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HIGH LEVEL HAZARD SAFETY ANALYSIS VOL 1 OF 3

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Exam Preview:

1. According to the reference material, the majority of fires analyzed for the DSA are referred to as compartment fires (i.e., fires in enclosed spaces such as gloveboxes or process rooms).
    a. True
    b. False
2. Regarding toxicity, impact on a facility worker is defined as being exposed to a chemical concentration reaching Protective Action Criteria (PAC)-2 or PAC/TEEL-3 levels based on a qualitative evaluation. Typically, PAC concentrations are evaluated over a __-minute period
    a. 10
    b. 15
    c. 20
    d. 30
3. Using Table 2 3. Correlation of Hazardous Energy and Material Sources to Accident Types/Categories, which of the following accident categories corresponds to Ionizing Radiation Sources?
    a. Natural Phenomena Hazards
    b. Nuclear Criticality
    c. Loss of Confinement/Spills
    d. Direct Radiological Exposure
4. According to the reference material, Fires have 3 stages or distinct regimes: (1) ignition, (2) growth, and (3) decay.
    a. True
    b. False

5. Using Table 2-9. Qualitative Likelihood Classification, what is the likelihood range (/year) for events that may occur several times during the lifetime of the facility (incidents that commonly occur).
   a. Likelihood $>10^{-2}$
   b. $10^{-2}>$likelihood $>10^{-4}$
   c. $10^{-4}>$likelihood $>10^{-6}$
   d. Likelihood $<10^{-6}$
6. Using Table 4-3. Groups of Like Events—Fragments from Explosions, which explosion material from the table had the highest source energy range (J)?
   a. Propane, anhydrous ammonia
   b. LPG
   c. Air
   d. Argon
7. According to the reference material, the severity of a lightning flash is usually defined by the peak amplitude of its return stroke current, which range from one to hundreds of kA. The upper one-percentile current has been determined to be about 200 kA.
   a. True
   b. False
8. Using Table 4-8. Exposure Time t_c to Reach the Pain Threshold, what is the exposure time to reach pain threshold for a source with a radiation intensity of 920 Btu/hr/ft^2?
   a. 40 seconds
   b. 30 seconds
   c. 16 seconds
   d. 9 seconds
9. According to the reference material, there are two main failure mechanisms for HEPA filter failure from smoke generated by a fire: plugging and blowout/media failure.
   a. True
   b. False
10. Using Table 4-9. Constant Volume Combustion Pressures for Various Gases, what is the constant volume combustion pressure for Propane?
    a. 8.15 bar
    b. 8.94 bar
    c. 9.44 bar
    d. 9.51 bar

CONTENTS

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ACRONYMS

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

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

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

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

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

1 INTRODUCTION

This Handbook contains methodology, data sources, and subject matter references for performing and reviewing hazard and accident analysis for Department of Energy (DOE) nonreactor nuclear facilities. The guidance offered supports development of a Documented Safety Analysis (DSA) required by 10 CFR[1] Part 830, *Nuclear Safety Management*, Subpart B, "Safety Basis Requirements."

The Handbook uses as a starting point drafts of a report prepared by the Safety Analysis Working Group of the Energy Facility Contractors Group. This early effort was sponsored by DOE's Office of Defense Programs (predecessor of NNSA) in the early 2000s. Although that report was not completed, some of its technical content has been incorporated into this Handbook.

The Handbook describes best practices gleaned from development of DSAs throughout the DOE complex and from insights acquired in the development of DOE-STD-3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis.* The Handbook provides many application examples that will be helpful to the analyst.

1.1 PURPOSE

The principal purpose of this Handbook is to guide development of the DSA safety analysis for nuclear facilities in order to satisfy the requirements of a safe harbor method set out in 10 CFR Part 830, Subpart B. The safety analysis process consists of three main steps:

- Hazard analysis (including hazard identification and evaluation);
- Accident analysis (including accident scenario definition and consequence analysis); and
- Preventive and mitigative control selection.

DOE-STD-3009-2014 provides criteria and guidance organized in the above manner. Further, it includes lessons learned from use of DOE-STD-3009-94, Change Notice 3 (CN3), *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analysis*, and other safe harbor methods. Therefore, this Handbook uses excerpts from DOE-STD-3009-2014[2] as the starting point for the amplifying guidance and good practices, but the scope of the Handbook is not limited to that standard.

The information in this Handbook is also relevant to other safe harbor methods for developing a safety basis document, such as DOE-STD-3011-2016, *Preparation of Documented Safety Analysis for Interim Operations at DOE Nuclear Facilities*, and DOE-STD-1120-2016, *Preparation of Documented Safety Analysis for Decommissioning and Environmental Restoration Activities*. The Handbook may also be use for upgrading existing DSAs to the new requirements of DOE-STD-3009-2014, or for updating DSAs for existing facilities based on their current safe harbor methodology.

1.2 OUTLINE

This Handbook is organized as follows:

- Chapter 2, *Hazard Analysis*, addresses hazard identification and evaluation, including hazard evaluation methods and safety control identification.

[1] Code of Federal Regulations.
[2] When used without a 2-digit or 4-digit year number after "DOE-STD-3009," the term refers to both the 1994 and 2014 versions. If a specific version is meant to the exclusion of the other, the year will be stated.

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- Chapter 3, *Accident Analysis*, provides a high level overview of the events that were identified in the hazard evaluation table to be evaluated for further accident analysis, provides an overview of the accident analysis process, and discusses two key topics: (1) assumptions and initial conditions; and (2) conservatism in analysis.
- Chapter 4, *Evaluation of Effects of Major Accident Types*, addresses the analysis of accident scenarios. The various topics covered provide information for evaluating the magnitude of the accidents and the resulting accident environments, so that the amount of radioactive or other hazardous material affected is defined. Toxic chemicals are a subset of hazardous materials that require additional dispersion and consequence assessment. In addition to evaluation of potential consequences to facility workers, this information is necessary to determine the source term available for release from the facility, and to evaluate the capability of safety structures, systems, and components (SSCs) to survive the accident environments and provide required safety functions when called upon.
- Chapter 5, *Source Term Analysis*, addresses development of the amount of radioactive material or toxic chemical released from a given confinement volume under the stress posed by insults from a hypothetical accident. Source term estimations include quantifying radioactive or toxic chemical material at risk, damage ratio, airborne release fractions or release rates, respirable fractions (for radioactive materials only), and leakpath factor.
- Chapter 6, *Atmospheric Dispersion*, addresses atmospheric transport and diffusion, meteorological data, and the models available for consequence assessment of radioactive releases to the atmosphere.
- Chapter 7, *Aquatic Dispersion and Groundwater Transport*, addresses surface water and ground water pathways, and the models available for consequence assessment of radioactive releases to aquatic water bodies and ground water.
- Chapter 8, *Radiological Consequence Assessment*, addresses the different types of radiation and the health effects they can have on the human body, its organs, and its tissues, and how radiological doses to receptors of interest may be estimated.
- Chapter 9, *Chemical Dispersion and Consequence Analysis*, addresses toxic chemical releases, their potential health effects and methods for estimating concentration at various distances.
- Chapter 10, *Hazard Control Selection and Classification*, addresses selection of safety significant and safety class controls that are credited in the hazard evaluation or accident analysis.
- Chapter 11 provides a complete list of references cited in the text.
- Appendix A, *Hazard Analysis Table Development*, provides guidance on constructing this table which is discussed in Chapter 2.
- Appendix B, *Criticality Accidents*, addresses this type of accident in greater detail.

2 HAZARD ANALYSIS

This chapter addresses hazard analysis (HA) techniques for the identification and evaluation of hazards, and the *identification* of controls to prevent or mitigate accidents. Hazard control *selection* is addressed in Chapter 10.

2.1 ELEMENTS OF HAZARD ANALYSIS

DOE-STD-3009[3] states that an HA consists of (a) hazard identification, (b) hazard categorization,[4] and (c) hazard evaluation. Hazard evaluation includes identification and safety classification of controls to prevent or mitigate potential hazard or accident scenarios.[5]

2.2 HAZARD IDENTIFICATION AND CHARACTERIZATION

The objective of hazard identification and characterization is to systematically and comprehensively identify radioactive and other hazardous materials within the facility, as well as natural phenomena hazards (NPHs) and external man-made events that may impact the facility and result in the release of these materials within the facility and to the environment. The hazard identification process includes characterizing hazardous materials (radiological and non-radiological) and energy sources, in terms of quantity, form and location. Examples of energy sources are falling objects, NPH-driven missiles, and other kinetic energy sources. Nuclear Criticality Hazard Evaluations are addressed in Section 2.3.2.

For DSAs prepared in accordance with 10 CFR Part 830, Subpart B, the key to successful hazard identification is ensuring comprehensive identification of the hazards associated with the full scope of facility processes, associated operations such as handling of fissionable materials, radioactive or hazardous wastes, and work activities covered by the DSA. Hazard identification does not yield specific hazard scenarios to analyze. Rather, it yields initial data from which hazard scenarios are subsequently developed. The overall quality of hazard scenario definition will be in direct proportion to the accuracy and completeness of the initial hazard information gathered.

The hazard identification process involves:

- Hazard data gathering;
- Summarizing hazard data in tables or data sheets; and
- Identifying standard industrial hazards (SIHs) needing further evaluation.[6]

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[3] As discussed in Section 1.1, when used without a 2-digit or 4-digit year number after "DOE-STD-3009," it refers to both the 1994 CN3 and 2014 versions of the DOE Standard. Otherwise, specific versions of DOE-STD-3009 are referenced throughout this Handbook.
[4] This Handbook does not address hazard *categorization*. Requirements and guidance for performing hazard categorization are provided in DOE-STD-1027-92, CN1.
[5] DOE-STD-3009-2014 defines a "hazard scenario" as "An event or sequence of events associated with a specific hazard, having the potential to result in undesired consequences identified in the hazard evaluation" and defines an "accident" as "A specific event or progression of a sequence of events resulting from an initiating event that is followed by any number of subsequent events that may lead to a release of radioactive or other hazardous material and/or exposure to a predefined receptor." The term "hazardous condition" has often been used in previous safety basis hazard evaluations instead of "hazard scenario." For the purposes of this Handbook, both terms are used interchangeably in Chapters 2, 3, 4, and 10 and in Appendix A when referring to the hazard evaluation.
[6] Such hazards might include electrical faults that could lead to a fire, or explosions harmful to nearby workers.

Comprehensive identification of hazards is best accomplished by a team comprised of safety analysts, system/process engineers, operational and support staff, industrial hygienists, and various subject matter experts (SMEs), as needed.

2.2.1 HAZARD DATA GATHERING

Gathering of hazard data commences with review of existing documentation, which includes the following:

- Facility and process descriptions (including available drawings and flow sheets);
- Historical radioactive and hazardous material inventory records;
- Existing safety documentation;[7]
- Operating and support procedures;
- Previous occurrence reports for the facility and relevant reports from general industry; and
- Facility design reports setting out the scope of new operations.

Once documented sources of hazards have been reviewed, a physical walkdown of the facility is undertaken to verify them and their locations. Such walkdowns are conducted with a floor plan noting the most significant details. Useful details may include information such as gloveboxes or containers, inventories and energy sources, system interconnections, and piping routes. Other details can be recorded during the walkdown in checklists and notebooks for completeness. If the facility is being designed, the floor plan can still be conceptually walked down using process and instrumentation drawings and process engineering drawings at whatever stage of development they are available. Hazard analysis is performed early in the project justification phase and during development of the Safety Design Strategy, continues during development of safety design basis documents as the design progresses, and is updated during development of the final DSA to authorize operations. If process and instrumentation drawings are based on evolving design of a new facility, the hazard identification will need to be reverified against the final design and as-built construction to support authorizing operations. The overall hazard identification and analysis is an iterative process during the design and construction phase of the project.

2.2.2 HAZARD DATA RECORDING

Checklists are used to ensure the hazard identification process is comprehensive and thorough. Checklists provide a generic list of hazards to look for in terms of radioactive and hazardous material types, energy sources, moving components, and the potential for falling objects. Hazard identification preparers use such checklists to systematically identify the presence or absence of hazards for a given area, from individual components/operations (e.g., gloveboxes) to entire rooms.

The raw data of a hazard identification can be recorded in a variety of ways. The critical information to be specifically noted in any recording mechanism is the hazard itself, its type, its magnitude and location, and sufficient descriptive notes to allow the HA team to place individual hazards in an appropriate context.

Materials of concern for release (or potential hazards in direct contact with materials of concern) are identified separately. Bounding inventory values of radioactive or hazardous materials are needed for the development of scenario-specific material at risk (MAR) for the hazard evaluation and accident analysis, consistent with the maximum quantities of material that are stored and used in facility processes.

[7] Safety data sheets (SDSs); waste data sheets; health and safety plans; procurement and inventory records; and annual reports, such as the Emergency Planning and Community Right-to-Know Act, Tier II Chemical, and EPA Toxic Release Inventory.

Inventory data may be obtained from flowsheets, vessel sizes, contamination analyses, maximum historical inventories, and similar sources.

An example of a checklist for a DOE nuclear facility is shown in Table 2-1. The "Disposition" column is optional and is discussed in Sections 2.2.3 and 2.2.4. Other types of checklists that have been developed in the DOE Complex, and which may reflect site-specific and facility-specific hazards. These can be used to identify hazards and energy sources. Commercial industry practices for hazard identification, such as those described in the Center for Chemical Process Safety's *Guidelines for Hazard Evaluation Procedures (*CCPS, 2008), provide guidance for the development of a comprehensive identification of hazards.

Table 2-1. Hazard Identification Checklist Example.
(Identify facility, location, or process)

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator/contributor)
1.0	**Electrical**			
1.1	Battery banks			
1.2	Cable runs			
1.3	Diesel generators			
1.4	Electrical equipment			
1.5	Heaters			
1.6	High voltage (> 600V)			
1.7	Locomotive, electrical			
1.8	Motors			
1.9	Power tools			
1.10	Pumps			
1.11	Service outlets, fittings			
1.12	Switchgear			
1.13	Transformers			
1.14	Transmission lines			
1.15	Wiring/underground wiring			
1.16	Other			
2.0	**Thermal**			
2.1	Boilers			
2.2	Bunsen burners/hot plates			
2.3	Electrical equipment			
2.4	Electrical wiring			
2.5	Engine exhaust			
2.6	Furnaces			
2.7	Heaters			
2.8	Lasers			
2.9	Steam lines			
2.10	Welding surfaces			
2.11	Welding torches			
2.12	Other			
3.0	**Pyrophoric Material**			
3.1	Pu and U metal			
3.2	Other (e.g., Zr)			
4.0	**Spontaneous Combustion**			
4.1	Cleaning/decontamination solvents			
4.2	Fuels (gasoline, diesel)			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator/contributor)
4.3	Grease			
4.4	Nitric acid and organics			
4.5	Paint solvents			
4.6	Other			
5.0	**Open Flame**			
5.1	Bunsen burners			
5.2	Welding/cutting torches			
5.3	Other			
6.0	**Flammables**			
6.1	Cleaning/decontamination solvents			
6.2	Flammable gases			
6.3	Flammable liquids			
6.4	Gasoline			
6.5	Natural gas			
6.6	Paint/paint solvent			
6.7	Propane			
6.8	Spray paint			
6.9	Other			
7.0	**Combustibles**			
7.1	Paper/wood products			
7.2	Petroleum-based products			
7.3	Plastics			
7.4	Other			
8.0	**Chemical Reactions**			
8.1	Concentration			
8.2	Disassociation			
8.3	Exothermic			
8.4	Incompatible chemical mixing			
8.5	Uncontrolled chemical reactions			
8.6	Other			
9.0	**Explosive Material**			
9.1	Caps			
9.2	Dusts			
9.3	Dynamite			
9.4	Electric squibs			
9.5	Explosive chemicals			
9.6	Explosive gases			
9.7	Hydrogen			
9.8	Hydrogen (batteries)			
9.9	Nitrates			
9.10	Peroxides			
9.11	Primer cord			
9.12	Propane			
9.13	Other (e.g., NiCd batteries)			
10.0	**Kinetic (Linear and Rotational)**			
10.1	Acceleration/deceleration			
10.2	Bearings			
10.3	Belts			
10.4	Carts/dollies			
10.5	Centrifuges			
10.6	Crane loads (in motion)			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator/contributor)
10.7	Drills			
10.8	Fans			
10.9	Firearm discharge			
10.10	Fork lifts			
10.11	Gears			
10.12	Grinders			
10.13	Motors			
10.14	Power tools			
10.15	Presses/shears			
10.16	Rail cars			
10.17	Saws			
10.18	Vehicles			
10.19	Vibration			
10.20	Other			
11.0	**Potential (Pressure)**			
11.1	Autoclaves			
11.2	Boilers			
11.3	Coiled springs			
11.4	Furnaces			
11.5	Gas bottles			
11.6	Gas receivers			
11.7	Pressure vessels			
11.8	Pressurized system (e.g., air)			
11.9	Steam headers and lines			
11.10	Stressed members			
11.11	Other			
12.0	**Potential (Height/Mass)**			
12.1	Cranes/hoists			
12.2	Elevated doors			
12.3	Elevated work surfaces			
12.4	Elevators			
12.5	Lifts			
12.6	Loading docks			
12.7	Mezzanines			
12.8	Floor pits			
12.9	Scaffolds and ladders			
12.10	Stacked material			
12.11	Stairs			
12.12	Other			
13.0	**Internal Flooding Sources**			
13.1	Domestic water piping			
13.2	Fire suppression piping			
13.3	Process water piping			
13.4	Other			
14.0	**Physical**			
14.1	Sharp edges or points			
14.2	Pinch points			
14.3	Confined spaces			
14.4	Tripping			
14.5	Other			
15.0	**Radioactive Material**			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator/contributor)
15.1	Radioactive material			
16.0	**Hazardous Material (Toxicological, Chemical, Biological)**			
16.1	Asphyxiants			
16.2	Bacteria/viruses			
16.3	Beryllium and compounds			
16.4	Biologicals/Biotoxins			
16.5	Carcinogens			
16.6	Chlorine and compounds			
16.7	Corrosives			
16.8	Decontamination solutions			
16.9	Dusts and particles			
16.10	Fluorides			
16.11	Hydrides			
16.12	Lead			
16.13	Oxidizers			
16.14	Poisons (herbicides, insecticides, fungicides)			
16.15	Other			
17.0	**Direct Radiation Exposures**			
17.1	Contamination			
17.2	Electron beams			
17.3	Radioactive material			
17.4	Radioactive sources			
17.5	Radiography equipment			
17.6	X-ray machines			
17.7	Other			
18.0	**Non-ionizing Radiation**			
18.1	Lasers			
18.2	Other			
19.0	**Criticality**			
19.1	Fissile material			
20.0	**External Man-made Events**			
20.1	Aircraft crash			
20.2	Explosion			
20.3	Fire			
20.4	Power outage			
20.5	Transportation accident			
20.6	Other			
21.0	**Vehicles in Motion**			
21.1	Airplane			
21.2	Crane/hoist			
21.3	Forklifts			
21.4	Heavy construction equipment			
21.5	Helicopter			
21.6	Train			
21.7	Truck/car			
21.8	Waterborne Vehicle			
21.9	Other			
22.0	**Natural Phenomena**			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator/contributor)
22.1	Earthquake			
22.2	Flood			
22.3	Lightning			
22.4	Rain/hail			
22.5	Snow/freezing weather			
22.6	Extreme straight-line wind			
22.7	Tornado			
22.8	Tsunami, seiche			
22.9	Volcanic ashfall			
22.10	Other			

An HA team safety analyst should work one-on-one with an individual SME and operations representatives to fill out those parts related to the SME's area of expertise and portions of the facility that have been segmented into process or area nodes for analysis as discussed later in this chapter. The multiple checklists from all the process or area nodes can be integrated into a complete draft of a hazard identification table and presented to the HA team for review, or the checklist for each node can be presented separately. Past experience has shown that this is a much more efficient way to complete the exercise than to have the entire HA team meet to discuss every item for every process or area node.

2.2.3 HAZARD SUMMARY DEVELOPMENT

DOE-STD-3009-2014, Section 4.0, DSA Section [3.3.2.1], states that the hazard identification data sheets (checklists) may be included in the DSA, or referenced as needed, and that a summary table that identifies hazards by form, type, location, and total quantity be presented, as well as a summary of major accidents or hazardous situations (e.g., fires, explosions, loss of confinement) that have occurred in the facility's operating history. The integrated checklist for the facility can be included in the DSA hazard identification results section. The process or area node checklists can also be used to develop a summary table to be included in the DSA. The range of information captured in the DSA hazard identification table is designed to ensure that the minimum hazard identification results are established, appropriate screening of hazards is performed, and information needed to perform an effective and efficient hazards evaluation is established. Table 2-2 is an example Hazard Summary Table form for a facility.

Table 2-2. Building XXX Hazard Identification Summary Table.

Hazard Type	Location	Form	Quantity	Remarks / Screening	References
Radioactive materials					
Direct radiation exposure					
Criticality accidents					
Hazardous chemicals (corrosives, toxics, reactions)					
Flammable/ combustible materials					
Explosive materials					
Electrical energy					
Kinetic and potential energy					
Pressure-volume					
Thermal energy					
NPHs					
Other					

These compilations of information reviews and facility walkdowns constitute initial information. Iterations between the hazard identification and hazard evaluation phases are likely necessary in order to ensure completeness.

2.2.4 EXCLUSION OF STANDARD INDUSTRIAL HAZARDS AND OTHER HAZARDOUS MATERIALS

The comprehensive hazard identification process in Sections 2.2.1 through 2.2.3 addresses all radiological and non-radiological hazards and energy sources. However, SIHs are not normally analyzed in a DSA hazard evaluation, unless chemical and industrial hazards result in a release of nuclear material, or an operator is incapacitated or prevented from taking credited action to prevent or mitigate a hazard scenario. DOE-STD-3009-2014, Section 3.1.1 states:

> Although the hazard identification process is comprehensive of all radiological and non-radiological hazards, DSAs are not intended to analyze and provide controls for standard industrial hazards such as burns from hot surfaces, electrocution, and falling objects. These hazards are adequately analyzed and controlled in accordance with 10 C.F.R. Part 851, *Worker Safety and Health Program*, and are analyzed in a DSA only if they can be an accident initiator, a contributor to a significant uncontrolled release of radioactive or other hazardous material (for example, 115-volt wiring as initiator of a fire), or considered a unique worker hazard such as explosive energy. The basis for any identified hazards excluded from further evaluation shall be provided. See Appendix A, Section A.1 of this Standard for further discussion on screening of standard industrial hazards and Section A.2 for a discussion on screening out certain chemicals based on low quantities or low hazard.

DOE-STD-3009-2014, Section A.1, provides the following SIH guidance:

> The Department of Energy (DOE) recognizes, via Title 10 of the Code of Federal Regulations (CFR) Part 830, the importance of including worker safety in safety analyses by specifically noting the worker as a population of concern. Developing a conceptual basis for the methodology used in this Standard requires answering the fundamental question of how worker safety is most appropriately addressed in the DSA. DSAs include hazard analyses and hazard controls for worker safety, unless the hazards and their potential consequences are due to standard industrial hazards.
>
> Standard industrial hazards are hazards that are routinely encountered in general industry and construction. These workplace hazards are addressed by provisions of 10 CFR Part 851, *Worker Safety and Health Program*, which requires identification and assessment of worker hazards and compliance with safety and health standards that provide specific safe practices and controls. Based on these provisions, evaluation of standard industrial hazards within DSAs is needed to the extent that these hazards act as initiators or contributors to accidents, or result from chemical or radiological hazards (for example, when an explosion is caused by radiolysis inside a tank). When standard industrial hazards are excluded from further evaluation, Section 3.1.1 of this Standard requires such conclusions to be included in the hazard identification, along with the basis used for exclusion.
>
> Standard industrial hazards that may be considered for exclusion from the DSA hazard evaluation include those in which a national consensus code and/or standard … defines and regulates appropriate worker safety practices. Specifically, the codes and standards required by 10 CFR 851.23, *Safety and Health Standards*, may be considered. Examples of hazards addressed by these requirements include confined spaces, electrocution, falling objects, non-ionizing radiation, hot work, and lasers. Toxicity of hazardous chemicals is addressed in Section A.2 rather than this subsection.
>
> [Unique hazards …]

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> Standard industrial hazards that have the potential to be an accident initiator involving chemical or radioactive material releases are retained as part of the DSA hazard evaluation. For example, the existence of 440-volt alternating current cabling in a glovebox could be identified as a potential accident initiator of a fire involving radioactive or other hazardous materials.

The evaluation of hazards associated with “other hazardous materials,” and especially a subset involving hazardous chemicals, warrants further discussion regarding which hazards can be screened out or screened in. Some of these non-radiological hazards may be determined to be SIHs, while others may require further evaluation in the DSA per 10 CFR § 830.204(b)(3) “that might contribute to the generation or uncontrolled release of radioactive and other hazardous material.” One aspect of the “generation or uncontrolled release of … other hazardous material” consideration is recognized in DOE-STD-3009-2014, Section A.1, which states: “Toxicity of hazardous chemicals is addressed in Section A.2 rather than this subsection” and is therefore not treated as a SIH. In addition to toxicity, other chemical hazards may require further evaluation.

The introduction of DOE-STD-3009-2014, Section A.2 clarifies that not all chemical hazards (even those that can cause serious injury or death) need to be evaluated in the DSA hazard evaluation:

> The DSA is not intended to deal extensively with chemicals that can be safely handled by implementation of a hazardous material protection program. Therefore, a screening process is established to select for DSA evaluation only those chemicals of concern (i.e., type and quantity that have the potential for significant health effect on the facility worker, co-located worker, or public) that are present in the facility or activity and present hazard potentials outside the routine scope of the hazardous material protection program.

The DSA hazard evaluation scope covers analysis of (a) hazardous chemicals affecting nuclear safety and (b) in some cases, chemical hazards that are outside the scope of the facility’s hazardous material protection program. The intent of DOE-STD-3009-2014 is to cover:

- radiation-related hazardous chemical events (examples: chemicals comingled with radiological waste, chemicals generated through radiological processes, and chemicals generated or released through processing of radioactive materials);
- nuclear safety-related hazardous chemical events (examples: events that affect a worker relied upon for a credited action, events that affect safety-related SSCs through corrosion, fire, or explosion); or
- unique hazardous chemical events, not addressed by 10 CFR Part 851, that could cause harm to workers, the public or the environment.

As an example of an excluded chemical hazard, consider a chemical supply tank in a nuclear facility that has no interaction with radioactive material until the chemical is discharged into the nuclear process. The chemical hazards presented by this tank, if they are routine and common in industry, should be screened out of the DSA hazard evaluation as an SIH because 10 CFR Part 851 requirements will apply.

However, when a chemical is used in or generated by a nuclear process (i.e., interacting with nuclear material), then such physical consequences from process accidents (e.g., over-pressurization) should be evaluated in the DSA hazard evaluation. DOE-STD-3009-2014, Section 3.1.3.1 states:

> Facility worker consequences, due solely to a standard industrial hazard, do not need to be categorized in the hazard evaluation if screened out per Section 3.1.1. However, the evaluation of radiological or chemical hazards that result in a prompt death or serious injury should be assigned a high consequence

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> per Table 1. Examples of such hazards might include the generation of flammable/explosive hydrogen gas by electrolysis of uranium in water or a spill of sodium hydroxide used in radioactive waste processing.

Another chemical hazard not screened out is described in the DOE-STD-3009-2014, Section A.1 that states: "Significant quantities of cryogenic material or compressed gases/liquids may also warrant consideration because of asphyxiation hazards that might affect the ability of facility operators to safely manage the facility. Such unique hazards are not treated as SIHs and are evaluated in the DSA." Note that the consideration is related to impacts on safely managing the facility. This situation would include incapacitation of operators required to perform specific administrative controls affecting critical safety functions.

In general, a chemical hazard should not be screened out if it affects a facility worker expected to perform safety-related actions. Control room workers are in this category, as are operators expected to carry out credited actions for a specific administrative control. DOE-STD-3009-2014, Section A.2 includes the following example: "chemicals that may be excluded from the DSA's hazard evaluation include … chemical is not listed in OSHA or EPA toxic chemical regulations or is not assigned a PAC 2 or 3 value."[8] Regarding toxicity, impact on a facility worker is defined as being exposed to a chemical concentration reaching Protective Action Criteria (PAC)-2 or PAC/TEEL-3 levels based on a qualitative evaluation. Typically, PAC concentrations are evaluated over a 15-minute period. However for a screening evaluation, a shorter time may be warranted if the worker becomes incapacitated due to the chemical exposure in a shorter than 15-minute time frame.

Section A.1 of DOE-STD-3009-2014 describes situations that should not be screened out when considering other unique hazards:

> Unique hazards may be present in facilities that are not specifically addressed by the above exclusion criteria, either because of quantities larger than typically used in general industry or because of unique DOE applications or operations. Such hazards may represent a potential hazard to an entire work area affecting multiple workers.

The intended distinction is to ensure analysis of "other hazardous materials" outside the scope of 10 CFR Part 851 that could affect nuclear safety. If these unique hazards could impair or disable control room operators or make uninhabitable entire rooms where nuclear operations are conducted, such hazards should be evaluated in the DSA.

DOE-STD-3009-2014 requires that "the basis for any identified hazards excluded from further evaluation shall be provided." Excluding a specific hazard or class of hazards should be accompanied by recording the applicable code or standard and the relevant site safety management program for implementing the code or standard. This basis may be included on the hazard identification table (see the "References" column in Table 2-2), or for more complicated justifications, in the DSA hazard identification results section. Either approach is suitable, as long as there is clear documentation of hazards screened out from the hazard evaluation.[9]

[8] See Section 9.3 for additional discussion of screening chemicals.

[9] Many SIHs are evaluated in the hazard evaluation as an initiator or contributor to a radioactive or other hazardous material release, which should be acknowledged somewhere in the hazard identification results section.

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2.3 INITIAL HAZARD EVALUATION DEVELOPMENT

2.3.1 OVERVIEW

Hazard evaluation is the starting point for control set selection to prevent or mitigate potential hazardous conditions (or hazard scenarios as defined in DOE-STD-3009-2014) that could result in undesirable consequences, and for the subsequent quantitative accident analysis. The definitions section of DOE-STD-3009 states that the hazard evaluation portion of a hazard analysis includes an examination of "the complete spectrum of potential accidents that could expose members of the public, onsite workers, facility workers, and the environment to" radioactive and other hazardous materials. The DSA hazard evaluation provides: (a) an assessment of the facility hazards associated with the full scope of planned operations covered by the DSA, and (b) the identification of engineered and administrative controls that can prevent or mitigate these hazards or hazardous conditions. It analyzes normal operations (startup, facility activities, shutdown, and testing and maintenance configurations) as well as abnormal and accident conditions. In addition to the process-related hazards identified during the hazard identification process, the hazard evaluation also addresses NPHs and man-made external events that can affect the integrity of an SSC. DOE-STD-3009-2014, Section 3.1.3 provides requirements and guidance on how hazard evaluations are to be performed for DOE nuclear facilities.

The initial hazard evaluation is accomplished by the following steps:

1. Define the scope of the HA. This scope can vary from a single process in a single room to an entire facility with multiple processes. Evaluation of the entire facility may be more efficiently performed by dividing it into smaller process or area nodes. The scope of activities to be evaluated by the analysis includes any activities that can occur when significant quantities of hazardous materials are present. These activities include (a) DSA-authorized processes and experiments in the facility, (b) off-shift activities, and (c) any hazard associated with maintenance and support activities that can occur when significant quantities of hazardous materials are present. (Quantities are significant if they can cause injury, for example, as related to asphyxiation in DOE-STD-3009-2014.) Physical boundaries, process/support system interfaces, and interfaces with other facilities need to be defined.

2. From the hazard identification results, evaluate hazards associated with authorized activities, man-made external events, or NPHs. Develop a comprehensive list of postulated hazard scenarios.

3. From the hazard identification results, evaluate radioactive and other hazardous materials and energy sources to determine possible interactions that could lead to accident conditions.

4. Evaluate circumstances such as equipment failures, process material hazards and failure of barriers, and mission activities that could affect the initiation and progression of the accident conditions.

5. Review applicable safety documentation, process history, occurrence reports, and other information sources to identify postulated or historical hazardous conditions and accidents associated with the facility.

All activities within the facility boundaries are considered in the analysis. The HA team defines where these boundaries, or process or area nodes, start and stop. Considerations include:

- Do activities start at the door of the facility, at the loading dock, or at an outside staging or storage area?
- If two facilities share common space, at what point does one facility analysis start and the other stop?
- Do immediately adjacent facilities pose hazards such as toxic materials?
- Are any hazards associated with the process or area nodes or facility boundaries that may warrant consideration of controls?

Following this initial evaluation, the process continues with the documentation of hazardous conditions and selection of unmitigated hazard scenarios based on potential interactions between hazardous materials and energy sources.

Typical hazards commonly associated with DOE nonreactor nuclear facilities are identified in Table 2-3. The table provides a suggested causal correlation between hazardous energy and material sources and potential accident types or categories.[10] Hazards identified in Table 2-3 do not always result in an accidental release of radioactive or other hazardous material required to be evaluated by DOE-STD-3009.

Table 2 3. Correlation of Hazardous Energy and Material Sources to Accident Types/Categories.

Accident Category*	Hazard Energy and Material Source Groups
FR-1: Fire	Electrical Thermal Friction Pyrophoric Material Spontaneous Combustion Open Flame Flammables Combustibles Chemical Reaction
EX-2: Explosion	Potential (Pressure) Explosive Materials Chemical Reactions
LC-3: Loss of Confinement/Spills	Radioactive Material Other Hazardous Material Toxic Chemical Chemical Reaction
DE-4: Direct Radiological Exposure	Ionizing Radiation Sources
CR-5: Nuclear Criticality	Fissile Materials
EE-6: Man-made External Events	Non-Facility Events (e.g., aircraft crashes) Vehicles in Motion Cranes
NPH-7: Natural Phenomena Hazards	NPH Events - Seismic, Extreme Wind, Flood, Lightning, Extreme Precipitation, Volcanic Ashfall

*The number assigned to the accident categories is for ease of data management, and any numbering scheme could be used if deemed necessary.

[10] A similar correlation is provided in DOE-STD-5506-2007, *Preparation of Safety Basis Documents for Transuranic (TRU) Waste Facilities*, Table 3.2-1, Hazard Sources and Potential Events.

A graded approach as defined in 10 CFR §830.3 and DOE-STD-3009 should be applied to the selection of hazard evaluation techniques and developing the hazard evaluations. The selection of techniques is based on several factors, including the complexity and size of the operation being analyzed, the type of operation, and the inherent nature of hazards being evaluated. A discussion of hazard evaluation techniques and recommendations can be found in Part I of CCPS, 2008, especially Chapters 4 and 5.

2.3.2 NUCLEAR CRITICALITY HAZARD EVALUATION

A criticality accident represents a special case for hazard evaluation. The criticality safety program requirements[11] are derived from the HA process established in the American National Standards Institute/American Nuclear Society (ANSI/ANS)-8 series of national standards (e.g., ANSI/ANS-8.1, *Nuclear Criticality Safety in Operations with Fissionable Material Outside Reactors*). These standards require a documented nuclear criticality safety evaluation demonstrating that operations with fissionable material remain subcritical under both normal and credible abnormal conditions. Criticality safety evaluations provide the technical basis for controls to prevent or mitigate criticality accidents. The ANSI/ANS-8 series requirements do not apply to critical assemblies or similar operations.

Section 3.1.3.2 of DOE-STD-3009-2014 provides requirements on what to include in the DSA hazard evaluation of criticality accidents, while Section 3.3.4 provides requirements on safety classification of criticality safety controls. Experience shows that only a few evaluations of criticality accident scenarios for a facility may need to be included in the qualitative hazard evaluation. Appendix B provides guidance on the magnitude and consequence analysis of criticality accidents and the estimation of fission product yield and particulate source terms.

2.3.3 CHEMICAL HAZARD EVALUATION

As discussed in Section 2.2.4, chemical hazards are screened to determine the need for further hazard evaluation. However, per DOE-STD-3009-2014, Section A.2, chemicals “that could otherwise be screened out, but have the potential to be an accident initiator involving radioactive or hazardous material releases, or could compromise the ability of the facility operators to safely manage the facility, are retained as part of the DSA hazard evaluation.” Chemical properties such as reactivity, toxicity, and incompatibility with other chemicals are thus included in the hazard evaluation.

Qualitative evaluation of toxic chemical consequences using any of the hazard evaluation techniques discussed later in this chapter is generally sufficient to provide a basis for comparison to consequence thresholds of interest for the selection of safety significant (SS) controls (i.e., serious injuries, fatalities, or significant chemical exposure).

However, for some situations, further quantitative analysis of consequences is necessary for control selection. [12] Later chapters of this Handbook will provide guidance on quantifying chemical source terms (Sections 5.3 and 9.5) and dispersion analyses to estimate concentrations to receptors (Chapters 6, 7

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[11] Criticality safety program requirements are established in DOE O 420.1C. This Order states that DOE-STD-3007-2007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities*, is the required method for performing criticality safety evaluations, unless DOE approves an alternate method. An update to that Standard has been issued in DOE-STD-3007-2017, *Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities*, which will be invoked in a revision to DOE O 420.1C.

[12] For example, see DOE-STD-3009-2014, Section 3.2.3.3 and Section A.2 for further information for evaluation of the toxicity hazard and determination of concentrations for the co-located worker (CW) at 100 m and maximally-exposed offsite individual (MOI).

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and 9). However, selection and application of appropriate source term and dispersion methods for evaluation of chemical hazards will need to consider special situations such as chemical reactions, chemical transformations in the plume, or heavier-than-air plume modeling.

2.4 HAZARD EVALUATION METHODS

2.4.1 COMMERCIAL INDUSTRY METHODS AND DSA HAZARD EVALUATIONS

Chapter 4 of CCPS, 2008 describes twelve methods that can be used in a hazard evaluation. The discussion is oriented toward the chemical industry, but the basic strengths and weaknesses of each method are generally applicable for the DSA hazard evaluation. The following sections discuss four of these methods as applied to several facilities described in DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, Appendix B.

None of these industry hazard evaluation methods were designed to generate a DSA hazard evaluation and do not yield hazard scenarios, nor were they designed to identify SS and safety class (SC) SSCs or specific administrative controls (SACs). Those results are uniquely defined for DOE usage to develop a DSA. Thus, one does not normally see the raw information generated from the industry hazard evaluation in a DSA; however, it is a necessary step to developing hazard scenarios. The hazard evaluation is performed to understand facility vulnerabilities and potential hazard scenarios. Those insights are then distilled into a DSA hazard evaluation table and are used for safety classification of controls and derivation of TSRs.

The common methods utilized vary in both complexity and focus. Each method has strengths and weaknesses, and depending on the scope of the HA, multiple HA methods may be used. For example, the Hazard and Operational Analysis (HAZOP) methodology is effective for analyzing a chemical process within a facility, but the "What-If" methodology is better suited for evaluating NPH and man-made external events with the potential to affect the entire facility.

2.4.2 METHOD #1: WHAT-IF?

The "What-If" method is a loosely-structured, brainstorming technique commonly used in the DOE complex by itself or in combination with other hazard analysis techniques such as Process Hazard Analysis (PrHA). As with any other hazard analysis method, the analysis typically is organized by facility operations, process, or activity location (e.g., a production support laboratory). Analysts utilizing this method formulate a series of questions, each beginning with the phrase "What if…?" for each process or activity. An example might be "What if the liquid tank in the support laboratory overflows?"

The hazard evaluation would discuss ways in which the tank might overflow (e.g., initiators and overall event progression sequences), the potential consequences of overflow, what preventive and mitigative control responses are available, and what additional measures may be recommended for consideration. The extent of the discussion is based on increasing potential consequences. If the liquid in question is simply water with trace contamination or less harmful chemicals, the discussion will reach resolution much more rapidly than if the liquid is radioactive or a highly volatile, toxic substance.

To provide proper structure for comprehensive results, the examination progresses in an organized manner, from the beginning of the activity/operation to the end. Well-designed checklists can provide additional structure that limits the potential for important events to be missed. This approach combines the "What-If" method with the simplest method for hazard evaluation that is a checklist that identifies already-known or understood hazards such as fires and explosions and can be augmented with specific design information. Furthermore, while a variety of potential outcomes can be identified, it is important to identify the ultimate consequence that is physically plausible. Analysts should not stop with the assumption that a given control will function. To do so can result in failure to identify vulnerabilities, and is also inconsistent with DOE's stated intent for unmitigated analyses.

The strengths of the "What-If" method include broad applicability, ease of use, and its adherence to natural thought processes. Weaknesses include a greater potential for neglecting interaction issues and for missing some events altogether. Another weakness of the What-If analysis is that many scenarios identified may result in no or insignificant consequences; thus, creating a large number of scenarios of no interest to the DSA process. A modified What-If analysis has also been used to identify scenarios with significant consequence potential for further analysis. Further analysis may include the DSA-required evaluation of the frequency, consequence, and risk for such scenarios of interest, or combining the results of the What-If analysis with other hazard analysis techniques, such as Process Hazard Analysis (PrHA). The quality of "What-If" results can vary significantly based on the experience of the individual leading the team effort. Generally, "What-If" analysis is most suited to simple operations and activities where the potential end states of each step are discrete and easy to identify. Manual operations/activities are often ideal for "What-If" analysis.

The H-21 TRU Waste Facility and the H-7 Production Support Lab discussed in DOE-HDBK-3010-94, Appendix B illustrate examples of facilities amenable to a "What-If" analysis. The common feature of these facilities is that they do not have complex processes. They consist of discrete, manual operations with well-defined interaction boundaries.

Consider the liquid sampling glovebox in the Production Support Lab. It is a non-complex operation where a laboratory operator analyzes 20 ml sample vials. A simple walkdown of the process generates obvious "What-If" questions as shown on Table 2-4.

Table 2-4. "What-If" Hazard Analysis Example H-7 Production Support Lab.

"What if…?"	Possible Consequences
1. …a collection of vials is dropped while being entered into the glovebox?	1. Broken vials, small Pu airborne release, minor worker exposure.
2. …the sample recycle bottle is dropped while coming out of the glovebox?	2. Spill, small Pu airborne release, minor worker exposure.
3. …liquid is spilled within the glovebox?	3. See #1 and #2 above, without direct worker exposure potential.
4. …the sample recycle bottle is overfilled (i.e., double batch of high concentration of fissile solution)?	4.a. Criticality Safety Evaluation shows large margin = no issue or 4.b. Criticality Safety Evaluation shows limited margin = potential criticality event
5. …the glovebox inventory of hexone solvent ignites?	5.a. Potential glovebox confinement breach and/or 5.b. airborne Pu release (larger release potential than spill)
6. …more samples are brought into the glovebox than its allowable storage spaces?	6. No specific consequence (potential deviation in operational practice that should be evaluated).
7. …planchettes are dropped outside of glovebox	7. No significant consequence (quantities of material are too small)

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The above list is not exhaustive, but demonstrates the basic concept. This questioning process would be repeated for each of the specific operations and general activities authorized in the facility. The resulting complete set of questions and answers would then be combined and amplified as necessary to generate specific hazard scenarios in the DSA hazard evaluation table. For example, if the potential exposure consequences are sufficiently limited, all liquid spills might be combined into one representative hazard scenario. Or, if only one or two of the liquid spill scenarios could pose significant exposure potential, those would be documented as individual events.

Care should be exercised when combining scenarios. There should be no attempt to combine scenarios until potential controls are identified. The considerations to determine if scenarios should be combined include identifying that proposed controls are either bounded or are the same for all bundled scenarios. In the hypothetical case presented in the previous paragraph, suppose one distinct spill with significant consequences is combined with all other spills. The hazard evaluation would then identify any credited controls for one scenario as applying to all glovebox liquid handling operations.

Dissimilar scenarios cannot be combined. For example, fires and spills should not be artificially combined into one event because they have differing consequences, separate initiators, and unlike controls. The required clarity of the analysis of the most important preventive and mitigative controls will be lost if these dissimilar scenarios are combined. Bounding scenarios is primarily a function of their controls. The example above only illustrates the identification of "what if" questions (which may help define initiating events or scenarios) for a single operation, and the associated possible consequences. It may not define a complete set of initiated events or define completely an accident scenario, nor include the controls to prevent or mitigate such scenarios.

2.4.3 METHOD #2: HAZARD AND OPERATIONAL ANALYSIS

This method, abbreviated "HAZOP," is designed to investigate chemical process and complex system performance requiring a more methodical approach to ensure completeness, which cannot be effectively accomplished with the "What-If" technique. It requires a significantly greater investment of time and resources than a "What-If?" analysis because team members are required to identify and assess the significance of system malfunctions or improper operations at each step of a process using a highly formal, systematic approach.

The HAZOP method first divides a process or system into discrete sections (defined as process or system nodes), with the intent or function of each section being well-defined. Figure 2-1 illustrates the complete HAZOP method, after defining the process or system nodes.

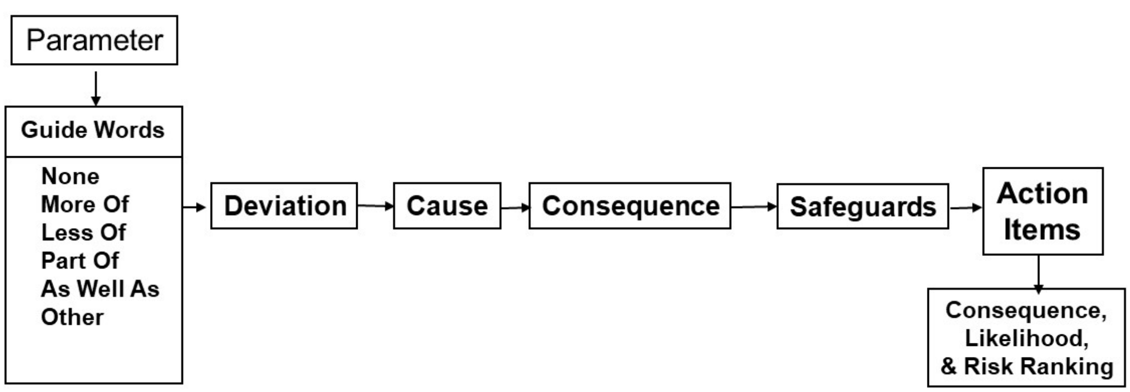

Figure 2-1. HAZOP Method Overview

The method then examines deviations in hardware and those caused by human interactions (such as those that occur during maintenance and operations) from design conditions by systematically combining each parameter of interest for the process or system with guide words. Examples of parameters include flow, pressure, temperature, composition, and even more conceptual items such as containment. Examples of guide words include “no, more, less, high, low, as well as, partial, reverse, wrong type, sooner than, later than, breach.” A HAZOP deviation matrix can be built to describe the evaluation criteria corresponding to a guide word for a given process or system parameter as illustrated in Figure 2-2.

Parameter	None	More Of	Less Of	As Well As	Part Of	Reverse	Other Than
Flow (rate or quantity)	No flow	High flow	Low flow	Contaminants	Wrong concentration	Back flow	Wrong material
Temperature		High temp.	Low temp.				
Pressure		High press.	Low press.				
Time	Misses a step	Too long Too late	Too short Too soon	Extra actions initiated	Some of actions in	Steps backwards	Wrong time

Figure 2-2. HAZOP Deviation Matrix

For example, the HAZOP team might start examining a process or system section by first identifying a parameter such as flow and the guide word “None”, and postulating a deviation of “no flow.” They would then identify the causes of no flow, qualitatively define the consequences of no flow, and what safeguards or controls are available or may be recommended for consideration, or other action items that may require further investigation. When significant consequence potential is identified, it is important to trace causality back to previous sections examined if the deviation of interest originates there. For additional perspective, consequence, likelihood, and risk rankings may be assigned to each of these significant deviations/cause conditions, or that may be accomplished in a subsequent DSA hazard evaluation. The team subsequently proceeds to other guide words for the selected parameter, such as “low flow,” followed by “high flow” and so on. This procedure yields an understanding of the integrated process or system behavior, as opposed to simply focusing on the discrete behavior of isolated components.

The HAZOP method brings to bear considerable structural rigor. It breaks down the entire process or system into a large number of discrete sections (pipe runs from Point A to Point B and individual vessels) and goes through a repetitive exercise to examine deviations in significant detail. Most deviations will not, in fact, involve any significant vulnerabilities, one reason that HAZOPs for large processes or systems are conducted over multiple days. The exercise simply takes time. Attempting to move swiftly through it tends to create an overload effect that defeats the purpose of this method.

The strengths of the HAZOP method are thoroughness enforced by structural rigor, focus on small details, adaptability to almost any process or activity, and generation of an organized evaluation record as an intrinsic part of the method. HAZOP also forces participants to properly define the process or activity at a detail level prior to beginning. Weaknesses include the fact that HAZOP is much more time and resource intensive than other methods. It is also vulnerable to poor initial organization. HAZOPs generally represent overkill for simple processes and predominantly manual activities, but are ideal for more complex processes, where the sheer magnitude of the potential deviations can overwhelm a “What-If” examination. Another weakness of the HAZOP method is that since it is focused on processes or

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systems, and their deviations, it often can miss more generic hazard scenarios such as external and natural phenomena events, or those not associated with process or facility systems.

Table 2-5 presents a HAZOP example for the Metal Dissolution Process described in DOE-HDBK-3010-94, Appendix B for the Plutonium Recovery Facility. This portion of the HAZOP evaluates a node defined by piping from the heat exchanger to the spray chamber as shown in Figure B.8 of DOE-HDBK-3010-94. The parameter examined is "Flow." Compared to the previous "What-If" examples, the rigorous and repetitive nature of the method is clear. "What-If" relies on the ability and experience of the analysts to ensure completeness; HAZOP relies more on the method's formal structure.

Table 2-5. HAZOP Example.

Note: Piping from Heat Exchanger to Spray Chamber (as shown in DOE-HDBK-3010-94, Figure B.6).

Parameter	Deviation (guide word)	Cause	Consequence	Safeguards or Controls	Likelihood	Consequence	Risk	Comments/Actions
Flow	No	1. Pump not working 2. Heat exchanger outlet valve incorrectly positioned 3. In-line filter clogged	Operational	Return line flow meter, Temperature sensors				Safe Condition: Dissolution reaction ceases without fresh acid flow Unsafe Condition: Potential to pressurize heat exchanger
Flow	No	1. Piping rupture	Plutonium solution spill	Glovebox, Glovebox ventilation, Critically safe drainage basin, Room air monitor, Room ventilation				
Flow	Low	1. Piping leak	Plutonium solution spill	Glovebox, Glovebox ventilation, Critically safe drainage basin, Room air monitor, Room ventilation				
Flow	High	1. Pump output excessive 2. Heat exchanger outlet valve incorrectly positioned	Temperature transient (more flow is heated less)	Temperature sensor on slab tank, Steam inlet control, Return line flow meter, Hydrogen detector, Shutdown interlocks, Air sparge				Unsafe Condition: More flow maximizes reaction. Unsafe Condition: Low acid temperature can yield undesired hydride sludge.
Flow	Wrong	1. Steam inlet off with heat exchanger leak	Plutonium solution enters heat exchanger condensate	Condensate collected in Raschig ring tank, Condensate samples				Action: Verify sampling frequency

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As noted previously, the traditional HAZOP table is not an example of the hazard evaluation table expected in an actual DSA, but with modifications as suggested in Table 2-5, it may be suitable. The HAZOP identifies process vulnerabilities and interactions from which a set of hazard scenarios are usually derived for the DSA hazard evaluation table. For example, a runaway exothermic reaction generating hydrogen is an event that would be expected in the DSA hazard evaluation table.

Depending on the HAZOP results, there could be multiple entries for the same event to identify different progression paths, some of which would be of concern, while others may not. Alternatively, one entry could cover all potential progression paths; however, all paths should still be assessed to determine which, if any, warrant specific control. Example outcomes include:

1. The hydrogen detector and shutdown interlock is adequate to credit for all scenarios; or,
2. An individual control in a specific progression path may require crediting as well, either due to the high likelihood of that progression path or its ability to minimize the effect of the hydrogen detector and associated interlocks.

These methods were not developed to credit SSCs. They are intended to address problems that may arise when deviations from design conditions occur. The method (or any HA method) may uncover safety issues to be further evaluated.

