeled as a single control volume, the lumped parameter modeling approach is equivalent to assuming the temperature within the room is uniform. However, subdividing the room into two or more vertically stacked control volumes is one means of approximately a stratified hot gas layer. Such as approach is taken in this example.

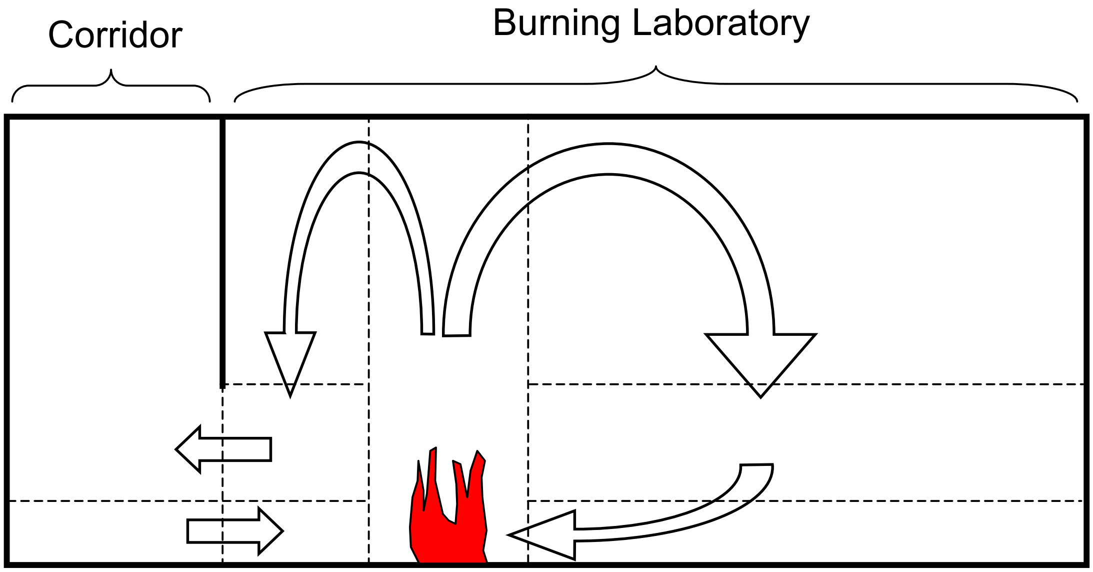

Figure 8–22 MELCOR Model of the Burning Laboratory Used to Reproduce Room Fire Characteristics Identified by CFAST

Several calculations were performed with the MELCOR model described above to examine the extent to which the LPF is sensitive to assumed values for uncertain modeling parameters. Such parameters include:

- Flow area for air infiltration into and leakage out of the facility (i.e., the nominal width of gaps in exit door frames).
- Wind speed external to the facility (wind produces a differential pressure across the building, thereby enhancing the driving forces to the environment through some leakpaths).
- Smoke density. Most fires generate substantial quantities of smoke, which moves around in the facility as an aerosol. High concentrations of the smoke can interact with suspended PuO_2 particles, affecting transport efficiencies. This interaction is modeled in MELCOR.
- HEPA filter collection efficiency.

Results of the MELCOR calculations are summarized in **Table 8-6**. Base case modeling assumptions are shown as Case #1 in the table. Alternative values for the parameters listed above and their corresponding effect on the LPF is shown in Cases 2-11. The calculated value of the LPF is shown to be particularly sensitive to the assumptions affecting the leak rate through cracks in doorways to the environment, and to assumptions regarding interactions between small PuO_2 particulate and smoke generated by the fire. Slight degradation in HEPA filter performance does not substantially impact the LPF.

Table 8-6 Results of MELCOR LPF Calculations: Example #3

Case	Crack Width (mm)	Wind Speed (mph)	Smoke Generated by Fire (kg)	HEPA Collect Efficiency	Leakpath Factor
1	**0.5**	**30**	**None**	**99.98%**	**3.9E-03**
2	**1**	30	None	99.98%	9.3E-03
3	**2**	30	None	99.98%	2.0E-02
4	**5**	30	None	99.98%	5.1E-02
5	0.5	**1**	None	99.98%	2.8E-07
6	0.5	**10**	None	99.98%	1.1E-04
7	0.5	**20**	None	99.98%	1.0E-03
8	0.5	30	**10**	99.98%	2.6E-05
9	0.5	30	**25**	99.98%	1.1E-05
10	0.5	30	**50**	99.98%	3.9E-03
11	0.5	30	None	**99.95%**	3.9E-03

In this example, the building exit doors are closed during the release period (i.e., evacuation of personnel from the building is assumed to be complete prior to failure of the container). Consequently, parameters influencing leakage through closed building exit doors have a direct effect on the LPF. As shown in the results for Sensitivity Cases 2 - 4, increases in the assumed width of cracks in exit doors affects the LPF in a nearly linear manner. The assumed speed of wind outside the building is also shown to have a significant affect on the LPF (Sensitivity Cases 5 – 7)[16]. Wind creates a differential pressure across the building, enhancing the driving force for building leakage. The effect on the LPF is more pronounced than that observed for variations in door leak area, however, because pressure is proportional to the square of wind velocity.

As shown in Sensitivity Cases 8 – 10, accounting for the release of substantial quantities of smoke during the fire also has a significant impact on the LPF. In this example, smoke is modeled as an aerosol that is released gradually during the fire. If large quantities of smoke are generated during the fire, interactions between soot particles and PuO_2 particles (i.e., agglomeration, which is modeled in MELCOR) increases the effective diameter the PuO_2 particles, thereby enhancing the rate at which they deposit within the building by gravitational settling, as shown in Table 8-2. Consequently, the calculated LPF decreases with increasing quantities of smoke generated by the fire.

In contrast to the sensitivity cases above, Case 11 show a negligible impact on the LPF. This case examined the effect of slight degradation in HEPA filter efficiency. Active ventilation systems were not operating in the calculations described in this example. Consequently, the effect of the (passive) flow through the filtered leakpath is negligible.

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[16] The wind direction assumed in each of the calculation is shown in Figure 8-22.

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