2.4.4 METHOD #3: FAILURE MODES AND EFFECTS ANALYSIS

The failure modes and effects analysis (FMEA) is a flexible tool for examining equipment, a process, or system failures (in this section, "system" also includes equipment or a process). It is particularly suitable for characterizing the performance spectrum associated with individual component failures within the system. Thus, it is ideal for identifying all potential failure modes for systems of interest typically of moderate complexity. In some cases, the impact may not just be the failure of the system to perform its intended function, but could result in an accident condition of interest, such as an explosion in a process line.

The analysis proceeds as follows:

- Identify the major components (example: detectors);
- Identify the systems using these components (example: ventilation);
- Identify all failure modes for each component (high, low, loss of signal);
- Identify the effects of component failures on the systems.

Finally, for system consequences of interest, such as failure of the system to perform its function or an accident of concern, the controls or safeguards to prevent such failures are identified.

FMEA equipment failures. As indicated, FMEAs are ideal for evaluating system failure modes, but are not well-suited to supporting the identification of process hazard scenarios. FMEAs also lack the structure to examine process upsets (e.g., reverse flow, process chemistry deviations) as initiators. Inexperience with using the method can also lead to an excessively narrow focus on individual failures as opposed to integrated process behavior. Therefore, because the FMEA is narrowly focused, it is usually applied in combination with other techniques such as fault tree analysis to provide a more detailed understanding on how a system could fail.

Table 2-6 shows an application of the FMEA method to the Metal Dissolution Process evaluated in Table 2-5 for flow from the heat exchanger to the spray chamber through a pipe. The component and the failure modes of interest within this process is those associated with the hydrogen detector.

Table 2-6. FMEA Example.

Process: Metal Dissolution Line   Component: Hydrogen Detector

Failure Mode	Effect	Safeguards	Comments/Actions
Fails high	Generates premature process shutdown for low H_2 concentration. Fails safe	Indication on operational console, Shutdown interlock.	Fail safe: None
Fails low	Failure to generate process shutdown, when required, leading to unsafe conditions (e.g., a potential for exothermic reaction and hydrogen explosion)	Indication on operational console, Spray chamber temperature sensor (also feeds shutdown interlock), Temperature indications on operational console	Potential accident of concern Increased hydrogen concentrations are generally accompanied by higher temperatures. A runaway exothermic reaction would still yield a shutdown. However, conditions short of that could yield H_2 concentrations in excess of the shutdown limit.
Fail as is	Failure to generate process shutdown when required See “Low Failure Mode”	See “Low Failure Mode”	Potential accident of concern See “Low Failure Mode” comments/actions
Loss of Power	Triggers shutdown interlock	Indication on operational console, Shutdown interlock.	Fail safe: None
Signal to Interlock, Mode A	Triggers shutdown interlock	Indication on operational console, Shutdown interlock.	Fail safe: None
Signal to interlock, Mode B	Failure to generate process shutdown when required See “Low Failure Mode” Effects	See “Low Failure Mode” safeguards	Potential accident of concern See “Low Failure Mode” comments/actions

2.4.5 METHOD #4: EVENT TREES AND FAULT TREES

Event trees and fault trees are formal logic constructs designed to document progression paths for an event. Event trees utilize inductive reasoning while fault trees utilize deductive reasoning. These two tools can be combined in a formal quantitative or probabilistic risk assessment, but such an assessment for an entire facility or process is not typical when evaluating DOE nonreactor nuclear facilities. Event trees and fault trees are normally used in DSAs as support tools to illuminate a specific issue of interest.

Inductive reasoning is often characterized as a “bottom-up” analysis since it starts with a specific premise and moves toward a general conclusion. An event tree correspondingly starts with a specific initiating event and moves toward a broad collection of potential outcomes. Regarding DSA hazard analysis, this approach results in event sequences with varying consequences in terms of radiological release potentials, based on the success and failure of any preventive controls that may terminate the event or mitigative controls that may reduce the consequences. A simple example of an initiating event might be “loss of cooling water to a furnace.” Every action that can result from that event then forms a decision point from which multiple possible outcomes branch. For example, suppose Alarm A is supposed to sound to generate an operator response if cooling flow is lost. The first decision point is therefore “Alarm A functions.” Two branches stem from that point: (a) if alarm A functions, the progression moves to a decision point labeled “Operator responds;” (b) if Alarm A does not function, operator response is initially bypassed and the resulting branch moves to a different decision point. The end result is a complete spectrum of outcomes, from successful to unsuccessful to catastrophic, which are characterized in terms of actions and controls associated with their progression. Each individual path through this event tree represents a separate event sequence. Thus, the minimum cut sets that yield failure of the system or its safety function can be defined. Event trees graphically depict the relationship between an initiating event and controls; thus, defining ranges of potential scenarios, their frequencies, and potential consequences based on the response of credited controls. Event trees, as well as fault trees, are typically used to support accident analyses and are not necessarily elevated to the DSA.

Deductive reasoning is often characterized as a “top-down” analysis since it uses general premises to arrive at a specific conclusion. A fault tree thus begins with the undesired end state as the top event such as a specified consequence of a potential accident and analyzes equipment failures and human errors that cause the top event. Such end states have often been identified by application of other hazard evaluation methods. For demonstration purposes, a simple example of an undesired end state is “the car does not start.” The next step down in the fault tree lists the immediate causes such as starter motor failure, spark plug failure, and lack of gas in the cylinder. The next step down lists all the potential causes for each immediate cause: no gas in supply tank, failure of the fuel pump, fuel line leak. These potential failure mechanisms are joined by “AND” or “OR” gates depending on whether multiple mechanisms (A “AND” B) are needed to cause the failure above or if a single mechanism (A “OR” B) suffices. This process ends either in basic occurrences that cannot be subdivided further or at a predetermined evaluation boundary. Again, the minimum cut sets that yield failure of the system or its safety function can be defined.

The strengths of this approach includes logical rigor, recording of results in a branch structure as the evaluation occurs, and direct support of numerical estimation of likelihood of the postulated significant consequences. Weaknesses include a tendency toward tunnel vision if the failure mode or safety function of interest is not precisely defined, as well as a significant resource and time investment to generate integrated results.

2.5 INITIAL DEVELOPMENT OF A DSA HAZARD EVALUATION TABLE

The commercial industry hazard evaluation methods previously discussed evaluated process upsets, equipment failures, human errors, and potential safety features. Table 2-7 shows how similar hazard studies can be used to start development of a hazard evaluation table for the DSA, based on an example of a vehicle collision plus fire involving TRU waste containers which has often been evaluated using the “What-If” method.

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Table 2-7. Initial Development of Hazard Evaluation Table.

Event No.	Event Description	Initiators	Preventive Features	Mitigative Features
FR-1	Fuel powered vehicle suffers a fuel leak due to an impact with TRU waste drums in the Shipping/Receiving Area and is ignited. A forklift carrying a single pallet with four drums impacts a stack (two high) of palletized drums with moderate to severe stress causing breach with material spill of 12 drums and ensuing pool fire that involves 88 additional drums in the Shipping/ Receiving Area. MAR: xx alpha curies in 100 drums (DOE-STD-5506-2007 statistical MAR distribution for Waste Isolation Pilot Plant complaint containers applied, see Table yy) INITIAL CONDITIONS: Staging area inventory limit; TRU waste in metal containers; Metal pallets.	• Operator error • Equipment malfunction • Vehicle impact with fuel spill • Ignition of combustible and/or flammable materials • Lightning • Wildland fire	SSCs: Concrete vehicle barriers. Waste staging building foundation. ADMINISTRATIVE: Procedures and Training Program (Forklift Operator training); Vehicle maintenance program; Fire Protection Program: • Combustible controls Waste handling operations curtailed outdoors during inclement weather; Movement of waste is to be accomplished using electric or manual powered equipment; Fuel exclusion zone in the Shipping/Receiving Area.	SSCs: None ADMINISTRATIVE Procedures and Training Program (workers trained to evacuate); Emergency Preparedness Program (emergency response activities).

Control identification occurs as part of the initial hazard evaluation development and is recorded in the hazard evaluation table as shown in Table 2-7. At this stage of developing the hazard evaluation table, all preventive and mitigative controls are listed that are available, or can be readily implemented, to demonstrate defense in depth as described in DOE-STD-3009.

2.6 LIKELIHOOD, CONSEQUENCE, AND RISK METHODS

The next step of the DSA hazard evaluation is to perform a qualitative estimate of the unmitigated consequences, likelihood, and optionally, risk ranking of the hazard scenarios. The following subsections present methods for these evaluations.

2.6.1 QUALITATIVE CONSEQUENCES

2.6.1.1 RECEPTOR CONSEQUENCE LEVELS

Table 2-8, reproduced from DOE-STD-3009-2014, Table 1, provides three qualitative consequence thresholds (bins) to estimate potential effects on facility workers, CWs, and the public (i.e., MOI).[13] High, moderate, and low consequence levels are quantitatively defined for the offsite public and CWs. High consequence levels are qualitatively established for facility workers consistent with DOE-STD-3009

[13] These bins are similar to consequence level thresholds defined in DOE-STD-3009-94, CN3.

guidelines for a significant worker consequence. Moderate and low consequence levels are not defined for facility workers, because qualitative analysis would not yield results that provide a meaningful comparison to a distinguishable threshold.[14]

Table 2-8. Consequence Thresholds.

Consequence Level	Public[1,4]	Co-located Worker[2,4]	Facility Worker[3]
High	≥25 rem TED[5] or ≥PAC[6]-2	≥100 rem TED or ≥PAC/TEEL-3	Prompt death, serious injury, or significant radiological and chemical exposure.
Moderate	≥5 rem TED or ≥PAC/TEEL-1	≥25 rem TED or ≥PAC/TEEL-2	No distinguishable threshold
Low	<5 rem TED or <PAC/TEEL-1	<25 rem TED or <PAC/TEEL-2	No distinguishable threshold

[1] MOI - A hypothetical individual defined to allow dose or dosage comparison with numerical criteria for the public. This individual is located at the point of maximum exposure on the DOE site boundary nearest to the facility in question (ground level release), or may be located at some farther distance where an elevated or buoyant radioactive plume is expected to cause the highest exposure (airborne release).

[2] A CW at a distance of 100 m from a facility (building perimeter) or estimated release point.

[3] A worker within the facility boundary and located less than 100 m from the release point.

[4] Although quantitative thresholds are provided for the MOI and CW consequences, the consequences may be estimated using qualitative and/or semi-quantitative techniques.

[5] Total Effective Dose (TED), 50-yr commitment.

[6] DOE's PAC - see Chapter 9.

High consequence thresholds identified in Table 2-7 do not represent acceptable exposure levels to the public or workers; they are merely criteria used to identify safety class and safety significant controls.

Qualitative judgment is inevitable in hazard evaluation. It is routinely utilized in industries outside DOE. *Guidelines for Hazard Evaluation Procedures* (CCPS, 2008, Pg. 22), notes the following:

> The subjective nature of these deliberations may trouble some people who use the results of these studies because this subjectivity creates a lack of confidence in the results. Some people incorrectly believe that if the analyst uses quantitative methods to express the significance of a problem, then the limitation of subjectivity will simply fade away. However, this is not the case. The apparent numerical precision of a QRA ["quantitative risk analysis" or "quantitative risk assessment"] can mask (1) a great deal of the judgment that influenced the selection of accident models and (2) large uncertainties associated with the data used to estimate risk.

Estimating consequences qualitatively requires consistent assignments of the high, moderate, and low consequence levels for similar scenarios. This may require "normalizing" hazard scenarios by comparing against one another for consistent assignment of a severity level and to verify no outliers exist absent a sound explanation. In addition, for those hazard scenarios that were selected as representative or unique design basis accidents/evaluation basis accidents (DBA/EBAs) for further quantitative accident analysis, insights from that quantitative analysis should be used to verify the qualitative consequence assignments for the hazard evaluation (i.e., an iterative process between the hazard evaluation and the accident

[14] Mitigated analysis that credits controls to reduce unmitigated high consequences to the facility worker generally show mitigated low consequences on the DSA hazard evaluation table.

analysis).

Assigning qualitative consequence levels may be informed by use of quantitative scoping estimates of effects on facility workers, CWs, and the MOI. Consequence estimation is performed differently for facility workers that may be near the source of the event or other areas within the facility where exposure may occur, as opposed to CWs or the public located at a distance from the facility. The latter often has a simplified quantitative basis. That is, it is a straightforward exercise to identify radioactive materials of greatest concern downwind using specific activity and dose equivalents that also incorporate the dispersion analysis. Likewise, chemicals that combine significant volatility and toxicity are easily identified. The safety analyst therefore starts with a short list of materials and release scenarios that are bounding. Bounding is intended to refer to the accident with the highest consequences among a group of similar accidents.

It is a simple matter to calculate "unit release" consequences at any distance of concern (within the capabilities of atmospheric dispersion tools being used) to yield "rules of thumb" for screening calculations such as rem/Curie released or concentration/mass released. These in turn are used to qualitatively scale given events into qualitative consequence bins or levels of severity (high, moderate, low) for the CW and MOI.

The CW scoping calculations may also provide the technical basis to meet the following requirement from DOE-STD-3009-2014, Section 3.1.3.1:

> Consequence determinations used for co-located workers in the hazard evaluation shall be supported by an adequate technical basis such as scoping calculations consistent with Section 3.2.4. Alternately, the quantitative evaluation of co-located worker consequences used to compare to Table 1 thresholds may be performed in the accident analysis and reported in the DSA Section [3.4].

2.6.1.2 FACILITY WORKER CONSEQUENCES

Given the qualitative nature of the consequence thresholds for facility workers in Table 2-8; the designation of facility worker consequences is based on first understanding how these type of consequence thresholds can be triggered by common hazards found in the DOE complex, or what these consequence thresholds mean in relation to radiological or hazardous chemical worker exposures. That is, facility worker consequences in many cases are based on accepted past-experience or consensus judgments from previous hazard evaluations throughout the DOE Complex, and not on quantitative calculations with their associated hard-to-defend assumptions and uncertainties. Thus, the following are recommendations and best practices to determine facility worker consequences.

Past experience and consensus judgments indicate that prompt death can only occur by a limited set of hazards and scenarios such as:

- nuclear criticalities,
- exposures at levels over 400 rads to penetrating radiation such as gamma or X-rays, and
- energetic releases of extremely hazardous chemicals.

Exposure to airborne (non-penetrating) radioactive material such as plutonium and uranium due to a wide range of accident scenarios such as fires or spills are unlikely to result in prompt death. However, these could result in significant radiological exposures depending on several factors associated with the hazard (e.g., inventory, form of material) and the scenario themselves; as discussed in more detail below.

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DOE has no simple numerical consequence metric to assess threshold consequences for facility workers. Because of the location of the postulated facility workers inside a facility or very near the source of a release, downwind considerations such as X/Q are not applicable. Therefore, the determination of facility worker consequences is usually based on judgment, and not quantitative calculations.

In order to use a quantitative metric, one would have to equate a "serious injury or significant exposure" to a mutually-accepted quantitative exposure level (either radiation dose or toxic concentration) to define a threshold numerical value that is equivalent to a high consequence as defined on Table 2-8. This has been accomplished in DOE-STD-3009-2014 for the co-located worker and public, but not for the facility worker. Some previous DSAs have been based on a metric that radiation exposures due to accident conditions that could lead to exceeding emergency planning threshold or process safety management levels may be considered significant, since the selected level implies the onset for potential long-term health effects. Nevertheless, if a quantitative approach is desired, agreement on what constitutes a significant exposure should be reached with the DOE Approval Authority before any quantification is performed in support of determining the facility worker consequences.

A quantitative analysis may not be necessary where insights from past industrial accidents are available, as may be the case for large-scale releases of toxic substances such as hydrogen fluoride. Local facility worker consequences should be evaluated with some sense of perspective and historical experience, as it is possible to conceive extreme events immune to any possible set of controls.

The analyst should focus on the work areas in which accidents may result in a release of radioactive or hazardous material. If quantitative analyses are to be performed to support facility worker consequences, the associated concentrations of such releases are typically evaluated without reliance on specific assumptions about worker placement and hypothetical work area volumes for mixing of the release. However, a conservative but reasonable period of exposure could be assumed. Further guidance on these issues is provided later in this section.

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The unmitigated consequence potential should not be underestimated, nor should unmitigated consequences be exaggerated (relative to historical experience) to a point where every exposure to the local facility worker is a high consequence event. DOE-STD-3009-2014 states:

> To ensure an informed and defensible qualitative evaluation, the determination of facility worker consequences should be based on a combination of the following:
>
> - Magnitude, type, and form of radioactive and hazardous materials involved in a hazard scenario;
> - Type and magnitude of energy sources involved in a hazard scenario;
> - Characteristics of the hazard scenario such as duration and the location where it may occur (e.g., in unmanned areas such as tank vaults); and
> - Potential for a hazard to impact workers' mobility or ability to react to hazardous conditions.

Some additional discussion of the fourth bullet is warranted. DOE-STD-3009-2014, Section 3.1.3.1 states that "the facility worker's mobility or ability to react to hazardous conditions should not be used as the sole or primary basis for determining facility worker impacts." This means that all four of the factors listed above ought to be considered collectively, not individually. A "see and flee" approach that results in unmitigated low consequences should not be used without due consideration of the accident characteristics. The last bullet, therefore, injects some realism into the event scenario for a "reasonable" unmitigated estimate of potential consequences to the facility worker. As an example, an assumption that a worker within a building is unaffected by a release from a building fire (based on hazard recognition and timely evacuation) would have to be justified by considering the location and characteristics of the fire relative to radioactive or hazardous material.

Although unmitigated analysis may not take credit for administrative controls or active engineered features, it is reasonable to assume that facility workers have some knowledge of the facility hazards and adequate training to react to hazardous situations. This assumption, however, is valid only when the accident is not disabling, provides obvious warning signs, and is slow-developing. However, care should be taken not to rely excessively on crediting this type of condition as defaults for unmitigated analysis. Any credit of this nature needs to be justified in the evaluation of the unmitigated consequences for facility workers, based on the contributing elements discussed in this section.

In evaluating the unmitigated consequences associated with a postulated hazard scenario, the following considerations may be important in assigning facility worker consequences:

1. Timing of radiological release: Hazard scenarios involving fires can develop quickly, but not so rapidly as to preclude evacuation in a reasonable period of time. Other scenarios, like criticality accident, explosion, and instantaneous release from confinement enclosures or containers can entail significantly more rapid radiological exposure. Another example is a long duration release such as during a spill of a radioactive or hazardous chemical liquid where a worker in the vicinity of the spill would not be expected to stand in the spilled liquid for an extended period of time. Therefore, though some exposure might occur, a conservative but reasonable time of exposure should be assumed.
2. Hazard warning: The availability of an obvious hazard warning and its timing relative to significant radiological or toxic chemical exposure may impact facility worker consequences. Warning may be provided by the event itself, as in smoke from a fire. However, engineered detection and notification systems such as air monitors are not credited for the unmitigated analysis. It is not reasonable to assume that a worker would remain in a room subject to flashover or toxic concentrations from a major fire in order to receive a significant radiological or toxic

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chemical exposure. A conservative but reasonable period of exposure should be assumed, including whether the workers may choose to respond to the event.[15]

These points should also be considered:

- If the facility worker would reasonably be aware of the event's occurrence, and could take self-protective actions after the event occurs to protect themselves from a fatality or serious injuries from the non-radiological or non-hazardous material consequences, assume that the facility worker will be exposed for a conservative, but reasonable period of time even when warning is provided by the event itself.

- In cases where the facility worker would not be reasonably aware of the event's occurrence (e.g., characteristics of the release such as no odors, no visibility of plumes or smoke, occurrence in areas that could mask the release), there is no specified period of exposure, such as two hours. Consider reasonable lengths of time the facility worker would normally be present based on the nature of planned activities.

3. Scenario effect on protective action capability: Hazard scenarios involving explosions and NPH-initiated failure of buildings or equipment can cause damage to structures or injury to personnel impeding egress, thus increasing potential radiological or toxic chemical consequences. The potential for human errors or equipment malfunctions, in response to mitigating or evacuation actions following the accident, should be considered. Such an error might be putting the ventilation system in an operational mode that will worsen the consequences due to smoke generation. Also of importance is the impact of a toxic chemical release on potential worker ability to take protective actions.

4. Potential exposure magnitude: Severity of radiological uptakes or chemical exposures is a function of the magnitude of the energy associated with the accident scenario, the quantity and specific activity or toxicity of the material estimated to be released, and the pathways for transport to and absorption by workers. Inhalation is most often the dominant exposure pathway for airborne radioactive material releases, though skin exposures to small quantities of some chemicals such as aqueous hydrofluoric acid can be fatal.

5. Location: The impact to facility workers could be affected by the location of the worker with respect to the location of the postulated scenario; or whether the accident being evaluated occurs inside or outside of structures. For releases outside of structures, consider the qualitative impacts on dose of the plume moving past the facility worker. For releases inside a nuclear facility, consider whether the release is being mixed within a relatively small work area volume, such as with glovebox operations or into a large open area such as waste container staging buildings. Also, for releases within the facility, consider facility layout and unique non-ideal conditions such as mining operations or areas of limited visibility that can make evacuation difficult to achieve quickly.

As a general rule-of-thumb application of the above considerations, examples of high unmitigated radiological or toxic chemical consequences to the facility worker are: (1) explosions, pressurized powders or high-concentration liquid sprays, and other energetic events that impact large quantities of radioactive material are considered to cause significant radiological exposure to the facility worker due to the rapid nature of the event, the resulting source term, and the inability of the worker to take protective action prior to receiving a substantial dose[16]; and (2) the prompt dose received from a criticality accident. Other types of events such as fires, spills, or dropping of a container require more careful evaluation of

[15] Workers may respond to incipient stage fires only with portable fire extinguishers, if they have been trained to use the extinguishers and feel safe in doing so.

[16] This also apples to the consequences of exposure to hazardous chemicals.

the characteristics of the actual accident event (e.g., time to develop) before credit can be given for the elements identified in this section. Any credit taken in the potential unmitigated consequences for facility workers needs to be justified.

2.6.1.3 STANDARD INDUSTRIAL HAZARD CONSEQUENCES TO FACILITY WORKER

Consequences to facility workers due to SIHs are included in the DSA when radiological or hazardous materials are involved and the SIHs are not screened out. These consequences are addressed in DOE-STD-3009-2014, Section 3.1.3.1 as follows:

> Facility worker consequences, due solely to a standard industrial hazard, do not need to be categorized in the hazard evaluation if screened out per Section 3.1.1. However, the evaluation of radiological or chemical hazards that result in a prompt death or serious injury should be assigned a high consequence per Table 1. Examples of such hazards might include the generation of flammable/explosive hydrogen gas by electrolysis of uranium in water or a spill of sodium hydroxide used in radioactive waste processing.[17]

For potentially serious injuries or fatalities, the event is assessed to determine whether the physical hazard associated with initiating or worsening a radiological or other hazardous material accident is a SIH or if it should be assigned a high consequence level. The primary consideration in determining whether the physical hazard is a SIH is if the regulated material (i.e., radioactive or other hazardous material) is not a primary cause or major contributor to the hazardous event, and that it is adequately addressed by 10 CFR Part 851 (and its adoption of OSHA and industry standards), 10 CFR Part 835, *Occupational Radiation Protection*, and Integrated Safety Management System HA requirements. These regulations and safety management programs are committed to in the DSA/TSRs. Examples of SIH accident initiators of a radioactive or other hazardous material release that may also cause physical injuries/fatalities are provided below to clarify that the unmitigated consequences do not include those SIH physical considerations. They illustrate that the unmitigated consequences do not include those SIH physical considerations, unless these could potentially affect their ability to safely manage the facility or respond to an accident condition. In that situation, the SIH should be considered for further analysis:

- **Thermal hazards** to the worker are due to welding equipment and combustible or flammable material fires ignited by typical ignition sources (e.g., electrical or thermal). The welding torch is a common SIH throughout various industries. The fires with typical ignition sources are also SIHs because the hazard and potential physical consequences are due to common types of equipment found throughout various industries. Both of these events are adequately regulated by 10 CFR Part 851, OSHA, NFPA, and national consensus standards.
- **Explosions** may involve ignition of flammable gases used with welding equipment; battery and fuel vapors; or offgasing from waste containers. The welding and equipment explosion and potential physical consequences are considered a SIH because these events commonly occur in general industry and are adequately regulated by 10 CFR Part 851, OSHA, and national consensus standards.
- **Missiles** are caused by an equipment explosion, failure of pressurized or mechanical system (e.g., air compressor or gas bottle), compressed gas cylinder failures, over-pressurization or deflagration of a hazardous (i.e., non-TRU) waste container, or from extreme straight-line winds, hurricanes and tornadoes. Missiles are considered an SIH because these events commonly occur in general industry and are adequately regulated by 10 CFR Part 851, OSHA, and national

[17] The above reference to Section 3.1.1 of DOE-STD-3009-2014 is located in Section 2.2.4 of this Handbook. Table 1 of the Standard is reproduced as Table 2-8 in this Handbook.

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consensus standards, or by the DOE NPH directives. However, if the missile physical consequence to the worker is due to the primary hazard being the regulated material, then those physical hazards are considered along with the radiological or other hazardous material consequences in assigning unmitigated consequences.

- **Equipment-related events** including vehicle/equipment load drops are SIHs because the hazards are presented by the equipment used in the work process, and the events are not caused by the regulated material. These events are adequately regulated by 10 CFR Part 851, OSHA, and national consensus standards.
- **Material and equipment movement** is a hazard presented by moving, lifting, dropping, vehicle-impact-induced movement, collapse due to corrosion/degradation, or movement due to a seismic event. The hazard is due to the size and mass of the object being moved and is not a hazard presented by the regulated material. The same hazard exists in various industries, such as construction. These events are adequately regulated by 10 CFR Part 851, OSHA, and national consensus standards.
- **Asphyxiant hazards** are presented by the use of small quantities of nitrogen and P-10 gas associated with loading or unloading shipping casks; acetylene or other compressed gases for maintenance activities and liquid nitrogen dewers for assaying waste containers; and exhaust buildup from material handling vehicles inside a facility. These hazards are common in various industries, and are adequately regulated by 10 CFR Part 851, OSHA, and national consensus standards. Smaller amounts of gases (i.e., nitrogen or argon) present for equipment calibration are in quantities that do not present an asphyxiation hazard. However, a large, rapid release of a nitrogen or argon from glovebox inerting systems for a nuclear process into a small confined occupied area that has an asphyxiation potential should be considered in assigning unmitigated consequences if the system has unique hazards requiring special design and controls that are not addressed by industry codes and standards.
- **Other impacts** encompass collisions from vehicles such as trucks traveling on the site, vehicles external to the site, and potential site aircraft crashes. These hazards exist in everyday life and are accepted by the public. Although no specific controls may be identified for these SIHs, the safety management programs, as committed to by the DSA/TSRs, which govern the conduct of activities involving various industrial hazards, will provide protection to the worker for these occupational hazards.

The qualitative evaluation for the facility worker may be supported by conservative quantitative scoping calculations, engineering judgment, and acquired knowledge. This qualitative approach is used because quantitative estimates are sensitive to a variety of possible assumptions such as facility worker position, circumstance, and close proximity to the point of release. Consequence estimates can rely on historical accident data or can be determined from: (1) simple bounding source term calculations, (2) existing safety documentation, and/or (3) qualitative assessment supported by calculations.

2.6.2 QUALITATIVE LIKELIHOOD

Likelihood of a hazard or accident scenario is assigned to qualitative bins defined by guidelines, which offer numerical ranges of two orders of magnitude or more. Table 2-9, reproduced from DOE-STD-3009-2014, Table 2, defines the qualitative likelihood bins.

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Table 2-9. Qualitative Likelihood Classification.

Description	Likelihood Range (/year)	Definition
Anticipated	Likelihood $>10^{-2}$	Events that may occur several times during the lifetime of the facility (incidents that commonly occur).
Unlikely	10^{-2}>likelihood $>10^{-4}$	Events that are not anticipated to occur during the lifetime of the facility. Natural phenomena of this likelihood class include: International Building Code-level earthquake, 100-year flood, maximum wind gust.
Extremely Unlikely	10^{-4}>likelihood $>10^{-6}$	Events that will probably not occur during the lifetime of the facility.
Beyond Extremely Unlikely	Likelihood $<10^{-6}$	All other accidents.

Although the exercise of determining accident likelihood is qualitative, safety analysts often develop a numerical basis for judgments to provide consistency. An example is provided in DOE-STD-3009 that a simple methodology for unmitigated likelihood assignment could be to assign a probability of "1" to non-independent events, "0.1" to human errors, and "0.01" to genuinely independent SSC failures that would be used to establish the initiating event likelihood[8] as described on Table 2-9. For the unmitigated analysis, these human errors and equipment failures cannot represent the failure probability of a preventive control that would otherwise provide a SC or SS safety function. To determine the likelihood of an accident scenario, only initiating events are expressed as rate of occurrence with the units of inverse time (i.e., per year), and other enabling events are expressed in terms of dimensionless failure probabilities.

Another methodology for unmitigated initiating event likelihood classification would be to use a summary of historical data. Historical accident data may be used as long as this data represents the frequency of initiating events for such type of scenarios, and not the frequency of the entire scenario. Thus, caution is necessary in using historical data to support unmitigated frequency estimates for hazard scenarios, since it may not result in conservative frequency estimates for such scenarios.

Conservative values are chosen to accommodate uncertainties in frequency levels used in Table 2-9. A conservative choice is particularly important when an event frequency is at the borderline, just below the next highest frequency level. For example, 9.7E-3/year is at the upper limit of the unlikely frequency level. Thus, considering the sources, methods, and uncertainty associated with this value, this event may be better assigned to a frequency level of anticipated. For initiating events at the borderline of frequency ranges, for the general rule is to assign to the next bin unless it can be justified based on the conservatism of the analysis. For example, an event just below a frequency of 10^{-2}/year may be conservatively considered assigned to the anticipated frequency level. The same applies for scenarios with frequencies slightly less than 10^{-4}/yr and 10^{-6}/year, i.e., may be assigned to the next higher frequency level of Unlikely and Extremely Unlikely, respectively. The exception for this is for Beyond Extremely Unlikely scenarios for external events only, which by default have always being defined as scenarios with a likelihood below 10^{-6}/yr.

The mitigated frequency of occurrence when crediting preventive controls could also apply simple numerical estimates to assign a lower frequency bin. For example, a 0.01 failure probability could be assigned to a preventive engineered control or a SAC based on the technical justification in DSA Chapter 4.

Estimating likelihoods qualitatively requires consistent assignments of the likelihood bins for similar scenarios. To achieve consistency, hazard scenarios should be "normalized" by comparison to one another.

2.6.3 QUALITATIVE RISK

The primary purpose of risk ranking is to support the selection of bounding DBA/EBAs for further quantitative accident analysis and determination of SC controls that are based on consequences, not risk rankings. However, risk rankings may also be used to support the hazard evaluation and SS control selection. Combining a likelihood and a consequence level leads to defining a qualitative risk level, sometimes called Risk Category or Risk Class. Table 2-10, reproduced from DOE-STD-3009-2014 Table A-1, provides an example of a risk ranking table that combines likelihood and consequence, which is based on using the consequence and likelihood thresholds in Table 2-8 and Table 2-9, respectively.

Table 2-10. Qualitative Risk Ranking Bins.

Consequence Level	Beyond[18] Extremely Unlikely Below 10^{-6}/yr	Extremely Unlikely 10^{-4} to 10^{-6}/yr	Unlikely 10^{-2} to 10^{-4}/yr	Anticipated Above 10^{-2}/yr
High Consequence	III	II	I	I
Moderate Consequence	IV	III	II	II
Low Consequence	IV	IV	III	III
Risk Category I = Combination of conclusions from risk analysis that identify situations of major concern Risk Category II = Combination of conclusions from risk analysis that identify situations of concern Risk Category III = Combination of conclusions from risk analysis that identify situations of minor concern Risk Category IV = Combination of conclusions from risk analysis that identify situations of minimal concern				

Beyond the qualitative application of consequences and likelihoods (or supplemented with quantitative perspectives) for the hazard evaluation, risk ranking serves the broader purpose of confirming for the DOE approval authority that the overall mitigated risk of facility operation is low. Risk ranking can also highlight a given scenario whose mitigated risk remains significant. Additional guidance on use of unmitigated risk estimates for control selection is provided in Chapter 10.

2.7 UNMITIGATED AND MITIGATED HAZARD EVALUATIONS

The DSA hazard evaluation is based on unmitigated and mitigated analyses that derive the selection of hazard controls. The guidance from Section 2.6 is applied to assign qualitative estimates of the unmitigated and mitigated consequences, likelihood, and optionally, risk rankings of the hazard scenarios.

An unmitigated hazard scenario is evaluated for each initiating event by assuming the absence of preventive and mitigative controls. Unmitigated likelihood and consequence estimates assume that active engineered and administrative controls are not available to reduce either the consequence or likelihood of the hazard scenario. However, the unmitigated analysis does assume that passive design features exist and provide their safety function if these features are not affected by the accident scenario, or these features are affected by the accident scenario and a separate assessment determines that they will survive accident conditions.

[18] For external events, likelihood below 10^{-6}/yr conservatively calculated is "beyond extremely unlikely."

Passive features assumed to perform their safety functions are evaluated per DOE-STD-3009 for potential designation as SC or SS SSCs and protection as TSR Design Features. In addition, the unmitigated analysis considers facility geometry and physical plausibility, and evaluates the unmitigated likelihood and consequence accordingly. For example, in an explosion scenario, the unmitigated likelihood would not be reduced by an engineered control, such as a vessel purge. However, the unmitigated likelihood of the explosion could be reduced based on physical realities of the facility, activity, or operation that will cause the explosion-initiating condition to occur (accumulation of minimum explosive concentration); no credit is allowed in the reduction of the likelihood for subsequent enabling conditions that will result in the explosion itself (e.g., presence of an ignition and/or oxygen). Thus, the likelihood of the scenarios should be based only the likelihood of the conditions leading to a physically meaningful initiating event, and not on the subsequence engineering or administrative controls that maybe available to prevent the explosion. Additional requirements and guidance on unmitigated analysis are provided in DOE-STD-3009-2014, Section 3.2.2.

Initial conditions may be necessary to define the unmitigated evaluation and are identified as shown on Table 2-7 and another example is provided later in Table 2-11. Credit for the initial condition is factored into the unmitigated likelihood or consequence assignments, and that initial condition is evaluated per DOE-STD-3009 for potential designation as a TSR control (e.g., MAR inventory-specific administrative control). Additional guidance is provided in DOE-STD-3009-2014, Section A.3, and is further discussed in Section 3.3 of this Handbook.

A mitigated analysis is performed to determine the effectiveness of SS and SC controls to protect CWs and the public. This analysis should be the same as the unmitigated analysis except that event likelihood is estimated with preventive controls available, and consequences are estimated with mitigative controls available. The selection of preventive and mitigative controls is a judgment-based iterative process to credit sufficient controls that provide confidence that the accident or release is prevented, or if not prevented, the consequences will be reduced to below thresholds of concern. Additional requirements and guidance on mitigated analysis are provided in DOE-STD-3009-2014, Section 3.2.3. The selection and classification of the hazard controls for the mitigated analysis are discussed in Chapter 10 of this Handbook.

2.8 HAZARD EVALUATION PRESENTATION IN DSA

Results for the unmitigated and mitigated hazard analyses are presented in the DSA hazard evaluation section as discussed in a DSA Section [3.3.2.3], Hazard Evaluation Results (see DOE-STD-3009-2014, Section 4.0). The DSA hazard evaluation table, or alternate hazard evaluation data sheet as described in DOE-STD-3009-2014, has certain essential characteristics:

- If multiple types of operations are being analyzed, the table is broken into separate sections where each section presents results for one specific type of operation.
- Specific hazard scenarios are described in terms of well-defined events. For example, a HAZOP may have dozens of entries for parameter-guide word combinations. These need to be turned into discrete events. A HAZOP may note that low flow caused by incorrect positioning of valves upstream has no major effect on a process other than operational disruption, while low flow due to a large leak represents a significant operator hazard. Those are two entirely different events.
- Initial conditions and assumptions are identified.
- Potential preventive or mitigative controls are identified.
- Unmitigated and mitigated consequences and likelihoods, and optionally, risk estimates, are identified to support control selection and classification. Source term parameters such as MAR,

Damage Ratio (DR), Airborne Release Fraction (ARF), and Respirable Fraction (RF) may optionally be listed.

Table 2-11 presents an example hazard evaluation table for presentation in the DSA, which builds upon the example provided in Table 2-7. This table includes both the unmitigated and mitigated analysis. There are many different formats that can be used to present this data, bearing in mind that the purpose is to achieve a comprehensive hazard evaluation and an unmitigated analysis of hazard scenarios in terms of potential consequences, their likelihoods, and identification of preventive and mitigative controls. The hazard evaluation table, in whatever format is chosen, should also present the mitigated analysis that credits safety controls, or this could be described in the DSA hazard evaluation results section. The mitigated hazard evaluation can be included as additional columns as shown on Table 2-11, or another convention is to use separate rows for the unmitigated and mitigated evaluations.

Appendix A provides another example of a hazard evaluation table for safety design basis documents, as part of the process to perform a Preliminary Hazard Analysis required by DOE-STD-1189-2016, *Integration of Safety into the Design Process*. Some additional data are included such as methods of detection and more emphasis on further planned improvements and investigations as the design matures.

Table 2-11. DSA Hazard Evaluation Table Example.

			Unmitigated Analysis					Mitigated Analysis		
Event	**Event Description**	**Event Causes**	**Freq. Level**	**Consequence Level**	**Risk Category**	**Preventive Features**	**Mitigative Features**	**Freq. Level**	**Consequence Level**	**Risk Category**
x	Fuel-powered vehicle suffers a fuel leak due to an impact with TRU waste drums in the Shipping/Receiving Area and is ignited. A forklift carrying a single pallet with four drums impacts a stack (two high) of palletized drums with moderate to severe stress causing breach with material spill of 12 drums and ensuing pool fire that involves 88 additional drums in the Shipping/ Receiving Area. MAR: xx alpha curies in 100 drums (DOE-STD-5506-2007 statistical MAR distribution for Waste Isolation Pilot Plant compliant containers applied, see Table yy) INITIAL CONDITIONS: **Staging area inventory limit;** **TRU waste in metal containers;** **Metal pallets.**	• Operator error • Equipmen t malfuncti on • Vehicle impact with fuel spill • Ignition of combustib le and/or flammable materials • Lightning • Wildland fire	U	Radiological FW – High CW – Moderate MOI – Low Hazardous Chemical FW – Low CW – Low MOI – Low RELEASE MECHANISM: Impact + fire – 12 drums, 10% DR, 1E-3/0.1 spill ARF/RF plus unconfined burning 1E-2 ARF/RF and 90% confined burning 5E-4 ARF/RF. Pool fire – Conservatively modeled in a single layer of drums with no stacking. Unconfined burning 1E-2/0.1 ARF/RF of 25% of drums that experience lid loss (22 drums) that eject 33% contents and have confined burning 5E-4 ARF/RF of remaining contents in those drums, plus confined burning of 66 drums that experience seal failures (0.5 DR).	 I II III III III III	SSCs: **Concrete vehicle barriers.** **Waste staging building foundation.** ADMINISTRATIVE: Procedures and Training Program (Forklift Operator training); Vehicle maintenance program; Fire Protection Program: • Combustible controls Waste handling operations curtailed outdoors during inclement weather; **Movement of waste is to be accomplished using electric or manual powered equipment (SAC);** **Fuel exclusion zone in the Shipping/Receiving Area (SAC).**	SSCs: None ADMINISTR ATIVE: Procedures and Training Program (workers trained to evacuate); Emergency Preparedne ss Program (emergency response activities).	BE U	Radiological FW – High CW – Moderate MOI – Low Chemical FW – Low CW – Low MOI – Low	 III IV IV IV IV IV

Notes:

1. Likelihood: A = Anticipated U = Unlikely EU = Extremely Unlikely BEU = Beyond Extremely Unlikely
2. Consequences: H = High M = Moderate L = Low
3. FW = Facility Worker CW= Co-located Worker at 100 m MOI = Maximally-exposed Offsite Individual at 2.9 km
4. Risk Classes: I = Combination of conclusions from risk analysis that identify situations of major concern
   II = Combination of conclusions from risk analysis that identify situations of concern
   III = Combination of conclusions from risk analysis that identify situations of minor concern
   IV = Combination of conclusions from risk analysis that identify situations of minimal concern

Bold/Underlined controls are credited in the mitigated analysis to reduce frequency, consequences, and Risk Class, or as Initial Condition

3 ACCIDENT ANALYSIS

This chapter provides an introduction to the accident analysis process. The starting point is a review of the hazard scenarios that were identified in the hazard evaluation table as discussed in Chapter 2 of this Handbook. Specific events are selected for further quantitative accident analysis. This particular chapter also addresses assumption and initial conditions, beyond DBAs/EBAs, and software quality assurance (SQA).

In general, formal accident analysis is performed for HC-2 facilities, and may or may not be necessary for HC-3 facilities. Accident analysis is the formal quantification of a subset of accidents, termed DBAs or EBAs by DOE-STD-3009. These accidents represent a complete set of bounding conditions. The basic components of accident analysis are accident type selection, accident scenario development, source term analysis, consequence analysis and control selection. This process is highly iterative to ensure accident scenarios are adequately developed, source term and consequence analysis is bounding, the suite of controls are comprehensive and tailored to reflect accident conditions, and all identified facility hazards are understood and properly controlled.

3.1 ACCIDENT TYPE SELECTION

It is expected that only a subsect of the total hazard scenarios identified in the hazard analysis will be evaluated as potential DBAs or EBAs in the accident analysis. The predominant purpose of accident analysis is to evaluate the need for SC controls to protect the public from radiological accidents. However, it may also be used to evaluate the need for defense in depth SS controls for protection of the public from radiological or toxic chemical accidents, or for protection of the CWs. The facility worker is not included in the scope of the DSA accident analysis and instead is addressed by the qualitative hazard evaluation discussed in Chapter 2 of this Handbook.

DBAs are accidents to be analyzed in a DSA for the design of a new nuclear facility and major modifications to an existing facility. The DSA will also include accident scenarios established during the design of an existing facility. DOE-STD-1189-2008 provides guidance for selecting and analyzing facility-level radiological and/or toxic chemical release events in the DBAs.

EBAs are postulated for existing facilities where DBAs were not identified as part of the design. The term EBA recognizes that an existing facility was not *designed* to DBAs to prevent or mitigate the accident, but rather is *evaluated* to ensure that it could do so with existing systems or added systems/controls. When an adequate set of DBAs does not exist, EBAs are selected from the following types of events:

- Operational accidents — process deviations (such as high temperatures and high pressures) and initiating events internal to the facility (such as fires, explosions, and loss of power resulting in release of radioactive or hazardous materials);
- NPH events such as earthquakes, floods, tornadoes, and wildland fires; and,
- Man-made external events such as an aircraft crash, external vehicular accident, or gas pipeline break.

Two types of EBAs, representative and unique, are defined in DOE-STD-3009-2014 for further quantitative accident analysis.

DBAs/EBAs are derived from the spectrum of hazard evaluation scenarios. Three screening steps convert the spectrum of hazard evaluation scenarios into the selected DBAs/EBAs:

- The first screening identifies potential consequences by population in relative bins of increasing severity. This step will discard scenarios whose higher consequence potential relates only to in-facility workers, because accident analysis focuses on consequences at a distance from the facility.

- The second screening looks at accident types. It is necessary for DSA documentation purposes to include at least one hazard and its consequence of each major accident type (e.g., fire, explosion, spill, NPH), unless the scoping calculations for the hazard evaluation demonstrate low consequences that do not have the potential to challenge the offsite Evaluation Guideline (EG) (DOE-STD-3009). These are called representative scenarios with similar preventive and mitigative control sets that bound the collective scenarios for that type.

- The final screening consists of looking at the remaining scenarios within a selected accident type to see if any would warrant safety SSC designation to protect the public (and CW if included in the DSA accident analysis, as mentioned above), but involve a different control set than the representative accident already chosen for that type. These are called unique accidents.

As an aid in screening the many hazard scenarios identified in the hazard evaluation, representative or unique EBAs may be selected based on organization by accident category (operational, NPH, man-made external event), accident type, and magnitude. Other means of grouping accidents may also be used, especially for complex facilities that may require a broad suite of hazard controls. The selected representative and unique scenarios are designed to bound all other postulated hazard scenarios, including high risk scenarios that still may challenge the EG (as determined during the hazard analysis process using the qualitative risk matrix in Section 2.6.3), or that may have high risk to the co-located worker if that is being evaluated in the accident analysis.

An example of an aid to screen hazard scenarios is provided in DOE-STD-5506-2007, Table 3.3-1, Minimum TRU Waste Activity/Hazard Evaluation Event Matrix. This table correlates 25 hazard scenarios or accidents by TRU waste processing activities for use in the hazard evaluation, or as EBAs. The minimum set of events addresses those with the potential for consequences that could be significant enough to warrant crediting preventive or mitigative controls, safety classifications of those controls, and explicit TSRs. Another example aid in screening hazard scenarios for EBA selection is NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook,* Table 2-2, Methods of Release of Radioactive Materials Anticipated for Nuclear Process Facilities.

3.2 ACCIDENT ANALYSIS PROCESS

The accident analysis process consists of the following sequence of steps intended to document numerical estimates of radiological and toxic chemical consequences to the public (or CW as needed for the DSA hazard evaluation):

1. Define the postulated accident scenario that releases radioactive material or toxic chemicals from the facility.
2. Estimate the damage to the facility to the extent it affects the potential MAR and source term released from the facility, e.g., loss of confinement areas.
3. Identify types and quantities of material involved in the accident MAR.
4. Determine the accident source term.
5. Conduct a dispersion analysis to determine the potential radiological dose or toxic chemical consequences.

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Chapter 4 addresses steps 1-3 for potential accidents at DOE nuclear facilities. Chapter 5 addresses step 4. Chapters 6, 7, and 8 address step 5 for radiological releases, while Chapter 9 addresses step 5 for toxic chemical releases.

The potential controls identified in the hazard evaluation are further evaluated in the mitigated accident analysis, using the control selection and classification process described in Chapter 10.

3.3 ANALYSIS INPUTS AND ASSUMPTIONS

For most DOE accident analyses, the phenomena being examined have aleatory and systemic uncertainties. Most often it is not possible to derive precise and absolute conclusions from first engineering principles. Therefore, it is important to document the inputs, frame of reference, initial conditions, and assumptions of the accident analysis to ensure that these are not only defensible but conservative. This applies to all elements of the accident analysis process from accident selection, to frequency estimates, and source term and consequence analyses. The focus in this section is on the analysis of inputs and assumptions related to defining scenarios and their frequencies. Section 5.4.1 addresses the use of technically justified input and assumptions related to source term and consequence calculations.

Both hazard and accident analyses make use of initial conditions (ICs) to define hazard or accident scenarios to be evaluated. Initial conditions are specific assumptions regarding a facility and its operations that are used to define these scenarios. When not referring to physical facility features, these are sometimes called "initial assumptions," which creates confusion regarding the need for TSR controls to protect these assumptions. The use of "IC" in this Handbook refers to *initial conditions*.

As discussed in DOE-STD-3009-2014, Sections 3.2.2 and 3.2.3, facilities are analyzed as they exist, or are designed, when quantifying meaningful release mechanisms. For design of new facilities, the unmitigated analysis may need to assume failure of the SSC to determine the potential consequences for safety classifications of SSCs and their appropriate design requirements, for example, design criteria for the selected NPH Design Category.

Accident scenario description includes, as appropriate, the operating mode of the system, all pertinent aspects of the physical configuration of the system and its environment, and relevant operating parameters, such as temperature, pressure, material inventories, and confinement, at the time the accident is postulated to begin. Not all of these assumptions are ICs. Where a range of possible ICs, physical properties, or environmental conditions exists, the range is specified, and the most conservative physically credible combination of normal operating conditions is chosen, and an explanation of why the choices are considered conservative should be provided.

As stated in Chapter 2, significant assumptions in hazard scenarios should be identified and justified, and this also applies to the accident analysis. Specific examples of ICs include:

- A vault or building can withstand NPH events according to its NPH Design Category.
- Facility geometry or layout limits accident progression or release with respect to in-facility transport.
- Solid TRU waste is contained in a certified Department of Transportation (DOT) Type-A drum (i.e., an additional barrier).
- A certain material is present only within a certified DOT Type B shipping container.
- Facility and process inventories are limited to those identified.
- A passive engineered SSC prevents significant consequences.

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ICs should not include administrative controls, except those necessary to limit the inventory of radioactive or toxic chemical materials, or as specified by the analyst and/or regulator. Controls should be selected to protect assumptions such as MAR critical to the consequence analysis. ICs, and in some cases the associated administrative control associated with the ICs, should warrant some level of Safety SSC designation or SAC to ensure that the assumptions remain valid throughout the operating life of the facility. Defining and documenting ICs and associated administrative controls ensures that they are appropriately controlled, classified as SC or SS, and preserved via TSR operating limits, design features, or SACs.

Initial conditions that clearly prevent an accident and are part of the facility design basis (e.g., the structure is designed to withstand vehicle impact) are encouraged. Other safety controls are discouraged from being used since they may skew the unmitigated risk levels and result in unanalyzed or inadequately controlled hazards. For example, a fire door may be improperly credited as an IC for preventing fire propagation. This control may fail (blocked open door) so it does not completely prevent the event, but only reduces the likelihood. If the likelihood reduction "moves" the event risk to a level that does not require further analysis, then the adequacy of the control is not evaluated and the safety functions of the door may not be properly determined. Additionally, this may lead to a larger control set since controls identified for other fire events (e.g., combustible loading limits) may be adequate to protect against this event.

Spreadsheet calculation and computer modeling of accident sequences can provide valuable insights on the sensitivity of parameters, as well as indicating what reasonably lower and upper limits of response might be expected so that an overall conservative consequence is estimated (see Section 5.4, Appropriateness of Source Terms). The foundation of any accident analysis can be reduced to a set of inputs and assumptions. An input can be defined as a value feeding into the analyses that can be measured confidently and is readily obtainable. It could, for instance, be the internal freeboard volume of a tank, the specific gravity of a solution, or the metal skin thickness of a 55-gallon drum. An input value would not be expected to change as more information relative to it is obtained. An assumption, on the other hand, is a value feeding into the analyses that is not known with reliability and accuracy. Significant judgment therefore enters into the process of selecting the value or parameter of interest.

To address the uncertainty associated with the impact of assumptions and input variables, the default values in DOE-STD-3009 and DOE-HDBK-3010 are to be used to ensure an overall conservative analysis, and an analysis that is conservative to the extent envisioned when the Evaluation Guideline was established. Section 5.4.1 provides additional guidance on the use of non-default values or values that depart from the default values in the above-mentioned standard or handbook.

Examples of assumptions would be the rate of in-facility dispersion of a flammable gas leaked into a ventilated volume, the degree to which two spilled chemicals that react together might intermingle (synergism), or the nature of the physical interactions occurring in a structural collapse. The flammable gas leak example can be calculated, but the means of calculation itself introduces an implicit set of theoretical assumptions and uncertainties. The other two examples intrinsically involve making judgments about what is likely to occur. Analysts should strive to use as few assumptions in the accident analysis as possible, but their presence to some degree is inevitable. This point is specifically emphasized in *Guidelines for Hazard Evaluation Procedures* (CCPS, 2008):

> Because many of the events considered by the team may never have happened before, the team must use their creativity and judgment to decide whether the potential causes and effects of the accident pose a significant risk. The subjective nature of these deliberations may trouble some people who use the results of these studies because this subjectivity creates a lack of confidence

in the results. Some people incorrectly believe that if an analyst uses quantitative measures to express the significance of a problem, then the limitation of subjectivity will simply fade away. However, this is not the case.

Another consideration is that there may be a difference between the level of conservatism of methods used to derive input parameters used for unmitigated dose consequence calculations and input parameters used to show that the design withstands physical stresses from the accident scenario. For example, dose consequence calculations may use an extremely conservative value or method to calculate aerosol generation for the purpose of determining the source terms and ultimately supporting classifying controls. However, these conservative values or methods may not be appropriate for design basis calculations.

3.4 BEYOND DESIGN/EVALUATION BASIS ACCIDENTS

The DSA [Section 3.4] Accident Analysis (see DOE-STD-3009-2014, Section 4.0) evaluates DBAs/EBAs for control selection and classification purposes. Section 3.5 of DOE-STD-3009-2014 provides guidance on the consideration of the need for analysis of accidents, which may be beyond the design basis of the facility. This section addresses accident analysis of these extreme events.

The purpose of an analysis of accidents beyond the design or evaluation basis of the facility is to provide (1) a perspective of the residual risk associated with the operation of the facility, and (2) additional perspectives for accident mitigation. That standard describes that Beyond Design Basis Accidents/Beyond Evaluation Basis Accidents (BDBAs/BEBAs) need not be analyzed to the same degree of detail as DBAs/EBAs. The analysis is intended to provide insight into the magnitude of consequences of such events and to identify potential facility vulnerabilities. The analysis has the potential, therefore, for identifying additional facility features that could prevent or reduce severe accident consequences. Unlike the unmitigated conservative analysis for DBAs/EBAs, a realistic analysis of potential BDBA/BEBA consequences may be performed to determine whether accidents have a much larger consequence (a "cliff edge effect") than the largest DBA/EBA.

After the March 11, 2011 Fukushima Dai-Ichi nuclear plant accident in Japan, DOE embarked upon several initiatives to investigate the safety posture of its nuclear facilities relative to Beyond Design Basis Events (BDBEs). These initiatives included issuing Health, Safety and Security (HSS) Safety Bulletin 2011-01, "Events Beyond Design Safety Basis Analysis," conducting pilot evaluations to refine possible process improvements, and conducting two DOE nuclear safety workshops. DOE issued two reports documenting the results of these initiatives: *Review of Requirements and Capabilities for Analyzing and Responding to BDBEs* (DOE, 2011); and *A Report to the Secretary of Energy: Beyond Design Basis Event Pilot Evaluations, Results and Recommendations for Improvements to Enhance Nuclear Safety at DOE Nuclear Facilities* (DOE, 2013). A summary description of the pilot evaluation process and results is provided in the HSS Operating Experience Level 1 notice (DOE HSS OE-1, 2013), "Improving Department of Energy Capabilities for Mitigating Beyond Design Basis Events." Additional details of the pilot activities are provided in a companion technical report, *Technical Details on Beyond Design Basis Event Pilot Evaluations* (DOE Technical Report, 2013).

The focus of the pilot evaluations was the review of BDBEs and response capabilities at four DOE nuclear facilities representing a range of DOE sites, nuclear facility types and activities, and responsible program offices. The pilot evaluations looked at (1) how BDBEs were evaluated and documented in each facility's DSA, (2) potential BDBE vulnerabilities and margins to failure of facility safety features as obtained from general area and specific system walkdowns and design documents reviews, and (3) preparations made in facility and site emergency management programs to respond to severe accidents. It also evaluated whether draft BDBE guidance on safety analysis and emergency management could be

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used to improve the analysis of and preparations for mitigating severe accidents (including BDBEs), which were updated and provided as Attachments 1 and 2, respectively, to the DOE HSS OE-1 (2013). The Attachment 2 safety analysis guidance may be used in annual updates to DSAs, and is reproduced here:

Attachment 2 - Documented Safety Analysis (DSA) Guidance

The purpose of this guide is to provide expectations for performing an enhanced evaluation of beyond design basis events (BDBEs) as a part of the annual DSA updates. It is generally expected that existing DSAs subject to the criteria of Action 2 already include an evaluation of BDBEs as required by DOE-STD-3009. The enhanced evaluation incorporates an analytical approach that was developed during the BDBE pilots, but documents the results of the analysis in the same manner as described in STD-3009. The enhanced evaluation process should incorporate lessons learned as described in "A Report to the Secretary of Energy: Beyond Design Basis Event Pilot Evaluations, Results and Recommendations for Improvements to Enhance Nuclear Safety at Department of Energy Nuclear Facilities," January 2013.

As with any DSA preparation and update activity, the BDBE evaluation should be conducted by a qualified team leader and a multidisciplinary team consisting of experts in the areas of facility operations, facility safety analysis, structural/mechanical engineering, NPH, and emergency management, the last of which is particularly relevant to the objective of this evaluation. The intent is to perform an expert-based and qualitative evaluation.

The facility's DSA should serve as a starting point for the evaluation of BDBEs. The DSA is expected to include a discussion of the BDBEs considered, and may include a discussion of analyses or enhancements made to the facility to meet DOE Order O 420.1 C, *Facility Safety*, requirement to evaluate the impact of changes in NPH data and/or analysis methodologies every ten years. The new analyses and enhancements should identify how the design has "evolved" to provide assurance of safety under events that are beyond the original design basis. As described in the HSS report to the Secretary referenced above, it is prudent for the team to perform a walkdown of the facility to support a qualitative evaluation of how a BDBE may impact the facility (the qualitative evaluation is discussed in the next section of this attachment) and to look for potentially unknown vulnerabilities to BDBEs (e.g., unsealed penetrations or low-lying electrical equipment in the case of flooding accidents).[19] This walkdown also ensures the reviewers are familiar with facility's size, key features and distances to other structures, and potential temporary service connections (like fire hydrants or well water sources).

This enhanced BDBE evaluation is intended to identify BDBEs that may cause a release of radioactive material beyond that analyzed in the unmitigated accident analysis in the DSA and/or to disable important controls relied on to mitigate the release of radioactive material. The types of BDBEs that should be evaluated include:

- Seismic events
- Floods
- Fires
- Lightning
- Wind and tornadoes
- Snow and ice

[19] An example might be unsealed penetrations or low-lying electrical equipment in flooding events.

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- Ash fall
- Accidental aircraft crash
- Station blackout, as an initiating event or as a consequence from any of the above events
- Cascading effects of design basis events analyzed in the DSA that were previously ruled out because of the low likelihood of associated multiple failures.

If BDBE's from the above list are excluded, the rationale for exclusion should be documented. The general categories of failures to be considered for each BDBE listed above include:

- Collapse of building structure and interior walls
- Breach of water storage pools or collapse of storage racks
- Loss of electrical power and emergency power equipment (e.g., transformers, switchgear, or motor control centers)
- Loss of electrical distribution systems (e.g., conduit or cable trays)
- Operational failure of active mechanical equipment (e.g., pumps, compressors, or fans)
- Loss of pressure boundary of static equipment (e.g., tanks, vessels, or gloveboxes)
- Failure of distribution systems (e.g., piping, tubing, or ducts)
- Failure of alarms
- Loss of an emergency response center.
- Adverse spatial seismic interaction (e.g., failure of adjacent buildings or failure of adjacent stacks)
- Adverse flood-inducing interaction (e.g., failure of an adjacent water tank)

The enhanced BDBE evaluation should provide a gross estimate of the bounding impacts associated with BDBEs. It is qualitative in that it relies on a simple "what if?" type of hazard evaluation technique where a multidiscipline team participates in a brainstorming session to methodically evaluate the potential failures in facility systems, structures, and components (SSCs) that could be caused by each type of BDBE. The evaluation should estimate the consequences associated with failures of SSCs that provide safety functions such as confinement, energy removal (e.g., decay heat removal or fire suppression), or prevention of energetic reaction (e.g., explosion). The evaluation may draw upon existing unmitigated accident analysis performed in the DSA.

This qualitative evaluation process is applied to each type of BDBE so different failure modes and associated effects can be understood. Although a seismic event will typically present the worst-case consequences, it is important to step through all applicable BDBEs using the same structured "what if?" brainstorming technique. This information can be important when considering potential mitigation strategies.

SSCs identified as mitigating BDBE consequences should be subjected to a margins assessment (MA) to provide insights into their margin-to-failure. This should be a qualitative assessment based upon expert judgment. Civil/structural engineers should perform the MA by reviewing existing design basis analyses and supporting calculations for SSCs. This information should then be used as a baseline to compare against a SSC's expected response to higher level stresses. A MA can be difficult to accomplish if facility design information is not available, i.e., for older DOE facilities. In this case, the MA may have to rely on bounding, simplified assumptions, and judgments by subject matter experts, supported by the results of structured walkdowns. For NPH events, the margins assessment should be accomplished by analyzing the facility for higher stress levels than the systems' design (for example, the next higher seismic performance or design category) based on qualitative expert judgment.

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Descriptions of performance capabilities of the existing SSCs should also be added to or referenced in the DSA, as new and relevant information is learned from above BDBE evaluation. SSCs that provide protection against BDBEs are typically SC controls, or a subset of these controls, credited in the DSA for design basis events. If the BDBE evaluation identifies non-credited SSCs, it is not expected that these SSCs would be classified as SC or SS based solely on BDBE consequences, and, therefore, additional TSRs for these SSCs would not be created. These may include facility features such as temporary utility connections (power or water) and critical parameter instrumentation readings that permit monitoring after a BDBE occurs. The DSA should identify these SSCs as important for providing additional mitigation of BDBEs, and these SSCs should be maintained within the facility configuration management and maintenance programs in the same manner that other non-SC and SS DSA controls are treated to preserve their safety function. PSOs should establish for their facilities whether the Unreviewed Safety Question program should be used to determine the approval authority for changes to BDBE controls, or whether more general provisions of maintenance and configuration control should be relied upon.

Based on the results of the enhanced BDBE evaluation, existing DSA descriptions of BDBE accident scenarios should be updated as necessary to clarify important assumptions needed to develop abnormal or emergency operating procedures. This may include details such as potential accident conditions associated with the range of BDBEs, cascading effects of certain scenarios, time-frames associated with scenario development, and time-critical mitigative actions. Additionally, emergency management plans for responding to BDBEs (updated using the guidance in Attachment I) could also identify potential facility design changes for consideration. An example would be the addition of standardized connections, outside the facility, that could be used to supply cooling water, deliver fire suppression water, or provide electrical power using resources obtained through emergency management mutual aid agreements. These improvements should also be conveyed as part of the DSA annual update.

Note that this guidance includes a BDBA/BEBA evaluation of accidental aircraft crashes. This is not specifically required by DOE-STD-3009-2014, or DOE-STD-3009-94, CN3, if less than a likelihood screening threshold. The most recent guidance on BDBA/BEBA evaluations provided in DOE-STD-3009-2014 states:

> Operational BDBAs/BEBAs are operational accidents with more severe conditions or equipment failures than are estimated for the corresponding DBA/EBA identified in the unmitigated analysis, or with likelihood of beyond extremely unlikely based on PRA results as described in Section 3.2.1. NPH BDBAs/BEBAs are defined by the initiating likelihood of the natural event itself (i.e., return period greater than the DBA/EBA return period for the next higher level as defined in DOE-STD-1020-2012). Man-made external events determined to be less than 10^{-6}/yr, conservatively calculated, do not require further evaluation in the DSA.

3.5 SOFTWARE QUALITY ASSURANCE

Software used in support of (a) DSA hazard and accident analysis calculations and (b) TSR implementation of SC and SS safety functions or SAC inventory control, is subject to the quality assurance requirements of 10 CFR Part 830 Subpart A, such as the DOE software quality assurance (SQA) guidance and applicable national consensus standards. SQA criteria for safety software are discussed in DOE O 414.1D, Chg. 1, *Quality Assurance*, and DOE G 414.1-4, *Safety Software Guide for* *use with 10 CFR 830 Subpart A, Quality Assurance Requirement.*[20] The analyst is encouraged to become familiar with these documents and the processes contained therein.

There are three subcategories of "safety software": (1) Safety System Software, (2) Safety and Hazard Analysis Software and Design Software, and (3) Safety Management and Administrative Controls Software. The Safety and Hazard Analysis Software is of primary concern to the DSA analyst. Software developers have the responsibility for ensuring that their software code has undergone appropriate SQA evaluation before it is distributed to the end users. Moreover, the software user has the responsibility of ensuring that the safety software to be used has successfully met all SQA processes prior to adopting it for any DSA analysis. As part of the SQA process, software developers should also provide technical manuals and user guides to assist the analyst in assessing appropriate application domains for the software to ensure its proper implementation. This documentation should address system requirements and their technical bases and describe default parameter values and default computational modes. The methodology for modifying these default values and modes should also be documented.

There are ten SQA requirements that need to be satisfied, but the heart of the SQA process is the verification and validation requirement. A comprehensive definition of verification and validation is provided in draft DOE G 414.1-4A, *Safety Software Guide for Use with DOE O 414.1D, Quality Assurance*. A simplified distinction between verification and validation is:

- Verification: The detailed examination of the code to ensure that the coding precisely and accurately reproduces the mathematical model approximations in its algorithms.
- Validation: Entails a comparison of the software model results to actual test or physical data through scientific assessment and benchmarking against other models.

Scientific assessment involves examination of encoded algorithms against theoretical principles and ground-truth data, where available, to assess the ability of those algorithms to accurately model the phenomena of interest. Benchmarking involves comparing the output of one software code with the output of similar code, or the results of a hand calculation or spreadsheet that serves as a baseline. This type of comparison does not necessarily constitute validation, but has merit as part of a validation procedure to the extent the baseline model is generally accepted as a reasonably accurate predictor for the phenomena of interest. Benchmarking can also provide insight into model limits of applicability, computing expense, input requirements, and important sensitivities or uncertainties. Ideally, computer code results should be compared against experimental results that were obtained in environments that mimic those to which the model will be applied. However, due to the expense associated with large-scale field tests or experiments, this type of data is generally very limited.

Parametric studies can uncover the sensitivity of a model to its various inputs. This can be extremely useful if it can be determined that the model is insensitive to certain parameters, such that validation does not need to overly concern itself with those parameters. Parametric studies can also be useful in situations in which there is a large variability or uncertainty associated with a particular input parameter. The results can be used in these cases to define parametric specifications that can establish conservative model predictions. The results of any sensitivity analyses should always be fully documented, as they are part of the framework that puts specific model results in proper perspective.

The capabilities of the techniques selected to perform the analysis should also be commensurate with the levels of detail required. This capability should be consistent with the "graded approach," which directs (among other criteria) that effort should be proportional to the complexity of the facility and the safety

[20] DOE G 414.1-4 was written for DOE O 414.1C and is currently being revised as DOE G 414.1-4A to conform to DOE O 414.1D.

systems relied upon to maintain an acceptable level of risk. For a more comprehensive discussion of graded approach, see DOE-STD-3009-2014, Section 2.2. Accordingly, assessment of the possible consequences of an accidental release of radiological or toxic chemical substances into the atmosphere requires computations that could range from developing estimates on a spreadsheet to applying advanced computer codes that address source term phenomenology and atmospheric transport and diffusion. These are listed below:

Several national consensus standards provide guidelines on verification and validation activities for scientific and engineering computer programs for use in the nuclear industry:

- ANSI/ANS-10.7-2013, *Non-Real Time, High Integrity Software for the Nuclear Industry – Developer Requirements*;
- ANSI/ANS-10.4-2008 (R2016), *Verification and Validation of Non-Safety Related Scientific and Engineering Computer Programs for the Nuclear Industry*
- ASME/NQA-1-2008, *Quality Assurance Requirements for Nuclear Facility Applications, Subpart 2.7*; and
- IEEE 1012-2004, *IEEE Standard for Software Verification and Validation*.

Safety analysis calculations in many cases are completed without the need to resort to DOE software toolbox codes, such as Hotspot, ALOHA, and MACCS2. Calculations that may fall into this category include:

- Hand calculations;
- Commercial software package, such as Excel and Mathcad, where the primary use of the software is ease of implementation in automating arithmetic operations;[21] and
- Non-DOE toolbox codes, such as MCNP, KENO VI, and other government or industrial codes that are widely accepted and meet the requirements of DOE O 414.1D or ASME NQA-1.

[21] These calculations (e.g., spreadsheets) also are subject to 10 CFR Part 830 Subpart A quality assurance requirements if the DSA relies on them. One of these requirements is that the technical reviewer have no active involvement in the development of the calculation.

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4 EVALUATION OF EFFECTS OF MAJOR ACCIDENT TYPES

4.1 INTRODUCTION

This chapter describes methods for developing information on accident progression and the effect of the accident on radioactive and hazardous material and SSCs. The following types of accidents will be considered in separate subsections:

- Fires (Section 4.2);
- Explosions (Section 4.3);
- Loss of confinement/spills (Section 4.4);
- Chemical reactions (Section 4.5);
- NPH events (Section 4.6); and
- Man-made external events (Section 4.7).

The information developed in these analyses, in conjunction with data and information in DOE-HDBK-3010-94, is used to determine the source term, which will be addressed in Chapter 5 of this Handbook. This information will provide the basis for:

- Identifying physical insults and stresses associated with the scenario that can impact SSCs and hazardous material;
- Establishing the MAR and DR for the scenario;
- Establishing the ARFs and RFs for the scenario;[22]
- Providing insights to establish an LPF for a mitigated analysis; and
- Determining release effects on the atmospheric dispersion analysis (such as buoyancy from energy of the release).

This information also assists in evaluating the effectiveness of the control set chosen to prevent or mitigate the accident as described in Chapter 2, *Hazard Analysis*, to determine whether the control can be credited to provide the safety function under the accident conditions. Regarding the methods, models, and input data presented in this chapter:

- There may be additional models available other than those presented;
- Other models may be more appropriate to use for certain conditions;
- Viability and applicability of a model should be evaluated by the analyst before using; and
- Use of the model needs to be justified in the accident analysis write-up.

[22] The convention “ARF/RF” is used throughout this Handbook. This term is adopted from DOE-HDBK-3010-94. The term represents the pair of recommended bounding values that are multiplied together to determine the airborne source term, and does not represent dividing the ARF by the RF.

4.1.1 INFORMATION FROM ACCIDENT ANALYSIS TO INCLUDE IN THE DSA

DOE-STD-3009 specifies the format and content of the accident analysis information to be presented in the DSA. Regarding the effects of accidents, Section 3.4.2 of the DSA should contain:

- For each operational DBA or EBA, a description of the unmitigated and mitigated scenarios, sufficiently documented to reveal the thought process used for the analysis. This description should include: (a) the initiating event and progression of the accident; (b) the amount of material release and magnitude of the energy release; (c) the physical conditions (such as temperature or pressure) relevant to accident progression; and (d) effects on SSCs and MAR.

- For each DBA or EBA caused by an NPH, a description of: (a) the unmitigated consequence assessment utilized to determine the NDC; (b) the return period of the resulting design basis NPH event; and (c) the magnitude of the design basis event.

- For each external-event DBA or EBA, a description of the external event likelihood along with its technical basis.

Taking fire events as an example, the DSA should qualitatively summarize the fire initiator, describe the event progression from fire initiation, to fire growth (including flashover if possible) through extinguishment without external intervention (such as fire suppression system or fire department response) for the unmitigated analysis, describe expected damages to SSCs, and ultimately define the impacts on the radiological or hazardous chemical MAR, including estimates of ARF, RF, and DRs. All important assumptions should be identified. Reference should be made to the engineering calculations that include the details of the analysis.

For all events (operational, NPH, and external man-made), the impact of the events on SSCs and their ability to function should be included. In such cases, this subsection should reference the analysis or facility documentation, summarize relevant assumptions, and discuss the degree of conservatism in the evaluation. For example, the fire accident summary in the DSA should provide the key inputs and assumptions used in the analysis, such as combustible loading assumptions, facility fire hazard analysis conclusions on adequacy of fire barriers, and physical design features such as rated barriers. Of particular importance are those assumptions that, if not protected by a TSR, would potentially increase the severity or impact of scenarios.

4.2 FIRE SCENARIO ANALYSIS

Quantitative analysis of fires may range from relatively simple to very complex calculations, depending on the fire hazards, facility design and features, and a variety of other considerations. The simple evaluations apply the five-factor source term formula from Chapter 5 along with dispersion and consequence analysis described in Chapters 6, 7, 8, or 9. More complex fire analyses include application of fire models, such as computer codes or hand calculations as presented in this section to determine the magnitude of the fire and its damage potential, to provide input to in-facility transport modeling, and/or buoyant plume modeling.

The majority of fires analyzed for the DSA are referred to as *compartment fires* (i.e., fires in enclosed spaces such as gloveboxes or process rooms). However, fires may also occur outside the facility's confinement features.[23] Knowledge of the effect of the fire on radioactive material or hazardous chemicals and SSCs response to fires will be useful in determining the source term (MAR, DR, ARF/RF,

[23] Examples: loading dock with doors open, outside staged waste containers, or wildfire.

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LPF) and whether the release may be a lofted plume due to buoyancy from the sensible heat of the fire. Maximizing heat rates is not always conservative when plume rise is taken into account due to increased lofting associated with higher heat plumes.

The fire phenomena also affects evaluation of the effectiveness of the control set and evaluation of fire effects on safety SSCs, for example, heat, smoke, and water impingement.

This section presents summary information needed to understand and evaluate the progression and severity of fire events. The following subsections describe the phenomenology of fire initiation, growth, and propagation. Analytical solutions are based on empirical correlations that have been shown to provide reasonable engineering predictions. References to publicly available methodology guides, manuals, standards, or codes are provided where applicable.

4.2.1 FIRE SCENARIOS

The DSA fire assessment should be performed in coordination with a designated fire protection engineer. Credible fire scenarios evaluated in the DSA hazard evaluation and the accident analysis should be consistent with the Fire Hazard Analysis (FHA) (See Section 4.2.2).

For all DBA/EBA scenarios, it is a best practice to include all details that have an effect on the analysis. These details may include room dimensions, contents, and materials of construction; combustible loading; arrangement of rooms in the building; sources of combustion air; position of doors and airlocks; and numbers, locations, and characteristics of occupants. All assumptions that may have a significant effect on the analysis should be listed. Details of the analysis are either presented in the DSA, or are documented in the FHA or in a supporting calculation that is then summarized and referenced in the DSA.

Typically, fire scenarios selected for analysis will include those which can result in significant release of radioactive material affecting workers or the public. Scenarios that result in similar consequences and controls (preventive and mitigative) may be analyzed as a group using the most limiting/severe conditions for that group. Fires can be further categorized as to the location and/or MAR involved in order to develop representative events to address the nature of fire hazards within a glovebox, within the facility areas serviced by the confinement ventilation, and external to facilities serviced by the confinement ventilation system.

The selected fire scenarios should consider:

- Configuration of the fire area and characteristics of the associated fire barriers;
- MAR quantities that could be involved in an accident;
- Presence, location and type of ignition sources;
- Combustible loading; and
- Specific hazards that necessitate unique controls to prevent or mitigate a fire accident.[24]

Application of these considerations should be documented and evaluated for the need to protect any assumptions as applicable. For example, an ignition source is generally assumed to exist; deviation from this accepted approach would require sufficient justification. Combustible loading is another area that requires significant attention to the assumptions made. Combustible loading assumptions should remain physically meaningful with respect to the facility operations while also being significantly conservative. It

[24] Materials of construction that are radioactive (considered as MAR) and are involved in the fire, and the chemical form of the radioactive material as different materials with separate chemical forms, may have a different ARF and RF.

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may not be appropriate, for example, to assume a large fuel spill near a glovebox line where vehicles cannot access but considerable ordinary combustible inventory may be possible in off-normal conditions such as recovery from a contamination event or construction activities. Where a fire scenario is particularly sensitive to the assumed combustible loading, a credited control is typically appropriate.

Scenarios that are analyzed as a group should be evaluated to ensure that the control set is effective for all scenarios in that group. For example, if a fire suppression system is a control for a group of scenarios, the fire suppression system needs to be evaluated to ensure that the system will actuate under all the scenarios.

4.2.2 FIRE ANALYSIS

Fires have four stages or distinct regimes: (1) ignition, (2) growth, (3) fully developed, and (4) decay. Ignition can occur when flammable vapors are present in sufficient quantity to be ignited. Vapors may result from release of a flammable gas, spillage of a flammable liquid, or the heating of a combustible liquid or solid material (i.e., pyrolysis). Following ignition of the initial fuel source, neighboring materials can be heated through direct flame impingement and/or heat transfer, causing propagation and overall growth of the fire.

A fire can become fully developed when it reaches either a fuel-limited or a ventilation-limited state. Scenarios, such as an outdoor pool fire, reach a fuel-limited state when the entire surface area becomes involved and sufficient oxidant, usually air, is available for combustion. Ventilation-limited fires occur in enclosures where sufficient openings and/or supply air are not available to provide enough air for combustion. A fire can remain in a fully-developed state until all available combustibles are burned or intervention takes place (e.g., fire-fighting response). Intervention of the fire can result in extinguishment or control. Figure 4-1 shows a conceptual model of the four fire regimes of fire growth without intervention as a function of Heat Release Rate (HRR) and time as presented in the fire science literature. That figure also conceptually shows the effects of intervention to extinguish or control the fire.

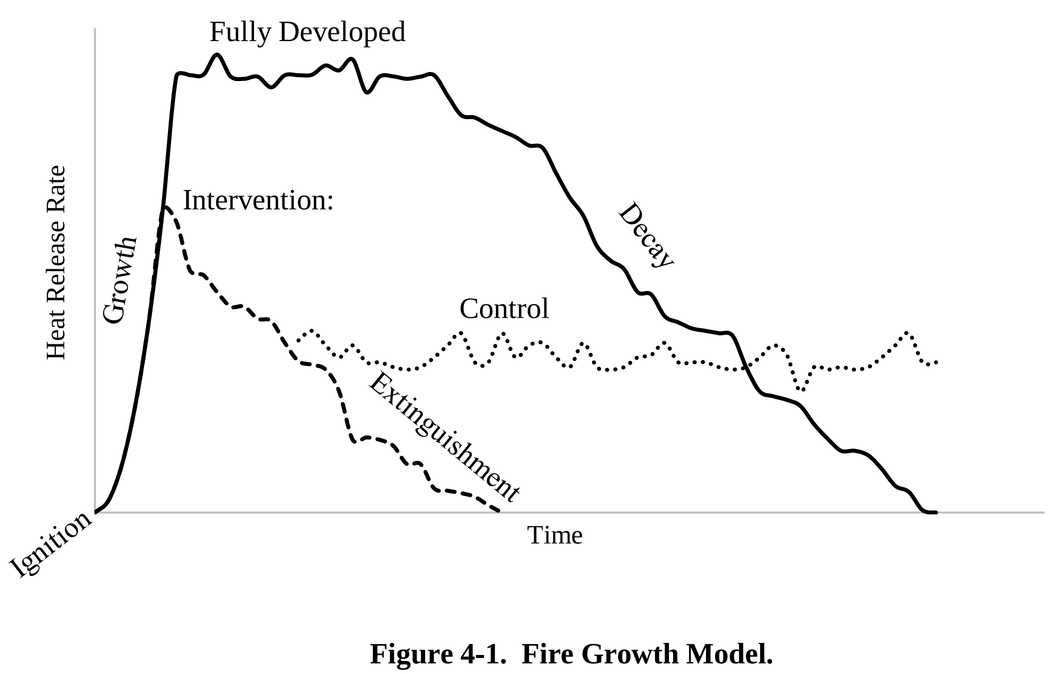

Figure 4-1. Fire Growth Model.

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The facility FHA should serve as the basic input to the DSA fire scenario development and any fire analysis performed to support the DSA. As directed by DOE O 420.1C, Chg. 1, *Facility Safety*, the FHA "… must be integrated into safety basis documentation." Integration of the FHA and DSA can be achieved through various approaches with the primary objective being the consistency of similar fire analyses, credited controls, and conclusions.

In general, the FHA will describe and assess various postulated fires with primary quantitative focus placed on the maximum possible fire loss, the maximum credible fire loss, and the fires selected as DBA/EBAs for the DSA.[25] Additional analysis beyond that performed in the FHA may be necessary to serve the purpose of evaluating the effect on MAR, equipment, structures, and safety SSCs. Input to DBA/EBAs taken from the FHA should be reviewed closely to ensure consistency with DSA principles (e.g., use of unmitigated scenarios) and for assumptions requiring protection.

It is beneficial to have the assumptions, analytical methods, and conclusions be closely related when these fires are described and analyzed in both the FHA and the fire analysis document supporting the DSA. Execution of the integration between the FHA and DSA has been continually improving in the DOE complex for many years. Detailed discussion of important concepts, approaches, and recommendations has been developed by the EFCOG/SAWG, *Fire Analysis for DOE Nuclear Facilities* (2008), which further evolved and updated the guidance in Appendix B, White Paper on Fire Hazards Analysis, in DOE-HDBK-1163-2003, *Integration of Multiple Hazard Analysis Requirements and Activities.*

Correlations based on experiments and testing for numerous phenomena related to fire have been developed and have been proven to be reasonable estimates for modeling and analysis. Much of these can be applied as hand calculations. The following introduces some basic calculation methods commonly used for accident analysis. In addition to governmental resources such as the U.S. National Institute of Standards and Technology (NIST) and the NRC, the Society of Fire Protection Engineers (SFPE) and National Fire Protection Association (NFPA) also provide numerous publications detailing quantitative fire analysis methodologies.

Extensive analysis techniques are documented and available in various NFPA standards, in the NFPA's *Fire Protection Handbook* (NFPA, 2008), in the SFPE's *Handbook of Fire Protection Engineering* (SPFE, 2008), and in other fire protection engineering references. Another useful reference document is NRC's NUREG-1805, *Fire Dynamics Tools (FDT^s): Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program.* FDT^s was developed using state-of-the-art fire dynamics equations and correlations, many of which were derived from the principles presented in the SFPE and NFPA handbooks and other fire science literature. The hand calculations that follow are primarily from NUREG-1805. In addition, there are spreadsheets associated with NUREG-1805, available for download from the NRC (http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/), that allow the user to input heat, diameter and fuel type, and the spreadsheet performs the calculation and provides a text listing of the equation being solved.[26]

The level of detail in the fire analyses should be performed using a graded approach, depending on the potential consequences of the DBA/EBA fire event. DBA/EBAs that do not challenge established thresholds generally do not require exhaustive analysis for a scoping assessment, and the level of detail for DBA/EBAs that greatly exceed the consequence thresholds of concern would have much greater

[25] The maximum possible fire loss and maximum credible fire loss scenarios are evaluated to meet fire protection program requirements based on other considerations such as property damage and economic loss, and may not be the bounding scenarios for release of radioactive or hazardous materials for the DSA evaluations.

[26] Applications of these spreadsheets and any other fire codes are subject to the DOE SQA requirements as discussed in Section 3.5 of this Handbook.

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expectations.

4.2.2.1 EXAMPLE ANALYTICAL METHODS

The following presents information to assist in understanding and evaluating the progression and severity of fire events. The analytical methods presented focus on simple fire phenomena that can be analyzed with a hand calculation. Multiple methods of calculation for fire dynamics phenomena may be available, each with varying applicability for specific scenarios. Understanding the limitations, uncertainties, and background of the chosen analytical method is essential to ensure proper application. The analyst should refer to NUREG-1805, the SFPE and NFPA handbooks, or other applicable fire science references for specific applications.

Complex models involving multiple rooms and openings or the need to understand detailed heat transfer characteristics can be more effectively modeled using computer-based analysis. The Consolidated Model of Fire and Smoke Transport (CFAST) Versions 3.1.7 and 5.1.1 is a Central Registry Toolbox Code approved by DOE for use in safety basis and FHA development. Further guidance on CFAST can be found in DOE-EH-4.2.1.4, *CFAST Computer Code Application Guidance for Documented Safety Analysis*. Another available code is Fire Dynamics Simulator, a computational fluid dynamics model of fire-driven fluid flow managed by NIST.

4.2.2.1.1 HEAT RELEASE RATE

In order to evaluate a fire scenario, the combustible loading and configuration need to be established (see Section 4.2.1 for additional guidance on initial conditions). It is usually necessary to first understand the unmitigated fire potential in terms of HRR. The two examples that follow detail common methods for determining the potential HRR for a fire involving liquids and solids. To determine the maximum potential HRR, the fires are assumed to be fuel-limited with adequate oxygen to support full involvement of the fuel. Note that this assumption will produce higher mass-loss rates, and thus shorter durations, than a ventilation-limited fire.

4.2.2.1.2 POOL FIRE HEAT RELEASE RATE

Liquid pool fires can occur following a spill or leak of flammable or combustible liquid. Common scenarios include:

- A confined spill into a diked area or sump followed by ignition;
- An unconfined spill onto a hard surface followed by ignition;
- An unconfined spill onto a permeable surface such as loose soil followed by ignition; and
- A flowing spill that is ignited.

Methods to establish the HRR for these scenarios are described in the SFPE Handbook. Contained spills are covered in the SPFE Handbook Section 3, Chapter 1, Heat Release Rates, and in NUREG-1805 Chapter 3, Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration, and Flame Height. Both of these references were used for the example provided below. The other three scenarios listed above are described in the SFPE Handbook Section 2, Chapter 15, “Liquid Fuel Fires.”

Typically, pool fires are assumed to be circular. It is common practice to estimate arbitrarily shaped fires using an equivalent area circle (see NUREG-1805, Section 5.3.1). Highly elongated shapes are not applicable to the methods described below (SFPE, 2008).

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Example: A 100 gal (0.38 m^3) kerosene spill, which is contained by a 3 m by 5 m diked area, is ignited. The objective is to estimate the HRR from the burning pool. Because the diked area is rectangular, an effective pool diameter needs to be estimated.

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(3m)(5m)}{\pi}} = 4.4m$$ **Equation 4-1**

Where:

D_{eff} effective pool diameter (m)

A pool fire area (m^2)

The HRR for a pool fire burning in still open air, is estimated using (from SFPE 2008):

$$\dot{Q} = \Delta h_c \dot{m}''_{\infty}\left(1 - e^{-k\beta Deff}\right) \times A$$ **Equation 4-2**

Where:

$\dot{Q}$ HRR (MW)

Δh_c net heat of combustion (MJ/kg)

$\dot{m}''_{\infty}$ mass loss rate per unit area (kg m^{-2} s^{-1})

$k\beta$ extinction absorption coefficient and beam length correction (m^{-1})

For kerosene, Equation 4-2 becomes:

$$\dot{Q} = \left(\frac{43.7MJ}{kg}\right)\left(\frac{0.039kg}{m^2 s}\right)\left(1 - e^{-(3.5m^{-1})(4.4m)}\right)[(3m)(5m)] = 25.6MW$$ **Equation 4-3**

For a uniform pool depth, the approximate burn duration for the fire is (SFPE, 2008)[27]:

$$t = \frac{\rho V}{\dot{m}''_{\infty}(1-e^{-k\beta D}) \times A}$$ **Equation 4-4**

Where:

t fire duration (s)

ρ liquid density (kg/m^3)

V spill volume (m^3)

[27] NUREG-1805, Section 3.3.1 provides another equation for the burning duration as {V / [A * regression rate]} or {(ρV) / [A * $\dot{Q}$ per unit area]}.

For the postulated 100 gal spill, the fire duration from Equation 4-4 is:

$$\boldsymbol{t = \frac{\left(820\frac{kg}{m^3}\right)(0.38m^3)}{\left(0.039\frac{kg}{m^2 s}\right)\left(1-e^{-\left(3.5\frac{1}{m}\right)(4.4m)}\right)[(3m)(5m)]} = 533\,sec = 8.9min} \qquad \textbf{Equation 4-5}$$

Note that this analytical method is limited to pool fires with diameters between 0.2 m and 50 m (SFPE, 2008).

4.2.2.1.3 PALLET FIRE HEAT RELEASE RATE

Wooden pallets are common in many facilities and can produce a high HRR. NUREG-1805, Table 2-8 provides HRR per unit area for various heights of stacked pallets, while SFPE Handbook Section 3, Chapter 1 provides a correlation to estimate the HRR from a stack of wood pallets based on height.

Example: For a 5 ft high pallet stack with a nominal area of 4 ft x 4 ft (1.2m x 1.2m), referencing NUREG-1805, Table 2-8, the HRR per unit area is 3,970 kW/m^2. The total HRR would be:

$$\boldsymbol{\dot{Q} = A\,\dot{Q}'' = (1.2m)^2\left(3,970\,\frac{kW}{m^2}\right) = 5,717kW = 5.7M} \qquad \textbf{Equation 4-6}$$

4.2.2.1.4 FLAME HEIGHT

Determination of a fire's flame height can be helpful in order to estimate the likelihood of further propagation or structural impacts. Flame height at sea level of a fire may be predicted using Equation 4-6, based on the 1995 Heskestad method (NUREG-1805 Section 3.4, Flame Height [which also includes the 1962 Thomas method], SFPE 2008). Flame height corrections at elevations significantly above sea level can be found in Section 2, Chapter 1 of the SFPE Handbook. Equation 4-7 represents the height of the flames above the base of the fire and is based on empirical test data.

$$H = 0.235\,\dot{Q}^{2/5} - 1.02D \qquad \textbf{Equation 4-7}$$

Where:

H	flame height above base of fire (m)
$\dot{Q}$	HRR (kW)
D	flame diameter (m), i.e., the diameter of the burning area as described in NUREG-1805.

<u>Example</u>: This equation can be applied to fires reasonably approximated by a circle. For this example, the flame height for the pallet fire discussed in Section 4.2.2.1.2 will be found (5 ft stack of 4x4 ft pallets).

The effective diameter from Equation 4-1 is:

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(1.2m)(1.2m)}{\pi}} = 1.4m \qquad \textbf{Equation 4-8}$$

The flame height from Equation 4-7 is:

$$H = 0.235(3{,}010\ kW)^{2/5} - 1.02(1.4m) = 4.4m \qquad \textbf{Equation 4-9}$$

4.2.2.1.5 ENCLOSURE FIRE DYNAMICS

Fires within an enclosure, such as a glovebox or a room in a building, exhibit distinct behavior that differs from well-ventilated fires. There are two primary differences when considering an enclosure fire: (1) interaction with the enclosure boundary; and (2) the development of an upper layer (hot, gaseous products) of the fire that collect in the compartment. In both cases, the enclosure boundary and the upper layer have the ability to reflect and radiate heat within the enclosure. Heat and mass transfer effects out of the boundary may also affect the behavior of the fire.

Flashover is a phenomenon of importance when analyzing enclosure fires. Flashover is “the rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure” (ASTM E176). The occurrence of flashover is dependent on many variables such as available vent area, heat transfer from the enclosure boundary, and HRR of the fire. Flashover occurs when the temperature of the enclosure, with consideration given to the radiative effects of the upper layer, is sufficient to effectively ignite all combustibles in the enclosure. Upon transition to flashover, the fire is in a ventilation-limited state.

4.2.2.1.5.1 PRE-FLASHOVER

Pre-flashover room temperatures can be estimated for simple geometries using energy balance techniques. NUREG-1805, Section 2.6 and the SFPE Fire Protection Handbook, Section 3, Chapter 6 (SFPE, 2008) describes methods that can be applied to

- Small to medium size room with natural ventilation such as a single open door or window; or
- Small to medium size room with forced ventilation.

The following analytical method predicts the temperature of the upper layer as a function of HRR. This methodology can be used to estimate the onset of flashover and can also be used as input to sprinkler or heat detector activation. This method is primarily applicable to thin walled, ventilated enclosures with high heat conductive boundaries.

Example: Room Fire with Forced Ventilation. A 500 kW fire occurs in a ventilated steel box. The box is 2.4 m wide, 6.0 m long, and 2.3 m high with 16 mm thick walls. The ventilation flow rate is 1,000 cfm (0.57 kg/s for air at standard temperature and pressure). Predict the upper layer temperature at 5.0 minutes.

The upper layer temperature is (Section 2.64.4 of SFPE, 2008):

$$\boldsymbol{T_g = \frac{\dot{Q}}{\dot{m}_g c_p + h_k A_T} + T_\infty} \qquad \textbf{Equation 4-10}$$

Where:

T_g	upper layer gas temperature (°K)
T_∞	ambient air temperature (°K)
$\dot{Q}$	HRR of the fire (kW)
$\dot{m}_g$	ventilation mass flow (kg/s)
c_p	specific heat of air (kJ/kg °K)
h_k	effective heat transfer coefficient (kW/m^2 °K)
A_T	compartment surface area (m^2)

The compartment surface area is:

$$A_T = 2(2.3m)[(6.0m) + (2.4m)] + 2(6.0m)(2.4m) = 67m^2$$ **Equation 4-11**

The effective heat transfer coefficient for a thin-walled compartment will range from 0.012 to 0.03 kW/m^2·K, calculated from the following (SFPE, 2008):

$$\boldsymbol{h_k = 30 - 18\left[1 - e^{\left(-\frac{50t}{p\delta c}\right)}\right]}$$ **Equation 4-12**

Where:

h_k	heat transfer coefficient [W/m^2 °K]
t	exposure time (s)
ρ	compartment boundary density (kg/m^3)
δ	compartment boundary thickness (m)
c	specific heat of compartment boundary (J/kg °K)

Using commonly available material properties for steel, at 5 minutes (300 seconds) the effective heat transfer coefficient is:

$$h_k = 30 - 18\left[1 - e^{\left(-\frac{\left(50\frac{W}{m^2{}^\circ K}\right)(300s)}{\left(7833\frac{kg}{m^3}\right)(0.0016m)\left(465\frac{J}{kg\,{}^\circ K}\right)}\right)}\right] = 13.4\ \frac{W}{m^2{}^\circ K}$$ **Equation 4-13**

The upper layer temperature is:

$$T_g = \frac{500kW}{\left(0.57\frac{kg}{s}\right)\left(1.01\frac{kJ}{kg\,{}^\circ K}\right) + \left(0.0134\frac{kW}{m^2\,{}^\circ K}\right)(67m^2)} + 293^\circ K = 623^\circ K = 360^\circ C$$ **Equation 4-14**

4.2.2.1.5.2 FLASHOVER

Upper layer temperatures, such as those found using methods discussed above, can be used to predict flashover. Upper layer temperatures of 500°C to 600°C are widely considered to be associated with the onset of flashover (NUREG-1805, SFPE 2008, NFPA 2008). More rigorous flashover prediction can be performed using methods from NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, or NUREG-1805 Chapter 13, which applies different correlations.

A common screening criterion for predicting flashover in a compartment with a single vent opening is detailed in the example below, based on the Thomas method (NUREG-1805 Chapter 13, SFPE 2008 Section 3 Chapter 6, NFPA 555) using the empirical formula presented in Equation 4-15. This example estimates the HRR necessary to achieve flashover; this can be compared to the HRR for the postulated fire as found using methods such as those presented in 4.2.2.1.

<u>Example:</u> Estimate the HRR required to cause flashover in a room 2.4 m deep, 6.0 m long, and 2.3 m high. The door is 2.36 m high and 1.19 m wide.

$$\dot{Q} = 7.8A_{room} + 378A_{vent}\sqrt{H_{vent}}$$ **Equation 4-15**

Where:

$\dot{Q}$	HRR required for flashover (kW)
A_{room}	total area of walls, floor, and ceiling, less the vent area (m^2)
A_{vent}	total vent area (m^2)
H_{vent}	height of vent (m)

The vent area associated with the door would be:

$$\boldsymbol{A_{vent} = (2.36m)(1.19m) = 2.81m^2}$$ **Equation 4-16**

The surface area of the compartment would be:

$$\boldsymbol{A_T = 2(6.0m)(2.4m) + (2.3m)[2(6.0m) + 2(2.4m)] - (2.81m^2) = 64.6m^2}$$ **Equation 4-17**

The HRR needed to create flashover with the door fully open is:

$$\boldsymbol{\dot{Q} = 7.8\left(64.6m^2\right) + 378\left(2.81m^2\right)\sqrt{(2.36m)} = 2,100kW}$$ **Equation 4-18**

4.2.2.1.6 SOLID FUEL IGNITION AND RADIANT HEATING

Describing the progression of a postulated fire requires analysis of potential propagation. Specifically, co-located combustible materials can be ignited by a fire. Determining if these combustibles will ignite in a given fire or determining the minimum separation distance to prevent ignition is an important consideration.

There are two basic ignition metrics: (1) heat flux; and (2) surface temperature. Both metrics may be used, but heat flux is the more common method to predict solid fuel ignition. There are multiple test methods be used to measure ignition heat flux. Results will vary with the test method. In general ignition heat fluxes will be lower for piloted tests than for autoignition tests (i.e., piloted tests include a flame or spark; autoignition tests do not). Ignition heat fluxes will also vary with the duration of the exposure. Lower fluxes require longer exposures to cause ignition. A commonly accepted default ignition heat flux used for cellulosic materials is 12.5 kW/m^2. For additional ignition flux data, see the *Ignition Handbook* (Babrauskas, 2003).

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One methodology to estimate the heat flux imposed on a target is based on Beyler's 2002 equation as presented in NFPA 555, SFPE 2008, and NUREG-1805 (Section 5.3.2 Solid Flame Radiation Model with Target At and Above Ground Level):

$$\dot{q}'' = F_{f-t}E_f \qquad \textbf{Equation 4-19}$$

Where:

$\dot{q}''$	heat flux at the target fuel package (kW/m^2)
F_{f-t}	view factor between the flames and a differential area on the target fuel package (dimensionless)
E_f	emissive power of the flames (kW/m^2)

When using the fire flame height estimation in Equation 4-7, the corresponding emissive power correlation is based on the Shokri and Beyler 1989 empirical correlation from experimental data as presented in NFPA 555, SFPE 2008, and NUREG-1805 Section 5.3.2:

$$E_f = 58(10^{-0.00823D}) \qquad \textbf{Equation 4-20}$$

Where:

E_f	emissive power of the fire (kW/m^2)
D	fire diameter (m)

Figure 4-2 shows the view factor for a differential planar element (dA_1) of an object at a specified distance (h) to a finite-length right circular cylinder, where the normal to the element passes through the one end of the cylinder and is perpendicular to the cylinder axis. The view factor (F) is calculated using the following equation (Siegel & Howell, 1992; NUREG-1805 Section 5.3.2.2, Configuration Factor F_{1-2} under Wind-Free Conditions, has different view factor equations from Beyler in 2002 for vertical and horizontal targets at ground level and above ground level):

$$F = \frac{1}{\pi H}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{L}{\pi}\left(\frac{(X-2H)}{H\sqrt{HY}}\right)\tan^{-1}\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right) - \frac{1}{H}\tan^{-1}\left(\sqrt{\frac{(H-1)}{(H+1)}}\right) \qquad \textbf{Equation 4-21}$$

Where:

F	view factor (dimensionless)
h	distance from the object to the centerline of the cylinder (m)
l	height of the cylinder (m)
r	radius of the cylinder (m)
H	distance from the object to cylinder radius ratio (h/r) (dimensionless)
L	cylinder height to radius ratio (l/r) (dimensionless)
X	$(1+H)^2+L^2$ (dimensionless)
Y	$(1-H)^2+L^2$ (dimensionless)

Since the above solution is for a right circular cylinder with the differential area at the base of the cylinder (i.e., fire), to obtain the peak heat flux, which occurs at the mid-height of the cylinder, the actual view factor is twice the value calculated using Equation 4-21, if the cylinder height is taken as half the fire height.

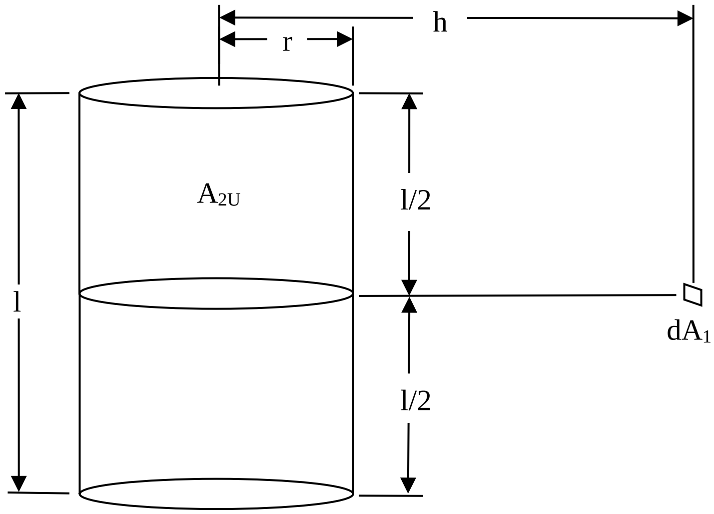

Figure 4-2. Adaptation of View Factor Geometry for a Fire Model.

Example: For a 2 MW fire with a base diameter of 1.2 meters, estimate the heat flux 0.5 meters from the fire at the mid-height of the flames.

The emissive power from Equation 4-20 would be:

$$\boldsymbol{E_f = 58\left(10^{-0.00823D}\right) = 57\,\frac{kW}{m^2}}$$ **Equation 4-22**

From Equation 4-7 the flame height would be:

$$\boldsymbol{H = 0.235\,(2{,}000kW)^{2/5} - 1.02(1.2m) = 3.69m}$$ **Equation 4-23**

The view factor for a fire to object separation of 0.5 m is presented below:

l = 3.69 m/2 m=1.845 m

r = 1.2 m/2 m=0.6 m

h =0.5 m + 0.6 m = 1.1 m

H = h/r = 1.1 m/0.6 m = 1.833 m

L = l/r = 1.845 m/0.6 m = 3.075 m

X = $(1+H)^2+L^2 = (1+1.833)^2+(3.075)^2 = 17.48$

Y = $(1-H)^2+ L^2 = (1-1.833)^2+(3.075)^2 = 10.15$

$$\boldsymbol{F} = \frac{\boldsymbol{tan^{-1}}\left(\frac{\boldsymbol{3.075}}{\sqrt{(\boldsymbol{1.833})^{2}-\boldsymbol{1}}}\right)}{\boldsymbol{\pi}(\boldsymbol{1.833})} + \frac{\boldsymbol{3.075}}{\boldsymbol{\pi}}\left(\frac{((\boldsymbol{17.48})-\boldsymbol{2}(\boldsymbol{1.833}))}{(\boldsymbol{1.833})\sqrt{\boldsymbol{17.48}(\boldsymbol{10.15})}}\right)\ \boldsymbol{tan^{-1}}\left(\sqrt{\frac{(\boldsymbol{17.48})((\boldsymbol{1.833})-\boldsymbol{1})}{(\boldsymbol{10.15})((\boldsymbol{1.833})+\boldsymbol{1})}}\right) - \frac{\boldsymbol{tan^{-1}}\left(\sqrt{\frac{((\boldsymbol{1.833})-\boldsymbol{1})}{((\boldsymbol{1.833})+\boldsymbol{1})}}\right)}{\boldsymbol{1.833}} = \boldsymbol{0.26}$$

As discussed previously this view factor is for a half-cylinder. The effective view factor is thus twice this value, or 0.52. The heat flux would thus be:

$$\dot{\boldsymbol{q}}'' = (\boldsymbol{0.52})\left(\boldsymbol{57}\frac{\boldsymbol{kW}}{\boldsymbol{m^2}}\right) = \boldsymbol{30}\frac{\boldsymbol{kW}}{\boldsymbol{m^2}}$$ **Equation 4-24**

Note that when using this method, the SFPE Handbook Section 3, Chapter 10, recommends a safety factor of 2 for heat fluxes in excess of 5 kW/m^2. Application of this safety factor would, thus, increase the prediction of heat flux in Equation 4-24 to 60 kW/m^2. Additionally, this methodology is based on data of pool fires; NFPA 555 endorses the use of this methodology when considering fuel packages but care should be taken when considering the flame height and emissive power of the postulated fire. It should be noted that applying the NUREG-1805 methodology does not include this doubling factor as it sums the horizontal and vertical view factors.

4.2.3 SOURCE TERM CALCULATION FOR FIRE SCENARIOS

DOE-HDBK-3010-94 (page 1-11) describes how a fire can cause an airborne release as follows:

> [Fire] generates heat and combustion gases that may destroy/stress the radioactive material and/or the substrate upon which radioactive materials may be deposited, compromise barriers, and/or pressurize containers/enclosure that may lead to the airborne release of contained radioactive materials. Mass flux of vapors from the reacting surfaces suspend material in air. This material is then entrained in general convective currents that provide transport for particulate materials.

The following discusses the effect of a fire on radiological and hazardous material in terms of parameters important to the source term calculations, thermal effects on SSCs, and smoke damage.

4.2.3.1 EFFECT ON HAZARDOUS MATERIAL

4.2.3.1.1 DETERMINING MAR FOR THE FIRE EVENT

One of the principal outputs of fire analysis is the determination of the affected MAR. In addition, the fire analysis provides information used in conjunction with DOE-HDBK-3010-94 to determine the DR and ARF/RF of the event.

The amount of MAR involved in the event may be the material within the area affected by the fire. For example, the analysis of a small fire within a glovebox that is shown to not propagate beyond the enclosure would consider only the MAR within the glovebox. For large fires, all hazardous material in areas potentially affected by the thermal energy or structural impacts of the fire should be included in the MAR. Therefore, establishing the boundary of the fire's impact area, for example, a rated fire barrier, is important when specifying each component of the MAR.

The determination of a bounding MAR that may be involved in a fire may need to include MAR in adjacent structures. Spatial separation between buildings is evaluated in the FHA and usually evaluated using NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*. This code provides information on the role of building type and the impact of distance between buildings on fire propagation. FM 1-20, *Protection Against Exterior Fire Exposure* (2016), may also be consulted. NFPA 80A separation values assume that fire department response will be timely. If an unmitigated separation evaluation is necessary, NFPA 80A recommends that the separation value be increased by a factor of three.

4.2.3.1.2 DETERMINING DR AND ARF/RF FOR THE FIRE EVENT

As further discussed in Chapter 5, DOE-HDBK-3010-94, states the following important consideration regarding MAR and DR:

> The damage ratio is the fraction of the MAR actually impacted by the accident-generated conditions. A degree of interdependence exists between the definitions of MAR and DR. If it is predetermined that certain types of material would not be affected by a given accident, some analysts will exclude this material from the MAR.

Justification of DRs for a fire scenario is generally a function of the size of the fire and facility configuration, as well as how the MAR is being defined due to its interdependence with the DR (see above MAR discussion and Section 5.2.2, Damage Ratio). For example, MAR for a single glovebox operation is normally associated with a 1.0 DR for a fire inside the glovebox, while MAR for a process area could have lower DRs as determined by the fire analysis. Including DRs <1.0 will require refined analysis to justify that the equipment and containers affected by the fire scenario act to limit interaction with the MAR.

Where test data or other criteria are established, DRs for containers can be based on calculations of heat fluxes to targets, sizes of fuel pool fires, and other factors. (see Section 4.2.2, Fire Analysis Methods). For example, the performance of standard 55 gallon drums in fire conditions have been studied in depth; using analytical methods to determine the fire scenario's interaction with a storage array, in concert with the published testing data, can be used as a basis for a DR < 1.0.

For more comprehensive analyses, CFAST or other fire modeling software, such as Fire Dynamics Stimulator, can be used to model the potential damages from fires. These damage estimates can then be used to assess appropriate DRs (see Section 4.2.2.3).

For TRU waste operations, DOE-STD-5506-2007 provides guidance for selection of DRs associated with fire events based upon the type of metal waste container involved and whether a fuel pool fire or an exposure fire is being evaluated. WCH-SD-SQA-ANAL-501, *Fire Protection Guide for Waste Drum Arrays* (Beyler and Guttok, 1996), is a source of experimental data regarding how waste drum arrays responded to pool fires.

Generally, DRs < 0.01 require extensive justification. Consideration needs to be given to describing scenarios, which attempt to use very small DRs to ensure that the bounding event is being described. If there is the potential for another scenario with a higher DR to occur, the differences between the scenarios needs to be clearly outlined in the DBA/EBA section.

The fire analysis should define the scenario progression adequately in order to determine the DR, and the ARF/RF using DOE-HDBK-3010-94. DOE-HDBK-3010-94 provides data on the ARF/RF for the following types of fire-related stresses affecting radioactive material that generate airborne releases:

- Heating of aqueous solution in flowing air without surface rupture of bubbles.
- Boiling (bubbles continuously breaking the surface of the bulk liquid with <30% of the volume of the liquid as bubbles).
- Volatiles such as iodine, under all conditions.
- Quiescent burning, small surface area pools, or small solvent layer over large aqueous layer burning to self-extinguishment.
- Vigorous burning large pools or solvent layer burning over limited aqueous layer with sufficient turbulence to disrupt bulk of aqueous layer.
- Large, vigorously burning organic fire that burns to complete dryness or burning solvent over aqueous phase burning to complete dryness for both phases (requires external heat source).
- Aqueous solution or air-dried salts under gasoline fire on a porous or otherwise absorbing surface.
- Airborne release of particulates formed by oxidation at elevated temperature, greater than room temperature but less than self-sustained oxidation (ignition).
- Airborne release of particulates formed by self-sustained oxidation.
- Airborne release of particulates during complete oxidation of metal mass.
- Airborne release during free-fall of molten metal drops.
- Plutonium compounds subjected to thermal stress (temperature <1000º C, natural convection).
- Contaminated combustible materials heated/burned in packages.
- Dispersed ash dropped into airstream or forced draft air.

Selection and development of ARF/RF is further discussed in Chapter 5.

4.2.3.2 THERMAL EFFECTS

Another output of the fire analysis is information useful in determining the environmental stressors on SSCs, in particular safety SSCs relied on to mitigate the event.

Failure of structural members can have a major impact on the accident progression; the fire analysis should consider structural members located near postulated fires. The strength and stiffness of structural steel begins to worsen when heated leading to possible deformation and failure. Structural, reinforced concrete also may begin to degrade when subjected to extreme temperatures. Building codes generally provide prescriptive fire ratings for structural members; however, detailed analytical methods can be used for design of critical structural components and should include heat transfer analysis and consideration of steel properties at elevated temperatures (Buchanan, 2001).

Radiant heating, direct flame impingement, and hot gas layers can cause the failure of both passive and active mechanical SSCs. Temperature limits of valves, motors, and sensors should be considered in conjunction with radiant heating models when reviewing effects to SSCs from postulated fires. Radiant heating and hot gas layer temperature models were presented in Section 4.2.2. Although most fire analysis relates to the direct release of hazardous material due to the effect of the fire itself, fire in control systems in adjacent areas could indirectly cause a release of MAR.

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Accordingly, the best practice is to calculate the potential thermal effects of the fire events to determine what SSCs would be available for both the unmitigated and mitigated consequence calculations.

4.2.3.3 SMOKE DAMAGE

The intent of this section is not to look at the effects of smoke on the workers or members of the public, but on equipment integrity. Smoke can damage equipment and render active SSCs either inoperable or behaving in an unpredictable manner. Sensitive electrical components such as programmable logic controllers used in safety-instrumented systems could fail due to smoke conductivity or corrosivity. Circuit bridging has been observed in testing of electrical components subjected to heavy smoke environments (NUREG/CR-7123, *A Literature Review of the Effects of Smoke From a Fire on Electrical Equipment*); consideration may need to be given to the failure state of electronics. Longer-term degradation effects of smoke (days to months) are also important considerations upon restart following a fire.

Smoke can also affect nuclear ventilation system High Efficiency Particulate Air (HEPA) filters causing them to clog. There are two main failure mechanisms for HEPA filter failure from smoke generated by a fire; plugging and blowout/media failure. Plugging occurs when the filter media becomes saturated with particles and prevents adequate airflow. Blowout/media failure occurs when holes or other openings in the media occur and allow particulate matter to pass through the HEPA filter. Both of these mechanisms are important, since they both will create unfiltered leakage paths, which increase the LPF, thus contributing to the amount of released material. The effect of HEPA filter failure needs to be included in assessment of radioactive releases in the FHA and DSA. In the case of plugging, the fire generates hot gases, which pushes smoke and contamination outward in the absence of adequate HEPA filter flows. With HEPA media failure the ventilation system flows are no longer effectively filtered. Filter clogging occurs before blowout/media failure, and therefore, has been used to determine when loss of confinement occurs.

Correlations have been developed by researchers and the fire protection industry and used in FHAs and DSAs to estimate the rate of smoke loadings on HEPA filters; however, there is no one universally accepted model, nor universally accepted criteria recommended for determining when plugging causes loss of confinement or filter blow-through. An example of one model is provided in *Analysis of Filter System Soot Loading for Postulated Fires in the K-Area Complex Container Surveillance and Storage Capability Project (U)* (Sprankle, 2007). Another example of smoke loadings on HEPA filters is in WIPP-058 (Revision 2), *DSA Supporting Calculation, Fuel Spill, HEPA filter Plugging, Fire Compartment Over-Pressurization, Facility Pallet Survivability, Lube Truck Standoff Distance, Waste Array Fire Spread, and Internal Drum Event Fire in CH Bay and Along Waste Transport*.

A good summary of performance of HEPA filters under accident conditions in terms of filter efficiencies and pressure differentials is provided in Appendix F, Filtration, of NUREG/CR-6410. Regarding smoke modeling and confinement ventilation systems, DOE-HDBK-1169-2003, *Nuclear Air Cleaning Handbook*, provides discussions in Sections 10.4 and 10.5. Section 10.4 provides these cautions on the use of modeling:

> Fire models for FHAs range from simple algorithms that predict thermodynamic changes in enclosures to complex programs that can account for heat, mass transfer, and smoke production in multiple enclosures. Many mathematical models have been installed in software codes and are available on the Internet bulletin boards of various government agencies. These codes can predict the development and spread of fire and smoke conditions through multiple rooms, and can account for changes in the structure and composition of enclosures. Application of these models requires considerable understanding of their use and limitations, statements of which are usually included in the instructional

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text published with the software codes. Reduction of complex models to simple terms supported by empirical data is often useful in predicting uncomplicated systems.

4.3 EXPLOSION SCENARIO ANALYSIS

The DSA analyzes explosion scenarios developed from hazardous or upset conditions that challenge the material at risk in non-reactor nuclear facilities involving tanks, pipes, vessels and/or containers, filled with flammable or non-flammable, gases or liquids, pressurized or not. Explosion events are assessed inside or outside the facility. An explosion scenario can arise from a wide spectrum of hazards, operational conditions, and from deviations in the safety requirements in the facility or its production process.

The quantitative analysis of the effects of an explosion on the SSCs establishes the basis to identify safety controls for preventive or mitigative considerations. The explosion scenarios, analyzed for the facility DSA, are used to demonstrate the effectiveness of the control strategy such as the ability of explosion barriers, efficient implementation of hazardous material protection, testing, surveillance and maintenance.

Explosion models using hand calculations are presented in this section to aid in the assessment of the explosion magnitude, and its damage potential, such as blast (overpressures), fragmentation, and thermal damages.

Explosion accidents that have unique dispersion characteristics may be modeled using phenomenon-specific codes more accurately representing the release conditions. Areal Locations of Hazardous Atmospheres (ALOHA) Version 5.4.6 is a chemical consequence code (see Section 9.7) that is capable of calculating consequences for Boiling Liquid Expanding Vapor Explosions (BLEVE), explosions due to delayed ignition and radiant heat from fires resulting from explosions.

The intention of this chapter is to provide basic insights and formulas for the various calculations presented with the expectation that further insight and clarification can be attained by consulting the referenced literature. Subsections 4.3.1 and 4.3.2 describe how an explosion event can be defined and analyzed. Subsection 4.3.3 briefly describes the damages to receptors and SSCs in terms of potential consequences and subsection 4.3.4 presents a brief assessment for the source term estimation for explosion scenarios. A specific case of a hydrogen explosion is presented in subsection 4.3.5.

4.3.1 EXPLOSION EVENT TYPES AND SCENARIOS

Explosions can be defined in a variety of ways. In the textbook *Explosion Hazards and Evaluation* (Baker et al., 1983), one finds the following general definition of an explosion:[28]

> In general, an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time in a sufficiently small volume so as to generate a pressure wave of finite amplitude traveling away from the source. This energy may have originally been stored in the system in a variety of forms; these include nuclear, chemical, electrical or pressure energy, for example. However the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that one can hear. Even though many explosions damage their surroundings, it is not necessary that an explosion produce external damage. All that is necessary is that the explosion is capable of being heard.

[28] This reference is also cited in NUREG/CR-6410 and NUREG-1805.

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NUREG-1805 states that "An explosion is defined as a sudden and violent release of high-pressure gases into the environment" and that "In its most widely accepted sense, the term 'explosion' means a bursting associated with a loud, sharp noise and an expanding pressure front, varying from a supersonic shock wave to a relatively mild wind." The NUREG also offers several other definitions and concepts of an explosion from the literature.

The word "explosion" thus applies to a variety of phenomena that can cause a range of damage from mild to severe. Generally, there are two categories of explosions 1) the result of purely physical phenomena such as the rupture of a high pressure air tank, or 2) as the result of a chemical reaction. Figure 4-3 provides a simplified explosion categorization for likely scenarios at DOE facilities. This section does not addresses natural explosions (lighting, volcanoes, meteors, atmospheric pressure change from tornado or hurricane), intentional explosions (nuclear, high explosives, firearms), dust explosions, runaway reactions, neither does it cover the toxicity and asphyxiation effects (see Chapter 9) as consequence of explosions since these events are subject to more detailed evaluations that are beyond the scope of this handbook.

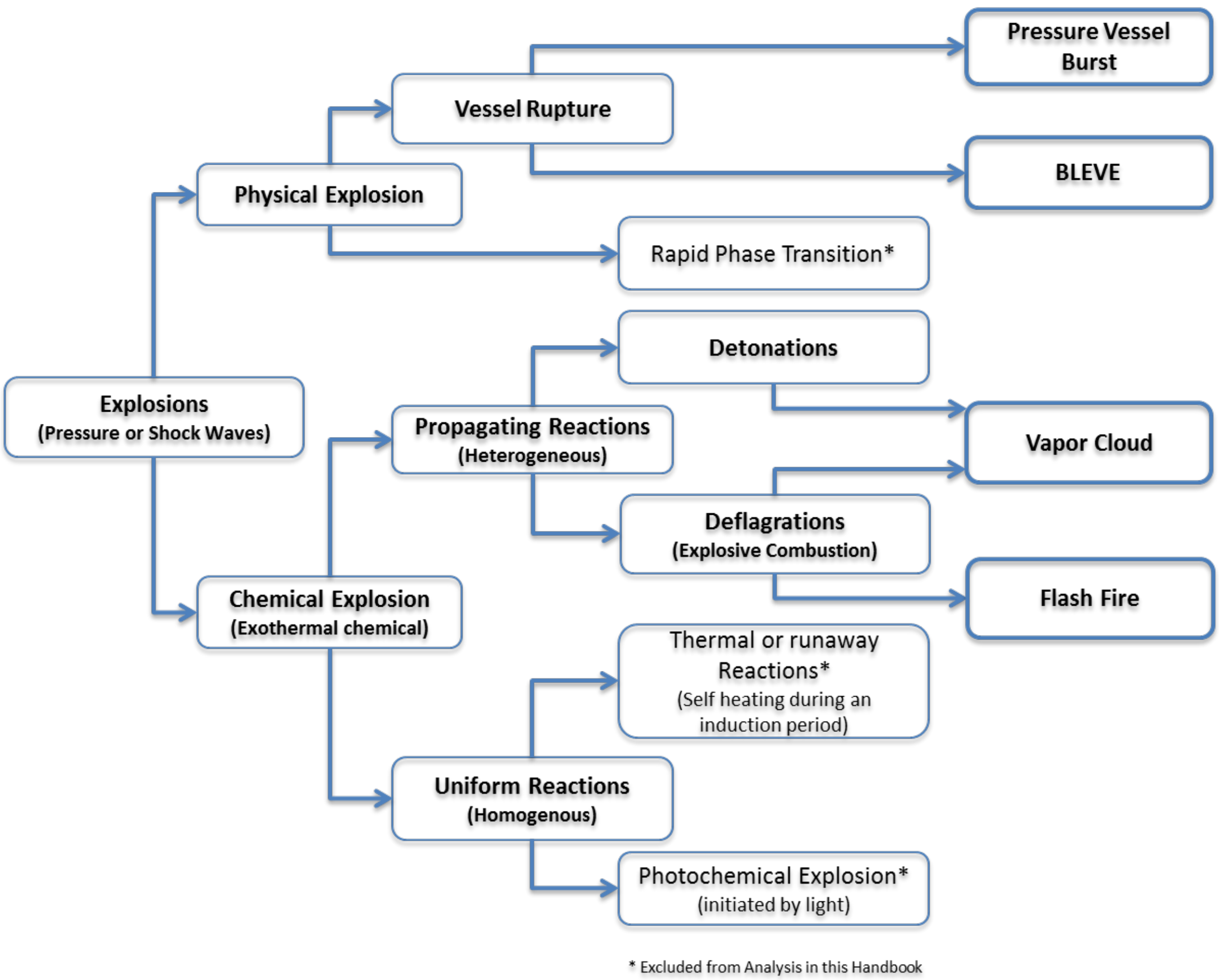

Figure 4-3. Simplified Explosion Categorization.

Special terminology associated with explosions is explained below.

Physical Explosion: Those caused when the high-pressure gas is generated only by mechanical means without any chemical change as in the following types of explosions:

- external heating of a tank resulting in increased internal pressure and resultant failure of the tank; and
- sudden release of super-heated liquid which flash-evaporates, causing a rapid explosion.(NUREG-1805, page 15-2)

Chemical Explosion: Caused when high-pressure gas is generated by a chemical reaction. The generation of high pressure gas is the result of exothermic reactions where the fundamental chemical nature of the fuel is changed. Chemical reactions of the type involved in an explosion usually propagate in a reaction front away from the point of initiation. NFPA 921, *Guide for Fire and Explosion Investigations,* states they "can involve solid combustibles or explosive mixtures of fuel and oxidizer, but more common will be the propagating reactions involving gases, vapors, or dust mixed with air. Such combustion reactions are called propagation reactions because they occur progressively through the reactant (fuel), with a definable flame front separating the reacted and unreacted fuel."

In a confined environment, a hydrogen explosion or other flammable gases released in the waste from the decomposition of water and other organics (via radiolysis, catalytic and other mechanisms) is also considered a chemical explosion. Dissolved hydrogen and small quantities of flammable organics may also be released from the waste. Since the waste tanks have an air atmosphere, quantities of oxygen sufficient to allow an explosion are assumed available. For the purpose of an unmitigated scenario, it is assumed that an ignition source is present." (WSRC-TR-2005-00467)

This type of explosion is commonly considered in the hazard and accident analysis for facilities where radiolysis is a hazard, such as high level waste facilities.

While fragmentation is also a concern, a major consequence of these explosions is the airborne release of the hazardous material that was in the vessel or pipe. Such airborne release can occur even if the vessel does not rupture. (see Section 4.3.5 Case: Source Term Calculation for Hydrogen Explosion) Basic "detonation" and "deflagration" descriptions are provided below:

Detonation: The literature offers several definitions, for example:

- A detonation is a propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance at or greater than sonic velocity in the unreacted material. (*Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs* [CCPS, 1994]).
- "Propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium." (NFPA 68, Definitions).
- In a detonation, the flame or combustion wave propagates through the reactants at supersonic speeds, typically on the order of 2,000 m/sec (6,562 ft/sec). (NUREG-1805, page 15-3).

Deflagration: Again, the literature offers several definitions, for example:

- A propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance rapidly but less than sonic velocity. (CCPS, 1994).
- "Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium." (NFPA 68, Definitions).

- In a deflagration, the rate of propagation is below the speed of sound in air at 20 °C (68 °F), which is approximately 330 m/sec (1,082 ft/sec). (NUREG-1805, page 15-3).

A brief description for each type of explosion, an associated scenario, and an example are provided in Table 4-1.

The DBA/EBA explosion outlined in the facility's DSA may be a single event consisting of any combination of the explosion types as listed in Table 4-1 and Figure 4-3. The DBA/EBA explosion event needs to identify the bounding explosion analyzed and any other explosion phenomena that are considered credible and bounded by the DBA/EBA selection. In the hazard evaluation, each explosion scenario needs to define the physical boundaries and the associated MAR so that the accident analysis can group the events into similar types to determine the appropriate control sets.

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Table 4-1. Types of Explosions Descriptions.

EXPLOSION TYPE	DESCRIPTION	SCENARIOS	EXAMPLES	EFFECTS OF CONCERN
Pressure Vessel Burst	The explosive rupture of a pressure vessel, where the stored energy is released instantaneously, creates a blast wave (i.e., shockwave) in the surrounding air and propels fragments. The shockwave and fragment characteristics depend on vessel contents, pressure, vessel geometry and mode of vessel failure. (Cain, 1996)	An air compressor, during an highly hypothetical event in which all the safety controls fail (relief valves, automatic controls, sensors, instrumentation), continues to run until the internal pressure of the vessel increases and ruptures the vessel. The rupture can occur at a substandard weld, a partial through-wall crack, fatigue from pressurization cycles, and corrosion resulting in wall thinning.	Pressure Vessel Explosion in Houston, TX at the Marcus Oil Facility in December 2004; no fatalities; significant material and structural damages in the neighborhood; Cause: faulty welds in a steel process pressure vessel https://www3.epa.gov/region10/pdf/rmp/cepp_newsletter_0308.pdf	• Overpressure, burst, shock, and/or blast effects • Fragmentation • Thermal effects (if the content in the pressurized vessel is a flammable liquid/gas)
Boiling Liquid Expanding Vapor Explosion (BLEVE)	The explosively rapid vaporization and corresponding release of energy of a liquid, flammable or otherwise, upon its sudden release from containment under greater-than-atmospheric pressure at a temperature above its atmospheric boiling point. A BLEVE is often accompanied by a fireball if the suddenly depressurized liquid is flammable and its release results from vessel failure caused by an external fire. The energy released during flashing vaporization may contribute to a shock wave. (CCPS, 1994)	An ammonia tank, during an highly hypothetical event in which all the safety controls fail (relief valves, automatic controls, sensors, instrumentation) and the tank is punctured by forklift tines at the time a fire in the vicinity exposes the vessel to high temperatures.	BLEVE explosion in Toronto, Canada at the Sunrise Propane Industrial Gases in August 2008; 6 people hospitalized; more than $1.8M in cleanup efforts; various causes: one is attributed to illegal transfer between vessels of liquid propane.	• Overpressure, burst, shock, and/or blast effects • Fragmentation • Thermal effects (if the content in the pressurized vessel is a flammable liquid/gas)
Vapor Cloud	The explosion resulting from the ignition of a cloud of flammable vapor, gas, or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure. (CCPS, 1994)	A flammable gas escapes from its containment and mixes with air to form a flammable mixture, and an ignition source causes the gas cloud to explode.	Vapor Cloud explosion in a city block of Allentown, PA in February 2011; 6 fatalities; $500K fine by the natural gas company UGI Utilities, Inc.; plus extensive costs for the infrastructure replacements of gas distribution system; cause: natural gas leak; Vapor cloud explosion in East Harlem neighborhood in Manhattan, New York; March 2014; 8 fatalities; property destruction; cause: natural gas leak	• Overpressure, burst, shock, and/or blast effects • Thermal effects
Flash Fire	A fire that spreads rapidly through a diffuse fuel, such as dust, gas, or the vapors of an ignitable liquid, without the production of damaging pressure. (NFPA 2113, General definitions)	Flash fire has a heat flux of approximately 80 kW/m^2 "for relatively short periods of time, typically less than 3 seconds." (NFPA 2113) "A flash fire requires an ignition source and a hydrocarbon or an atmosphere containing combustible, finely divided particles (e.g., coal dust or grain) having a concentration greater than the lower explosive limit of the chemical. Both hydrocarbon and dust flash fires generate temperatures from 538 °C to 1038 °C (1000 °F to 1900 °F). The intensity of a flash fire depends on the size of the gas or vapor cloud. When ignited, the flame front expands outward in the form of a fireball. The resulting effect of the fireball's energy with respect to radiant heat significantly enlarges the hazard areas around the gas released" (NFPA 2113, Topic A.3.3.16)	A polyethylene dust explosion at West Pharmaceutical Services in Kinston, NC, in Jan. 2003, 6 fatalities and 39 workers injured. Cause: Ignition of a fine plastic powder, which had accumulated above a suspended ceiling over a manufacturing area at the plant.	• Overpressure, burst, shock, and/or blast effects • Thermal effects

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4.3.2 EXPLOSIONS ANALYSIS

This section provides basic descriptions and calculation methods associated with the type of explosions and effects that receive the greatest attention for DSA hazard and accident analysis in the DOE Complex. They are:

1. <u>Overpressure, burst, shock, and/or blast effects</u>. Blast calculation assesses the sudden release of a gas into the surrounding area after a functional vessel rupture (argon, nitrogen tanks) or from a vapor cloud explosion. The goal is to calculate the expansion energy, shock wave, or shock effect, using one of the methods presented to the analyst in the following subsections.

2. <u>Fragmentation</u>. All explosion calculations that involve sudden vessel failures, such as Pressure Vessel Ruptures or a BLEVE result in vessel fragmentation and thus invoke fragment release calculations. The nature of this calculation is to assess either analytically or statistically, the distance, velocity, and energy of a fragment that could impact the MAR.

3. <u>Thermal Analysis</u>. Thermal effects from explosions when the mix is combustible are of utmost importance in addition to the overpressure and fragmentation effects, if applicable. The analysis expands to the calculation of damage distances from the heat flux and the thermal radiation of the vaporized mass that could result in a fireball if the liquid in the failure vessel is combustible. There are several alternate correlations in the literature than those presented here that may be conservative for a DSA accident analysis to determine the thermal radiation distance from an explosion (see NUREG-1805; ALOHA, 2013; *EPA Risk Management Program Guidance for Offsite Consequence Analysis* [EPA-550-B-99-005]; and *Handbook of Chemical Hazard Analysis Procedures* [ARCHIE, 1989], and their original sources referenced in those documents).

The following sections provide basic methods to assess the effects of explosions, following the order of types listed in Table 4-1.

4.3.2.1 PRESSURE VESSEL BURST

Catastrophic vessel ruptures can occur due to a variety of initiating events such as external fire, metal fatigue, erosion, corrosion, oxidation, installation violations of the American Society of Mechanical Engineers (ASME) codes and standards, (such as the ASME boiler and pressure code) poor maintenance, excessive internal pressure buildup, deficiencies in the safety management program and/or from physical impacts (vessels punctured by forklift tines, vehicle accident outside the facility).

The DSA hazard and accident analysis evaluates explosive hazard scenario to estimate the effects on surrounding SSCs. Assessment of pressurized vessel burst is performed for the following three main effects:

1. Blast effects. Simple calculation of blast effects from vessel bursts are presented for ideal gases. Particular attention across the DOE complex is given to the potential for explosion events from hydrogen generation.

2. Fragmentation effects from pressure vessel burst could also be calculated with particular emphasis if the MAR is present within nearby locations.

3. Thermal radiation effects (if the content in the pressurized vessel is a flammable liquid/gas) are associated with the fireball and depends on its diameter, height, and the combustion duration.

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4.3.2.1.1 BLAST EFFECT FROM PRESSURE VESSEL BURST

Baker et al., 1978 and Baker et al., 1977 present a method for predicting blast effects following the rupture of gas-filled pressure vessels, either spherical or cylindrical. The relevant steps in the calculation from those references are depicted in Figure 4-4.

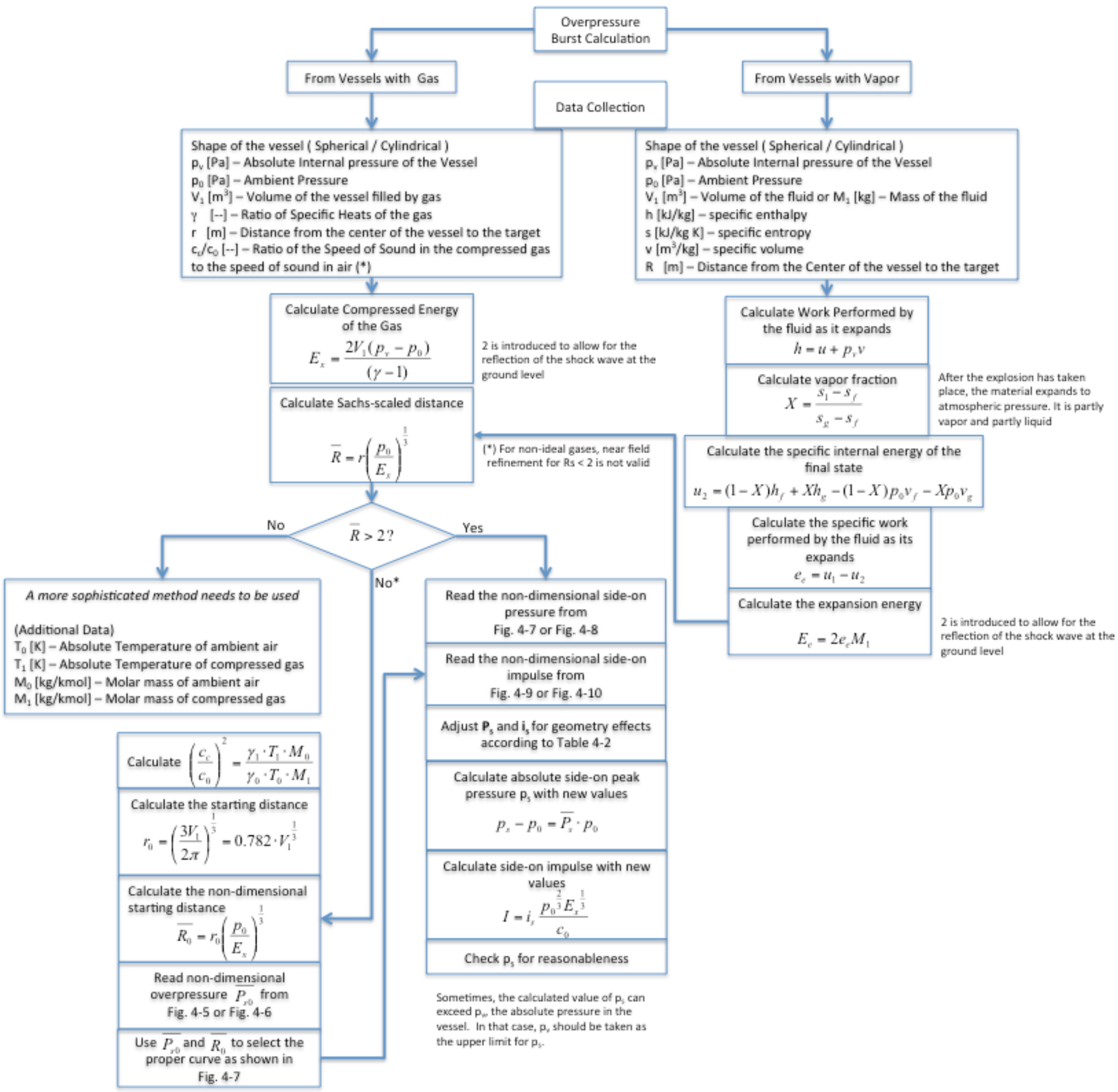

Figure 4-4. A Methodology Example for Calculations of Overpressure Effects.
(Source: Created from discussions in Baker et al., 1977 and Baker et al., 1978)

The method applies to:

1. Gases that can reasonably be approximated as ideal (for example, vessels with hydrogen that rupture); and

2. Non-ideal fluids or superheated liquids (for example, a pressure vessel filled with liquefied propane that ruptures as the result of a fire).

Blast Effects of Gases that can Reasonably be Approximated as Ideal in a Spherical Vessel

The blast effect (overpressure and specific impulse) at a specific distance from a burst vessel is presented with an example as given in Baker et al., 1977. The example uses close to normal temperature and pressure conditions (P=1 atm; T=273.15 K + 20 °C=293.15 K).

- Vessel diameter r_o: 1 m.
- Ratio of specific heats of the gas in the vessel to air (γ = 1.4)
- Gas pressure in the vessel $P_1 = 1.013\text{x}10^6$ Pa
- Gas temperature in the vessel T_1= 273.15 K + 26.85° C = 300 K
- Ambient pressure P_a= 1 atm = $1.013\text{x}10^5$ Pa

The overpressure versus distance relationship for a bursting gas vessel is strongly dependent upon the pressure, temperature, and ratio of specific heats of the gas in the vessel. For high pressures and temperatures, relative to the air outside the vessel, the overpressure behavior is much like that of a blast wave from a high explosive.

The steps to follow are:

a. Calculate the non-dimensional starting distance R_0

$$R_0 = \frac{1}{\left[\frac{4\pi}{3}\frac{\left(\frac{P_1}{P_a}-1\right)}{(\gamma-1)}\right]^{1/3}} = \frac{1}{\left[\frac{4\pi}{3}\frac{\left(\frac{1.013\cdot 10^6}{1.013\cdot 10^5}-1\right)}{(1.4-1)}\right]^{1/3}} = 0.2197 \qquad \textbf{Equation 4-25}$$

b. Determine the overpressure at the interested distance (r = 5.0 m)

$$R = \frac{r}{\left[\frac{4\pi r_0{}^3}{3}\frac{\left(\frac{P_1}{P_a}-1\right)}{(\gamma-1)}\right]^{1/3}} = \frac{\frac{r}{r_0}}{\left[\frac{4\pi}{3}\frac{\left(\frac{P_1}{P_a}-1\right)}{(\gamma-1)}\right]^{1/3}} = 0.2197\cdot\frac{5.0}{1.0} = 1.099 \sim 1.1 \qquad \textbf{Equation 4-26}$$

c. With ($\frac{P_1}{P_a} = 10$ and $\frac{T_1}{T_a} = \frac{300}{300} = 1$) on Figure 4-5 find the non-dimensional starting pressure P_{s0}. This pressure is estimated to be $P_{s0} \sim 1.7$

For gases with γ = 1.667 use the graphic presented in Figure 4-6.

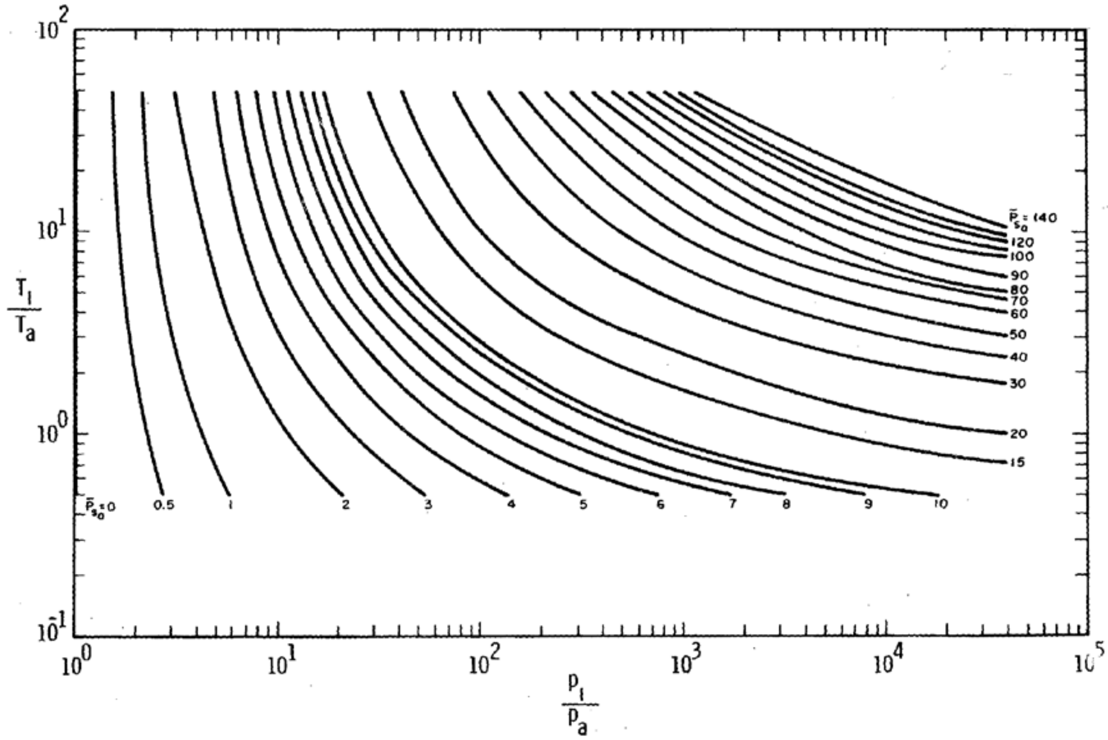

Figure 4-5. Temperature vs. Pressure Ratio for γ = 1.4
(Source: Baker et al., 1978 Figure 2-2; Baker et al., 1977 - Figure 2.20)

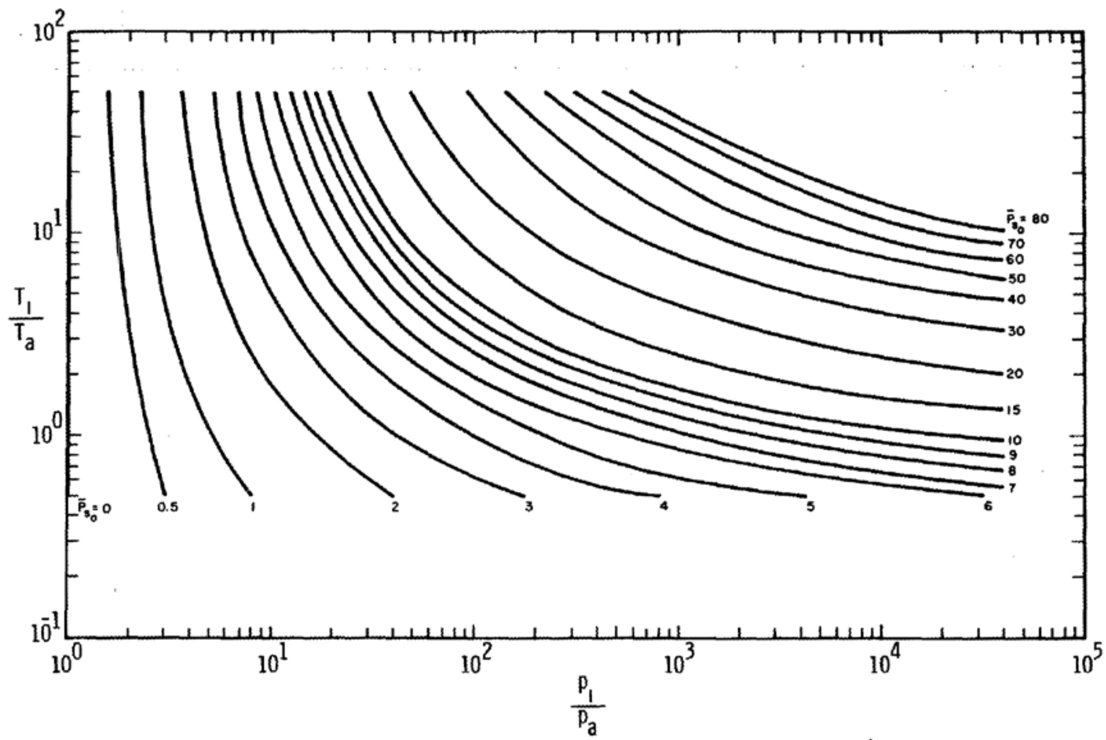

Figure 4-6. Temperature vs. Pressure Ratio for γ = 1.66.
(Source: Baker et al., 1978 Figure 2-3; Baker et al., 1977 Figure 2.21)

d. On Figure 4-7 look for the curve that corresponds to the interception of points $\overline{R_0} = 0.2197$and$\overline{P_{s0}} = \sim 1.7$. Then move on the curve to the point intercepted by $\bar{R} \sim 1.1$ and read on the vertical axis the value that corresponds to the starting the overpressure at 5 m. This is equal to $\bar{P_s} = 0.26$

For values of R>2 use the graphic presented in Figure 4-8.

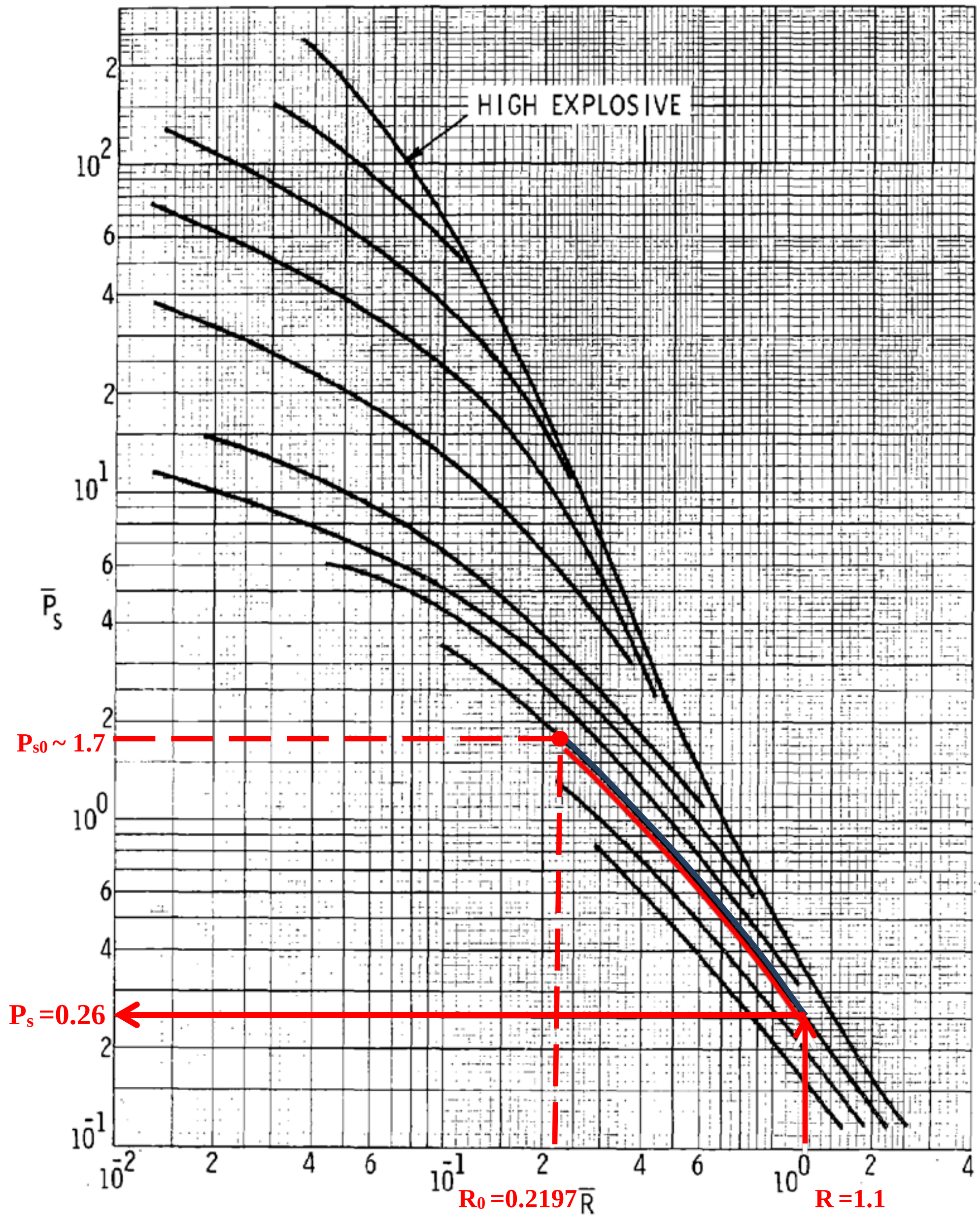

Figure 4-7. P_s vs. R_s for Overpressure Calculations
(Source: Baker et al., 1978 Figure 2-5; Baker et al., 1977 Figure 2.18)

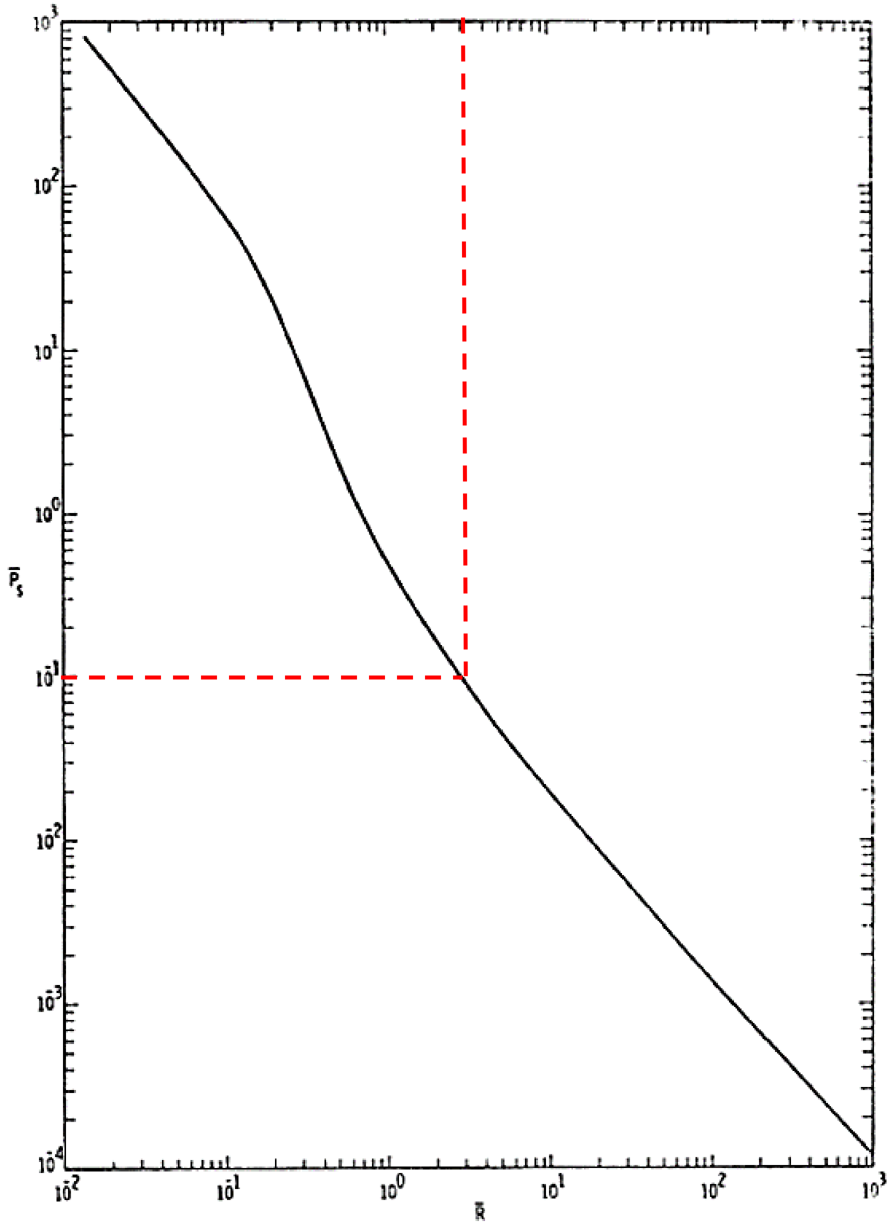

Figure 4-8. Ps vs. Rs for Pentolite
(Source: Baker et al., 1977 Figure 2-19)

To find the specific impulse:

a. Given the calculated $\bar{R} = 1.1$ at the distance of 5.0 m, the non-dimensional, side-on impulse can be found from Figure 4-9 ($\bar{I}$~0.046).

For values of R<1, use the graphic in Figure 4-10.

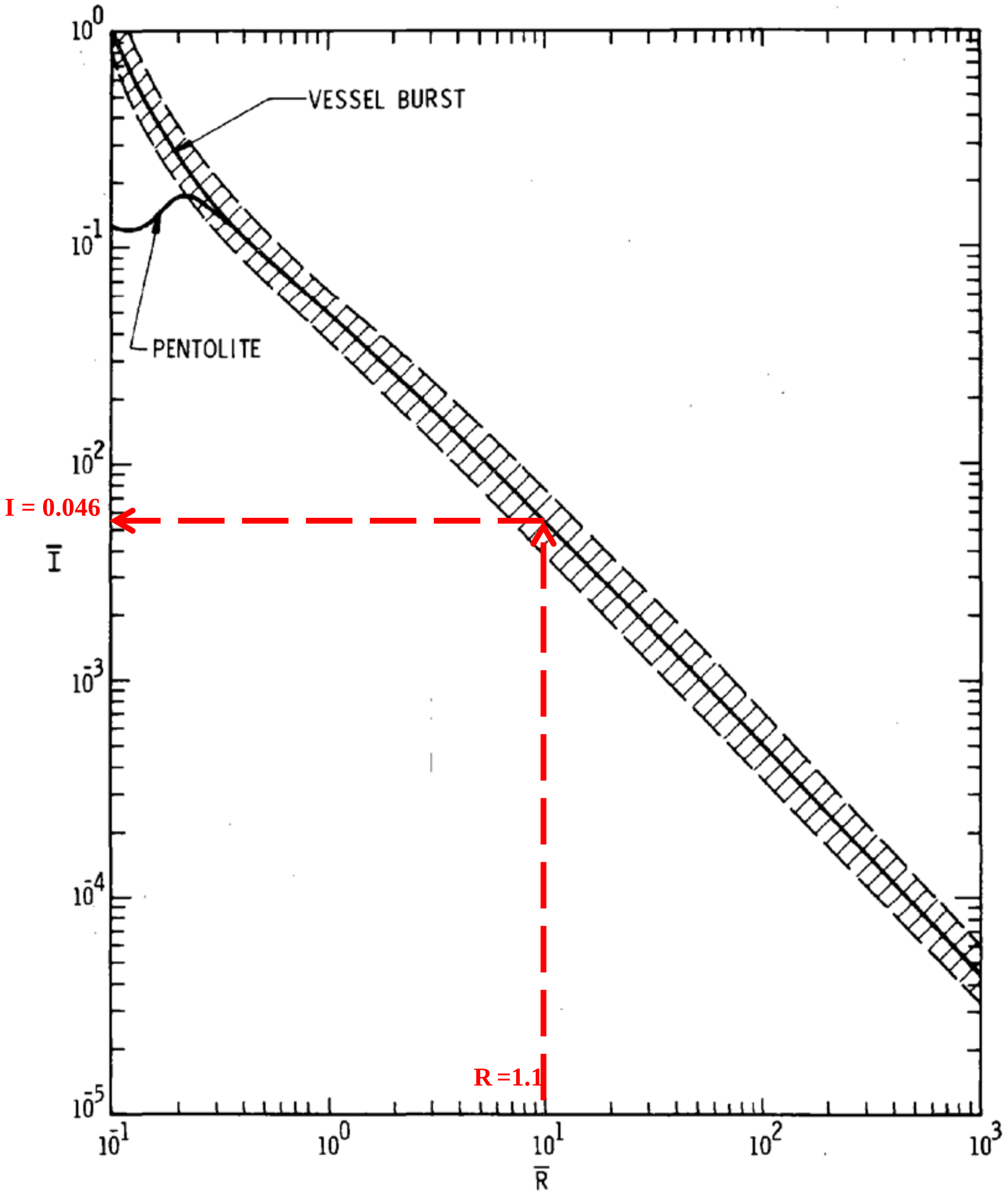

Figure 4-9. I_s vs. R_s for Gas Vessel Bursts and Pentolite
(Source: Baker et al., 1978 Figure 2-6; Baker et al., 1977 Figure 2.23)

b. The energy inside the vessel can be calculated as:

$$E = \frac{4\pi r_o^3}{3}\left(\frac{P_1 - P_a}{\gamma - 1}\right) = \frac{4\pi r_o^3}{3}\frac{(1.013\cdot10^6 - 1.013\cdot10^5)}{(1.4-1)} = 9.55\cdot10^6\,J \qquad \textbf{Equation 4-27}$$

If surface burst is assumed, and a reflected shock wave is considered, then this energy value should be multiplied by 2. NOTE: This is not considered in this example.

c. Impulse (I) is calculated from:

$$\bar{I} = \frac{I \cdot a_a}{P_a^{2/3} \cdot E^{1/3}} \Rightarrow I = \bar{I}\,\frac{P_a^{2/3} \cdot E^{1/3}}{a_a} = \qquad \textbf{Equation 4-28}$$

$$= 0.046\,\frac{(1.013 \cdot 10^5)^{2/3} \cdot (9.55 \cdot 10^6)^{1/3}}{331} = 64\ Pa \cdot s$$

Where: a_a is the speed of sound

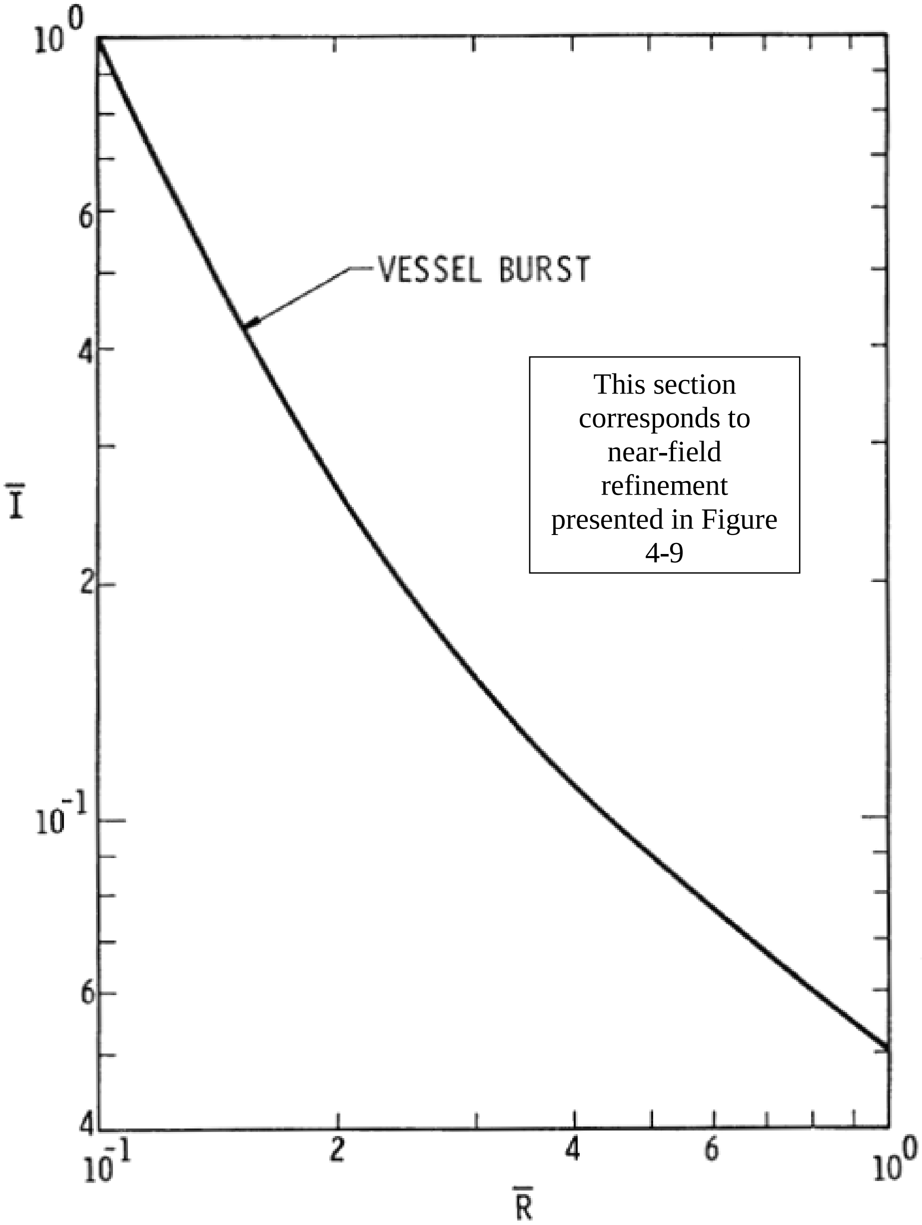

Figure 4-10. I_s vs. R_s for Gas Vessel Bursts (Small R_s**)**
(Source: Baker et al., 1978 Figure 2-7; Baker et al., 1977 Figure 2.24)

Blast Effects of Gases that can Reasonably be Approximated as Ideal in a Cylindrical Vessel

For a cylindrical vessel, given the length L and the diameter D, use its volume V_v in the equations above, performing the calculations as for a spherical vessel. After P_s and I have been determined, further corrections are necessary according to the following table: Based on text in Baker et al., 1977 (page 67), Table 4-2 summarizes adjustment factors Factors for P_s and I_s for Cylindrical and Spherical Vessels based on R_s.

Table 4-2. Adjustment Factors for P_s and I_s for Cylindrical and Spherical Vessels based on R_s.

Vessel Type	R_s	Multiply for:	
		P_s	I_s
Cylindrical	< 0.3	4	2
	0.3 to 1.6	1.6	1.1
	1.6 to 3.5	1.6	1
	> 3.5	1.4	1
Spherical	< 1	2	1.6
	> 1	1.1	1

(Source: Adapted from Baker et al., 1977 page 67.)

The difference between spherical and cylindrical vessel bursts is only known qualitatively. Therefore, these corrections are very crude.

Blast Effects with Non-ideal Fluids (Vapors)

In practice, most vessels are filled with non-ideal fluids or with superheated liquids. For a pressure vessel filled with propane that ruptures as the result of a fire, the following steps to be followed are similar but not identical to those above.

a. Collect the following data:

- shape of the vessel (spherical or cylindrical).
- absolute internal pressure p_v at the moment of vessel failure;
- ambient pressure p_0
- quantity of the fluid (volume V_c or mass M_c)
- distance R from the center of the vessel to the target;
- specific enthalpy *h*
- specific entropy *s*
- specific volume ν

b. Calculate the work performed by the fluid as it expands

The work done by an expanding fluid is defined by the difference in internal energy between the fluid's initial and final states.

For many situations of interest, for example, a BLEVE from a ruptured propane tank, the values of *h*, *s*, and ν in the initial state are those for saturated vapor or liquid. They can be read from thermodynamic graphs or interpolated from thermodynamic tables given the temperature or pressure in the vessel. Therefore, the specific internal energy of the system immediately prior to the explosion can be calculated. These methods are based on extensive research, experimental work, historical data, and empirical deductions. Equations can be found in thermodynamic textbooks, and physical data for the gas in question can be selected by using a tool such as the one provided in: http://webbook.nist.gov/chemistry/, "Thermophysical Properties of Fluid Systems." An example of selecting these values for evaluating blast effects is provided in CCPS, 1994.

After the explosion has taken place, the material expands to atmospheric pressure p_0. It is partly vapor and partly liquid.

c. Calculate:

- the fraction X that is vapor is given,
- the specific internal energy of the final state u_2,
- the specific work performed by the fluid as it expands e_e
- the expansion energy E_x

The factor of 2 is introduced to allow for the reflection of the shock wave at the ground.

For common fluids, tabulations or graphs exist from which e_e can be directly read.

At this point, the analyst should return to the steps above for ideal gases. Note that the near-field refinement for $R_s < 2$ is not valid for non-ideal gases or flashing liquids. In this case, a conservative estimate of blast effects can be obtained by calculating the energy E_{TNT} presented in the TNT-equivalency method presented in Section 4.3.2.3.4.

4.3.2.1.2 FRAGMENTATION FROM PRESSURE VESSEL BURST

In principle, it is possible to estimate the mass distribution of fragments, their shapes, initial velocity, and its angle of elevation, for any site-specific situation, to determine the SSCs or MAR, struck by the fragment. Quantitatively justifying (demonstrating) for the DSA accident analysis that an operational accident is not plausible per DOE-STD-3009-2014 requires an estimate of the mass distribution of fragments, their shapes, initial velocity, and its angle of elevation.

Two approaches are provided, one analytical and the other statistical.

Analytical Approach

Although it is essentially simple and straightforward, the analytical approach is a highly conservative methodology where consideration should be given to estimating the uncertainties of the results. The relevant steps for the fragmentation effect on adjacent SSCs are depicted in Figure 4-11. These equations can be found in CCPS, 1994. The methodology consists of the following steps:

Step 1. Collect important data related to the vessel in the analysis. This includes design characteristics and vessel configuration as well as the thermodynamic properties of the fluid in the vessel, and operational conditions.

Step 2. Calculate available energy. Calculate the energy of the compressed gas in the vessel, assumed to be converted into kinetic energy of the fragments.

Step 3. Calculate initial velocity of the fragment. Several formulas are represented in the figure from the various methods suggested by the literature to calculate the initial fragment velocity. These methods are based on extensive research, experimental work, historical data, and empirical deductions.

Step 4. Determined the distance ranges, R (Figures 4-11 and 4-12).

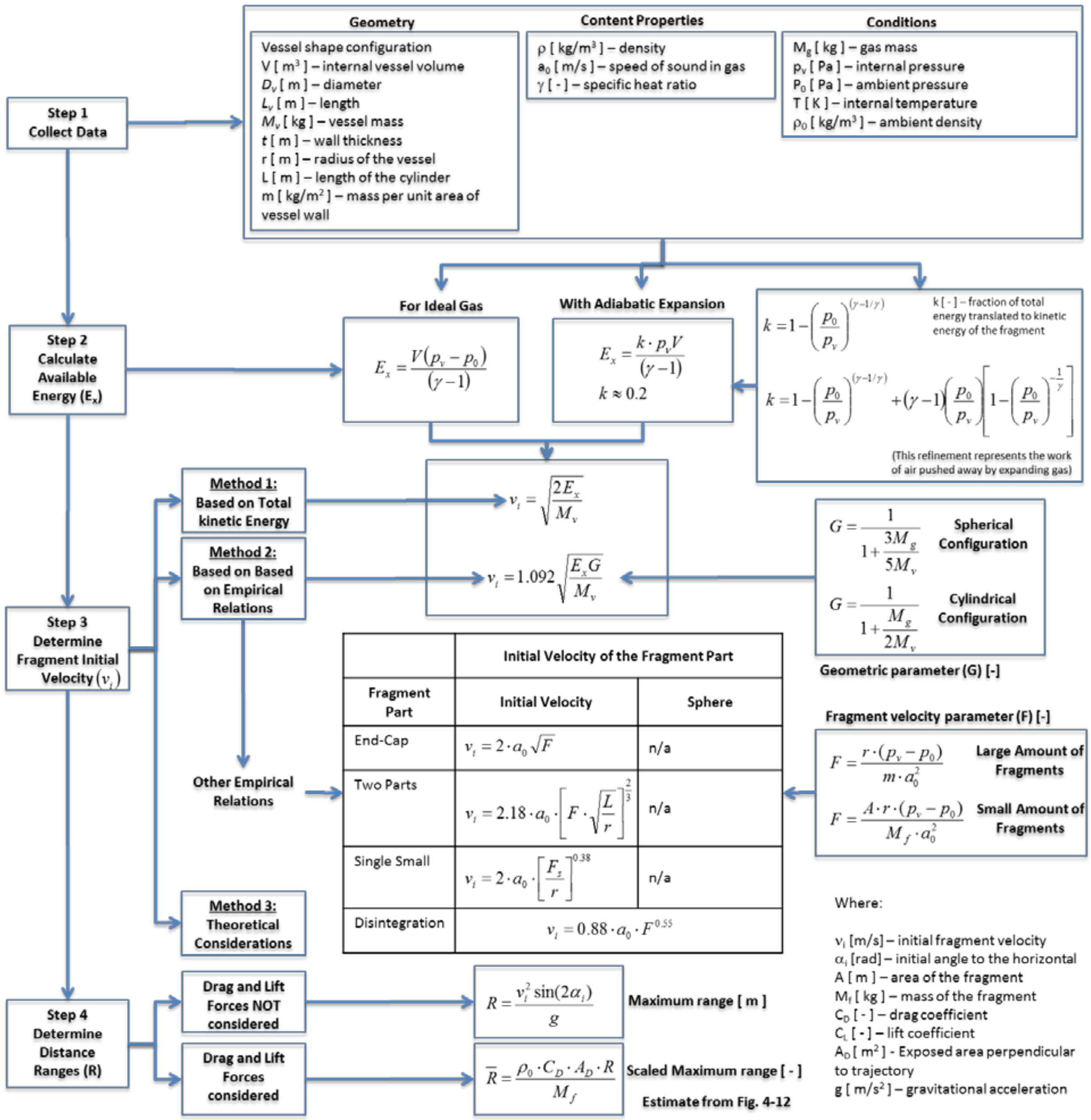

Figure 4-11. A Methodology Example for Calculations of Fragmentation Effects.
(Source: Adapted from CCPS, 1994)

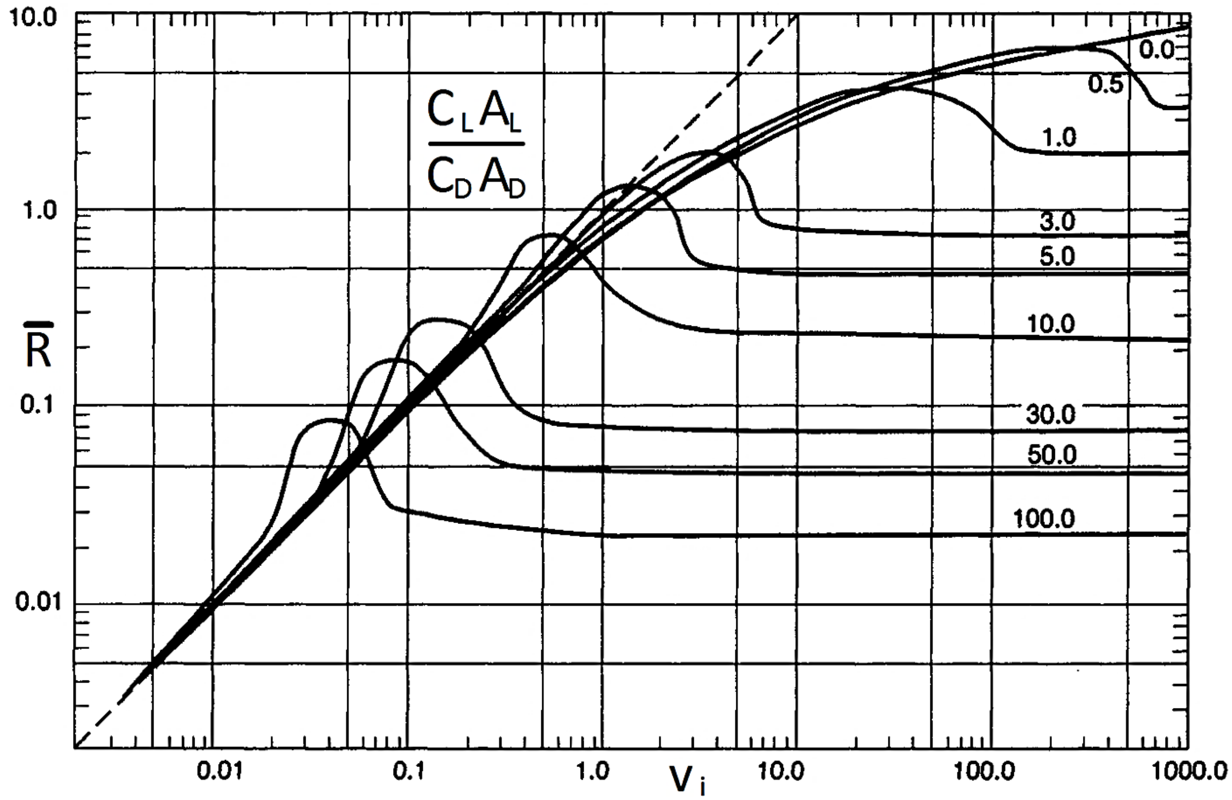

Figure 4-12. Scale Curves for Fragment Range Predictions
(Source: Baker et al., 1978 Figure 4-5; CCPS, 1994 Figure 6.36)

The set of curves in Figure 4-12 above provide predictions of the range distribution from various lift/drag ratio of the fragments based on its velocity. C_D is the dimensionless drag coefficient and A_D is the fragment area perpendicular to the flying trajectory. C_L is the dimensionless lift coefficient and A_L is the fragment area in parallel to trajectory. For fragments where the lift coefficient is zero, the line of importance is denoted by a ratio equal to zero. The higher the drag forces the shorter the distance will be estimated for the fragment in question given its velocity. If a fragment is, for example, a metal plate, then lifting forces will increase the ratio, making the distance prediction shorter as well.

Statistical Analysis

In practice, there is only statistical information on which to base predictions of the fate of any fragments following a pressure vessel burst or a BLEVE.

An analysis in *Workbook for Estimating the Effects of Accidental Explosions in Propellant Ground Handling and Transport Systems* (Baker et al., 1978), considered 20 accidental explosions. The data was organized into six groups, which are summarized in Table 4-3.

Table 4-3. Groups of Like Events—Fragments from Explosions
(Source: Adapted from Baker et al., 1978 Table 4-3).

Group Number	Number of Events	Explosion Material	Source Energy Range (J)	Vessel Shape	Vessel Mass (kg)	Number of Fragments
1	4	Propane, anhydrous ammonia	1.5E+5 to 6E+5	Railroad tank car	25,500 to 83,900	14
2	9	LPG	3,800 to 4,000	Railroad tank car	25,500	28
3	1	Air	5E+11	Cylinder, pipe and spheres	146,000	35
4	2	LPG, propylene	550	Semi-trailer (cylinder)	6,300 to 7,800	31
5	3	Argon	2.4E+9 to 1.1E+10	Sphere	46 to 187	14
6	1	Propane	25	Cylinder	510	11

Statistical analyses were performed on each group to yield estimates of fragment range and mass distributions.

Figure 4-13 and Figure 4-14 can be used to estimate the percentage of fragments which will have a range, $R_{i'}$, equal to or less than a particular range. Figure 4-15 and Figure 4-16 present the fragment mass distributions for groups 2, 3, and 6.

Using this data, the analyst can obtain helpful information; for example:

- For a specific vessel, determine which of the groups 1 through 6 it most closely resembles (Table 4-3).
- Choose a specific percentile (e.g., 50 percent for the median case, 95 percent for a conservative case) and read off the corresponding range from Figure 4-13 or 4-14.
- Within this range, consider whether there are any structures that are particularly vulnerable to missiles, or groups of people who may be within range.
- Consider whether any additional design or procedural measures to reduce the likelihood of the initial explosion or to protect the potential target are necessary. This additional design or procedural measure is necessarily a qualitative analysis.

The reference gives an example on how to use the graphics:

> For example, if we wished to estimate the percentage of fragments which would have a range equal to or less than 600 m for an explosion involving a rail tank car filled with propane (group 1), we would refer to Figure 4-6,[29] and on the range axis (abscissa) at 600 m go upward to the intersection of the group 1 line. Then, at the intersection point read the percentage value from the ordinate, which is 96%. Conversely, if we wanted to know what range 90% of the fragments would not exceed, we would enter the chart on the 90% line, go over to the intersection of the group 1 line and read downward to the range axis the value of 380 m. (Baker et al., 1978)

[29] Figure 4-6 is Figure 4-13 in this document.

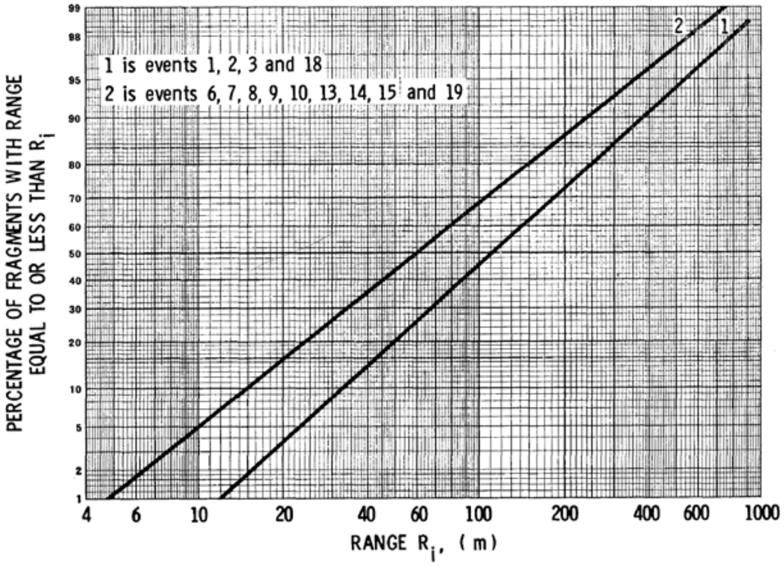

Figure 4-13. Fragment Range Distribution for Event Groups 1 and 2 (Source: Baker et al., 1978 Figure 4-6)

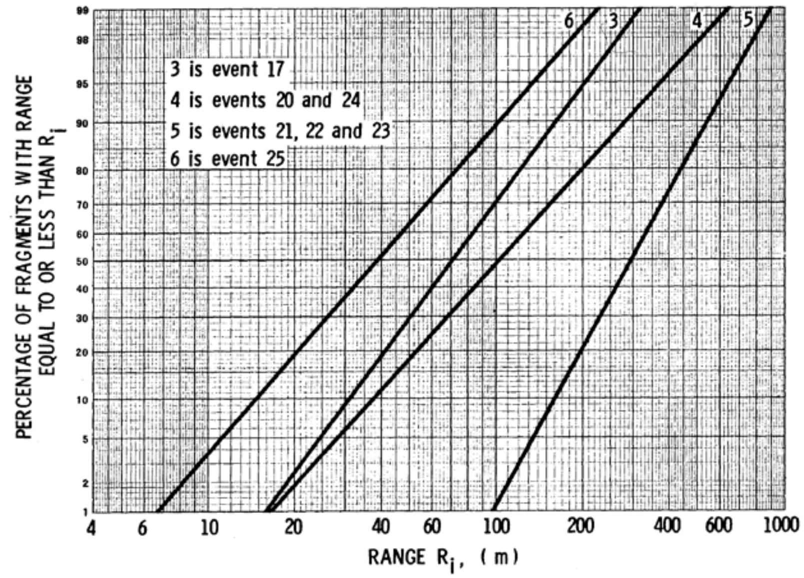

Figure 4-14. Fragment Range Distribution for Event Groups 3, 4, 5 and 6 (Source: Baker et al., 1978 Figure 4-7)

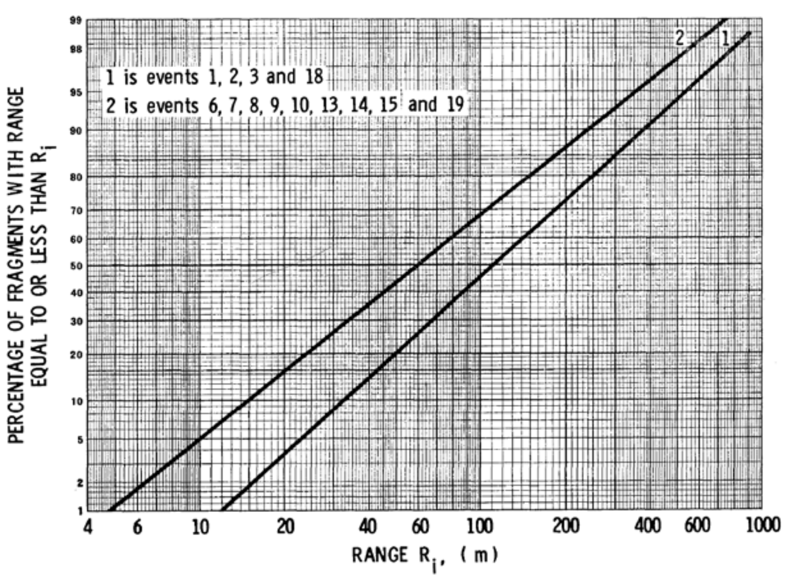

Figure 4-13. Fragment Range Distribution for Event Groups 1 and 2 (Source: Baker et al., 1978 Figure 4-6)

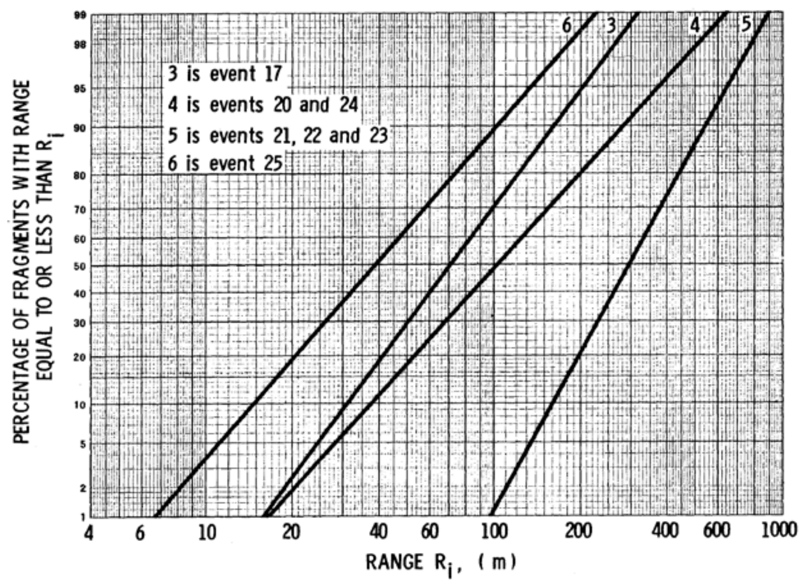

Figure 4-14. Fragment Range Distribution for Event Groups 3, 4, 5 and 6 (Source: Baker et al., 1978 Figure 4-7)

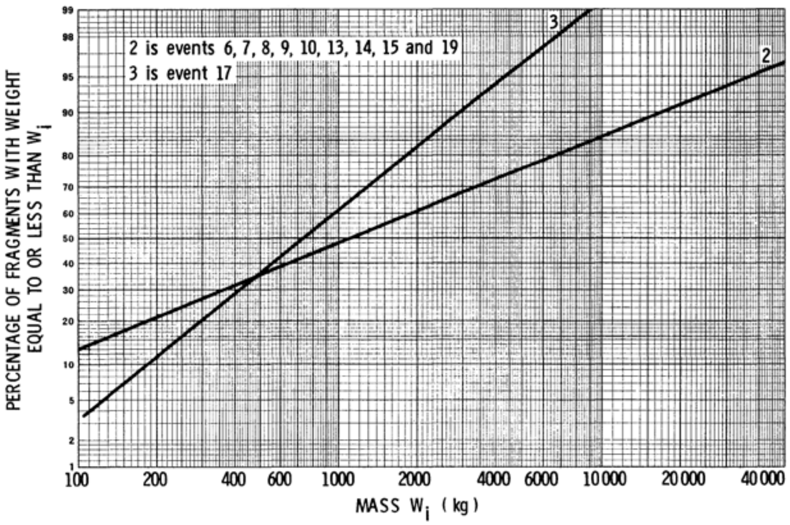

Figure 4-15. Fragment Mass Distribution for Event Groups 2 and 3 (Source: Baker et al., 1978 Figure 4-8).

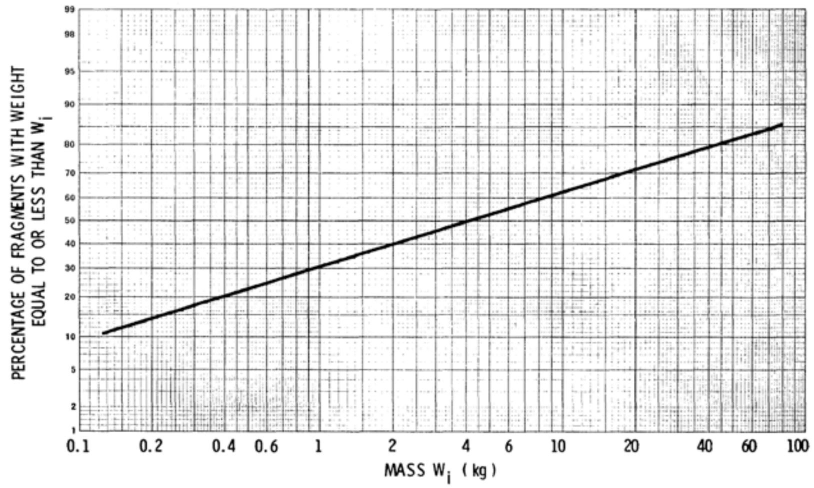

Figure 4-16. Fragment Mass Distribution for Group 6 (Source: Baker et al., 1978 Figure 4-9).

4.3.2.1.3 THERMAL EFFECTS FROM PRESSURE VESSEL BURST

The fire analysis Section 4.2.3.2 of this Handbook provides an explanation of the thermal effects of an unmitigated event that involves a developed fire. The difference between the thermal radiation from a fire and explosion pressure vessel burst with combustion, resides in the conditions capable of sustaining a prolonged fire versus a relatively short amount of time that the fireball lasts during an explosion. Nevertheless, formulations from the literature are presented to the analyst in Section 4.3.2.2.3 in this Handbook that is also applicable to a pressure vessel burst fireball.

4.3.2.2 BLEVE

NUREG-1805 defines a BLEVE as follows:

> … a catastrophic rupture of a pressurized vessel containing a liquid at a temperature above its normal boiling point with the simultaneous ignition of the vaporizing fluid. A short-duration, intense fireball occurs if the liquid is flammable. During the rupture of the vessel, a pressure wave may be produced and fragments of the containment vessel will be thrown considerable distances.

In other words, to consider an explosion of a vessel containing pressurized liquid a BLEVE, conditions, such as instantaneous depressurization and significant superheating of the liquid, need to be met to cause a near instantaneous evaporation.

A common misconception is that the BLEVE produces the pressure that results in a catastrophic vessel failure. Vessels may experience any number of insults, but not all of them result in a BLEVE, which occurs independently of a vessel failure. That is, the explosion does not cause the vessel to fail, it is the failure of a vessel that leads to a sudden depressurization of superheated liquid.

Sudden vessel depressurization of superheated liquid leading to a BLEVE may result from:

1) Failure of equipment such as valves and vaporizers.
2) Human errors made by operators, maintenance, or delivery personnel.
3) External impacts (such as pipe whip) where vessel integrity has already been compromised by heating and internal boiling.
4) Other causal chains such as extensive corrosion and extreme seismic events.

As stated above, sudden depressurization of a vessel from impact without external heating may not result in a BLEVE, but may result in other situations that warrant evaluation. For example, it could lead to a pool fire if the breach is below the vapor-liquid interface and the liquid is combustible or flammable. Or it could lead to a jet fire if the content release is pressurized and contacts a sufficient energy source. The jet fire would need to come from a breach in the vapor space and be turbulent enough to entrain and mix air. However, if the jet flame could impinge on another vessel, a BLEVE of the adjacent vessel could occur.

Unmitigated assessment of BLEVE is performed similarly to pressure vessel burst, for (a) blast effects, (b) fragmentation effects, and (c) thermal effects.

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4.3.2.2.1 BLAST EFFECT FROM BLEVE

Blast effect assessment is performed in similar fashion as with pressure vessel burst described above. See subsection 4.3.2.1.1 of this Handbook. (CCPS, 1994, Section 9.2)

4.3.2.2.2 FRAGMENTATION FROM BLEVE

Fragment effect assessment is performed in similar fashion as with pressure vessel burst described above. See subsection 4.3.2.1.2 of this Handbook.

4.3.2.2.3 THERMAL EFFECTS FROM BLEVE

The thermal effects from a BLEVE can be evaluated similar to the thermal effects from a pressure vessel burst with combustion, as discussed in Section 4.3.2.1.3, based on the fire analysis methodologies.

Fireball Diameter and Duration

In order to simplify calculations of BLEVE effects, it is often assumed that the fireball touches the ground, the fireball is spherical and its center is at height $D_c/2$. This should give a somewhat conservative estimate of radiant heat flux. Note that in practice, the fireball rises as a function of time and that greater accuracy requires the use of numerical models.

The fireball diameter and its duration can be calculated by the following equations (CCPS, 1994; ALOHA, 2013 page 68; EPA-550-B-99-005, page D-22):

$$D_c = 5.8 \cdot m_f^{1/3}$$ **Equation 4-29**

$$t\_c = 0.45 \cdot m\_f\hat{}(1\ /\ 3) \qquad for\ mf\ <\ 30{,}000\ kg$$ **Equation 4-30**

$$t\_c = 2.6 \cdot m\_f\hat{}(1\ /\ 6)tc \qquad for\ mf\ >\ 30{,}000\ kg$$ **Equation 4-31**

Where:

D_c [m] – final fireball diameter

m_f [kg] – mass of fuel in fireball

t_c [s] – duration of fireball

Damage Distance

From the equations to determine q (heat flux) and F (view factor) the hazard distance, L (i.e., the maximum distance at which that level of damage will occur) can be calculated as (from as cited in CCPS, 1994, pages 178-179):

$$L = \left(\frac{D_c}{2}\right)\sqrt{\left(\frac{E \cdot cos\,\Theta \cdot \tau_a}{q}\right)}$$ **Equation 4-32**

For propane BLEVEs, the following empirical, simplified formula for the hazard range that could inflict severe burns to people was developed (original source from Lihou and Maund, 1982, "Thermal Radiation Hazard from Fireballs," *I. Chem. E. Symp. Ser., No. 71* as cited in CCPS, 1994 page 183):

$$L \sim 3.6 \cdot m_f^{0.4}$$ **Equation 4-35**

Heat Flux

Finally, the incident radiation per unit area at which a receptor receives thermal radiation or the heat flux that causes a specific level of damage over a minimum duration is given by (CCPS, 1994 page 178 and ALOHA, 2013 page 65, which are similar to the fire analysis discussion in Section 4.2.2 of this Handbook):

$$q = E_s \cdot F \cdot \tau_a$$ **Equation 4-34**

Where:

> q [kW/m^2] – rate at which thermal radiation is received by the receptor/incident radiant heat flux
>
> E_s [kW/m^2] – surface emissive power. A value of 350 kW/m^2 for E_s is consistent with experiments on BLEVEs for most hydrocarbons involving a vapor mass of 1,000 kg or more.
>
> $F = D_c^2 \cos\Theta / 4L^2$ [dimensionless] – View factor. For a point on a plane surface at a distance L from the center of a spherical fireball (with no obstructions between)
>
> Θ is the angle between the normal to the surface and the line connecting the point to the center of the fireball.
>
> τ_a [dimensionless] – atmospheric transmissivity (CCPS, 1994 Equation 9.1.6)
>
> RH is the relative humidity

$$\boldsymbol{\tau_a = log[14.1 \cdot RH^{-0.108}\left(L - \frac{D_c}{2}\right)^{-0.13}}$$ **Equation 4-35**

Fuel Contribution to Fireball

A simple rule of thumb based on a "Study of Fireball Following Steam Explosion n-Pentane" (Hasegawa and Soto, 1977) is that the amount of gas in a BLEVE can be taken to be three times the flash fraction, up to a limit of 100 percent.

4.3.2.3 VAPOR CLOUD EXPLOSION

In the DOE Complex, examples of vapor cloud ignition involve the release of different gaseous mixtures into the environment and depending on the time factor, could envelope the MAR in the proximity of the vapor cloud.

Depending of the substance content and its flammability, a vapor cloud ignition can be developed into a deflagration or detonation. The initiation energy plays a fundamental role after a flammable gas has ignited. Detonations and deflagrations are often distinguished by the speed or rate of propagation of the combustion wave through the material.

In a deflagration, the flame or combustion wave is below the speed of sound in air at 20 °C (68 °F), which is approximately 330 m/sec (1,082 ft/sec).

In a detonation, the flame or combustion wave propagates through the reactants at supersonic speeds on the order of 2,000 m/sec (6,562 ft/sec).

4.3.2.3.1 VAPOR CLOUD DEFLAGRATION

A vapor cloud deflagration is characterized by the sudden energy release when the gas ignition results in a pressure increase starting at the ignition location (center of initial cloud). For an unconfined vapor cloud deflagration, the pressure wave, sometimes referred to as a constant-volume combustion pressure, expands from the initial location at a subsonic propagation rate and reduces rapidly as a function of distance. The combustion propagates through the gas medium from mass diffusion and heat transfer. This phenomenon can exert excessive force on confinement features (e.g., cause a glovebox breach or overturn a vessel) or can cause collateral damage due to debris impacts to the MAR from failed equipment and interior furnishings, examples being collapse of lighting, piping, ventilation ductwork. For a confined vapor cloud deflagration in a process room or enclosure, for other than minor deflagrations, the damage is not caused by a pressure wave as a function of distance and instead it is due to a uniform pressure rise in the room which can fail structural boundaries causing debris-impacts to the MAR.

4.3.2.3.2 VAPOR CLOUD DETONATION

A Vapor Cloud Detonation is considered when the gas ignites in a detonation with a sudden release of energy and a pressure increase at the ignition location. However, even if the flammable gas concentration levels are high, detonation may not occur if the geometry is not favorable for a shock wave to occur. (It is generally known that the pressure wave for a detonation, resulting in an overpressure, is referred to as a shock wave or Chapman-Jouguet (CJ) pressure). Long pipes are a more favorable geometry for a detonation to occur than a vessel with a length to diameter ratio of one and no interior obstructions.

4.3.2.3.3 VAPOR CLOUD DEFLAGRATION AND DETONATION PRACTICAL DIFFERENCES

When comparing a deflagration to a detonation, the pressure wave progresses outward from the detonation source at a much higher rate. The pressure wave for a detonation travels at supersonic velocities. At the wave front, the unburnt gases are compressed. The combustion occurs at the wave front from the compressive heating of the gases.

The practical distinction between deflagrations and detonations relates to the amount of damage caused by the overpressures and depend on the material involved in the detonation or deflagration.

For example, the overpressure in a typical unconfined deflagration wave without obstructions is on the order of 1 atmosphere (14.70 psi) for C_2H_2 in air (NUREG-1805). By contrast the pressure attained during a detonation can be up to 20 atmospheres (294 psi), which would cause significant debris impacts from failed equipment and structural features.

In closed vessels, deflagration overpressures from stoichiometric fuel-air concentrations at initial conditions (25 C and 1.013 bar) when the burning rate is low (Bjerketvedt et al., 2012), are summarized in Table 4-4, for various explosive substances. In addition, according to the *Loss Prevention in the Process Industries* (as reported in the 1980 first edition of Lees, 1996), the CJ pressure is approximately twice of the constant-volume combustion pressure. Doubling the pressures increases in Table 4-4 result in pressures during a detonation of up to 20 atmospheres (294 psi).

Table 4-4. Deflagration Overpressures in Closed Vessels
(Source: Extracted from Bjerketvedt et al., 2012 Table 4.5).

	Hydrogen	Ethylene	Propane	Methane
P (bar)	8.15	9.51	9.44	8.94

Original source as cited in Bjerketvedt et al., 2012: Baker, W.E., et al., 1983. *Explosion Hazards and Evaluation*, Elservier Science Publishing Company, Amsterdam.

According to the *Loss Prevention in the Process Industries* (as reported in the 1980 first edition of Lees, 1996), the CJ pressure is approximately twice of the constant-volume combustion pressure. Doubling the pressures increases in Table 4-4 results in pressures during a detonation of up to 20 atmospheres (294 psi).

4.3.2.3.4 BLAST EFFECT FROM VAPOR CLOUD EXPLOSION

Different techniques are used for determining the blast effect from vapor cloud explosions. The two techniques discussed in this section can roughly be characterized as being applicable to near- and far-field impacts.

The TNT-equivalency method is recommended for determining far-field potential damage. It takes the fuel (flammable gas) energy and determines an equivalent energy of TNT.

As long as the far-field potential damage is the concern, the TNT-equivalent method is a poor model for a gas explosion. This method is known to give non-conservative results for peak overpressure in the far field, because the positive phase duration and shape of the blast waves are not well reproduced. For this reason, determining peak overpressure for the purpose of accident analysis can lead to erroneous results. In order to apply the model, conservative TNT-Equivalency values, α_e, are introduced as seen in the content of this section.

The Multi-energy method is better suited to determining near-field potential damage than the TNT model, although can also be used for determining far-field evaluations. Through the use of this method's scaling equations, side-on and overpressures and duration of pressures can be determined. The Multi-energy method provides a better prediction of the positive phase duration of the pressure and shape of the blast waves.

TNT-Equivalency Method

A "TNT-equivalency" concept has been used in the literature for evaluation of potential damage from an explosion overpressure, and in particular, has been applied to the evaluation of vapor cloud explosions. Baker et al., 1977 summarized it as follows:

> A common method of assessment of possible energy release or correlation of the results of experiments has been to assess the energy release on the basis of equivalent pounds of TNT. This method is used because a large body of experimental data and theoretical analyses exist for blast waves generated by TNT or other solid explosives. Although the comparison with TNT is convenient, the correlation is far from exact. Specific energies, which can be released, i.e., energy per unit volume or mass of material, differ quite widely between TNT, various liquid propellants or mixtures of liquid propellants and oxidizers, and gases stored in pressure vessels.

The concept of TNT-equivalency was introduced for blast prediction purposes when the mechanisms of blast generation in vapor clouds were not fully understood. The method simply converts the available combustion energy into an equivalent charge weight of TNT. This TNT method is for gas explosions outside of facilities that are unconfined explosions, i.e., this method is not valid for inside building explosions). The "TNT-equivalency factors" come from assessing the damage to the exterior of buildings from the gas explosion vs. the quantity of TNT to cause the same damage.

A simplified method for assessing the blast wave effects from a vapor cloud explosion is based on blast wave energy, i.e., TNT-equivalent. NUREG-1805 Equation 15-1, NRC Regulatory Guide 1.91, *Evaluation of Explosions Postulated to Occur at Nearby Facilities and on Transportation Routes Near Nuclear Power Plants*, and SFPE, 2008, estimate the energy released as follows:

$$\boldsymbol{E_{TNT} = \alpha_e H_f W_f} \qquad \textbf{Equation 4-36}$$

Where:

E_{TNT} [J] = explosive energy released or blast wave energy

W_f [kg] – the mass of fuel involved. The weight of the fuel W_f in the cloud is equal to the flash fraction (F) times the quantity (mass) of fuel released.

H_f [kJ/kg] – theoretical net heat of combustion of the fuel in question. This information is available in NUREG-1805 Table 15-2, Heat of Combustion, Ignition Temperature, and Adiabatic Flame Temperature* of Flammable Gases; and in Factory Mutual Loss Prevention Data Sheet 7-42, "Guidelines for the Estimation of Property Damage from Outdoor vapor cloud explosions in Chemical Processing Facilities," March, 1990 (as cited in NRC Regulatory Guide 1.91).

α_e [dimensionless] – TNT-equivalency based on energy; the fraction of available combustion energy participating in blast wave generation

Note that the literature on this subject does not use consistent terminology, hence it is common that TNT-equivalency (α_e) is also called equivalency factor, yield factor, efficiency, or efficiency factor.

For a catastrophic failure of a vessel containing a gas liquefied under pressure (such as liquid propane), some fraction (F) of the liquid flashes into vapor and the rest cools to the boiling point of the liquid (or lower). The flash fraction can be determined on the basis of actual thermodynamic data using the following equation:

$$\boldsymbol{F = 1 - exp\left(-\frac{C_p \Delta T}{L}\right)} \qquad \textbf{Equation 4-37}$$

Where:

- F [dimensionless] – Flash Fraction
- C_p [kJ/(kgK)] – mean specific heat of the flashing material at constant pressure
- ΔT [K] – difference in temperature between the temperature of the vessel and the atmospheric boiling point
- L [kJ/kg] – latent heat of vaporization

Some of the unvaporized liquid from the ruptured vessel forms aerosols, and thus adds to the fuel in the vapor cloud. The UK Health and Safety Executive recommends calculating the cloud inventory by using the flash fraction and then multiplying by 2 to allow for spray and aerosol contributions to the cloud.

The corresponding TNT equivalent mass in (kg), W_{TNT}, is:

$$\boldsymbol{W_{TNT} = \frac{E_{TNT}}{H_{TNT}}} \qquad \textbf{Equation 4-38}$$

Where:

W_{TNT} [kg] – equivalent mass of TNT or yield

H_{TNT} [J/kg] – heat of combustion of TNT

The heat of combustion of TNT is 4,680 kJ/kg per EPA-550-B-99-009 Section C.1, Equation for Estimation of Distance to 1 psi Overpressure for vapor cloud explosions. However, other values have also been selected, e.g., 4500 kJ/kg was used in NUREG-1805, Section 15.8.2, TNT Mass Equivalent Calculations, and 4,420 kJ/kg was used in the 1995 second edition of the *SFPE Handbook of Fire Protection Engineering* (as cited in NRC Regulatory Guide 1.91).

If the explosive energy is not calculated, the TNT equivalent mass can be determined from:

$$\boldsymbol{W_{TNT} = \alpha_e \frac{(H_f W_f)}{H_{TNT}} = \alpha_m W_f} \qquad \textbf{Equation 4-39}$$

Where:

$\alpha_m = \alpha_e\ (H_f / H_{TNT})$ [dimensionless] – TNT-equivalency based on mass

In order to apply the TNT-equivalency model, a conservative value of α_e (TNT-Equivalency value based on energy) is selected. A brief discussion of practices for choosing these values is provided below.

For stoichiometric, hydrocarbon-air detonation, the theoretical maximum efficiency of conversion of heat of combustion into blast is approximately 40% (CCPS, 1994, Section 4.3.1). In practice, because vapor cloud explosions are usually deflagrations and not full detonations and gas mixtures in air are rarely fully stoichiometric, the efficiency is usually less than 40%.

Table 4-5 provides a range of values of α_e that have been estimated based on past accidents or recommended (see CCPS, 1994 or the original references for further discussion and understanding of their bases to select a conservative value for purpose of the DSA accident analysis).

Table 4-5. Sources for TNT Equivalency Factor Estimations.

References	α_e
Dow Chemical (CCPS, 1994, Section 4.3.1; Brasie and Simpson, 1968)	$0.02 \leq \alpha_e \leq 0.05$
United Kingdom Health and Safety Executive (CCPS, 1994, Section 4.3.1; HSE, 1979)	$\alpha_e = 0.03$
Exxon (CCPS, 1994, Section 4.3.1; unpublished)	$0.03 \leq \alpha_e \leq 0.10$
Industrial Risk Insurers (CCPS, 1994, Section 4.3.1)	0.02
Factory Mutual Research Corp (CCPS, 1994, Section 4.3.1) {Note: These values are also recommended in NRC Regulatory Guide 1.91.)	0.05-0.15
The U.S. Environmental Protection Agency (EPA-550-B-99-005) in its guidance for explosion modeling in the context of its Risk Management Program regulations, recommends: • For worst-case explosion analysis • For "alternative" or "more likely" scenarios	 0.1 0.03

Original sources (as cited in CCPS, 1994):

Brasie and Simpson, 1968. Brasie, W.C. and D.W. Simpson, "Guidelines for Estimating Explosion Damage," Proc. 63rd Nat. AIChE Meeting, American Institute of Chemical Engineers, New York, NY.

HSE, 1979. "Second Report of the Advisory Committee on Major Hazards," Health and Safety Executive, United Kingdom, London, UK.

Industrial Risk Insurers, 1990. "Oil and Chemical Properties Loss Potential Estimation Guide," *IRI-Information February 1, 1990*.

Factory Mutual Research Corporation, 1990. "Guidelines for the Estimation of Property Damage from Outdoor Vapor Cloud Explosions in Chemical Processing Facilities," Technical Report, March.

For other than catastrophic releases (such as a jet release from a vessel containing a gas under pressure or a gas liquefied under pressure, where the release approximates a steady state), it is in principle possible to use an atmospheric dispersion model to determine the amount of fuel at any one time that lies between the upper and lower flammable limits.

EPA-550-B-99-009, Section C.1 assumes that the entire contents of the cloud is within the flammability limits for a worst-case release scenario. As shown in Table 4-5, EPA-550-B-99-009 also assumes that 10% of the flammable vapor in the cloud participates in the explosion blast wave. This Handbook considers the EPA worst-case guidance conservative for the purposes of the DSA accident analysis; however, the TNO Multi-Energy method discussed in the next subsection may be more defensible.

Once W_{TNT} has been determined, the "scale distance" can be calculated by the following simple expression:

$$Scaled\ Distance = \frac{Actual\ Distance}{\sqrt[3]{W_{TNT}}} \Longrightarrow \bar{R} = \frac{R}{\sqrt[3]{W_{TNT}}}\left[\frac{m}{\sqrt[3]{kg}}\right]$$ **Equation 4-40**

This equation has been plotted in Figure 4-17 where the side-on overpressure can be estimated on the vertical axis. The figure is from 1976 a paper by V.C. Marshall, "The Siting and Construction of Control Buildings – a Strategic Approach," *I. Chem. E. Symp. Series, No. 47* (as cited in CCPS, 1994 page 117).

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Alternate correlations to determine the overpressure distance from an explosion have been used in other methods (EPA-550-B-99-005; NRC Regulatory Guide 1.91; ARCHIE, 1989).

There are, however, certain caveats. The TNT-equivalent methodology explosion is a poor model for a gas explosion. In particular, the positive phase duration and shape of the blast waves are not well reproduced. However, TNT-equivalency methods are satisfactory, so long as far-field potential damage is the concern.

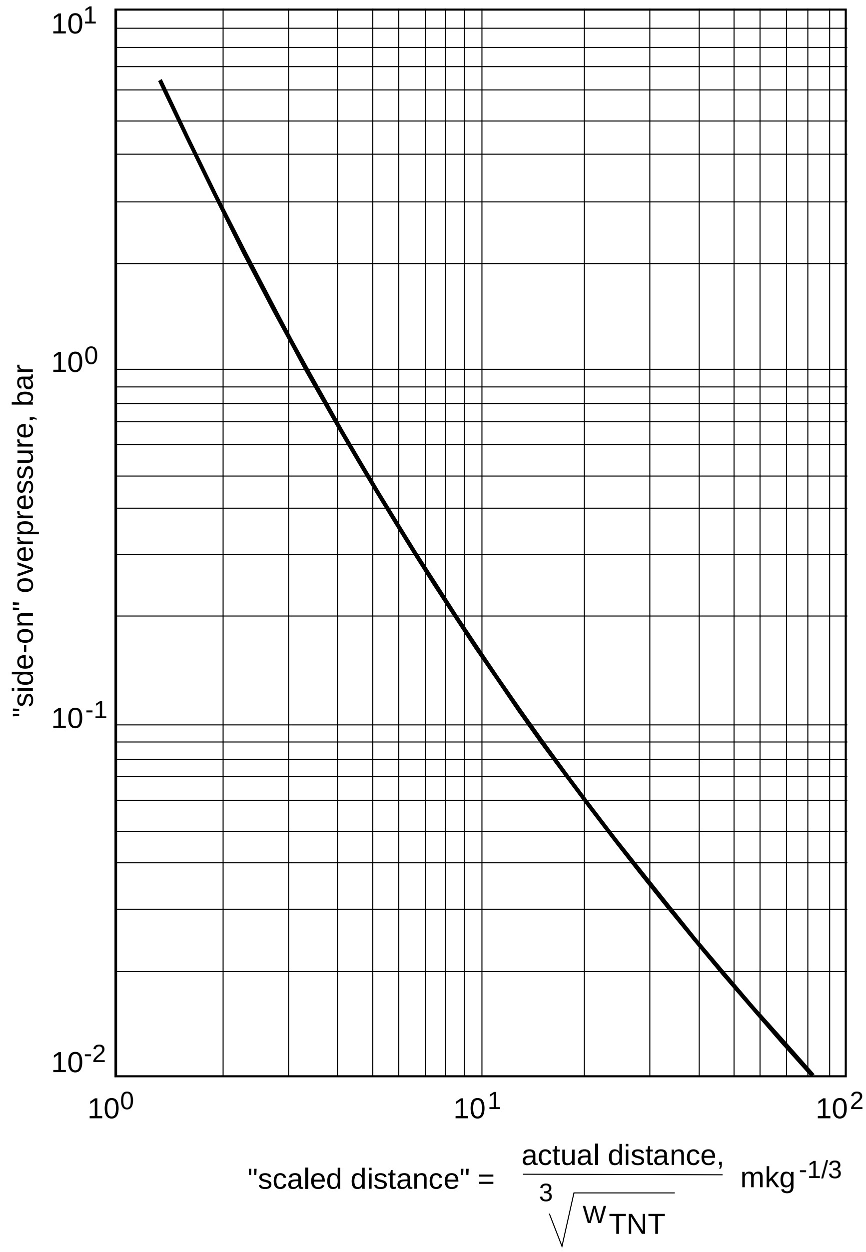

Figure 4-17. Hopkinson-Scaled TNT Charge Blast
(Source: 1976 Marshall paper as cited in CCPS, 1994 Figure 4.18)

TNO Multi-Energy Method

A summary of the necessary steps to apply the TNO Multi-Energy method with the needed calculations is provided in Figure 4-18.

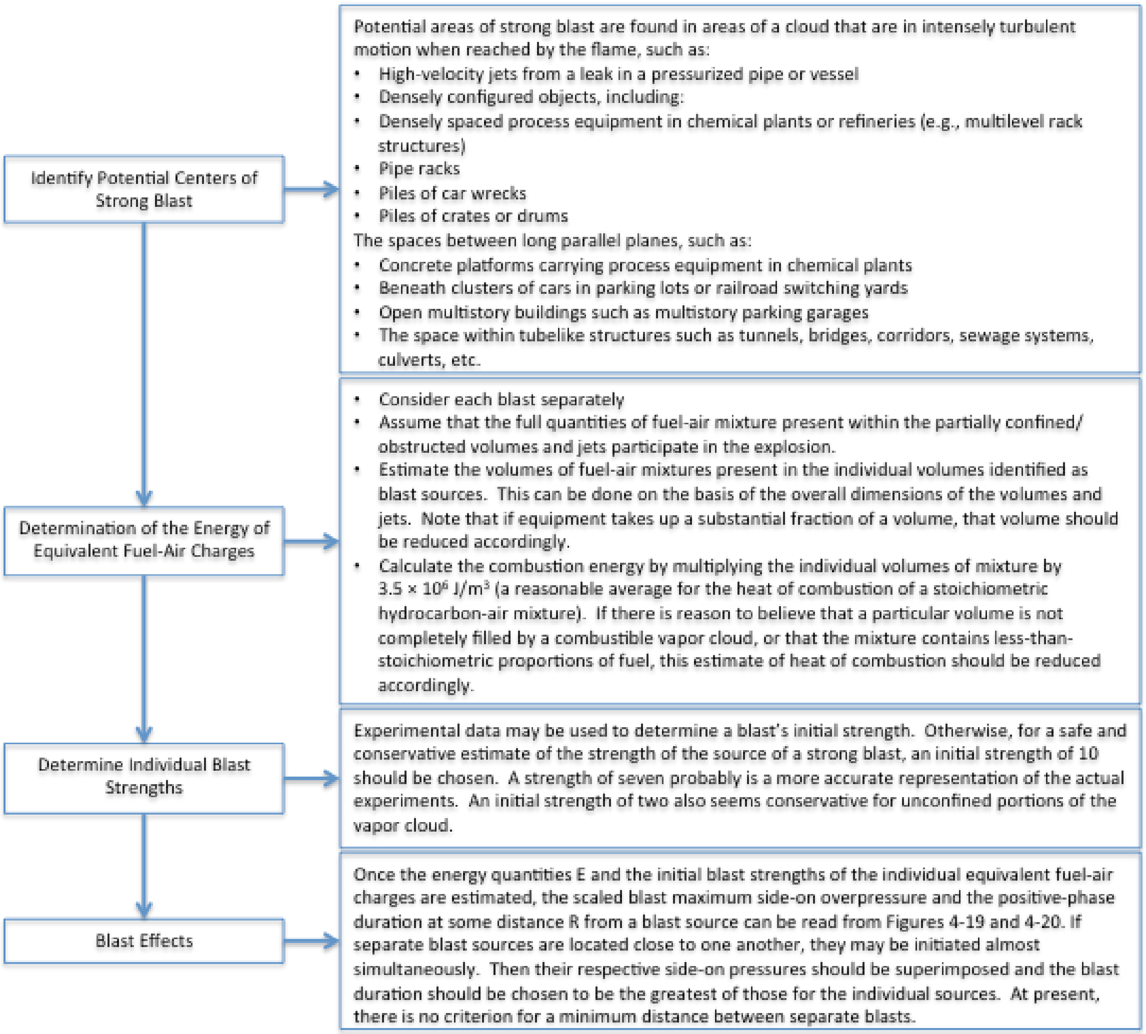

Figure 4-18. Multi-Energy Calculation Method Steps
(Source: Adapted from CCPS, 1994)

The basic tool for the application of the TNO Multi-Energy model is based on a set of scaling equations also known as Sach's scaling equations. Additional information on the Multi-Energy Method to establish a conservative evaluation for the DSA accident analysis can be found in CCPS, 1994, Section 4.3.2, Methods Based on Fuel-Air Charge Blast (other methods are also provided that reference), or in the original development of that method in "The Multi-Energy Method—A Framework for Vapor Cloud Explosion Blast Prediction" (van den Berg, 1985).

The scaling equations are:

$$\overline{R_s} = \frac{R}{\sqrt[3]{\frac{E}{P_0}}} \qquad \textbf{Equation 4-41}$$

$$\overline{t_{+s}} = \frac{t_+ c_0}{\sqrt[3]{\frac{E}{P_0}}} \qquad \textbf{Equation 4-42}$$

$$P_s = \overline{\Delta P_s} P_0 \qquad \textbf{Equation 4-43}$$

Where:

R_s [dimensionless] – energy scaled distance

Once calculated, a number ranging from 1 (very low strength) up to 10 (detonative strength) represents the initial blast strength in Figure 4-19 and Figure 4-20.

In addition, Figure 4-19 and Figure 4-20 show a rough indication of the blast-wave shape, which corresponds to the characteristic behavior of a gas-explosion blast.

R [m] – actual distance from source of explosion

E [J] – charge combustion energy

P_0 [Pa] – ambient pressure

t_{+s} [dimensionless] – positive-phase duration as a function of the combustion

t_+ [s] – the positive-phase duration

c_0 [m/s] – ambient speed of sound

P_s [Pa] – side-on blast overpressure

ΔP_s [-] – Scaled side-on blast overpressure

R_o [m] – charge radius

Once P_s has been estimated form the graphic, use Equation 4-42 to calculate the positive phase duration and Equation 4-43 to calculate the overpressure.

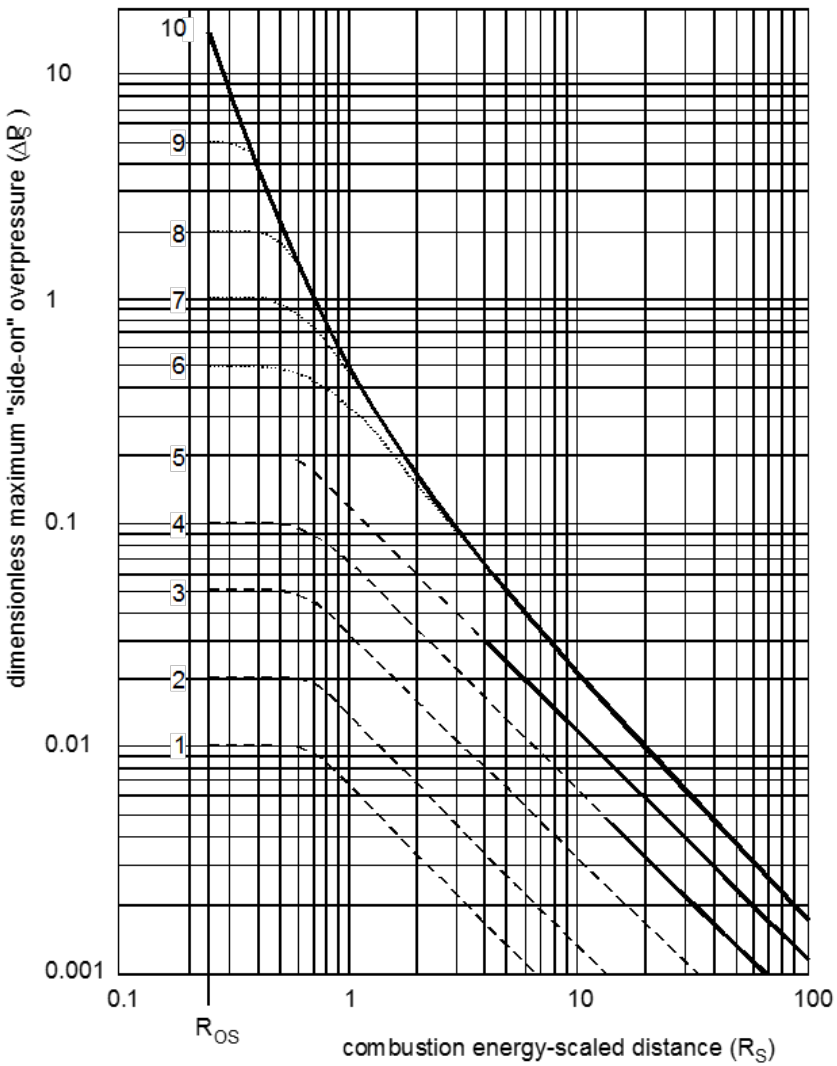

Figure 4-19. Sachs-Scaled Side-on Peak Overpressure of Blast from a Hemispherical Fuel-Air Charge
(Source: Adapted from CCPS, 1994 Figure 4.24)

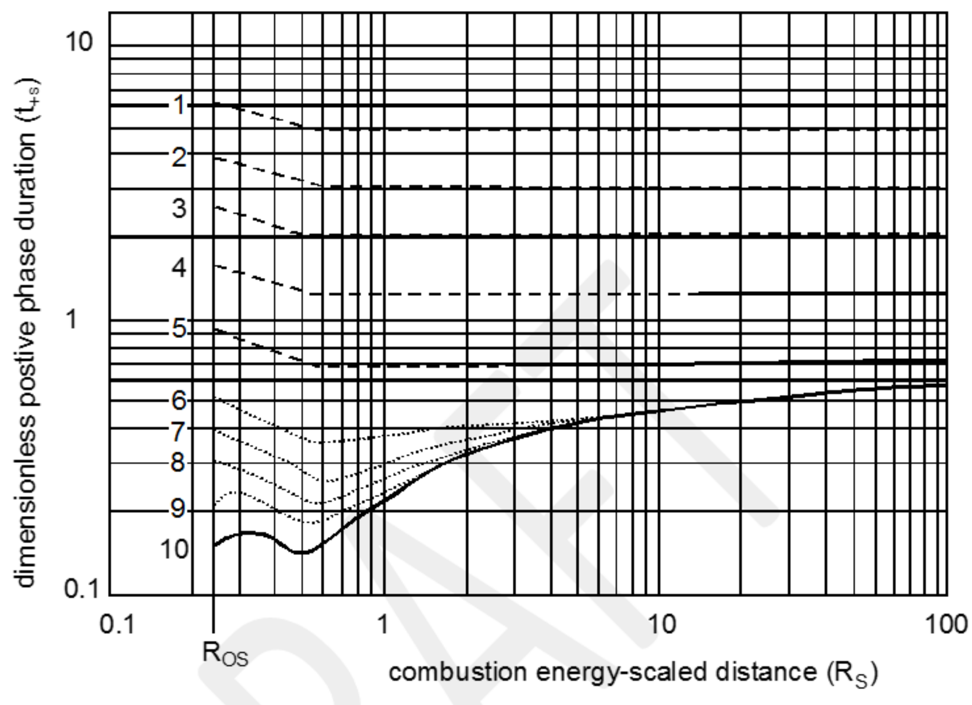

Figure 4-20. Sachs-Scaled Positive-Phase Duration of Blast from a Hemispherical Fuel-Air Charge
(Source: CCPS, 1994 Figure 4.24)

4.3.2.3.5 FRAGMENTATION FROM VAPOR CLOUD EXPLOSION

Fragment effect assessment is not performed for vapor cloud explosion since the vapor cloud is the result of a flammable gas release over time t and it does not involve catastrophic functional failures of receptacles (vessels, containers, jugs) containing the gas, vapor, or mixture. If a vapor cloud explosion is credible, then fragmentation and other failures of SSCs should be considered.

4.3.2.3.6 THERMAL EFFECT FROM VAPOR CLOUD EXPLOSION

The thermal effects from a vapor cloud explosion can be evaluated similar to the thermal effects from a pressure vessel burst with combustion, as discussed in Section 4.3.2.1.3, based on the fire analysis methodologies.

4.3.2.4 FLASH FIRE

A flash fire is the non-explosive combustion of a vapor cloud—it does not produces a blast. (See Section 4.2; see also the scenario description summary in Table 4-1.)

4.3.3 CONSEQUENCES OF EXPLOSIONS BEYOND RELEASES OF HAZARDOUS MATERIALS

Consequences of explosions are characterized for the purpose of the DSA hazard and accident analysis to assess the potential unmitigated damages that explosions can inflict to the public, the co-located workers the facility worker, and to the environment.

Unmitigated consequences of the explosions are grouped in:

- Damages caused by overpressures of vessel burst, BLEVEs and vapor cloud explosions;
- Damages caused by fragmentation of vessel burst and BLEVEs; and
- Damages caused by thermal radiation from the fireball generated after a vessel burst, BLEVEs and vapor cloud explosions.

Section 9.5.5 of this handbook presents a brief summary of consequences of energetic events which includes detonations, deflagrations, BLEVEs, and impacts from radiant heat exposure to fires. This section also discusses ALOHA V 5.4.6 which is a Central Registry toolbox code that is capable of providing quantitative results from each of these energetic events.

4.3.3.1 DAMAGE CAUSED BY OVERPRESSURE (DETONATIONS AND DEFLAGRATIONS)

NUREG-1805 Section 15.8 describes the potential damage from overpressure as follows:

> The damage caused by a shock or blast wave striking an object or a person is a complex function of many factors, and it is well beyond the scope of this chapter to describe all of the complex interactions involved. Instead, we will simply refer to the wave as a rapidly expanding shell of compressed gases. We can then measure the strength of the wave in terms of units of pressure (psi), and we can relate the effects of peak overpressure within the wave (i.e., the maximum pressure in the wave in excess of normal atmospheric pressure) to the level of property or personal injury that is likely to result.

Table 15-1[30] lists damage effects on people and property, which might be expected to result from explosions characterized by various peak overpressures (Clancey, 1972). Peak overpressures in a shock or blast wave are highest near the source of the explosion and decrease rapidly with distance from the explosion site. The extent of damage incurred is heavily influenced by the location of the blast relative to nearby reflecting surfaces.

Table 4-6. Estimated Damage Attributable to Explosive Overpressure.
(Source: Adapted primarily from NUREG-1805, Table 15-1,
with additions as noted from other references)

Overpressure * (psig)	Expected Damage
0.03	Occasional breaking of large windows that are already under strain.
0.04	Glass failure caused by loud noises (143 dB) or sonic booms.
0.1	Breaking of small windows under strain.
0.15	Typical glass failure.
0.4	Some damage to house ceilings; 10% window glass breakage.
0.4	Limited minor structural damage.
0.50–1.0	Windows usually shattered; some damage to window frames.
0.7	Minor damage to house structures.
1.0	Houses made uninhabitable by partial demolition.
1.0	ALOHA V. 5.4.6 PAC: Shatters glass. EPA-550-B-99-009 applies this threshold for vapor cloud explosions to define the endpoint distance for worst-case evaluation. NRC Regulatory Guide 1.91 conservatively selected this value below which no significant damage would be expected, which establishes the safe distance from a source of potential explosions to critical plant structures for a nuclear power plant.
1.0–2.0	Failure and buckling of corrugated metal panels; housing wood panels are blown in.
1.0–8.0	Slight to serious injuries (e.g., skin lacerations from flying glass).
1.3	Slight distortion of the steel frames of clad buildings.
2	Partial collapse of walls and roofs of houses.
2.0–3.0	Shattering of non-reinforced concrete or cinder block walls.
2.3	Lower limit of serious structural damage.
2.4–12.2	Up to 90% eardrum rupture among exposed populations.
2.5	50% destruction of home brickwork.
3	Distortion of steel frame buildings; may pull away from their foundations.
3.0–4.0	Ruin of frameless steel panel buildings.
3.5	ALOHA V. 5.4.6 PAC: Serious injury.
4	Rupture of cladding of light industrial buildings.
5	Snapping of wood utility poles.
5.0–7.0	Nearly complete destruction of houses.

[30] Table 4-6 in this document.

Overpressure * (psig)	**Expected Damage**
7	Overturning of loaded train cars.
7.0-8.0	Shearing of flexure causes failure of 8–12-inch thick non-reinforced brick.
8.0	ALOHA V. 5.4.6 PAC: Destruction of buildings.
9	Demolition of loaded train cars.
10	Probable total destruction of building.
15.5 - 29	Up to 99% fatalities among exposed populations as a result of direct blast effects. (ARCHIE, 1989 Table B.1)

* These are the peak pressures formed (in excess of normal atmospheric pressure) by blast and shock waves.

For SI units, 1 psi = 6.894757 kPa.

Sources:

Clancey, V.J., "Diagnostic Features of Explosion Damage," *Sixth International Meeting of Forensic Science*, Edinburgh, England, 1972 (as cited in NUREG-1805 Table 15-1, Estimated Damage Attributable to Explosive Overpressure (Clancey, 1972)).

Lees, F.P., *Loss Prevention in the Process Industries,* Vol. 1, Butterworth, London and Boston, 1980 (as cited in ARCHIE, 1989 Table B.1, Explosion Overpressure Damage Estimates).

Additional sources added, as identified above:

EPA-550-B-99-009.

NRC Regulatory Guide 1.91, page 3.

ALOHA V. 5.4.6 PAC values.

4.3.3.2 DAMAGE CAUSED BY FRAGMENTATION

Damages caused by fragments originating from an explosion may have a significant impact on surrounding SSCs. Section 4.3.2.1.2 discusses the techniques that determine the characteristics (shape, velocity, angle of elevation) of fragments on SSCs or the MAR. By knowing the characteristics of fragments, it is possible to judge whether a SSC will continue to operate after an explosion.

In the qualitative analysis of consequences to the facility worker, fragmentation injuries to the facility worker should be considered.

4.3.3.3 DAMAGE CAUSED BY THERMAL EFFECTS TO FACILITY WORKERS

The information collected in Table 4-7 summarizes the type of injury that may result from various thermal dose levels. A thermal analysis may be performed to show the thermal dose as a function of distance, and the impact of the thermal dose to the worker. The analysis can be the basis for establishing a barrier around a flammable area to prevent workers from entering the area and becoming potential casualties, unless the workers have appropriate personal protective equipment, or for emergency planning and responses.

However, DOE-STD-3009-2014, Section 2.6.1.3, excludes the minor consequences in the previous paragraph for qualitatively assessing consequence levels for facility worker hazard analysis. If the event is classified as a SIH, then Chapter 4 of DOE-STD-3009-2014 is not applicable. For an explosion that is not a SIH, then the thermal effects as well as physical injury from flying shrapnel need to be considered in the qualitative consequence assessment for the facility worker in the DSA.

Table 4-7. Approximate Rate of Radiant Flux

(Source: NFPA 921 Table 5.5.4.2.8, CCPS 1994 Table 6.6, ALOHA V. 5.4.6 PAC)

Approximate Radiant Heat Flux [kW/m^2]	**Comment or Observed Effect**
170	Maximum heat flux as currently measured in a post-flashover fire compartment. (1)
80	Heat flux for protective clothing Thermal Protective Performance (TPP) Test. [a]
52	Fiberboard ignites spontaneously after 5 seconds. [b]
37.5	Sufficient to cause damage to process equipment. Minimum energy required to ignite wood at indefinitely long exposures. (2)
29	Wood ignites spontaneously after prolonged exposure. [b]
20	Heat flux on a residential family room floor at the beginning of flashover. [c]
16	Human skin experiences sudden pain and blisters after 5-second exposure with second-degree burn injury. [a]
12.5	Wood volatiles ignite with intended exposure [d] and piloted ignition.
10.4	Human skin experiences pain with 3-second exposure and blisters in 9 seconds with second-degree burn injury. [a,b]
10.0	ALOHA V. 5.4.6 PAC: Potentially lethal within 60 seconds.
9.5	Pain threshold reached after 8 s. Second degree burns after 20 s. (2)
6.4	Human skin experiences pain with a second exposure and blisters in 18 seconds with second-degree burn injury. [a,e]
5.0	ALOHA V. 5.4.6 PAC: Second degree burns within 60 seconds.
4.5	Human skin becomes blistered with a 30-second exposure, causing a second-degree burn injury. [a]
4.0	Sufficient to cause pain to personnel if unable to reach cover within 20 s; however, blistering of the skin (second degree burns) is likely; 0 percent lethality. (2)
2.5	Common thermal radiation exposure while firefighting. [f] This energy level may cause burn injuries with prolonged exposure.
2.0	ALOHA V. 5.4.6 PAC: Pain within 60 seconds.
1.4	Thermal radiation from the sun. Potential sunburn in 30 minutes or less.[g]
1.0	Approximate solar radiation intensity on a clear, hot summer day. (2)

(1) NFPA 921 Table 5.5.4.2.8

Original sources as cited in NFPA 921, Table 5.5.4.2.8

[a] From NFPA1971, *Standard on Protective Ensemble for Structural Fire Fighting*.

[b] From Lawson, “Fire and the Atomic Bomb.”

[c] From Fang and Breese, “Fire Development in Residential Basement Rooms.”

[d] From Lawson and Simms, “The Ignition of Wood by Radiation,” pp. 288-292.

[e] From Tan, “Flare System Design Simplified,” pp. 172-176.

[f] From U.S. Fire Administration, “Minimum Standards on Structural Fire Fighting Protective Clothing and Equipment.”

[g] From Bennett and Myers, *Momentum, Heat, and Mass Transfer*.

(2) CCPS 1994, Table 6.6

(3) ALOHA V. 5.4.6 PAC values added above, as identified.

Table 4-8 shows the time restrictions on workers with respect to potential thermal radiation from a fire to avoid reaching the pain threshold.

Table 4-8. Exposure Time t_c to Reach the Pain Threshold.

Radiation Intensity		t_c
[Btu/hr/ft^2]	[kW/m^2]	[s]
500	1.74	60
740	2.33	40
920	2.90	30
1,500	4.73	16
2,200	6.94	9
3,000	9.46	6
3,700	11.67	4
6,300	19.87	2

Source: API 521, 1982, *Recommended Practice 521*, American Petroleum Institute (as cited in CCPS, 1994, Table 6.5, Exposure Time to Reach the Pain Threshold (API 521, 1982).

Figure 4-21 shows the combination of heat flux and time that result in various injury levels to a worker (CCPS, 1994, Figure 6.10).

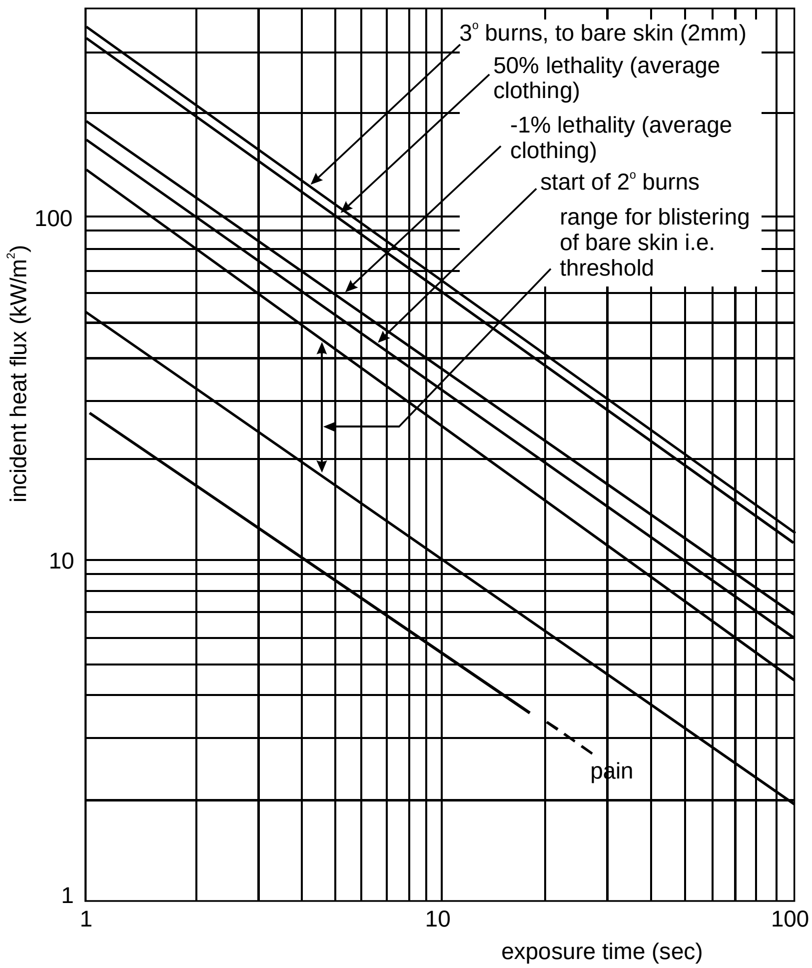

Figure 4-21. Injury and Fatality Levels for Thermal Radiation
(Source: CCPS, 1994 Figure 6.10)

ALOHA, 2013, Section 6.2, Levels of Concern for Thermal Radiation, reviewed the literature to present the technical basis for thresholds that are used in the ALOHA code: 10 kW/m^2 for a fatality; 5 kW/m^2 for second degree burns on unprotected skin; and 2 kW/m^2 for pain. A value of 1.7 kW/m^2 was reported to not even cause pain regardless of exposure time, and the 5 kW/m^2 was based on the U.S. Department of Transportation regulations for liquid natural gas facilities.

4.3.3.4 DAMAGE CAUSED BY THERMAL EFFECTS TO SSCS

In addition to potential adverse personnel impacts, thermal flux can adversely impact SSCs. Thermal flux data can be used to determine appropriate locations for SSCs to prevent adverse effects of a potential fire. A fire analysis as discussed in Section 4.2.2 is completed to determine the potential heat flux over the fire duration. With the transient heat flux profile, it is possible to use Table 4-7 and Table 4-8, to determine potential injury to workers and damage to SSCs.

From Table 4-7 it can be observed that process equipment and buildings suffer severe damage for incident heat fluxes of 37.5 kW/m^2 and 12.5 kW/m^2 respectively. As a rule of thumb, flammable materials in buildings and process installations would be damaged after having been exposed to the above-quoted heat fluxes for longer than 1,000 s (CCPS, 1994).

4.3.4 SOURCE TERM CALCULATION FOR EXPLOSION SCENARIOS

The following discusses the effect of an explosion on radiological and hazardous material in terms of parameters important to the source term calculations, as further discussed in Chapter 5, *Source Term Analysis*. This section provides basic guidance in the determination of MAR, DR, and ARF/RF to estimate the release from an explosion event, and considerations related to release durations. No additional considerations are presented for the selection of a mitigated LPF for explosions since the analysis would be unique for the type of explosion and facility features (refer to Section 5.2.5 for further discussion of LPFs for a mitigated analysis).

4.3.4.1 EXPLOSION MAR

For vessel bursts or BLEVEs, the MAR, quantity, form, and location is subject to assessment of following:

a. For events where the MAR is outside of the exploding vessel, the effects of the blast are assessed as a function of distance.
b. The impacts from fragments over a specific distance. The material could be in the nearby proximity or directly within the reach of fragments projected by the burst vessel.
c. The thermal effects, as the result of thermal radiation produced during BLEVEs. If flammable substances are released out of a pressurized vessel and form a cloud, the impact on the MAR will depend on the distance the MAR is from the edge of the flammable cloud/fireball.

For vapor cloud explosions, the MAR, quantity, form and, location is subject to assessment depending on the conditions where the explosion scenario event develops, for example:

a. A confined vapor cloud explosion causes a uniform pressure rise in the room until the walls/ceiling fails, resulting in potential debris impacts to the MAR throughout the room.
b. For large enough enclosures or unconfined vapor clouds, where no significant over-pressure is predicted; depending upon the size of the vapor cloud; the MAR may be determined by a physical area subject to accelerated airflow that could suspend powders and liquids. If the vapor cloud produces detonation-like overpressures (e.g., as predicted with the TNO Multi-Energy Method), detonation and over-pressurization to rupture (if applicable) explosive forces on the MAR are assessed.
c. No fragmentation is considered since the vapor cloud is the result of a gas release over time. If a vapor cloud explosion is credible, then fragmentation and other failures of SSCs should be considered.
d. Thermal effect is assessed on MAR if the material exposed to the thermal radiation is in the area or in the proximity of the ignited cloud.

Explosions have a primary and secondary effect. The primary effects are discussed above. A secondary effect is the possibility of secondary fires of other combustibles/flammables in the room or facility. These fires could impact MAR that was not directly affected by the original explosion, or serve as a mechanism for damaging the same MAR in a second way.

4.3.4.2 EXPLOSION DAMAGE RATIO (DR)

Generally, a DR of 1.0 is appropriate for the unmitigated case, unless it is feasible to justify a technical basis for a different value. For all explosion cases, the type of explosion, distance, and mitigative and/or design control features are taken into account to justify the calculated results that various types of material and/or quantity either would not or would be subjected to certain physical stresses.

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For vapor cloud explosions, additional considerations include height of the cloud, radius, impulse, and energy content. Fragmentation effects also consider energy deposited at impact, and the size of the fragments.

Section 5.2.2 provides a discussion of DRs. Additional guidance regarding explosions DRs are provided in Section 5.2.2.2, Examples.

4.3.4.3 EXPLOSION ARF/RF

In the development of DOE-HDBK-3010-94, available experiments and other data were correlated with the major types of material forms present at DOE nuclear processing and material handling facilities. The MAR is not necessarily the explosive material, but rather the material exposed to the explosion stresses of shock (detonation) and blast (deflagration) waves from an explosive source. In some cases the material is the explosion source.

The Material at Risk (MAR) pertinent to the major types of radioactive materials that were addressed include:

1. Gases, most specifically tritium;
2. Liquids
   a. Aqueous solutions
   b. Organics, combustible liquids
3. Solids
   a. Metals
   b. Nonmetallic or composite solids
   c. Powders
4. Surface contamination
   a. Contaminated, combustible solids
   b. Solid, noncombustible unyielding surface
   c. HEPA filters – venting of pressurized gases through filters

An important distinction to mention is that the TNT equivalent method, as discussed in section 4.3.2.3.4, is used to calculate shock effects (detonations) on MARs located in the near field (or practically adjacent) where the explosion occurs, but this equivalency should not be associated with the MAR itself, unless any of the listed above materials in question is the explosive source.

4.3.4.4 EXPLOSION RELEASE DURATION

For unmitigated explosions indoors and all explosions outdoors, the release duration for atmospheric dispersion should be the same as the sampling time base for the dispersion parameters (viz., 3 or 10 minutes), as discussed in Chapter 6, *Atmospheric Dispersion*.

For mitigated explosions inside facilities, the analyst may consider the use of a leakpath factor from the facility geometry to effect a longer release time than 3 or 10 minutes. The analyst is cautioned that Section 5.2.4 of this states that the total airborne quantity is assumed to exit the facility at one moment in time because simple physical principles showing holdup may not be available. If crediting the facility with holdup, the analyst should use acceptable physical principles to show that facility holdup is possible, and more importantly, obtain approval from the regulatory authorities that facility holdup is an acceptable mitigation. In many cases, building holdup does not limit the total release but only serves to spread the total release over a longer time period. Section 5.2.4 provides a discussion of events that are not amenable to potential facility holdup calculations.

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For explosions releasing hazardous chemicals located outdoors, the release duration should be considered to be 1 minute when calculating the 15-min time weighted average (TWA) as discussed in Chapter 9, *Chemical Dispersion and Consequence Analysis*.

4.3.5 CASE: SOURCE TERM CALCULATION FOR HYDROGEN EXPLOSION

The source term is dependent on whether a detonation or deflagration occurs. The explosion is modeled in the source term calculation using either the detonation model or deflagration model, depending on the flammable gas concentration.

- If the hydrogen concentration is below the LFL, no event will occur. A concentration of 12% volume at 25 °C and 1 atmosphere is conservatively selected for detonation of hydrogen and air system in vessels.
- If the hydrogen concentration is between 4% and the 12% volume at 25 °C and 1 atmosphere in the hydrogen-air system, a deflagration is assumed to occur.
- If the hydrogen concentration is at 12% or above, a detonation is assumed to occur. There is some uncertainty in the 12% value due to equipment geometry [unfavorable to Deflagration to Detonation Transition (DDT)] and lack of a credible ignition source. However because of the uncertainty in the 12% value, the analyst should use the 12% for hydrogen LEL. The consequences of a detonation are large and it is conservative to assume that the 12% value is appropriate for hydrogen's LEL.

The above values were taken from (Klotz, 2005: Section 2 for the 4% value, Section 5 for the 12% value). Different values apply for other flammable gases. The conditions for achieving DDT deal in particular with the geometry and path of the flame front. Since some process areas have a geometry that is favorable for DDTs (e.g., a tank with numerous obstructions), a concentration of 12% at 25 °C and 1 atmosphere in air has been conservatively used for the DSA accident analysis. Other factors, such as presence of water vapor and energy of the ignition source, affect this parameter and would make a detonation less likely, but are conservatively ignored.

The following subsections are structured to address the important parameters and considerations for selecting MAR, DR, ARF/RF, and release duration, rather than as a narrative scenario of a case study that would be documented for the DSA or its supporting calculation.

The LFL value of 4% for hydrogen should be corrected if used for other than the 25 °C and 1 atmospheric conditions. The following correction is used for air temperature greater than 25 °C (Klotz, 2005, p. 7):

$$LFL_{H2} = LFL_{H2@4\%} - 0.0011 \times (T - 25)$$ **Equation 4-44**

Where:

LFL_{H2} = hydrogen LFL at temperature T, volume %
$LFL_{H2@4\%}$ = hydrogen LFL at 25 °C and 1 atmosphere, volume %
0.0011 = Attenuation Factor
T = temperature, °C

There are different values for the Attenuation Factor in the literature. If a different factor can be justified by the user for their unique situation, then the justification should be provided in the document that the user produces. Different flammable gases have different Attenuation Factors. There are also different correction formulas for LFL in the literature. If a different correction formula is applicable for the event scenario under evaluation, the analyst should consider the different correction formula and provide justification for using the different correction formula.

It is conservative to use no correction for temperature less than 25 °C.

The LFL and LEL values for hydrogen are given at one atmosphere pressure. The data base for LFL and LEL values at other than atmospheric pressure is near zero. Typically, most LFL and LEL calculations are completed for near atmospheric pressure and any potential correction for pressure is negligible. If experimental data become available for pressures different than atmospheric, then the new data should be examined for applicability to the analyst's event scenario. If a pressure correction is needed and no experimental data are available, a suggested correction from the ideal gas relationship is:

$$LFL_{H2} = LFL_{H2@1atm} \cdot \left(\frac{P_{1atm}}{P_{act}}\right)$$ **Equation 4-45**

Where:

LFL_{H2} = hydrogen LFL at pressure P_{act}, volume %
$LFL_{H2@1atm}$ = hydrogen LFL at 25 °C and 1 atmosphere, volume %
P_{1atm} = standard atmospheric pressure, atm
P_{act} = actual atmospheric pressure, atm

LEL values can be corrected using the same formulas as above. However in practice, LEL corrections are seldom performed as the correction is generally very small. Also, hydrogen LEL values in the literature shows some variation from the 12%. A potential small correction to the 12% value is generally not worth the effort.

The hydrogen LFL and LEL values in this section are based on an oxidizing environment of air. A different oxidizing environment could lead to different results.

The preceding paragraphs have discussed the LFL and LEL for hydrogen in air. In many cases across the DOE complex, hydrogen is not the only flammable gas in a vapor space. For a combination of flammable hydrocarbons, Le Chatelier's Law [Joseph M. Kutcha, "Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries – A Manual", Bureau of Mines Bulletin 680, 1985, Equation 35; Michael G. Zabetakis, "Flammability Characteristics of Combustible Gases and Vapors", Bureau of Mines Bulletin 627, 1965, Equation 46] is used to develop a composite LFL or CLFL. Two similar expressions for Le Chatelier's Law are:

$$CLFL = \frac{1}{\sum_i \frac{M_i^{mole}}{M_{tot}^{mole} \cdot LFL_i}} = \frac{1}{\sum_i \frac{f_i}{LFL_i}}$$ **Equation 4-46**

Where:

CLFL = composite LFL, volume %
LFL_i = the lower flammability limit of gas i, volume %
M_i^{mole} = the mole fraction of flammable gas i
M_{tot}^{mole} = the total mole fraction of all flammable gases
f_i = fraction of combustible gas represented by the i^{th} combustible

An example calculation for a vapor space containing two flammable gases follows. Let the fraction of gas1 with a LFL of 2% in the vapor space equal 0.011 while gas 2 with a LFL of 5% has a fraction in the vapor space equal to 0.035. The flammable fraction for gas 1 is 0.011 / (0.011 + 0.035) = 0.239 and for gas 2 is 0.035 / (0.011 + 0.035) = 0.761. The resulting CLFL is:

$$CLFL = \frac{1}{\frac{f_1}{LFL_1}+\frac{f_2}{LFL_2}} = \frac{1}{\frac{0.239}{2\%}+\frac{0.761}{5\%}} = 3.68\% \qquad \textbf{Equation 4-47}$$

The preceding paragraphs have discussed the LFL of gases and potential corrections to the nominal LFL value of a gas. For control of flammable gases, the industry standard for allowable LFL or CLFL conditions is NFPA 69. This standard states that the concentration of a flammable gas is controlled to 25% of the LFL (or CLFL) unless there is real-time monitoring of the gas concentration, in which case the gas concentration is allowed to reach 60% of the LFL or CLFL. In DOE facilities, the control points for flammable gas concentrations are typically the 25% or 60% levels, depending on the control is use. There are cases where LFL (CLFL) levels different than 25% or 60% are allowed, depending on the process and what is allowed by the local regulatory agencies. Also, allowable gas concentrations during accident conditions may be allowed to differ from the 25% or 60% guideline values in NFPA 69.

Controlling LFL or CLFL conditions is typically accomplished with purge flows through the vapor space containing the flammable gas. The purge flow is based on the maximum LFL or CLFL level that is permitted by the facility in question.

4.3.5.1 GAS EXPLOSION SOURCE TERM (ST)

The source term from a gas explosion is based on the TNT-Equivalency model. As discussed in Section 5.2, the source term is determined from the five-factor formula:

$$ST = MAR \times DR \times ARF \times RF \times LPF \qquad \textbf{Equation 4-48}$$

Where:

MAR = material at risk
DR = damage ratio
ARF = airborne release fraction
RF = respirable fraction
LPF = leakpath factor

In fitting this formula to a gas explosion over a liquid containing radionuclides, the TNT equivalent mass from Equation 4-38 provides the equivalent of the MARxDR. If one prefers to define DR = 1, then Equation 4-38 defines the MAR. For an explosion, the ARF/RF is one. The LPF equals one for unmitigated analyses and is usually one for mitigated events as acceptable methodologies for determining LPF values less than one are not available. The end result is that the source term (ST) is simply the result from Equation 4-38. In this example, the TNT equivalent mass model simply converts energy into a quantity of liquid that is vaporized to become a ST for radiological dose calculations.

An additional item should be considered in using the ST from the previous paragraph in determining a receptor dose consequence. This item is whether the radionuclides in the liquid MAR are uniformly distributed throughout the liquid. The ST from the simple TNT model is the surface of the MAR. If settling of solids in the original liquid mass has occurred, then the radionuclide content of the evaporated liquid would be less than the original uniform distribution of radionuclides in the liquid. Another scenario is that the waste material has trapped flammable gas that is suddenly released. As part of the release, there is the possibility that the rising gas bubbles in the waste will bring more hazardous materials to the top layer of liquid that is susceptible to evaporation from the gas detonation.

In the previous paragraphs, the MAR is defined as the quantity of liquid that is evaporated. The original quantity of material in the tank is more accurately termed the MAR.

This treatment for an explosion assumes that the explosion is the only stress imposed on the original mass of liquid involved in the explosion.

4.3.5.2 GAS DEFLAGRATION SOURCE TERM (ST)

Calculations for determining a ST for a flammable gas deflagration are more involved than the calculations for a detonation event. There is no single set of equations available for a deflagration event. Depending on the defined accident scenario from the HA process, there are different paths that a release can take. For example, a deflagration may or may not rupture the vessel or pipe containing the flammable gas that caused the deflagration.

With deflagrations, it is possible to have multiples stresses on the MAR in a vessel, depending on the accident scenario progression. For the deflagration discussion in the following paragraphs, the accident scenario is assumed to occur inside a vessel.

The initial step in a deflagration is to determine the mass quantity that is evaporated from the liquid surface due to the deflagration. The fraction of energy available for evaporation is determined:

$$F = \frac{A_F}{A_W + A_C + A_F}$$ **Equation 4-49**

Where:

E_T - total energy from the combustion of flammable gas
A_F - footprint area (the liquid surface area)
A_W - area of exposed walls
A_C - ceiling area

In this equation, the fraction of the energy (F) that is deposited into the liquid surface is taken to be equal to the fraction of the total surface area represented by the liquid; this assumes that no energy is lost by venting and that the heat flux from the product gas volume is uniform. One difficulty in using the equation is that the liquid level in the vessel experiencing the deflagration can vary, resulting in different values for A_w. To eliminate this potential question on side wall area, A_w can be set to zero and the area ratio reduces to the simple value of 0.5 because for a simple vessel model, $A_F = A_C$.

Equation 4-49 assumes that the flammable gas is uniformly distributed throughout the vapor space. Also, the heat flux from the hot gas after the deflagration is uniform on the vessel walls, vessel top surface, and waste surface that surround the vapor space of the vessel. If a localized deflagration is possible near the waste surface, the analyst will need to justify the use of Equation 4-49 or a possible modification to Equation 4-49.

Once the fraction of energy is calculated from Equation 4-49, the mass quantity that is evaporated from the deflagration is determined:

$$MAR = \frac{E_H * F}{(C_p * \Delta T + H)}$$ **Equation 4-50**

Where:

E_H – Total heat from combustion of flammable gas

C_p - Specific heat of liquid
ΔT - Temperature differential to raise the liquid temperature to boiling
H - Latent heat of vaporization of liquid

As in Section 4.3.5.1, the MAR from the above equation is defined as the actual quantity that is evaporated from the deflagration and not the original mass of the liquid exposed to the deflagration. Typically, the original mass would be defined as the MAR but the value from Equation 4-50 is used as the MAR variable in the five-factor formula.

With a deflagration for a stoichiometric gas/air mixture in an enclosed space, there is a pressure increase and this increase is specific for different gases. This pressure is referred to as the adiabatic, constant-volume combustion constant (AICC) pressure, and the table below provides examples of AICC pressures.

Table 4-9. Constant Volume Combustion Pressures for Various Gases.

Gas	P (bar)
Hydrogen	8.15
Ethylene	9.51
Propane	9.44
Methane	8.94

Source: D. Bjerketvedt, et al., "Gas Explosion Handbook," GexCon, (internet version).

At this point in the analysis, specific information is needed regarding the accident scenario sequence for a deflagration. Possible accident sequences are discussed in the following paragraphs.

One possible accident sequence for the deflagration is that the deflagration has pressurized the vessel, and that the relief is through a simple vent pipe through which the gas flow is not choked. The analyst for a simple unmitigated analysis can use the MAR from Equation 4-50. The unmitigated ST for this MAR is determined from Equation 4-48 with DR = 1, LPF = 1, and ARF/RF = 0.1 × 1.0. This ST is due to the original stress on the MAR. In this scenario, no entrainment of liquid in the vessel occurs and the dose consequence is totally dependent on the ST from Equation 4-50.

A second accident scenario for the deflagration assumes that the vessel containing the deflagration bursts. In this scenario, venting of the pressurized liquid from the vessel occurs as well as the release of the ST from the evaporation of the waste from the first accident scenario in the previous paragraph. Depending on the pressure magnitude (AICC value) and on the location of the venting process, different ARF/RF values are used for the venting calculation. Section 3.1, subsection "Explosive Stress" of DOE-STD-3010 presents information on the selection of ARF/RF values.

A third accident scenario for the deflagration assumes that the vessel breach is well above the liquid level in the vessel. In this scenario, the analyst is referred to the technique described in (Paddleford, D. F. and J. K. Thomas, 1995.) The total ST for this third scenario would be sum of the STs from the volume of vaporized waste and from the mass quantity that is entrained and exits through the breach in the vessel wall.

The above accident scenarios for a gas deflagration do not include all possible STs. The analyst should carefully review the accident scenario as defined by the HA process and determine the appropriate analytical technique to determine the STs.

4.4 SPILLS

A spill is of concern in accident analysis, as it results in an airborne release of radiological and toxic chemical materials from the puddle that is formed through evaporation. DOE-HDBK-3010-94 describes a spill event as follows:

> Material experiences instability/shear stress at the surface of the mass resulting in sub-division of the overall mass. Airflow patterns around and through the material mass, including induced turbulence, accelerate overall sub-division. Mass breakup is further enhanced by impact with ground surface. The material sub-division can generate particles sufficiently small that they remain airborne for a significant period of time.

4.4.1 TYPES OF LOSS OF CONFINEMENT/SPILLS AND SCENARIOS

Spills can be defined as the accidental falling or flowing of material out of a confinement boundary. Spills can result from either a closed confinement system (e.g., sealed drum or tank) or an open confinement system (e.g., open container being handled in a glovebox [GB]). The GB, room, and exterior building walls can also be considered confinement barriers, but these barriers are used to determine the leak path of the spill.

DOE-HDBK-3010-94 provides estimates of ARF/RFs for the following spill/loss of confinement events:

- Free-fall spill of aqueous solutions, 3-m fall distance.
- Free-fall spills of slurries, 3-m fall distance, <40% solids.
- Free-fall spills of viscous solutions, viscosity >8 centipoise.
- Free-fall spills of aqueous solutions, slurries and viscous solutions, fall distances >3 m.
- Free-fall spill of cohesionless powders <3m.
- Free-fall spill of cohesionless powders >3m.
- Suspended solid dispersed into flowing air.
- Aqueous solution, slurries, and viscous liquids (non-Newtonian fluids) spilled onto a hard, unyielding surface.

Spills of powders, liquids, or gases can be initiated via human error or by an external energy source. Examples of such events include puncture of a container by a forklift or missile, crushing of a container, drop of container, or other impact, shock, vibration, and abrasion forces.

For nonvolatile and volatile liquids, evaporation is generally the dominant mechanism for release of hazardous materials. For spills of these types, the surface area of the spill and temperature of the pool formed by the spill dominate the release. DOE- Central Registry Toolbox codes such as EPICode and ALOHA, have pool evaporation models that can be used to evaluate spills of liquids and volatile organic compounds. See Section 9.7 for a further discussion of these codes.

For spills of gases and cryogenic compounds, the impact on surrounding equipment needs to be considered. Concurrent spills of dissimilar compounds from a common-cause event (e.g., seismic) may result in adverse chemical reactions. Analysis of adverse chemical reactions is discussed in Section 4.5 of this Handbook.

4.4.2 ANALYSIS OF SPILLS

The analysis of spills requires the analyst to be able to identify the amount of material that is spilled and the mechanical mechanism involved, that is, the accident phenomenology, so that the MAR, DR, ARF, and RF can be determined utilizing information in DOE-HDBK-3010-94. Spill source terms is further discussed in Chapter 5. NUREG/CR-6410, Section 3.2.3.3, provides the following descriptions of insults to containers or enclosures that may result in a spill:

A. Puncture-Perforation of a container or confinement can release materials in a number of ways. For the release of a volatile material, evaporation is the dominant mechanism (Brereton et al., 1997). Some solids (e.g., phenol) may vaporize/sublime on release from perforated containers. Materials that are flammable gases or have combustible vapors can be vented and, in the presence of an ignition source, result in secondary fires. Solutions with non-volatile solvents and powder may vent if the volume is pressurized and can vent either above the level of the material in the vessel (fragmentation of the liquid by bubble formation and rupture at the surface, or separation of particles at rest by the expansion of the gas in the inter-particle void space) or below it (spray formation of liquids either at temperatures above or below the boiling point of the solvent, or by venting of pressurized volume containing powders). Free-fall spill/release of a solid may be followed by a period of evaporation or even sublimation for volatile solids.

B. Free-Fall Spill (Result of Perforation) - The release and free-fall of liquids and powders can result in suspension from shear stress at the air-material interface. A falling slug can thus shed particles/droplets during the fall. Air resistance can result in the disruption of the face of the falling slug of powder, and particles can be shed into the area of lower pressure resulting from the restoration of the streamlines on the back face of the slug. Impact can induce breakup of solids, powder slugs, and liquids. Volatile materials may evaporate on release (Brereton et al., 1997).

C. Crush-Impact - This phenomenon imposes force on the surface of the material impacted and can fragment both solids (brittle fracture, displacement of powders) and liquids (splashing and droplet formation by displacement and shear). If the force is applied to less than the total surface of the material, fragmentation of the material is limited to the volume that experiences shock wave transmission and reflectance in solids, or the surface area affected for liquids.

D. Shock-Vibration - If the surface is not fragmented, particles lying on the surface (surface contamination, corrosion products) can be jarred from the surface and suspended by vibratory/shock effects.

E. Abrasion - This phenomenon consists of forces applied to the surface layer that induce fragmentation of the surface by mechanical action. Particles generated may be suspended by the mechanical action more efficiently than by aerodynamic forces.

The following three subsections provide a brief treatment of glovebox spills, spills from material handling and waste container accidents, and spills due to over-pressurizations. Aerodynamic entrainment is also briefly treated. Pressurized gas releases are addressed in Section 9.5.2.

4.4.2.1 GLOVEBOX SPILLS

Loss of confinement inside a GB could be caused by an operator inadvertently dropping an open can of material during an operation such as a bagout operation, by equipment failure, or by an airflow reversal. A spill from a can or bottle may occur as the result of a human error while performing some particular action in the GB. A chemical reaction could also occur either inside or outside a container, resulting in a container breach. The MAR is the amount of material that could be spilled from the GB. The DR represents the amount damaged from the accident, while the ARF/RF can be determined by the energy of the released material if any is imparted on it from the release event, height of the release, and environmental conditions (i.e., temperature, pressure, humidity) into which the spill occurs. The release from the glovebox into the process room is of interest for evaluation of consequences to the FW, while the release to the environment is of interest for evaluation of consequences to the CW and MOI.

4.4.2.2 MATERIAL HANDLING AND WASTE CONTAINER ACCIDENTS

A number of energy sources can cause a spill or loss of confinement during material handling. The movement of waste containers or primary containers with dispersible forms of Pu or U used in processes can be subjected to such energy sources. The most common include: (1) kinetic energy sources such as maintenance equipment (e.g., drills, grinders), handling equipment (e.g., forklifts), and internally generated missiles (e.g., shrapnel from failed rotating plant equipment); (2) potential energy sources (e.g., high storage shelves); (3) NPHs (e.g., earthquakes); and (4) man-made external events (e.g., airplane crashes). In addition, chemical reactions such as from nitric acid or chlorinated solvent corrosion of the container and exothermic pyrophoric Pu reactions can also fail the primary confinement boundary. Loss of confinement events involving a single drum, crate, or container can result from all energy sources during handling operations. Events involving multiple drums, crates, or containers require a large energy source from mechanical equipment such as a forklift truck.

Table 4-10 provides an example of an approach for defining spill sizes for handling accidents for containers without interior packaging and for tanks/piping. Evaluating different spills sizes may be important if the preventive or mitigative controls that need to be credited are different, otherwise, the bounding spill size important to establishing the safety basis within a likelihood category is generally evaluated.

Spill sizes, however, depend heavily on spill type, interior packaging, size of packaging, internal pressure, orifice size, and form and type of hazardous material. For example, the amount of material released from a drum punctured by a fork lift may be different from the amount released from an identical drum that fell from the top of a stack of drums from the effects of an earthquake. Also, if the material within a container is packaged in additional containers, such as plastic bags, not all of these interior containers would be breached in an accident. A drum puncture, for example, would probably breach only one interior container, so that the amount of spilled material (i.e., MAR) would be reduced by a factor equal to the number of bags in the drum, assuming each bag contains the same amount.

Table 4-10. Spill Sizes for Handling Accidents.

Spill Size	Drums	Tanks/Piping
Small	one drum	≤10% content of tanks/piping
Medium	Two to three drums	>10% but <50% content of tanks/piping
Large	≥ four drums	100% content of tanks/piping

4.4.2.3 OVER-PRESSURIZATIONS

Over-pressures can result from a build-up of pressure in a container through increasing temperature or through radiolysis, or from the force of a pressure wave of an explosion. For a pressurized container, a small hole in the vessel can result in a spray release of liquid or rapid depressurization and release of powder whereas a rupture of the container of powder would release a cloud of powder. Explosions that cause over-pressurizations are discussed in Section 4.3.

4.4.2.3.1 PRESSURIZED POWDER RELEASES

If the gases in and around a powder are compressed, the gases will expand rapidly during a sudden release of pressure, resulting in airborne dispersal of the powder. Experiments involving the venting of pressurized powders is discussed in Chapter 4, Solids, of DOE-HDBK-3010-94, in which different amounts of powders are subjected to sudden venting under a variety of over-pressures. In general, the larger the over-pressure the larger the amount of powder that becomes airborne, but does not change the original host material particle size distribution.

4.4.2.3.2 PRESSURIZED LIQUID RELEASES

There are three main regimes of pressurized venting of liquids: (1) venting below liquid level, (2) venting above liquid level, and (3) venting of superheated liquid (i.e., flashing spray). This phenomenon covers general pressurized venting, including deflagration induced pressurized venting effects. Experiments involving the venting of pressurized liquids is discussed in Chapter 3 of DOE-HDBK-3010-94. Further discussion is provided in Section 9.5.2 of this handbook.

4.4.2.4 AERODYNAMIC ENTRAINMENT

Aerodynamic entrainment needs to be considered in two situations: (1) air flow past material spilled on the floor or ground, and (2) backdraft of a confinement ventilation system.

Air and other gases passing over a surface or directed onto a surface can induce flow and turbulence that can suspend particles on or from the surface impacted. The presence of obstructions around or over the surface can affect the air flow and, therefore, the suspension of materials from the surface. Sources for gases at accelerated velocities are the passage of or impact by the pressure impulse generated by explosions, ambient or extreme wind conditions, or other conditions such as indoor ventilation airflows.

In DOE-HDBK-3010-94, the approach has been to consider aerodynamic entrainment or resuspension[31] conditions as best evaluated for quantification of hazardous release scenarios using empirical relationships based on field and laboratory data. While the transport phenomena described in Chapters 6 and 9 are applicable to these situations and improve the understanding of the effects of these phenomena, the analyst is directed to Chapter 5 for quantitative inputs applicable to the accident conditions being addressed so that the physical release potential from aerodynamic entrainment/resuspension is conservatively estimated as defined for the DOE-STD-3009 unmitigated analysis. Two scenarios below are discussed in more detail.

- **Air flow past spilled material:** An airborne release rate (ARR), and the length of time that air is flowing past the material, are required to estimate the potential airborne release from postulated accident conditions. In some situations, the release rate may not be uniform with time.

- **HVAC backdraft (or flow reversal):** For the airflow reversal scenario resulting from a loss of HVAC Zone I functionality, a GB breach could occur and result in the release of holdup material in the GB and exposed material in open containers within the GB. Since the Zone II Ventilation System is still functional, the rest of the building ventilation system is operating under partial system flow or even near normal ambient conditions depending upon the ventilation system design. Other factors that affect the airflow reversal scenario are the DR for the holdup material and the release duration.

4.5 ANALYSIS OF CHEMICAL REACTIONS

Several specific chemical reactions rise from the hazards analyses and may require accident analysis due to their ability to contribute to the airborne release of radioactive materials or toxic chemicals in nuclear materials processing and waste management as they can lead to loss of confinement, fire and/or explosions. This section briefly discusses a selection of reactions relevant to DOE accident analysis, including:

- Organic-Based Ion Exchange Resin Reaction;
- “Red Oil” Reaction;
- Organic Reaction Event; and
- Hydroxylamine Nitrate Reaction.

This information may be useful in identifying and analyzing chemical reaction events. It may also be useful to determine whether a fire, explosion, or loss of confinement may occur (which can be further evaluated per information provided in Sections 4.2, 4.3, and 4.4 of this handbook).

4.5.1 ORGANIC-BASED ION EXCHANGE RESIN REACTION

Synthetic ion exchange resins are used in nuclear processing operations such as with plutonium nitrate solutions. Because the separation and purification processes involve contacting nitric acid solutions with

[31] Resuspension as used when referring to the stress caused by an accident or to calculate the airborne source term, refers to the initial suspension of materials from the surface of the particulate mass being affected by the accident stress or air turbulence. This should not be confused with a more limited definition of resuspension used in the Chapter 6 and 7 atmospheric dispersion analyses that refers to the amount of contaminated materials initially deposited as the plume travels downwind that becomes airborne again due to wind effects overcoming saltation.

organic materials, conditions for safe operation should be clearly defined and resolutely maintained.

Under conditions of rapid reaction between nitric acid and organic materials, the nitrogen oxides produced by the reaction are also reactive, and this further tends to accelerate the reaction. The result in a confined system can be rapid and accelerating pressurization, with the resulting hazard of bursting the ion exchange column or vessel.

The presence of a large number of active sites designated to exchange ions accompanied by extensive polymer cross-linking in the overall resin matrix creates an inherent potential for instability in the type of resin used. Under the right circumstances, this instability can be expressed in a wide variety of exothermic reactions. A variety of reactions is possible, but once the thermal excursion reaches an autocatalytic state, an over-pressurization incident of some type is the inevitable result.

Various types of theoretical models for assessing the airborne release have been postulated. Precedents within DOE for source term estimation have used the model of a thermal explosion since this model seems to predict damage that best matches what has been historically observed. The model is based on exothermic resin degradation reactions, including the recombination of plutonium with nitrate. In thermal explosion events, the initial source of the resin exotherm is highly localized. The localized area may dry out the resin and heat it above the resin autocatalytic ignition temperature, at which point the column condition can no longer be stabilized. Accelerated heat and gas generation results in rapid pressure build up to the onset of structural failure of the ion exchange vessel.

A pressurized spray of superheated liquid occurs when the vessel fails either catastrophically or leaks. For a catastrophic failure, the amount of release depends on the failure pressure of the ion exchange column since this will determine the degree of superheating. The ARF increases with higher degrees of superheat. Assuming the properties of water as expressed in the steam tables, a superheat of 50 °C corresponds to 0.76 MPa (110 psia), and a superheat of 100 °C corresponds to 3.1 MPa (450 psia). If the accident occurs with process solutions present, the ARF should be obtained from DOE-HDBK-3010-94, Section 3.2.2.2 for blast effects over the surface of the liquid and Section 3.2.2.3 for venting below or above the liquid surface, and Sections 4.4.2.2 and 4.4.2.3 for blast effects and venting of solids/powders, respectively. Ignition of the dried-out organic resin, such as polystyrene resin, whether still in the ion exchange column or packaged as waste, may occur before, during, or after the explosion and represents another potential source term mechanism (1E-2 ARF / 1.0 RF per Table 5-1 of Chapter 5).

4.5.1.1 REACTIONS OF NITRIC ACID WITH ORGANIC MATERIALS

Nitric acid, in addition to being a strong acid, is a powerful oxidant when concentrated. It "reacts violently with many organic compounds, for example turpentine, charcoal, and charred sawdust. The concentrated acid may react explosively with ethanol. Nitric acid is used with certain organics, such as furfuryl alcohol and aniline, as rocket propellant" (Clarke and Mazzafro, 1996). The explosive properties of such reactions are aggravated by the production of gaseous reaction products, including steam, carbon dioxide, and nitrogen oxides. The concentrated acid can induce nitration in many organic compounds, including both aromatic and aliphatic hydrocarbons, and the products may be unstable to shock or heat.

The nitrating reaction of concentrated HNO_3 with organic materials proceeds by one of several mechanisms. With aromatic compounds and alcohols, the reaction is believed to involve the ion NO_2^+. Consider a reaction of nitric acid (HNO_3+) with benzene (C_6H_6) and ethanol (C_2H_5OH).

Reaction of nitric acid with aromatic compound and ethanol

$$HNO_3 + C_6H_6 + C_2H_5OH \Longrightarrow NO_2^+ + H_2NO_3- + H_2O + 8CO_2 \quad \textbf{Equation 4-51}$$

From the principles of mass action, it is evident that in strong acid this equilibrium is shifted to the right. In dilute nitric acid, this equilibrium is shifted to the left and the rate of nitration is negligible. The addition of sulfuric acid favors the nitrating reaction, and sulfuric acid is used for this purpose in the chemical industry.

Another mechanism that leads to the nitration of aliphatic hydrocarbons involves reaction of the NO_2 radical. This normally occurs only with concentrated acid at very high temperatures. However, ionizing radiation produces this radical in nitrate solutions (Miner, 1969), making such reactions possible at ordinary temperatures. Nitric oxide also reacts with metal to create hydrogen gas. Other hazards involving nitrates and organics are mentioned in Section 4.5.3.

4.5.1.2 COMPOSITION AND REACTIONS OF ION EXCHANGE RESINS

Synthetic ion exchange resins are made in many types, and used for a wide variety of industrial purposes. Those used in nuclear separations processes are primarily of two types: cation exchange resins, and strong base anion exchange resins. Both cation and anion exchange resins are composed of polystyrene with active sites chemically bound to the aromatic rings. Cation resins contain sulfonic acid groups, which carry a negative charge and bind the positively charged cations through electrostatic forces. The active sites in anion resins are quaternary amine groups, which take on a positive charge that need to be neutralized by a negative ion.

Other active groups, such as chelating agents, are sometimes present in resins used for specialized purposes, such as concentrating samples for chemical or radiochemical analysis. Full characterization of ion exchange resins requires specifying resin bead sizes and the extent of cross-linking. Small resin particles permit more rapid exchange, but offer greater resistance to flow. Development of macroreticular resins, which contain large channels that facilitate diffusion, has enabled improved sorption and desorption kinetics. The extent of cross-linking determines the rigidity of resins, and their tendency to shrink and swell as the solution composition varies.

4.5.1.3 CHEMICAL DEGRADATION OF ION EXCHANGE RESINS

Both strongly basic anion and cation resins are quite stable in neutral and moderately acid aqueous solution at ordinary ambient temperatures. Strong-base anion resins are used for plutonium and neptunium separations at nitric acid concentrations in the range of 6 to 8 molar (M). Chemical degradation of the resin is unimportant under these conditions. However, at higher acidities there is an increasing likelihood of reaction between the nitric acid and the amine groups that give the resin its character. The rate of nitric acid reaction with the resin also increases with temperature. Acidity control and low temperatures are therefore important safety factors. For example, at the Savannah River Site, column temperatures during anion exchange processing of plutonium are limited to a maximum of 60 °C, and the nitric acid concentration is held below 9 M. Temperature control becomes especially important when processing highly radioactive alpha-emitting isotopes, such as Plutonium-238 or Americium-241. In these, nearly all the decay heat is released within the ion exchange bed on which they are sorbed.

A number of incidents have occurred in the chemical process industry when weak-base anion resins were exposed to nitric acid. A review has recommended that nitric acid not be used with these resins, as they are apparently more sensitive to attack by nitric acid than the strong-base resins (Calmon, 1980). Calmon also recommends that the presence of ions such as copper, which may catalyze resin decomposition, should be excluded from processes involving nitric acid and resins.

4.5.1.4 RADIATION EFFECTS ON ION EXCHANGE RESINS

Like all organic material, synthetic ion exchange resins are degraded by ionizing radiation. Although aromatic compounds are less vulnerable to radiation degradation than aliphatic compounds, ionizing radiation can still break chemical bonds within the ring and elsewhere in the resin. Additionally, free radicals formed by radiolysis of water in the resin bed can remove bound hydrogen or attach to the resin. Substituent groups may be removed, and the resin backbone may cross-link. The extensive literature on radiolysis of ion exchange resins has been reviewed by Pillay (1986). Again, the highest radiation dose rates are associated with short-lived alpha-emitting isotopes, which release nearly all their radiation into the bed on which they are sorbed.

Empirical relationships have been developed to establish the maximum radiation dose that a resin can tolerate. For very radioactive material, such as Curium-244, only a single use of a given resin batch may be allowed. For less radioactive material, such as Plutonium-239 or Neptunium-237, repeated use over a long period is allowable. The U.S. Nuclear Regulatory Commission (NRC) adopted a maximum allowable dose to anion resin of 1E+08 rad (1E+06 gray) based on a survey of practices in the nuclear power plant industry and considering uncertainties (NUREG/CR-2830, *Permissible Radionuclide Loadings for Organic Ion-Exchange Resins from Nuclear Power Plants*), a value that also has been adopted at some DOE sites such as Savannah River (Smith, F.G., et al., 2007). Generally, the effectiveness of the resin as a separations medium begins to degrade before nitration makes the resin itself a reaction hazard. However, the handling of spent resins should take into account the possibility of radiation-induced nitration, which makes the resin more flammable and more easily subject to chemical degradation.

4.5.1.5 INCIDENTS INVOLVING CHEMICAL REACTIONS OF RESINS

A number of events, including vessel rupture, fire, and explosion, have occurred in ion exchange equipment exposed to nitric acid. Calmon (1980) has reviewed 14 events occurring prior to 1980, including 8 in nuclear processing operations. Pillay (1986) cites 13 articles dealing with incidents in the nuclear industry, including those cited by Calmon. Several of these incidents were reviewed by Miles (1969). There has also been at least one serious incident in Russia that has not been described in western literature. It was informally reported during bilateral meetings on safety at Hanford in 1993.

Cation resin is considered less vulnerable to degradation than anion resin. However, a major incident in 1976 (BNWI--107) involved the explosion of a cation column at Hanford that had been loaded with more than 100 g americium, and allowed to stand for more than five months as the result of a plant shutdown. The resin was Dowex 50, 8 percent cross-linked, and the liquid phase was 7 M nitric acid. The column was 6-in. schedule 10 stainless steel pipe. On resumption of work, the column pressurized and burst violently, causing considerable damage and one serious injury. The resin had been exposed to a high radiation dose from absorbed americium during the outage. It is unclear whether the pressure relief vent was open at the time of the accident.

The Russian incident of 1993 involved an anion column loaded with the highly radioactive isotope Plutonium-238. As the result of a valve leak, the column dried out, and the cooling jacket was unable to maintain the central part of the column at a safe temperature. (Heat transfer through dry resin is poor.) The resin was heated by the radioisotope and reacted with enough violence to burst the column. This operation was in a remote facility, and there was no personal injury. However, cleanup and repair were very difficult.

4.5.1.6 DISCUSSION OF ACCIDENT CONDITIONS

Precautions against resin reactions are of two types: (1) those that prevent the reaction from occurring, and (2) those that mitigate the results.

Precautions to prevent a runaway reaction include temperature control, acid concentration control, and providing adequate cooling. Because most of the heat transfer within a column of resin involves the aqueous phase the column should not be allowed to dry out. At the Savannah River Site, a maximum flow interruption of 48 h is allowed for processing Pu-239, and a maximum interruption of 15 min is allowed when processing Pu-238. Maintaining flow carries away heat, and helps prevent the formation of bubbles in the resin bed. As previously indicated, maximum values for radiation doses (10^8 rad), nitric acid concentration (9 M) and temperature (60 °C) are also imposed. The values chosen were based on experience and on the results of laboratory studies of the materials and reactions.

Another method of prevention is to use resins less susceptible to these phenomena. For new resins or processes, the reactivity of the system should be determined using techniques such as thermogravimetric analysis, differential thermal analysis, and differential scanning calorimetry.

Mitigation primarily takes the form of venting. The design of vents should take into account measured reaction rates and the corresponding gas generation. Design is important; vents should be of the "ever open" type wherever possible. Where this is not possible, as in high-pressure separations systems, careful analysis of the system and control of operating parameters is important to ensure safe operation.

4.5.2 "RED OIL" REACTION

4.5.2.1 BACKGROUND AND PRIOR RED OIL INCIDENTS

The Plutonium Uranium Extraction (PUREX) solvent extraction process (and its variants) uses tri-n-butyl phosphate (TBP) and concentrated nitric acid as two principal components (>70 wt% HNO_3). These components, under certain extreme conditions of heating (temperatures greater than 135 degrees C) and strong nitric acid concentration, can react in an uncontrolled manner that could result in very serious consequences such as over-pressurization and rupture of a vessel, and fire or deflagration of flammable gases generated. The stronger the concentration of the nitric acid, the more violent the reaction. In the absence of high temperatures, or the presence of dilute nitric acid (e.g., 30 wt% HNO_3), this reaction does not occur.

Incidents with TBP and concentrated nitric acid are often referred to as "red oil" incidents because of the red oily intermediates that form in the TBP phase in the course of the reaction. The red oily intermediates are nitrated compounds that are flammable and produce significant amounts of NO_x gases. Red oil looks similar to the red fumes present with red fuming nitric acid (> 90 wt% HNO_3).

The consequences from a TBP/nitric acid runaway reaction (i.e., "red oil explosion") can vary significantly depending upon assumed initial conditions and vessel design and other factors, which influence the accident progression. Common to all scenarios is the oxidation of TBP by nitric acid or nitrates dissolved in it. Possible scenarios range from benign reactions to intense uncontrolled reactions followed by primary vessel failure and/or flammable gas deflagration. Small-scale reactions between

TBP and nitric acid can result in slow reactions similar to boiling and a more reactive scenario. In the slow reaction, the release of radioactivity from the vessel would be very small due to a small airborne and respirable release fraction product of 3E-5 ARF / 1.0 RF (see Chapter 5, Table 5-1 for simmering liquid). In the more reactive scenario in which the solution boils, the fraction of radioactivity released could be as high as 2E-3 ARF / 1.0 RF (see Chapter 5, Table 5-1). (See also the DOE-HDBK-3010-94, Section 3.2.2.2 for blast effects over the surface of the liquid; Section 3.2.2.3 for venting below or above the liquid surface). For worst-case uncontrolled reactions of large quantities of TBP and nitric acid in vessels without adequate venting, an ARF/RF as high as 1E-1 has been postulated based on insights from the Tomsk-7 accident considering source term contributions from the initial explosion that ruptured the vessel, subsequent deflagration of combustible gases released into the room that blew out the building walls, and the ensuing fire (Howard, 1994).

While proper vent area will ensure process vessel integrity, a pressurized radiological release or free-fall spill of liquids would be expected. Also, the consequences of potential flash fire or deflagration of the vented gases on containment structures should be evaluated as well as radiological source terms based on the type of accident stress.

Several reported incidents of damage have occurred in the nuclear industry as the result of high-temperature reactions between TBP and nitric acid or nitrates. The most recent was the damaging explosion at the Tomsk-7 nuclear fuel reprocessing plant in Russia during April 1993 (Hyder, 1996; IAEA, 1998). At least four incidents in North American plants have been attributed to such reactions. Two of these were at the Savannah River Site. One other incident in the Soviet Union has been informally reported.

Damaging incidents occurred at Hanford and the Savannah River Site in 1953 (Colven et al., 1953; Campbell and Mailen 1998). In each case, TBP solution was inadvertently allowed to enter an evaporator in which a nitrate solution was being concentrated at a relatively high temperature. The damage at Hanford was minor; however, the unit at the Savannah River Site was destroyed by the explosion. Temperature controls were established by the two sites following investigations of these incidents, and these have successfully prevented any recurrence within the DOE complex. However, an incident that damaged a Canadian evaporator in 1980 appears to have been caused by a nitrate-TBP reaction (Hyder, 1994a).

A damaging incident at the Savannah River Site in 1975 resulted from the accidental introduction of TBP into a vessel in which uranyl nitrate was being calcined (Gray, 1978). In this case, the calciner was adequately vented, but flammable fumes were released to the process room and ignited, producing a fireball deflagration and a pressure wave loading in that blew out the lightly constructed walls.

The explosion in the Tomsk-7 plant involved reaction of strong nitric acid with organic material originating from the PUREX solvent extraction process. The organic material was not well characterized but presumably contained TBP and its degradation products. The materials were contacted in a tank that also contained evaporator bottoms (probably still thermally hot). There was no venting or pressure relief until a substantial pressure had been generated in the vessel. During a period of about 100 min, an accelerating reaction occurred that overwhelmed the pressure relief and finally burst the vessel. Substantial damage to the building was done by the resulting pressure wave and/or ignition of flammable gases released from the vessel.

Investigations of the above incidents have produced much of the available information on TBP-nitrate reactions. Hyder (1996) summarized investigations regarding TBP-nitrate reactions and provided an interpretation of the experimental results and their pertinence to past incidents. Experimental studies were conducted at the Savannah River Site by Nichols in the 1950s (Colven et al., 1953) and by a team under Harmon in the middle 1970s (Harmon et al., 1976). Other investigations have been made at Hanford (Wagner, 1953; Watkins and Gordon, 1993), by the Du Pont Engineering Department at the Savannah River Site (Hyder, 1996), and in Russia (Vladimirova et al., 1991). Additional studies have been conducted at the Savannah River Site and Los Alamos (Hyder, 1994b; Davis et al., 1966; Smith and Cavin, 1994; Fauske, 1994).

The Defense Nuclear Facilities Safety Board issued a technical report on red oil hazards and explosions, DNFSB/TECH-33**,** *Control of Red Oil Explosions in Defense Nuclear Facilities* (2003). It is an assessment of the potential for a red oil explosion in the DOE defense nuclear facilities complex. This reference describes the connection between the process of solvent extraction and red oil production, identifies the types of process equipment and the necessary materials capable of producing red oil, defines what red oil is and what conditions cause it to decompose in a runaway reaction, summarizes four of the previous red oil events described above, and provides discussions of controls for prevention or mitigation of a red oil explosion (generally categorized as controls for temperature, pressure, mass, and concentration).

Reactions of concern involve oxidation of TBP by nitric acid or nitrates dissolved in it. The oxidant content is a small fraction of the amount required for complete oxidation, and most of the TBP is unaffected by this reaction. In sealed tubes the products include principally carbon monoxide, carbon dioxide, water, nitrogen gas, nitrogen oxides (NO and N_2O), and phosphoric acid. Other non-volatile organic materials are also produced, but have not been well characterized. In open vessels, intermediate products such as NO, NO_2, and CO can escape, and the amount of oxidation is less. The heat produced is also much less, as reactions giving these products are less energetic. Heat produced ranges from a measured value of about 100 cal/g in DTA experiments (Watkins and Gordon, 1993), to a calculated value of about 340 cal/g for sealed-tube experiments (Hyder,1994b).

At high temperatures (above 130 C), TBP is thermally decomposed to 1-butene and phosphoric acid. This appears to be the principal source of flammable gas produced in this reaction. This decomposition is endothermic and requires the oxidation reaction (or some other heat source) to produce the necessary heat (Harmon et al. 1976; Watkins and Gordon, 1993).

TBP that has been contacted with aqueous solutions will contain some water (Davis et al., 1966). Savannah River Site experiments (Smith and Cavin, 1994) have shown that heat removal by evaporation is very effective if the water content can be maintained and water vapor removed by proper venting of the atmosphere above the TBP. Hanford experiments have also confirmed this phenomenon (Watkins and Gordon, 1993). Further, the experiments indicate that if the vessel were adequately vented, the transport of water from the underlying aqueous phase to the TBP phase would be sufficient to maintain continuous evaporation and a net cooling.

Formation and thermal decomposition of red oil during unit operations of nuclear fuel cycle process flowsheets is a severe risk. Solvent extraction is a cost effective industrial process to recover, purify, or separate metals. Although several solvents can effectively extract uranium, plutonium, or thorium from acid solutions, the commercially chosen solvent is only TBP. Results of unique experiments on adiabatic thermal decomposition of red oil, red oil equilibrated with excess of 4N nitric acid and 100% TBP equilibrated with excess of 4N nitric acid are discussed (Kumar et al., 2011). The provision of sufficient vent area in the equipment to avoid closed-vent conditions during worst case scenario needs to be considered (Kumar et al., 2011).

If sufficient venting of process vessels is available for the quantity of TBP present, failure of the process vessel can be precluded. The basis for determining the proper vent area is the work by Fauske & Associates for the Savannah River Site (1994). In this experimental work a number of tests were performed with the Reactive System Screening Tool (Creed and Fauske, 1990) and Vent Sizing Package (Fauske and Leung, 1985) calorimeters. These small (10 ml and 110 ml, respectively) calorimeters have been specifically developed for the purpose of studying runaway reactions and determining vent sizes to support safe design and operation in the commercial chemical industry.

In open (well-vented) systems, a runaway is much less likely to occur because of release of reactive intermediate gases and evaporative cooling mechanisms. The Fauske experiments show, that even when runaway is induced in the TBP and nitric acid system, dangerous pressure buildup is prevented with practical vent sizes. In particular, scale up of a test in which TBP was saturated with concentrated (> 70 weight percent) nitric acid indicated pressures should remain low (less than 22 psig) provided the effective vent area was greater than 0.0022 in^2/kg of TBP and nitric acid solution. By contrast, identical tests with a closed system, i.e., no vent, was destructive, and an identical test with the vent but with a back pressure of 2 atm. (to simulate the Tomsk control valve opening pressure) resulted in a large pressure with severe bulging of the test vessel

4.5.2.2 DISCUSSION OF RED OIL ACCIDENT CONDITIONS

A discussion of the operating or faulted conditions that resulted in each of five historical accidents follows:

- Savannah River Site, TNX Facility, 1953. TBP was inadvertently introduced into an evaporator concentrating uranyl nitrate solution. The evaporation was poorly controlled, and the uranyl nitrate was heated to incipient solidification. Gases from the reacting TBP pressurized and/or ignited and the burst the evaporator.
- Hanford, 1953. This event was very similar to the 1953 event at the Savannah River Site. Pressurization occurred, but it was not sufficient to burst the vessel.
- Savannah River Site. A-Line, 1975. TBP was inadvertently introduced into a heated calciner. Venting allowed gases to escape the primary vessel; however, they were flammable and a deflagration occurred in the process room.
- Port Hope, Ontario, 1980. TBP was inadvertently introduced into a uranyl nitrate evaporator. It appears that the evaporator was operated at a temperature much higher than the normal conservative value. A pressure pulse damaged the upper part of the unit.
- Tomsk-7, Russia, 1993. Concentrated nitric acid was contacted with an undetermined but large amount of PUREX organic residues (possibly containing aromatic and cyclic contaminants) in a feed tank. The tank also contained hot, freshly evaporated uranyl nitrate solutions, and was initially unvented. The reaction of nitric acid and the organic material pressurized and destroyed the vessel. The pressure surge, and possibly an external ignition of the released gases, seriously damaged the building.

In four of the five events, TBP was externally heated in the presence of nitrate to a relatively high (though in no case well determined) temperature. In the cases of the evaporator incidents, two errors were involved: introduction of TBP and heating to a high temperature. In the case of the Savannah River Site A-Line calciner, the high temperature was essential to the process, and safety was dependent on keeping TBP out of the unit.

Temperature controls placed on the Savannah River Site, and at other locations, since the 1953 incident have succeeded in preventing further evaporator incidents. It is noteworthy that the TBP in the calciner incident had passed through an evaporator without incident because of these temperature controls. Replacement of batch calciners by continuous calciners has reduced the potential for inadvertent reaction in the Savannah River Site A-Line. This, along with material control measures, has prevented a recurrence of the 1975 incident.

The Tomsk-7 incident involved the following conditions: contact of strong nitric acid with a large volume of TBP (possibly containing aromatic and cyclic contaminants); a quiescent system with no mixing, hence the organic material need not be in thermal equilibrium with the underlying solution; no venting, and hence no evaporative cooling. In contrast, all similar tanks at the Savannah River Site are vented and mixed. Nitric acid concentrations are limited, as are the volumes of TBP allowed to pass into such tanks.

4.5.2.3 APPROACH TO PREVENTING RED OIL ACCIDENTS

The information in the previous sections indicates the set of reactions that take place in an organic-nitric system are exothermic with the reaction rate being a very strong increasing function of temperature. They also indicate the overall reaction rate and energy released is significantly higher in a closed system, as opposed to an open system, because of more energetic intermediate reactions and higher boiling points that results from the increase in constituent partial pressures.

The basic approaches to prevent an uncontrolled reaction include the following administrative controls:

- **Prevent high temperature TBP and nitric acid by ensuring that the cooling mechanisms are capable of removing the heat being generated.** The reaction will only run away if the temperature exceeds some critical value (dependent on TBP mass and vessel heat removal mechanisms) above which the rate of heat generation exceeds the rate of heat loss. Vessel cooling systems can remove sufficient heat. Vessel agitation systems can ensure sufficient aqueous phase mixing with an organic phase to ensure evaporative cooling. In unagitated vented vessels (e.g., evaporators), the transport of water from the underlying aqueous phase to the TBP phase can be sufficient to maintain continuous evaporation and net cooling. This approach is valid for temperatures up to at least 121 C and organic depths to at least 6.2 ft (Smith and Cavin, 1994).
- **Maintain the vessel vent areas to reduce constituent partial pressures in the vessel that could feed back to increase energy release rates and limit evaporative cooling.** If the mixture is open to the atmosphere, evaporation of water, diluent, and nitric acid is an efficient heat loss mechanism, which will limit the temperature of the mixture to the atmospheric pressure boiling point. Also, adequate venting allows the escape of reactants and intermediates from the reaction mixture, and limits the extent of the reaction. In contrast, a closed, inadequately vented system allows the pressure to increase as gaseous reaction products accumulate, which raises the boiling point, suppresses the heat loss due to evaporation, and retains partially reacted intermediates, which can continue to react and generate heat. Process vessels can readily have vents of sufficient area.
- **Limit the mass of TBP present.** The total amount of heat generated and total amount of gases generated will be proportional to the amount of TBP that is reacted. With limited amounts of TBP, uncontrolled reactions can be accommodated with minimal consequences.
- **Limit the acid concentration.** The reaction rate is proportional to the acid concentration.

4.5.2.4 PREVENTIVE CONTROLS

The preventive controls that can be employed to prevent runaway TBP reactions in a processing facility are given below:

- Ventilation system for the process vessel
- Ventilation system for the process room
- Agitation system for the process vessel;
- Evaporator maximum temperature interlock with steam heating system
- Liquid level instrumentation and low level interlocks
- Vessel vent areas
- Sampling of vessels for TBP content
- Time between vessel transfers
- Controls to prevent transfer of solvent wash solutions to acidic evaporators
- Procedural requirements to compare specific gravities of feed tank solutions
- Control of TPB mass of various process locations

With potentially large quantities of TBP, sufficient preventive measures should be selected from the above list to ensure the likelihood of uncontrolled reactions in beyond the extremely unlikely likelihood bin. For small to intermediate quantities of TBP, the approach in the previous section can be used to predict consequences that may be acceptable.

4.5.3 ORGANIC REACTION EVENT

4.5.3.1 BACKGROUND AND DISCUSSION

Nitrated organic compounds are in widespread use as propellants and explosives. The generation or accumulation of such materials in nuclear facilities may present a risk of runaway reaction, loss of confinement, fire, or explosion. The materials of primary potential concern include organic compounds containing nitrate or nitrite, but also may concern mixtures of organic material and nitric acid. These materials may be solids, liquids, gels, or slurries.

Waste materials are a particular concern. Once a material is set aside as waste, it is easy to ignore, especially if it is kept in a remote tank or waste drum because of its radioactivity. Such materials may include spent resins, degraded solvents, analytical reagents, lubricants that have been exposed to acid, and the like. In this environment, over a long time, further reactions may occur. For example, the explosion at Tomsk-7 appears to have involved degraded, impure solvent that had been stored for a long time in contact with nitric acid solution in a radioactive environment. The resulting material appears to have been highly reactive toward strong nitric acid.

Another concern is the accumulation of materials in unexpected locations. Decomposition of sulfamic acid during processing has led to the accumulation of ammonium nitrate, a potentially explosive material, in the offgas system. The “red oil” incident in the SRS A-Line involved a situation in which, unexpectedly, the organic phase was denser than the aqueous material in the tank with it, and so settled to the bottom. It was then unknowingly drawn off and sent to a drying kettle, where it decomposed into flammable gases.

Ammonium nitrate (NH_4NO_3) is a colorless crystal that is a powerful oxidizer used in commercial explosives. It has a heat of formation of–340 kJ/mol at 25 °C. Ammonium nitrate can undergo a decomposition reaction when heated to 250 °C, and can react with other constituents at a variety of temperatures. Ammonium nitrate fuel oil is a type of reaction with a maximum energy release at a concentration of 94 percent ammonium nitrate with 6 percent absorbed fuel oil. Ammonium nitrate may react with other organics less vigorously at other concentrations.

An uncontrolled reaction can occur in waste tanks or drums when organic salts are in contact with nitrate/nitrite salts, if high concentrations of both exist and temperatures are above the reaction onset temperature. Decay heat and chemical reactions can lead to waste heating over relatively long periods. Increasing temperatures result when heat is dissipated to the environment at a rate slower than it is generated within the waste. The increase in reaction rate with temperature provides a positive feedback mechanism and can lead to an energetic event. Reactions produce high-temperature gases that pressurize the tank. A tank breach results in a pressurized release of reaction product gases that entrains aqueous tank material.

In the chemical and radiological conditions found in the Hanford Site tanks, the organic materials in the solution decompose to low energy compounds such as formate, oxalate, and carbonate. These low energy compounds do not support deflagration propagation. This aging process greatly reduces hazards associated with organic materials in these tanks (Meacham et al., 1998).

The radiological source term from an organic reaction is evaluated based on whether the consequences are from a chemical detonation or thermal runaway reaction with rapid generation of gases that could over-pressurize and rupture the vessel or container leading to a high pressure release of the radioactive material. In addition to or instead of a pressurized release of radioactive material, if the vented gases are flammable, the physical consequences of potential flash fire or deflagration on containment structures is evaluated to estimate the radiological source terms based on the type of accident stress.

An organic fuel-oxidizer reaction causing a release of radioactive material occurred on February 14, 2014 at WIPP. The DOE Accident Investigation Board determined that the release was a result of an exothermic reaction involving the mixture of the organic materials (Swheat Scoop® absorbent and/or neutralizer) and nitrate salts present inside a single TRU drum. Chemical reactions heated the drum's contents, leading to a thermal runaway reaction with an exponential temperature rise in the core and rapid generation of gases. Gas generation exceeded the drum's relief venting capacity. The drum lid extruded beyond the lid retention ring, deflected the lid, and resulted in a rapid release of the materials from the drum. The combustible gases and solids ignited, spreading the fire to other combustible materials (fiberboard and polyethylene slip sheets, reinforcement plates, stretch wrap, cardboard stiffeners and polypropylene super sack fabric) within the waste array. The energetic release propelled TRU waste from the drum up into the polypropylene magnesium oxide (MgO) super sacks on top of the container stack, onto adjacent stacked waste containers, and throughout the underground exhaust path from the drum's location. The results of the Phase 2 investigation were issued on April 16, 2015, and are available at: http://energy.gov/em/downloads/radiological-release-event-waste-isolation-pilot-plant-february-14-2014.[32]

Dealing with waste materials therefore involves locating them, sampling them, and developing safe-handling methods. Each case is likely to be unique. The methods for evaluating the problems are general, however, and have been based on long experience in the chemical industry.

[32] For a detailed discussion of the reaction mechanism, see SRNL-RP-2014-01198 and Clark and Funk, 2015.

4.5.3.2 ANALYTICAL AND TEST METHODS

A variety of methods have been developed for characterizing the hazards associated with potentially reactive chemicals. In general, reaction of unstable chemical systems will be initiated or accelerated by heating. The tests therefore generally involve heating of small samples under controlled conditions. Differential thermal analysis (DTA) is important in identifying exothermic processes as a function of temperature. The combination of DTA, thermogravimetry, and analysis of the offgases can provide an adequate description of reactivity in many cases. These techniques are adaptable to contained and shielded facilities. For systems in which venting is provided to control the pressure, the method of Fauske has been widely used in the chemical industry to determine vent sizes. This method was used in evaluating the red oil problem. However, it does not appear to have been applied to contained radioactive facilities. Instrumented bomb calorimetry was also applied in studies of the red oil reaction, but again in nonradioactive facilities.

Where the explosive potential is of concern, tests using small explosive initiators have been developed within the explosive industry. These methods are difficult to adapt to radioactive systems, and have mainly been applied to nonradioactive materials. The potential initiator of an explosion is usually fire or heating, so the methods given above will give an indication of the explosive potential.

4.5.3.3 PREVENTION AND MITIGATION

Prevention of these reactions first involves locating and characterizing the materials, identification of possible reactive chemicals from references, such as *Brethericks' Handbook of Reactive Chemical Hazards* (Urben, 2006), and developing an appropriate handling and storage plan. In some cases it may be possible to destroy the material safely. For handling and storage, temperature control is important. Contact with potentially reactive materials should be prevented. When safety analysis determines that the most likely concern for initiating reaction is an external fire, as is often the case, then measures to prevent such fires can be imposed.

Venting will also be important. Nitrogen oxides from slow reactions should not be allowed to accumulate. These can accelerate nitrate oxidation.

4.5.4 HYDROXYLAMINE NITRATE REACTION

Hydroxylamine, NH_2OH, has been used in the nuclear industry as a reducing agent and in decontaminating solutions. It is used as the nitrate (HAN) or sulfate (HAS) salt in solution. It has the advantage of reducing plutonium smoothly to the trivalent state without creating solid waste.

Hydroxylamine is unstable against decomposition in the presence of nitric acid, and this reaction is catalyzed by dissolved iron. This reaction occurs more readily at higher nitric acid concentrations. It appears that the formation of nitrous acid (HNO_2) is an important element in the mechanism. The net reaction is:

$$\text{Reaction of nitric acid and Hydroxylamine} \Longrightarrow 3\ HNO_2 + 7\ H_2O + 2\ HNO_3 \qquad \textbf{Equation 4-52}$$

This reaction, once begun, can accelerate to a dangerous rate, producing great quantities of gas and pressurizing containers. At least seven damaging incidents involving the decomposition of HAN have occurred in DOE facilities. The last of these occurred in May 1997 at the Plutonium Reclamation Facility in Hanford.

Since the vented gases are not flammable, the radiological source term from decomposition of HAN that results rapid generation of gases that could over-pressurize the vessel or container is based on a pressurized release of the solution. For over-pressurization of process solutions present, the ARF should be obtained from DOE-HDBK-3010-94, Section 3.2.2.2 for blast effects over the surface of the liquid and Section 3.2.2.3 for venting below or above the liquid surface.

4.5.4.1 PREVENTION AND MITIGATION

The recommendations in DOE/EH-0555, *Technical Report On Hydroxylamine Nitrate*, include the following:

- HAN concentrations should not be allowed to exceed 2 M, and the nitric acid concentration should be less than twice the HAN concentration.
- The long term storage of in-process HAN-nitric acid solutions should be avoided.
- Tankage containing HAN solutions should be evaluated to ensure adequate venting in the event of rapid HAN decomposition.
- In preparing HAN solutions the sequence of mixing is important in avoiding autocatalytic systems.
- Care should be taken to avoid the accumulation of HAN solutions as heels or in process lines.
- Strict procedures should be used to avoid contaminating HAN or its solutions with metal ions.
- HAN solutions should be maintained below 40° C.

The detailed recommendations consider five scenarios and discuss the precautions necessary in each case.

4.5.5 CHEMICAL REACTIONS ACCIDENT ANALYSIS

Estimating the consequences from plausible scenarios that have radioactive materials involved in a chemical process to accident analysis in a DSA may be challenging. Evaluate a loss of confinement and/or a fire or explosion event as separate events. For example, if a process with plutonium dissolved in nitric acid has a loss of confinement event and the vessel loses enough liquid such that the plutonium in solution dries and is exposed to ambient oxygen, then the risk of a pyrophoric fire exists after the loss of confinement event. Consider the radiological and chemical consequences with any event involving radioactive material involved in a chemical reaction accident.

For a thorough evaluation, use the source term parameters that provide a conservative conclusion that drive a control set. Changing the parameters by an order of magnitude may not change the conclusion or the resulting control set.

For example, use DR of one for resin columns, waste drums or process vessels. Evaluate the total MAR in the vessel for the loss of confinement and fire or for an explosion of a vessel. Evaluate accident progression from loss of confinement to fire or explosion and with a range of ARF/RF in the range of 1E-2 to 1E-4, which approximates the information from the DOE-HDBK-3010-94 for these type accidents, as summarized in Chapter 5 of this Handbook.

By using a bounding MAR of the entire vessel contents, a DR of one, an ARF/RF in the range of 1E-2 to 1E-4, and a LPF of one, a conservative accident analysis can be described in a DSA. Simple and conservative analysis can be used as a starting point. In some cases, no further insight or changes to the control set would result from expending analytical effort on a more refined analysis. In other cases, refinements could provide insight, but in all cases, the analysis should be bounding, technically justified, and consistent with DOE Standard 3009. If the resulting consequence driven control set can enable safe operations without being too difficult to implement, then the source term parameters used are sufficient. Only if further refinement in a particular parameter is needed to reduce consequences to receptors do the accident analyses warrant such refinements. If the postulated event in the DSA closely resembles an event that has either happened in the past or has been analyzed in a technical journal or report, then this information can be used to support a technical justification of the DR, ARF, and RF. A technical justification that cites actual or previously analyzed events should discuss whether these events bound the severity of the accident conditions postulated in the DSA and describe how any non-bounding aspects of the cited events were addressed in the derivation of DR, ARF, and RF.

4.6 NATURAL PHENOMENA HAZARD EVENTS

Natural phenomena hazard (NPH) events are quantitatively evaluated in accident analysis due to their ability to contribute to the airborne and/or waterborne release of radioactive and toxic chemical materials that may result when SSCs fail to perform their safety function during and after the NPH events. Furthermore, the NPH events may cause fires or explosions that could provide energy for transporting the radioactive and toxic chemical material and at the same time degrade the functions of the SSCs.

4.6.1 NPH EVENT TYPES

NPH events that affect DOE sites are:

- Seismic events (earthquakes);
- Extreme winds (straight-line winds, tornadoes, and hurricanes);
- Floods (seiches, tsunamis, storm surges);
- Extreme precipitation;
- Lightning;
- Volcanic eruptions (ashfall); and
- Wildland fires.

DOE-STD-1020-2016 provides criteria and guidance for evaluation and design for all of these NPHs, except wildland fires, which is addressed in DOE-STD-1066-2016, *Fire Protection*. Additional guidance on implementing DOE-STD-1020-2016 is available in DOD-HDBK-1220-2017, *Natural Phenomena Hazards Analysis and Design Handbook for DOE Facilities*.

4.6.2 NPH EVENT ANALYSIS OVERVIEW

Unmitigated accident analysis of NPH events is performed differently for safety basis documents for new nonreactor nuclear facilities and major modifications to existing nuclear facilities, than for existing facilities where the DSA is to be updated as a result of revised NPH criteria based on periodic reassessments. These approaches are addressed in the following subsections, followed by a summary of the general methodology for these evaluations.

4.6.2.1 ACCIDENT ANALYSIS FOR A NEW NUCLEAR FACILITY OR MAJOR MODIFICATION OF AN EXISTING NUCLEAR FACILITY

In preparing a safety design basis document for the purpose of designing a new nuclear facility or major modification of an existing nuclear facility, the evaluation of NPH events is different from the evaluation of operational accidents. The magnitude of a design basis NPH event (e.g., the peak ground acceleration from an earthquake) is determined based upon: (a) the unmitigated dose consequences of the SSC failure that determines the NPH design category (NDC) of that SSC as described in Section 2.3 of DOE-STD-1020-2016 and the associated performance goal (expressed as annual probability of failure), and, (b) a factor that is a measure of the degree of inherent conservatism in the design criteria and analysis methods specified for the NDC of the SSC in DOE-STD-1020-2016 and the categorization scheme described in supporting national consensus standard ANSI/ANS-2.26-2004. DOE-STD-1020-2016 also provides direction on how to determine the site-specific NPH hazard values corresponding to each NDC level. Some of these values can be directly obtained from national consensus standards[33] while a site-specific probabilistic NPH hazard analysis (e.g., Probabilistic Seismic Hazard Assessment) may need to be performed if consensus standards are silent on them or do not provide the requisite level of specificity.

For new facilities, the NDC of an SSC establishes a risk-based target performance goal for the SSC, and the return period[34] of the specific hazard, as established in DOE-STD-1020-2016, to which the SSC will need to be designed. The NDCs were formerly called Performance Categories (PCs) in previous versions of the DOE NPH design-related orders, guides, and standards, which are roughly equivalent from a performance goal perspective to the numerical assignments for NDC. For example, a PC-3 SSC may be viewed as equivalent to an SDC-3 SSC.

Subsections 4.6.3 through 4.6.8 provide additional guidance on unmitigated analyses of specific NPH types to estimate radiological and toxic chemical source terms based on conservative estimates of MARs and DRs. Atmospheric dispersion, aquatic dispersion and radiological dose calculations are performed in accordance with Chapters 6, 7, and 8 of this Handbook. To determine MARs and DRs for safety classification and NDC categorizations of the SSCs during a new facility design, the unmitigated consequence analysis should assume that the building structure inside which the SSCs are located would not maintain confinement and may collapse during the design basis NPH event.

The NDC for SSCs that provide protection from toxic chemical hazards are determined based on the unmitigated consequences of SSC failure from an NPH event, similar to the unmitigated consequence methodology for radiological releases. The methodology for this unmitigated analysis should be consistent with DOE-STD-3009-2014 and Chapter 9 of this Handbook, to determine the need for SS SSCs, which influences the NDC determinations. The higher of the NDCs determined from the application of radiation dose criteria and the criteria for toxic chemical consequences should be used; therefore, it is possible that an SSC categorized as NDC-2 based on radiation hazards may be assigned to the NDC-3 category based on toxic chemical hazards.

4.6.2.2 ACCIDENT ANALYSIS FOR EXISTING NUCLEAR FACILITY DSA

For existing facilities, the NDC or PC establishes the return period of the specific NPHs to which the SSC design will need to be evaluated. For the DSA evaluation of NPH impacts on existing facilities, the initial step is to establish, for each SSC, which NDC from the requirements in DOE-STD-1020-2016 should apply, or which PCs from the previous DOE NPH standards apply as discussed below. Evaluations of SSC capacities should have previously been performed as required by an implementation plan when required by the DOE Program Secretarial Office per DOE O 420.1B or DOE O 420.1C, and its facility conditions assessment should be used for the development of the existing DSA.

[33] ASCE 7-10, ANSI/ANS-2.3-2011 (R2016), *Estimating Tornado, Hurricane, and Extreme Straight Line Wind Characteristics at Nuclear Facility Sites*.

[34] The return period is the reciprocal of the frequency of exceedance of the NPH event: a 100-yr flood has a 1E-2/yr frequency of exceedance.

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DOE O 420.1C and DOE-STD-1020-2016 require that sites with any facilities rated NDC-3 or higher, review existing NPH assessments every 10 years. The results of the updated evaluations should be used in the unmitigated radiological and toxic chemical consequence evaluations to support any required updates of the accident analyses.

If a new NPH assessment yields increased NPH loads and they exceed the capacity of existing SSCs, the DOE Site Office would evaluate and determine whether to upgrade SSCs and whether such evaluation results need to be integrated with the DSA annual update. DOE-STD-1020-2016, Section 9.3, *Facility Condition Assessments*, allows for a factor of two reduction in the return period and lesser design loads, with caveats, when evaluating existing SSCs. If an engineering evaluation concludes that the existing structure will not withstand the higher NPH loads, with allowances, a collapse event should be further evaluated in DSA Chapter 3 accident analysis as an EBA.

Situations where increased NPH loads exceed the capacity of existing SSCs should also be evaluated to determine whether this new information requires entry into the Potential Inadequacy of the Safety Analysis (PISA) process. This evaluation can be performed using DOE Guide 424.1-1B, *Implementation Guide for Use in Addressing Unreviewed Safety Question Requirements*. For SSCs that are found deficient, a fragility analysis or seismic margin study may be performed to assist in the PISA and Unreviewed Safety Question Determination, and to justify continued operation of the facility.

Another outcome of a new NPH assessment is that higher NPH loads might be within the DBA and EBAs already evaluated in the DSA. Thus, no changes would be necessary for the DSA upgrade.

In performing an NPH engineering evaluation for the existing facility, an unmitigated dose consequence analysis is required that would assume that the structure will suffer major damage, exceed Limit States, and/or collapse. This evaluation is used to determine the safety significance of the SSCs, i.e., whether the SSCs provide a SC or SS safety function. If the engineering evaluation concludes that the SSCs can withstand the NPH loads, then the unmitigated analysis can also credit the SSC as an initial condition that provides the SC or SS safety function and would be protected by a TSR Design Feature. This analysis applies only to passive features. Chemical consequences can be evaluated in the same manner as discussed for new facilities or major modifications, as described in Section 4.6.2.1.

For an unmitigated analysis in Section 3.2.2 of DOE-STD-3009-2014, if a building structure, or any of its components, is credited to maintain confinement, the NPH engineering evaluation using the revised or updated NPH loads is required to demonstrate that the building structure and its components that have confinement function will not be deformed more than the Limit State commensurate with the permissible leak rate (see Section 5 and Appendix B of ANSI/ANS-2.26-2004; R2010). To ensure required confinement function, such an evaluation considers not only the relationship between the predicted deformation level/Limit State and leak rate, but also the existence of various openings and penetrations in the building components. The analyst should carefully consider and account for any leak paths that could be caused by expected event-driven actions such opening exterior doors to facilitate personnel evacuation. However, if other SSCs fail at the revised NPH loads, the unmitigated dose consequence analysis should recognize that some damage to other SSCs, such as fire sprinklers, may occur and could cause collateral damage resulting in potential radiological or hazardous chemicals releases.

The unmitigated radiological and toxic chemical consequences of the SSC failure that determines the NDC of an SSC is based on the same criteria and methods described above for evaluation of new facilities and major modifications, and guidance from other chapters of this Handbook. Subsections 4.6.3 through 4.6.8 address additional guidance for unmitigated analyses of specific NPH types to estimate source terms based on conservative estimates of MAR and DRs.

With respect to evaluation of existing structures, systems and components (SSCs) following an updated NPH assessment (required periodically by DOE-STD-1020-2016, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, and its 2012 predecessor), a question arises regarding selection of the appropriate bounding DBA or EBA. Two outcomes are possible: (1) the original DBAs or EBAs developed for the design or evaluation of the facility are bounding; or (2) new EBAs with higher NPH loads are defined by the NPH assessment are bounding. New bounding EBAs would require further DSA evaluation using the results of the facility condition assessments required by DOE-STD-1020. If the existing DBAs or EBAs are bounding, then a DSA revision should:

- Document that the updated NPH evaluations did not change the existing accident analyses in the safety basis document. If the safety class and safety significant SSCs have been concluded to provide their safety functions for the applicable NPH EBA criteria for existing facilities, their failure during a higher level NPH event is considered to be a Beyond DBA and therefore the consequence of their failure is not evaluated in the DSA Chapter 3 accident analysis, except in regards to potential cliff edge effects associated with evaluation of Beyond DBAs (addressed in the next bullet).

- Evaluate SSCs for Beyond DBAs using NPH event return periods applicable for an NPH Design Category (NDC) one level higher than the design or evaluation basis NDCs. For example, if the design or evaluation basis NDC of an SSC is NDC-3, its Beyond DBA can be defined using a return period applicable to NDC-4. See Section 3.4, Beyond Design/Evaluation Basis Accidents, of this Handbook for further discussions.

- For existing facilities, all SSCs, including confinement barriers, that have been evaluated to meet the requirements of DOE-STD-1020-2016 or its predecessor used for the existing DSA accident analysis, can be credited when considering potential interaction effects of these SSCs on SSCs of the same or lower NDC level.

4.6.2.3 GENERAL METHODOLOGY

For preparing the DSA of a nuclear facility, the list of DBA/EBAs would include those resulting from NPH events. The selection of the size of these NPH events and their evaluation and mitigation are required to be performed in accordance with DOE-STD-1020-2016 and the accompanying NPH Handbook.

In general, for all nuclear and hazardous facilities in the DOE complex, DBA/EBAs related to NPH events selected per the criteria in DOE-STD-1020-2016 are evaluated using requirements and guidelines given in DOE-STD-3009-2014. For TRU waste facilities, additional NPH event evaluation guidance is provided in DOE-STD-5506-2007. Since the NPH evaluation provisions in DOE-STD-5506-2007 were developed independent of those in DOE-STD-1020-2016; therefore, during the DSA development process, some inconsistencies between the provisions in these two documents may be identified. Any such identified inconsistency should be reported to the DOE with proposed resolution.

SSC failures from NPH events may also cause toxic chemical releases from nonreactor nuclear facilities with chemical hazards requiring further DSA evaluation as described in Section 2.3.2, Chemical Hazard Evaluation, of this Handbook. NPH-induced toxic chemical releases are evaluated in a similar manner to other operational accident types as described in Chapters 3 and 4 of this Handbook. For example, an NPH event can cause spills of process solutions or powders and result in impacts of debris on process equipment or impact of process equipment with the floor, or potential fires or explosions. The DR, ARF and RF are similar to those from operational accidents. Moreover, care should be taken to determine if the effect of the NPH will cause abnormal process conditions. These types of events should be identified and analyzed in the DSA. For example, it might be more conservative to assume that a process tank remains intact, but suffers an overpressure event due to lack of power or cooling. Failure of tanks or vessels could result in energetic chemical reactions, which may cause a release as discussed in Sections 4.3 through 4.5. A rupture of a line could result in a spray release.

NPH events can initiate several separate accident progressions (e.g., fires, explosions, spills, collapses) simultaneously. Therefore, the overall consequence analysis should sum up the contributions from all the individual accident progressions.

4.6.3 SEISMIC EVENTS

Seismic events result in ground motions that can affect all the SSCs in a facility, so the unmitigated consequences, assuming the failure of all SSCs—including the facility structure itself—should be considered. The seismic ground motions result in accelerations and displacements that are transmitted into the facility structure and to all the systems and components in the facility structure. Seismic events can also result in soil-structure interactions, ground displacements that can impact the behavior of the facility structure foundations and result in failures. The facility's foundations should be evaluated to address any potential structural concerns. Seismic events can cause secondary events, such as failure of ground slopes near the facility structure, tsunamis, and seiches, which can result in additional flooding concerns, facility fires, explosions, deflagrations, and unwanted interaction between SSCs in the facility.

NPH requirements for seismic events are provided in Chapter 3 of DOE-STD-1020-2016. The unmitigated accident analyses performed for the facility determines the SDC of the SSCs, which, in conjunction with a proper seismic hazard analysis, defines the size of the seismic event to be used to design/evaluate the facility SSCs. According to DOE-STD-3009, accident analysis for a seismic event is intended to determine the unmitigated consequences of release of the radioactive and/or toxic chemical inventory of the facility. As stated above, the results of the accident analysis determine the SDC for the facility SSCs.

The simplest evaluation of the unmitigated consequence assessment is to consider all hazardous material to be released in a seismic event, that is, all the facility MAR is included with DR=1. While this assumption may not be true in all situations, the analyst should justify taking an approach that does not not make this bounding assumption.

The initial conditions and assumptions for the analysis are documented and evaluated to determine if controls are needed to maintain the validity of the evaluation. If the presence of an assumed passive SSC prevents significant consequences, it is evaluated for classification as either SS or SC (see section A.3 in Appendix A of DOE-STD-3009-2014). Earthquake experience information or previous seismic evaluations of similar SSCs may be used to estimate the extent of MAR and DR for each SSC. These judgments of damage, MAR, and DRs should be determined working with the discipline engineers responsible for the seismic design and evaluation. Accordingly, to analyze the seismic event, the analyst should:

1. Define the scenarios;
2. Identify the type of material involved and appropriate MAR, DR, and LPF (for mitigated scenarios only);
3. Determine the unmitigated consequences;

4. Determine the SSCs which will be used to mitigate or prevent the consequences; and
5. Define the SDC for the SSCs that mitigate or prevent the consequences.

4.6.4 EXTREME WIND EVENTS

Extreme wind events can be straight-line winds, tornado, or hurricane. A tornado can also insult a SSC from a rapid atmospheric pressure change. NPH requirements for extreme wind events and evaluation of SSC capabilities or damages is provided in Chapter 4 of the DOE-STD-1020-2016. The unmitigated accident analyses performed for the facility determines the Wind Design Category (WDC) of the SSCs, which, in conjunction with a proper extreme wind hazard analysis, defines the size and return period of the extreme wind event to be used to design and evaluate the facility SSCs.

According to DOE-STD-3009, accident analysis for a wind event is intended to determine the unmitigated consequences of release of the radioactive and/or toxic chemical inventory of the facility. As stated for seismic events, the results of the accident analysis determines the WDC for the facility SSCs. For extreme wind events, if properly designed in accordance with the requirements of DOE-STD-1020-2016, the facility structure can usually be considered to protect the systems and components inside of it. This is dependent on the number of openings in the facility structure, which could result in internal wind-induced pressures on the systems and components inside of it. The facility structure's failure should be considered in determining the unmitigated consequences of the release of the hazardous material to the environment.

The initial conditions and assumptions for the analysis are documented and evaluated to determine if controls are needed to maintain the validity of the evaluation. If the presence of an assumed passive SSC prevents significant consequences, it is evaluated for the need to classify as either SS or SC (see section A.3 in Appendix A of DOE-STD-3009-2014). Wind experience information or previous wind evaluations of similar SSCs may be used to estimate the extent of MAR and DRs for such SSCs. These judgments of damage, MAR and DRs should be determined working with the discipline engineers responsible for the wind design and evaluation.

SSCs located outside of the facility structure are also susceptible to the extreme winds and associated missiles. The failure of these SSCs should also be considered in the accident and consequence analyses. To analyze the extreme wind event, the analyst should:

1. Define the scenarios;
2. Identify the type of material involved and appropriate MAR, DR, and LPF (for mitigated scenarios only);
3. Determine the unmitigated consequences;
4. Determine the SSCs which will be used to mitigate or prevent the consequences; and
5. Define the WDC for the SSCs that mitigate or prevent the consequences.

4.6.5 FLOOD AND PRECIPITATION EVENTS

Flood events for a facility can result from several sources, such as river flooding, dam, levee, or dike failure, storm surge, tsunami, seiche, landslide, extreme precipitation (both rainfall and snow/ice) run-off, and extreme precipitation loading on roofs, parapets, or outside utilities. Floods can also cause water-borne debris impacts which should also be considered.

NPH requirements for floods and extreme precipitation events are provided in Chapters 5 and 7 of DOE-STD-1020-2016. The unmitigated accident analyses performed for the facility determines the Flood

Design Category (FDC) of the SSCs which, in conjunction with a proper flood hazard analysis, defines the size of the flood event to be used to design/evaluate the facility SSCs. For dry sites, which are defined as sites that have no external flood threat outside of extreme precipitation, the unmitigated accident analyses performed for the facility determines the Precipitation Design Category (PDC) of the SSCs which, in conjunction with a proper extreme precipitation hazard analysis, defines the size of the extreme precipitation event to be used to design/evaluate the facility SSCs.

According to DOE-STD-3009, accident analysis for a flood or extreme precipitation events is intended to determine the unmitigated consequences of release of the radioactive and/or toxic chemical inventory of the facility. As stated for seismic and extreme wind insults, the results of the unmitigated accident analyses determine the FDC and PDC for the facility SSCs.

For flood and extreme precipitation events, if properly designed in accordance with the requirements of DOE-STD-1020-2016, the facility structure can usually be considered to protect the systems and components inside the facility structure. This is dependent on the number of openings in the facility structure, which could result in inflow of flood water. The facility structure's failure should be considered in determining the unmitigated consequences of the release of the hazardous material in the facility. The initial conditions and assumptions for the analysis are documented and evaluated to determine if controls are needed to maintain the validity of the evaluation. If the presence of an assumed passive SSC prevents significant consequences, it is evaluated for the need to classify as either SS or SC (see section A.3 in Appendix A of DOE-STD-3009-2014). Flood and precipitation experience information or previous flood and precipitation evaluations of similar SSCs may be used to estimate extent of MAR and DRs for such SSCs. These judgments of damage, MAR, and DRs should be determined working with the discipline engineers responsible for the flood and extreme precipitation design and evaluation. Some SSCs, even though capable of withstanding mechanical loads from flood water, may fail to perform their safety function when subjected to water intrusion or inundation. These modes of failure should also be considered in performing flood and extreme precipitation hazard evaluations.

SSCs located outside of the facility structure would be susceptible to the flood, extreme precipitation, and associated water debris. The failure of these SSCs should also be considered in the accident and consequence analyses.

To analyze the flood and precipitation events, the analyst should:

1. Define the scenarios;
2. Identify the type of material involved and appropriate MAR, DR, and LPF (for mitigated scenarios only);
3. Determine the unmitigated consequences;
4. Determine the SSCs which will be used to mitigate or prevent the consequences; and
5. Define the FDC and PDC for the SSCs that mitigate or prevent the consequences.

4.6.6 LIGHTNING EVENTS

Chapter 6 of DOE-STD-1020-2016 is focused on NPH design criteria and does not provide a detailed discussion about the effects of lightning events or guidance regarding the safety analysis. Accordingly, the following additional guidance is provided with respect to the DSA evaluation.

Lightning is a high-current electrical discharge in the atmosphere with a path length measured in kilometers. Natural lightning is almost always associated with clouds, normally those of severe weather (e.g., thunderstorms), but can also be present in volcanic clouds and clouds from dust storms.

Assessing the severity and frequency of lightning strikes at, or nearby, a site is essential because lightning can:

- Start a fire inside a building, outside of a building but within the industrial area, or on the area surrounding the industrial area of a site; fire can also arise from contact of combustibles with a lightning-heated non-combustible;
- Can start a wildland fire at sites surrounded by forests intense enough to breach site barriers;
- Breach a building, providing an open pathway for radioactive or other hazardous substances to be released into the atmosphere;[35] and
- Cause failure of sensors, communications and electronic components, and power supply systems.

The analyst can consult a map of the United States given in the *Standard for Installation of Lightning Protection Systems*, NFPA 780 (NFPA, 2017).[36] NFPA 780 provides an Annex L, Lightning Risk Assessment, which may be applied in the facility FHA when determining the requirement to install a lightning protection system. Per NFPA 780 Section L.1.4, "Lightning risk for a structure is the product of the lightning frequency, exposure vulnerability, and the consequence of the strike to the structure or object." The results of the lightning frequency calculation can be directly used to estimate the DSA likelihood of a strike to the facility. This frequency calculation relies on local ground flash density data as referenced in NFPA 780 and other factors such as the footprint of the facility ("equivalent collection area") to estimate the" annual threat of occurrence (lightning strike frequency)." The NFPA risk assessment methodology also estimates a "tolerable lightning frequency" and "acceptable frequency of property loss" based on other considerations, and these frequency estimates should not be used for the DSA determination of the likelihood. The DSA likelihood determination may further modify the annual threat of occurrence lightning strike frequency to estimate the likelihood of a lightning-induced fire or fire from a lightning-induced wildland fire based on facility-specific justifications.

The severity of a lightning flash is usually defined by the peak amplitude of its return stroke current, which range from one to hundreds of kA. The upper one-percentile current (i.e., 99 percent of all lightning flashes have a lower current) has been determined to be about 200 kA. Lightning scientists identify this level of current as the severe threat level. The 50th percentile value lies in the 20-30 kA range.

For flat terrain without buildings or other structures, the probability of a lightning strike is the same throughout the area. However, structures, especially tall ones such as stacks, water towers, and power poles, are more likely to attract lightning and thus increase the probability of a strike at those locations, while concomitantly decreasing the probability at other nearby locations. These taller structures provide some protection for nearby shorter structures. The extent of this protection, however, is not readily quantifiable except for properly grounded conductive structures (or buildings protected by a code-compliant Lightning Protection System). Elevated conducting wires that are horizontal and grounded can also protect facilities below them. Power lines could therefore be considered to provide some protection for certain buildings. In general, the stacks, water towers, and power lines may offer protection for only a

[35] Because filter plenums are electrically conductive, they can attract lightning and can therefore be breached by lightning even within a building. This phenomenon would provide another leak path to the environment as well as a hazard to personnel within the building.

[36] This standard was originally issued as NFPA 78, *Lightning Protection Code*.

small portion of an industrial area.

If a particular facility is not protected, the expected number of lightning strikes per year can be determined by multiplying the footprint area of the facility by the lightning strike density applicable for the site. This quantitative estimate of the annual frequency of lightning strikes to the facility can then be used to qualitatively assign a hazard scenario likelihood as suggested on Table 2-9.

Not every lightning strike is damaging to structures. The amount of structural damage depends on the amount of current in the return stroke, the magnitude of any continuing current, and the susceptibility of the target to lightning damage. Electronic equipment, for example, is more susceptible to failure from a lightning strike than a concrete pad is to fire damage. The main danger from lightning for the site is from fire, as fire can potentially lead to a release of radioactive or toxic chemic material. Lightning-induced fire can be caused in several ways:

1. Fire can be started in dry combustible material, such as a wooden structure or dry grass, by the weak "continuing current" between lightning strokes.[37] About 20 percent of the lightning strikes have a continuing current large enough to start such a fire (Hasbrouck, 1989). The magnitude of the peak current is not relevant for this circumstance, as the return stroke is too brief to start a fire. This type of fire will be mainly confined to wildland fires and wooden power poles, unless there are wooden structures on the site and a lack of a requirement that any wood brought onto the site be treated with fire retardant. Range fires can occur only when the wildland grass is dry during drought conditions. Lightning-induced wildland fires should be anticipated. In addition, power poles have been set on fire by lightning, showing that this type of fire also needs to be anticipated.

2. If a facility is constructed of non-combustible building materials, a so-called Highly Protected Risk (HPR) facility, or if it is constructed as a Faraday cage, the frequency of a lightning-induced in-facility fire is qualitatively assessed as *extremely unlikely*, whether or not the facility has a properly functioning lightning protection system, unless the NFPA 780 lightning risk assessment determines that the probability of a lightning strike is so small that a lightning protection system is not required by the code.

3. For a facility that has a code-compliant lightning protection system that can perform its designed function as determined by the FHA or Fire Protection Engineering, a qualitative reduction of one likelihood bin for the mitigated analysis may be taken for lightning-induced in-facility fires. This is based on the general rule of thumb discussed in Section 2.5.2, Qualitative Likelihood, for failure of a SSC.

4. A lightning strike on a building can induce large currents in the electrical wiring in the building. It is possible that the high current will cause a breakdown in both the insulation on the wiring and the insulation provided by the air, causing an electrical arc to form between the wire and a nearby grounded object. (This is called a "side-flash.") A follow-on current from the electrical circuit would then sustain the arc and could continue for many seconds or even minutes, long after the lightning strike is gone. Combustible material in the immediate vicinity could then be ignited. Although arcing is more likely with the larger-current strikes, any magnitude of strike should be considered. This type of fire for facilities without functional lightning protection systems should

[37] The continuing current will probably not start a fire within a concrete structure or Butler-type building.

be considered as the same likelihood as determined above from the NFPA 780 method.

5. A lightning-induced spark in the building could ignite volatile gases, such as from rags damp with cleaning fluids. This could occur with a lightning strike of any magnitude current. This type of fire may thus be considered *less likely* for facilities with functional lightning protection systems depending on process-specific and facility-specific considerations.

For DOE facilities performing explosive operations, and/or handling nuclear weapons, lightning represents an additional hazard. For a more complete discussion, refer to Chapter X of DOE-STD-1212-2012, *Explosives Safety*. Lightning presents a hazard to explosives in at least five ways:

1. The electrical current produced by a voltage gradient resulting from a lightning strike could initiate the explosives directly.

2. The surface flashover or arcing of the generated electrical current between conductive surfaces that are not at equilibrium could initiate the explosives directly by the heat, sparks, and molten metal generated by the arc.

3. This same arcing could cause damage or fires in electrical fixtures and equipment.

4. Lightning could initiate a fire involving combustible materials in the facility, including the containers around explosives.

5. The spalling generated by the heat of the current flowing through the structural components of the facility could initiate, by impact, unprotected explosives. In addition, lightning could affect support systems such as fire protection and security. Lightning can reach a structure not only by direct strike, but also indirectly by coupling to a conductor that penetrates the structure.

From this information the analyst can determine the potential impact of lightning strikes on hazardous materials. The methodology to analyze lightning-initiated accidents is to:

1. Define the scenario;
2. Estimate the damage to facility SSCs and support systems from lightning strikes;
3. Identify materials and appropriate MAR, DR, and LPF (for mitigated scenarios only); and,
4. Calculate the radiological or toxic chemical consequences for this type of event.

4.6.7 VOLCANIC ERUPTION AND ASHFALL EVENTS

Volcanic eruption events can pose a number of hazards to facilities such as ashfall (“tephra”), lava flows, ballistic projections, pyroclastic flows, mudflows, low-level seismic activity, ground deformation, tsunami, atmospheric effects, and emission of gasses that can result in acid rains. For existing DOE sites, the primary volcanic hazards are from ashfall. Designing facilities to withstand any other volcanic hazard is not feasible, and such hazards should be mitigated by siting facilities far enough from active volcanoes to preclude being affected by these hazards. The primary issues with ashfall are the potential clogging of ventilation systems and equipment exhaust, structural roof loading, and other concerns include disruption or shorting of electrical equipment and interference with emergency response.

Volcanic eruptions may pose hazards to select DOE sites in the western United States. For practical application, volcanic hazards are assessed at DOE sites and facilities lying within 400 kilometers of a volcanic center that erupted within the geologic Quaternary Period (i.e., 2.6 million years before present).

Chapter 8 of DOE-STD-1020-2016 provides NPH requirements for volcanic eruption events. The unmitigated accident analyses performed for the facility determines the Volcanic Design Category (VDC) of the SSCs, which, in conjunction with a proper volcanic hazard analysis, defines the size of the volcanic-induced event to be used to design/evaluate the facility SSCs.

According to DOE-STD-3009, accident analysis for a volcanic eruption event is intended to determine the unmitigated consequences of release of the radioactive and/or toxic chemical inventory of the facility. As stated above, the results of the accident analyses determine the VDC for the facility SSCs. For volcanic eruptions, the facility structure can usually be considered to protect the systems and components inside the facility structure with the exception of the potential clogging of ventilation systems from ashfall which have openings to the outside of the facility structure. The facility structure's failure should be considered in determining the unmitigated consequences of the release of the hazardous material in the facility.

SSCs located outside of the facility structure could be susceptible to the volcanic ashfall and potential extreme rainfall induced by the volcanic eruption. The failure of these SSCs should also be considered in the accident and consequence analyses.

To analyze the volcanic ashfall events, the analyst should:

1. Define the scenarios;
2. Identity the type of material involved and appropriate MAR and DR (for mitigated scenarios only);
3. Determine the unmitigated consequences;
4. Determine the SSCs which will be used to mitigate or prevent the consequences; and
5. Define the VDC for the SSCs that mitigate or prevent the consequences.

4.6.8 WILDLAND FIRES

Wildland or range fires (also called wildfires) present an external exposure to site facilities, and as such, their potential severity needs to be evaluated. The potential severity of a wildland fire may be assessed through an analysis of the chief factors that contribute to its growth and spread. These factors include the characterization of the fuel available, the terrain, and environmental conditions. The damage potential from a wildland fire is dependent on factors such as including the construction of potential target structures, spatial separation distances, existing automatic fire suppression, and the effectiveness of the responding fire fighters.

A wildland fire in the site buffer zone or exclusion area of the DOE site may threaten the structural integrity (i.e., MAR confinement capabilities) of site facilities located in this region, as well as facilities located in the site's industrial area that normally have minimal or extremely limited vegetation. The fire may spread by flame or radiative heat from building-to-building, or it may be spread to various building roofs by flying brands. Wildland and other fire hazard potentials are addressed in a facility FHA. (See Appendix B of DOE-STD-1066-2016, *Fire Protection*, for details.) An FHA analysis of wildland fire potential should be incorporated into the DSA. The following section details the methods available to subject matter experts in determining wildland fire potential.

4.6.8.1 WILDLAND FIRE EVENT DESCRIPTION AND ANALYSIS

Wildland fires may be caused by various natural and human initiators. These initiators include lightning, human action, mechanical incidents, and an explosion and/or fire at an off-site facility. Lightning can occur any time of the year; however, it is primarily a spring and summertime phenomenon. Human action-caused incidents include improper disposal of smoking materials, poor control of a campfire, hot work, prescribed burns, ignition by tracer fire during training, ignition by explosives during training, carelessness, and arson. Mechanical incidents include sparks generated from railways and passing automobiles.

The methodology to analyze a wildland fire is to:

1. Define the bounding scenario.
2. Identify the type of material involved and appropriate damage ratios.
3. Determine the consequences.
4. Determine appropriate design/operational criteria for the SSCs needed to prevent or mitigate the event.

Expected wildland fire intensity may be determined by characterizing the material available for combustion, such as trees, grasses, forbs (weeds), and low shrubs. Vegetation types are to be identified within the outlying areas, such as marshland, woodland, shrubland, and grassland. Other vegetation types may be located in small isolated pockets. The average plant production in terms of kilograms per hectare or tons/acre is estimated.

In the bounding scenario, a wildland fire would burn the entire area surrounding a site. Some facilities within this area (for example, those of wood construction) would be damaged or potentially destroyed. Smoke might necessitate site evacuation, road closures, and reconfiguration of building ventilation systems. In general, wildland fires are of such an extent and unpredictable nature that multiple buildings/facilities will likely be threatened, requiring fire department and other firefighting resources to be deployed accordingly.

NFPA 1144, *Standard for Reducing Structure Ignition Hazards from Wildland Fire* (2013), provides guidance for the analysis of the susceptibleness of a structure to wildland fires. The NFPA standard identifies the elements of the structure and the surrounding environment that require evaluation. These elements contribute to the safety analyst's understanding and selection of controls for the mitigated analysis.

NFPA 1144 provides an example hazard assessment in its Table A.4.1.2, "Example of Structure Assessment Rating Form." The five areas of evaluation are:

- Overview of the surrounding environment – topography, weather, and surrounding structures;
- Chimney to eaves – roof construction, skylights, and roof attachments;
- Top of exterior wall to foundation – wall construction, openings and penetrations;
- Foundation to Immediate Landscaped Area (ILA)[38] – vegetative fuels and other combustibles around the structure, heat and flame sources, other structures and vehicle parking within 30 ft;

[38] ILA definition: "The area of the structure ignition zone extending at least 30 ft (9 m) from the foundation of the structure, including the footprint on decks and all extensions, and the area in which vegetation has been modified for reduced flammability or aesthetic purposes, such as lawns and gardens." This area is often referred to as "defensible space."

- ILA to the extent of the Structure Ignition Zone (SIZ) [39] – vegetation, heat and flame sources, and vehicle parking between the outer edge of the ILA and the extent of the SIZ.

The FHA application of this hazard assessment methodology will result in four hazard ratings that can be used to aid in assessing the likelihood of a wildland fire causing a release of radiological or hazardous chemical MAR. The evaluation areas also aid in identifying existing passive design features that may be credited in the DSA unmitigated hazard evaluation or accident analysis or may need to be improved to provide the necessary protection of MAR. This NFPA methodology may be used to perform iterative analysis as well since it identifies controls (e.g. vegetation control/treatment within the SIZ).

This Handbook provides some amplifying information on the NFPA 1144 table (highlighted in yellow in the example that follows) for use by fire protection subject matter experts in the DSA development/ revision process. Annex A of NFPA 1144 provides additional detailed explanatory information that may provide insights into assigning a value where a range of values is provided. If not obvious, assigned values should be documented with a basis either within the cell or use of footnotes, as illustrated in the example provided in the next subsection.

Building design, location and construction standards that reduce structural susceptibility to wildland fires are provided in Chapter 5 of NFPA 1144, in NFPA 1141 (2017), *Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas*, and in local building codes. Section 4.2.5.8 of NFPA 1144 states, "Any structure that fails to comply with the requirements of Chapter 5 shall be deemed to increase the risk of the spread of wildland fire to improved property and the risk of fires on improved property spreading to wildland fuels."

Some additional sources of guidance for fire hazards analysis, building design and construction, exterior exposure protection, and wildland fire management are:

- DOE-STD-1066-2016, *Fire Protection*, was developed to address the special or unique fire protection issues at DOE facilities and includes guidance (and additional references) for wildland fire management and facility design against wildland fire exposures. Specifically, Chapter 8 addresses wildland fires.

- NFPA 801 (2014), *Fire Protection for Facilities Handling Radioactive Materials*, addresses fire protection requirements intended to reduce the risk of fires and explosions at facilities handling radioactive materials. NFPA 801, Section 5.5 specifically states, "Buildings in which radioactive materials are to be used, handled, or stored shall be fire-resistant or noncombustible construction in accordance with NFPA 220, *Standard on Types of Building Construction*, Type I or Type II construction."

- NFPA 80A (2012), *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*, provides guidance on fire exposure hazards. NFPA 80A, Chapter 4 provides guidance for determining minimum building separation distances, and Chapter 5 identifies various means by which facilities may be protected from fire damage due to exterior exposure.

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[39] SIZ definition: "The "ignition zone" includes the area around a specific structure and associated accessory structures, including all vegetation that contains potential ignition sources and fuels that can affect ignition potential during an intense wildland fire." The zone extends 0–200 ft (0–60 m) out from a structure's foundation.

- NFPA 1143 (2014), *Standard for Wildland Fire Management,* provides guidance that aids in the development of wildland fire management programs, which include the full range of activities and functions necessary to plan, prepare, and respond to potential fires.

4.6.8.2 EXAMPLE: WILDLAND FIRE FACILITY/STRUCTURE HAZARD ASSESSMENT

A simple example of the application of the Wildland Fire Facility/Structure Hazard Assessment is presented in Table 4-11. For this example, the most significant characteristics of the facility are listed below. However, for specific facilities, additional detailed information should also be available. The values for the hazard risk ratings and the Hazard Rating Scale are established in NFPA 1144. For each of the example characteristics listed below, cross-references are provided as a brief basis for the selected values in Table 4-11. Note that the evaluated characteristics include existing facility controls.

Topographical Features (TF):

- The facility location is in a semi-arid region {evaluated as identified by TF1}
- The region has a history of wildland fires (about 1 every 10 years) {justifying a relatively high rating of 4 as shown for TF2};
- The surrounding environment is timberland (mostly ponderosa pine) and grassland with minimal slash or undergrowth due to regular forest management, thus there is moderate wildland combustible material present {evaluated as identified by TF3}.
- The location may be subjected to significant straight, dry winds, as well as thunder/lightning storms {supporting values identified by TF4}.
- The nearest sloping grade of greater than 15% is more than 400 ft from facility, except for the northerly direction where a slope of 15% to 20% begins at 30 ft from the facility and continues out several hundred feet {thus resulting in relatively low values for the evaluations of topography slope (rating range from 0 to 15) and the Building Setback (rating range of 0 to ~5) for which slopes greater than 30% are several hundred feet away; evaluations are identified as TF5}.
- A neighboring structure is a single story transportable building of combustible materials with an attached wood deck with no underpinning or screening. This structure is 60 to 70 feet away {evaluated as a moderate risk of 3 (for a risk factor range of 0 to 5) for separation of structures as shown by TF6}.

Fuel Modifications and Vegetation (FM):

- Large trees have been removed and the brush is thinned out to a distance of at least 210 ft. Trees and brush are removed out to 100 ft, leaving primarily grasses and forbs. {This fuel modification treatment significantly reduces the flame and radiative heat threat to the structure from the SIZ, justifying very low values from 30 to 100 feet; when properly performed it may be judged to support the low values identified by FM1}.
- A controlled defensible space, concrete slab, is provided for a minimum of 30 ft from the foundation of the structure in all directions {essentially eliminating combustibles and justifying a value of 0 for FM2; without this defensible space the hazard risk would significantly increase}.

Building Construction (BC):

- Although the concrete structure of the walls are 1 to 2 hour fire resistance capable, multiple penetration seals in several concrete walls are not fire-rated, resulting in fire resistance vulnerabilities in the exterior walls {judged for this example to pose a significant fire propagation risk into the building and thus elevated value of 9 for the siding identified by BC1};

- There are no skylights in the roof and the facility roof has been evaluated by fire protection engineering and is considered to meet UL Class A/FM Class 1 requirements (i.e., provides adequate fire resistance, supporting a very low risk evaluation shown by BC2);
- Large external ventilation fan suction and discharge duct openings are not covered by metal screening, making it possible for sparks or fire brands to reach combustible ventilation filters (hence a high hazard value of 20 is assigned as shown by BC3);
- Existing gutters are constructed of metal (supporting a very low risk evaluation shown by BC4);

Additional Fuel Modifications Relevant to Fire Hazards (FM):

- Vehicles are parked within the SIZ on paved parking lots clear of vegetation. (FM3)
- The facility is equipped with a concrete dock (deck) for equipment and material shipping and receiving. (FM4)
- No vehicles are parked or left unattended within 30 ft of the facility. (FM5)
- No other significant combustibles are permanently located or stored within 30 ft of the facility. (FM6)

Additional Fire Risk Factors (FF):

- An above ground, dry transformer (1750 kVA) is located approximately 50 feet away from the building exterior, stepping down 13.8 kV commercial power to 600 V electrical service for the facility (evaluated as a moderate utility fire hazard shown as FF1). There is no gas service to this facility.

Fire Protection System (FP):

- Facility is equipped throughout with an NFPA-compliant wet-pipe sprinkler fire suppression system (therefore the building can be considered fully protected, resulting in a 0 hazard rating under the Fixed Fire Protection category identified as FP1).

Table 4-11. Example Application of Wildland Fire Facility/Structure Hazard Assessment

Analyzed Parameters	**Environment ‡**	**Building Structure ‡**		**Landscape/Combustibles ‡**	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
Topographical Features					
Topographical features that adversely affect wildland fire behavior (4.2.1*)	3 {TF1, TF3, TF5, general judgement}				
Areas with history of high fire occurrence (4.3.4*)	4 {TF2}				

Analyzed Parameters	**Environment ‡**	**Building Structure ‡**		**Landscape/Combustibles ‡**	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
Areas exposed to unusually severe fire weather and strong, dry winds (4.2.1.3*)	5 {TF4}				
Local weather conditions and prevailing winds (4.2.1.2*)	4 {TF4}				
Separation of structures on adjacent property that can contribute to fire spread/behavior (4.2.1.3*)	3 {TF6}			0 {TF6}	3 {TF6}
Vegetation—Characteristics of predominant vegetation					
Light (e.g. grasses, forbs, sawgrasses, and tundra) NFDRS Fuel Models** A, C, I, N, S, and T	5 {TF3, FM1}			0 {FM2}	0 {TF3, FM1}
Medium (e.g. light brush and small trees) NFDRS Fuel Models** D, E, F, H, P, Q, and U	0 {TF3, FM1}			0 {FM2}	5 {TF3, FM1}
Heavy (e.g. dense brush, timber, and hardwoods) NFDRS Fuel Models** B, G, and O	0 {TF3, FM1}			0 {FM2}	0 {TF3, FM1}
Slash (e.g. timber harvesting residue) NFRDS Fuel Models** J, K, and L	0 {TF3, FM1}			0 {FM2}	0 {TF3, FM1}
Topography					
Slope 5-9%				0 {TF5}	0 {TF5}
Slope 10-20%				4 {TF5}	2 {TF5}
Slope 21-30%				0 {TF5}	0 {TF5}
Slope 31-40%				0 {TF5}	0 {TF5}
Slope >41%				0 {TF5}	0 {TF5}
Building Setback, relative to slopes of ≥ 30%					
≥30 ft (9.14 m) to slope	NA {TF5}				
<30 ft (9.14 m) to slope	NA {TF5}				
Roofing Materials and Assembly, nonrated***		0 {BC2}			
Ventilation Soffits, without metal mesh or screening		20 {BC3}			

Analyzed Parameters	**Environment ‡**	**Building Structure ‡**		**Landscape/Combustibles ‡**	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
Gutters, combustible		0 {BC4}			
Building Construction (predominant)					
Siding and Deck—noncombustible/fire-resistive/ignition-resistant ††			9 {BC1, FM4}		
Siding—noncombustible/fire-resistive/ignition-resistant siding, but Deck—combustible ††			NA {BC1, FM4}		
Siding and Deck—combustible ††			NA {BC1, FM4}		
Fire resistance of wall components (e.g. doors, windows, and penetrations) are also considered in the building construction evaluation. Value (0 to 9) of item 1 above may increase up to 9 based on extent of vulnerabilities created in the walls. Likewise the value (10 to 14) of item 2 may increase up to 14 due to vulnerabilities.					
Fences and Attachments					
Combustible					
Non-combustible			1.	NA {None}	
Placement of Gas and Electric Utilities					
2. One underground, one aboveground	3 {FF1}				
Both aboveground					
Both underground					
Fuel Modifications within structure ignition zone					
71-100 ft (21-30 m) of vegetation treatment from the structures	3.				0 {FM1, FM3}
30-70 ft (9-21 m) of vegetation treatment from the structures					0 {FM1, FM3}
<30 ft (9 m) of vegetation treatment from the structures				0 {FM2, FM5, FM6}	
Note: Evaluate the presence and location of heat sources, flame sources and vehicle parking from the foundation to the ILA (4.2.4.2 and 4.2.4.5*) and throughout the SIZ (4.2.5.3 and 4.2.5.5*). For example, even with no vegetation in the Defensible Space (<30 ft), the presence of fuel, heat and flame sources (e.g. propane tanks, parked vehicles, combustible waste containers) could be sufficient cause to result in a high evaluation value of 15.					

Analyzed Parameters	**Environment ‡**	**Building Structure ‡**		**Landscape/Combustibles ‡**	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
Fixed Fire Protection (NFPA 13, 13R, or 13D sprinkler systems)					
No Protection					
Protected	4.		0 {FP1}		
TOTALS	**27 (Moderate)**	**20 (Moderate)**	**9 (Slight)**	**4 (Slight)**	**10 (Slight)**
Hazard Rating Scale (Total the above individual ratings and compare the totals to scale below for an estimated structure ignition hazard (probability) from Wildland Fire.					
Slight	0-14	0-14	0-14	0-14	0-14
Moderate	15-29	15-29	15-29	15-29	15-29
Significant	30-49	30-49	30-49	30-49	30-49
Severe	≥50	≥50	≥50	≥50	≥50
Note: The estimated hazard rating of structure ignition should be used as a guide to aid in determining scenario/event frequency in the DSA hazard analysis. Each of the individual columns (areas of evaluation) above assess a group of features/controls that reduces the likelihood that a wildland fire will breach the facility external structure. The likelihood that the structure will be breached by the wildland fire is determined primarily by the most vulnerable feature (highest column value). For this example, the assessed hazard rating of structure ignition is Moderate. The hazard rating of structure ignition should be used as an input to the DSA HA qualitative selection of wildfire event frequency (unmitigated and mitigated) while considering other factors (e.g. location and containment of MAR, credited controls).					

‡ The gray shaded areas of the table are not applicable (NA) to the "Analyzed Parameters" listed in column 1.

* Ref. NFPA 1144, 2013 Edition

** National Fire Rating Danger System (NFDRS) Fuel Models correspond to the type of vegetation/forest surrounding the facility.

*** Additional information on roof ratings and the impacts of firebrands to facility roofs may be found in LA-UR-14-27684, *Analysis of Wildland Fire Hazard to the TWF at Los Alamos National Labs* (Gilbertson, 2014).

†† The NFPA Table A.4.1.2 provides numerical and value rankings (low, medium, high). The user is urged to assign the value ranking of low, medium, or high based on the other ignition factors prevalent at the assessment site. For example, a deck made of combustible materials might rank low if it is small in size and the rest of the site is in a low fuel loading area that will not promote a large amount of firebrands. That same deck might rate high if it is in an area of high fuel loading that will promote numerous firebrands. Numeric values can be substituted as a local option. [Ref. NFPA 1144, 2013 Edition] For this Handbook, using a range of numerical values is presented as a means to address the evaluation of vulnerabilities in the fire resistance of the exterior construction; thus, incorporating the evaluation of vulnerabilities with the goal of improving DOE-complex wide consistency in the final hazard rating.

The hazard rating results of Table 4-11 for the probability that a wildland fire in the vicinity of the facility will breach the structural barrier provides input into the DSA hazards analysis likelihood determinations. This evaluation should be performed for both the unmitigated (no controls) and mitigated (controls in place) cases to provide input and justification to the unmitigated and mitigated DSA hazard analysis wildland fire scenarios, respectively. If this is not performed in the facility FHA, it could be added to the DSA hazard evaluation.

As stated in the footnote to Table 4-11, additional information on roof ratings and the impacts of firebrands to facility roofs may be found in LA-UR-14-27684, *Analysis of Wildland Fire Hazard to the TWF at Los Alamos National Labs* (Gilbertson, 2014). That reference also provides guidance on assigning likelihoods based on whether the roof is combustible or noncombustible and consideration of the wildland fire separation distance.

The design features and controls (engineering and administrative) that are assumed in Table 4-11 for the reduction of the hazard rating are carried forward to the DSA as appropriately credited or defense-in-depth controls. The evaluated characteristics in the above example that may be considered as candidate controls include the fire resistance of the exterior walls, roof rating, and defensible space configuration control.

For the radiological consequence analysis, the damage ratio for the wildland fire is facility dependent, and considers the capability of other MAR containment components to withstand the fire. ARF and RF estimates are evaluated the same as those for operational facility fires as addressed in Section 4.2. The LPF is assumed to be 1 for an unmitigated wildland fire that results in a release of MAR from a facility because the facility structural boundary is assumed to be significantly breached.

The Table 4-11 example documents the results of the FHA assessment of wildland fire, which should be interpreted and included in the FHA or referenced to a supporting analysis. The DSA Chapter 3 hazard evaluation or accident analysis would then summarize the analysis and reference the FHA, add the mitigated analysis if not already included in the FHA, and expand on how the likelihood was assigned, identify protection features, and evaluate their safety significance.

4.7 MAN-MADE EXTERNAL EVENTS

Man-made external events can cause a breach in the structure of a facility and cause a release of radioactive or hazardous materials. The following events may be evaluated in a DSA accident analysis: (1) aircraft crashes, (2) vehicle crashes, and (3) loss of power to safety-related SSCs that provide a safety function to prevent or mitigate accidents.

Additional external events may also need to be evaluated for a DSA depending on:

- site characteristics, such as nearby facilities with accident potentials that can affect the facility being evaluated,
- nearby natural gas distribution lines or other gas lines not servicing the facility,
- explosion from a train derailment (for trains not related to facility operations),
- underground transformer explosions, and
- events involving storage tanks external to the facility that are not associated with facility operations.

Some of the methods presented in this section and in earlier sections of Chapter 4 regarding fires, explosions, and loss of confinement accidents assist in evaluating these other external events, although a special engineering analysis of the accident phenomena associated with the external event may also be needed.

4.7.1 AIRCRAFT CRASHES

The analysis of aircraft crash impact involves the following steps.

1. Performing a screening analysis based upon MAR, frequency, and consequences.
2. Defining the scenario.
3. Identifying the type of material involved and appropriate DR and LPF (for mitigated scenarios only).

4.7.1.1 SCREENING ANALYSIS

Guidance and criteria for evaluating airplane crashes are given in DOE-STD-3014-2006, *Accident Analysis for Aircraft Crash into Hazardous Facilities*. The assessment is presented in three phases:

1) determination if there is enough hazardous material in the facility to pose a threat to the public or workers;

2) determination of the estimated probability per year (i.e., frequency) of an aircraft crash into a facility with hazardous materials; and

3) determination if an aircraft crash into the facility would penetrate to the location of the hazardous materials and release it into the atmosphere.

If the relevant determination in any of these three phases falls below screening guidelines, the threat of an aircraft crash is considered insignificant for that facility.

For phase one, the screening guidelines are based on the assumption of the total release into the atmosphere of all of the hazardous material in the facility from an aircraft crash. The screening criteria for the public, for example, are a radiological dose to the MOI of less than 25-rem TED and a toxicological exposure of less than PAC level 2 (PAC/TEEL-2). Similar criteria apply to the worker. If the amount of hazardous material is insufficient to reach these levels, an aircraft crash into the facility is considered insignificant and phases two and three need not be evaluated as the scenario has been screened out.

For phase two, the screening criterion is a crash frequency of less than one crash per million years into the facility. Below this frequency, aircraft crashes are not considered significant and phase three need not be evaluated (see DOE-STD-3014-2006 and DOE-STD-3009).

For phase three, the screening criteria deal with the robustness of the facility. If an aircraft or any of its parts could not penetrate to the location of the hazardous material, an aircraft crash is not considered significant for that facility.

Refer to DOE-STD-3014-2006 for details on performing these analyses. The following observations are based on experience with applying that standard at multiple DOE sites.

1. Crash probabilities are estimated separately for airport operations (take-offs and landings) from nearby airports and from overflights from more distant airports and are then summed. A variety of aircraft types regularly operate near DOE sites. These include general aviation, commercial, and

military. There are typically no special restrictions in place for the air space around and above a DOE site, although sectional charts may carry an advisory relative to flights below a certain altitude, such as 1,000 feet. Overflights occur occasionally along predefined navigational pathways (Airways). Helicopter operations should also be considered, such as from hospital "Flight-For-Life" and spraying operations. Site-supervised overflights may also be performed by rotary-wing and fixed-wing aircraft for photographic and other purposes. In addition, a nearby airport may host air shows featuring military aircraft conducting displays and acrobatic activities. Small aircraft (those that weigh less than 12,500 pounds) operating from nearby airports are major contributors to the numbers of aircraft in the vicinity of a DOE site.

Although a pilot would be expected to attempt a minimal-impact landing, data show that the pilot has no control in approximately 76% of accidents and only limited control 19% of them (Cooper and Chira-Chavala, 1998). An aircraft-fuel fire may also accompany this accident. The estimation of the probability of an aircraft accident involving a site facility is based on the air traffic associated with the nearby airports and overflights, and the aircraft crash rate. The aircraft accident rate from airport operations is estimated as the product of the number of flights and the aircraft accident rate per square mile for airport operations (Boonin, 1974; DOE-STD-3014-2006). These data provide accident probabilities for impact locations as a function of distance from an airport. The aircraft crash rate from general aviation overflights is also significant and needs to be considered.

2. For fixed-wing aircraft, the estimated annual aircraft crash frequency from airport operations is calculated from aircraft crash rate for each flight phase (take-offs, landings, and in-flights), aircraft category (general aviation or commercial), flight source, and effective area of facility, including physical footprint, skid-in area, and shadow. The values of estimated number of site-specific airport operations, for each aircraft category and flight source, are found in airport operations data (http://www.airnav.com/airports/).

3. The crash rates from general aviation, commercial, and military *overflights* are provided in Appendix B of DOE-STD-3014-2006, *Accident Analysis for Aircraft Crash into Hazardous Facilities*, for each DOE site, as well as the maximum, minimum, and average rates for continental United States. The rates for a given site are added to the rate determined from operations at nearby airports to get the total rate. For general aviation, it was found that the overflight crash data may not be accurate for a given DOE site, as the database was limited by the paucity of crash data available when DOE-STD-3014-2006 was initially prepared in 1996. It would be appropriate for the safety analyst to do a reanalysis for a given DOE site. The National Transportation Safety Board (NTSB) database should be consulted to determine the total number of crashes within a certain distance from the site. The distance chosen should be small enough to be representative of the Site, but large enough to include a sufficient number of accidents so that meaningful statistics can be derived. For sites in more heavily populated areas, the "certain distance" could be as little as 25 miles, whereas for sites in less populated areas, it could be as much as 50 miles to obtain an adequate data sample.

4. Another parameter to calculate the likelihood of an aircraft cra*shing into* a facility is the aircraft crash location conditional probability at the facility location (x,y) relative to the runway. The coordinates x and y are relative to the runway, with the origin being at the center of the runway, positive x in the direction of takeoff or landing and positive y in the direction 90° counterclockwise from positive x (i.e., to the left). The bearing of the airport from the facility (θ) from geographic north, the bearing of the runway (φ) from magnetic north, and the distance (R) between the facility and runway are needed to calculate the (x,y) coordinates of the facility from the center of the runway.

   The coordinates of a facility relative to the runway are thus

$$x = -R\cos(\theta - \varphi)$$

$$y = R\sin(\theta - \varphi) \qquad \textbf{Equation 4-53}$$

The calculation of *R* is based on the differences in latitude and longitude of the facility and the referenced airport.

Runway labels are expressed as degrees azimuth /10. Thus, runway 22 has a bearing of 220 degrees azimuth and runway 4 has a bearing of 40 degrees azimuth. Runways 4 and 22 are physically the same but differ in designation depending on the direction of motion of the aircraft, with 4 being to the northeast and 22 to the southwest. Runways may also have a left/right (L/R) designation if there are two runways side-by-side with the same orientation; sometimes, C is used for Central. The true runway bearing may differ slightly from its designation. For example, runway 22 might have a bearing anywhere between 215 degrees azimuth and 225 degrees azimuth from magnetic north. The difference between geographic north and magnetic north, the magnetic declination, needs to be considered and if it is smaller than the uncertainty in the runway bearing it may be ignored. The magnetic declination can be found at National Oceanic and Atmospheric Administration National Geophysical Data Center website http://www.ngdc.noaa.gov/ngdc.html and selecting Magnetic Field Calculators.

5. The values of effective area are dependent on the dimensions of the facility and aircraft type. As the effective area depends on the side of the building the aircraft crashes into, it should be evaluated for all reasonable approach directions and the largest value used. If two adjacent buildings are spaced apart less than the wingspan of the plane, the effective area will be the combination of the two buildings.
6. For buildings that are partially protected by other buildings or a hillside, the analyst should use the building dimensions appropriate for the direction of approach of the aircraft to the exposed walls. To be conservative, assume that the aircraft will approach from the side that gives the largest unprotected target area.
7. Do not assign conditional probabilities to different parts of the plane, such as the probability of the engine hitting the building versus the wings.
8. Helicopter crashes are treated differently from fixed-wing aircraft crashes. The helicopter crash frequency into a facility is given by:

$$F_H = N_H P_H A_H (2/L_H) \qquad \textbf{Equation 4-54}$$

where N_H is the number of helicopter local overflights per year at the site,
P_H is the probability of a helicopter crash (2.5E-5 per operation),
A_H is the facility footprint area,
L_H is the average length of the flight path over the site.

The term $2/L_H$ arises from the conservative assumption that the helicopter crash takes place within 0.25 miles from the centerline of the flight path. This gives a total area in which the helicopter crashes of 0.5 miles wide and L_H miles long, for a conditional probability of $1/(0.5L_H) = 2/L_H$ per square mile. If the value of L_H is not available, it can be estimated as the distance to the nearest heliport.

4.7.1.2 AIRCRAFT CRASH DAMAGE ASSESSMENT

If an aircraft crashes into the portion of a facility housing radioactive or other hazardous materials, that material could be released by an ensuing fire (Section 4.2), explosion (Section 4.3), and/or by loss of containment (Section 4.4), or potentially may cause releases from chemical reactions (Section 4.5).

4.7.2 VEHICLE CRASHES

Two types of vehicle crashes need to be considered: (1) A vehicle crashing into a facility causing a release of hazardous material from that facility; and (2) A vehicle transporting hazardous materials is damaged en route and material is released from the vehicle.

4.7.2.1 VEHICLE CRASH INTO FACILITY

The accident analysis methodology for an external vehicle crash into a facility is:

1. Identify the scenario;
2. Identify whether a fire initiator is present;
3. Identify the type and quantity of hazardous materials involved and appropriate MAR, DR, and LPF (for mitigated scenarios only); and
4. Calculate the consequences of the accident.

If a vehicle crashes into the portion of a facility housing radioactive or other hazardous materials, that material could be released by a fire (Section 4.2), explosion (Section 4.3), and/or by loss of containment (Section 4.4). The analyst should determine the likelihood of such an accident based on the location of the MAR in the facility relative to the route the vehicle would take to impact that portion of the facility. Although it may not affect the likelihood of the vehicle crash causing a release, the location of SSCs should be considered if a vehicle crash into SSCs could initiate an accident progression. Vehicles to consider would include automobiles, trucks and vans, and railroad cars if a rail line passes near the facility.

The vehicle momentum, robustness of the facility walls, amount of fuel in the vehicle (assume the maximum), any combustibles it contains, and the facility combustibles at the crash site needs to be estimated. Then, following the guidance in Sections 4.2, 4.3, and 4.4, the source term can be estimated.

4.7.2.2 ONSITE TRANSPORTATION ACCIDENT

Transportation of radioactive and hazardous materials presents special hazards to operations and to personnel at the site due to the close proximity of these vehicles to facilities and the reduced level of containment of the materials while outside buildings. These types of materials include special nuclear material (SNM), residues, TRU waste, TRU mixed waste, low-level waste, low-level mixed waste, Resource Conservation and Recovery Act (RCRA)-regulated waste, Toxic Substances Control Act (TSCA)-regulated waste, mixed TSCA waste, samples, contaminated soil, incoming bulk shipments of fuels, acids, bases, miscellaneous chemicals, compressed gases, and laboratory reagents.

The accident analysis methodology for transportation accidents is:

1. Identify the scenario;
2. Identify whether a fire initiator is present (generally, one is present if the accident involves a motor vehicle);
3. Identify the type and quantity of hazardous materials involved and appropriate MAR, DRs, and LPFs (for mitigated scenarios only); and
4. Calculate the consequences of the accident.

The analyst should examine shipping records to determine the frequency, type of material, and quantity of shipping, both on-site and to/from off-site. The shipment of bulk fuels and toxic chemicals also needs to be quantified. This would include the type of material, the total amount shipped, the average and maximum delivery size, and which facilities are involved. Each site should have an on-site transportation manual that lists the packaging configurations currently approved for on-site and off-site use. For example, no package may be used for Pu or uranium unless it has received a criticality safety evaluation and has been determined to remain subcritical. It is not uncommon for transportation accidents to occur at a site. Most of these accidents involving radioactive material transfer would not be severe, and there could be minor releases. Loading and unloading accidents are the most common and could involve forklifts.

In estimating the MAR in a transportation accident, the maximum number of packages that can fit on a truck should be assumed, unless a specific justification is stated for a different number. An example of truck capacities is shown in Table 4-12, which provides the capacities of transport vehicles for a full load of each type of package that can be hauled. Different size vehicles used at a particular DOE site for transport of containers should be evaluated. Because of the requirement to keep radiation exposure levels in the truck cab below 5-mrem/hr, these capacities are conservative for SNM and waste drums. If analysis with these capacities provides unacceptable consequences, then the truck inventory should be limited by administrative controls.

For a single drum accident, the maximum amount of material allowed by criticality limits should be assumed to be in the drum. For large numbers of drums, where the actual inventories may be vastly different from the allowed inventories, it may be acceptable to use, inventory estimates from specific process knowledge (DOE-STD-5506-2007, Section 4.3.2). However, the importance of this assumption affects the need for an administrative control to preserve it. For container types other than drums, determine the maximum amount allowed by conditions imposed on that container type.

Table 4-12. Example of Transport Vehicle Package Capacities.

Transport	Truck Bed Size	SNM and Residues		
		Number of 10-Gallon Drums	**Number of 30-Gallon Drums**	**Number of 55-Gallon Drums**
Enclosed Metal Van	7’ 7” × 12’	54	28	18
Enclosed Metal Van	7’ 7” × 13’ 9”	66	32	21
Dump Truck	7’ 6” × 15’ 10”	72	36	24
Box Van	17’ 8” × 15’ 11”	168	90	72
		LLW and Hazardous Waste		
		Number of Half-Size Crates	**Number of Full-Size Crates**	**Number of 55-Gallon Drums**
Flat Bed Trailer (for on-site transfers)	8’ × 55’	10 (weight limited)	12 (weight limited)	112
Tractor Trailer Van (for off-site shipment)	8’ 6” × 53’ or two 25’ long in tandem	10 (weight limited)	12 (weight limited)	208

The MAR released by crash should be determined depending upon the result of the event, i.e., whether it results in a fire (see Section 4.2), explosion (see Section 4.3), or loss of containment (see Section 4.4).

4.7.3 LOSS OF POWER TO SAFETY-RELATED SSCs

The accident analysis methodology for loss of power to safety-related SSCs that may provide a safety function to prevent or mitigate accidents is:

1. Identify the scenario;
2. Identify the type and quantity of materials present;
3. Identify whether a fire initiator is present; and
4. Calculate the consequences of the accident.

The NRC has requirements and guidance for a “station blackout DBA” for a commercial nuclear reactor, where station blackout means loss of AC power within a facility (i.e., loss of all onsite and offsite sources), except that battery power may be credited for the duration analyzed to ensure safe shutdown. For a DOE nonreactor nuclear facility DSA, DOE-STD-3009 requires an unmitigated analysis that does not credit any active power sources, including battery power.

Loss of power scenarios are of interest in this Handbook in terms of the potential for releases of radioactive or hazardous materials. If the safety SSC is preventive, evaluate whether the failure of the safety SSC in question (upon loss of electrical power) could cause or initiate a hazardous condition or an accident involving the release of radioactive or hazardous materials. If the safety SSC is mitigative, the analyst could consider whether failure of the safety SSC in question could occur simultaneously with other existing analyzed accident scenarios (i.e., a common cause event like NPH).