Range Commanders Council
Range Safety Group

SUPPLEMENT: STANDARD 321-23

COMMON RISK CRITERIA STANDARDS FOR NATIONAL TEST RANGES: SUPPLEMENT

ABERDEEN TEST CENTER
DUGWAY PROVING GROUND
ELECTRONIC PROVING GROUND
REAGAN TEST SITE
REDSTONE TEST CENTER
WHITE SANDS TEST CENTER
YUMA PROVING GROUND

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION PATUXENT RIVER
NAVAL AIR WARFARE CENTER WEAPONS DIVISION CHINA LAKE
NAVAL AIR WARFARE CENTER WEAPONS DIVISION POINT MUGU
NAVAL SURFACE WARFARE CENTER DAHLGREN DIVISION
NAVAL UNDERSEA WARFARE CENTER DIVISION KEYPORT
NAVAL UNDERSEA WARFARE CENTER DIVISION NEWPORT
PACIFIC MISSILE RANGE FACILITY

96TH TEST WING
412TH TEST WING
ARNOLD ENGINEERING DEVELOPMENT COMPLEX

SPACE LAUNCH DELTA 30
SPACE LAUNCH DELTA 45

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUPPLEMENT: STANDARD 321-23

COMMON RISK CRITERIA FOR NATIONAL TEST RANGES: SUPPLEMENT

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Prepared by

RANGE SAFETY GROUP
RISK COMMITTEE

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Table of Contents

List of Figures

List of Tables

Changes to this Edition

This document is an updated version of RCC Document 321-20 Supplement (*Common Risk Criteria for National Test Ranges - Supplement*). The following is a list of changes.

a. General Changes: version information and acronym updates.

b. Extensive catastrophic risk changes to Section 4.3, Table 4-9, and subsequent table number updates. Added Table 4-10 to show catastrophic risk equation has been compared to commonality criteria in an example study. Updated Chapter 4 table values, formats, and references. Included fatalities as needed throughout Section 5.5.

c. Updated and cleaned up Section 4.6 with 2020 National Space Policy, and consistency with Missile Defense Agency criteria. Added in acceptable launch collision avoidance practices for satellite cluster and parent child deployment strategies as well as covariance data and normality testing. Added arrival time to “dispersions” as needed in Subsection 5.8.6.

d. Removed provisional wording regarding neighboring operational personnel (NOP) throughout.

e. Added Subsection 7.5.3, New Propellant Characterization, and testing recommendation and procedures.

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Foreword

The Risk and Lethality Commonality Team (RALCT) was formed in 1996. The RALCT was formed for reaching a consensus on reasonable common standards for debris protection criteria and analytical methods. The initial version, RCC 321-97, was very useful, but was limited in scope due to the complexity of the subject and time constraints. This standard was updated in 1999 and again in 2002 to provide greater detail. In August 2004, the Range Commanders Council (RCC) Range Safety Group (RSG) determined that RCC Document 321-02 (Common Risk Criteria for National Test Ranges, Subtitle: Inert Debris), should be updated and expanded for other flight safety hazards (in addition to inert debris) and consequences potentially generated by range operations.

The RALCT became a standing committee under the RCC RSG in 2004. It was renamed the Risk Committee in February 2005 and developed RCC 321-07. The Committee updated RCC Document 321-07 to include guidelines for assessing the acceptability of conditional risks associated with launch control measures, an approach and sample criteria for evaluating the range safety hazards to critical assets and guidelines for accounting for and reporting the uncertainty in risk model predictions.

RCC 321-16 further updated the standard to include updates to ship protection guidelines, updates to aircraft protection guidelines, and updates to COLA standards and guidelines. RCC 321-17 added a two-tiered risk management process for the protection of public infrastructure and included provisional acceptable risk criteria for public infrastructure.

The current update provides further guidelines and models for protection of aircraft, ships, spacecraft, public infrastructure, and critical assets. Discussions on approaches for addressing hazards other than debris hazards were expanded in the supplement both explicitly and by reference to other publicly available documents, such as FAA advisory circulars.

The previous version of this document, RCC 321-20 Supplement, provided additional detailed information to assist in implementation of the standards in the basic document. The criteria in the 321 standard should not be considered absolute; rather, the standard and this supplement are intended to provide guidance on defining acceptable approaches for analysis of hazardous range operations and to assist the user in developing more consistent risk assessments.

This supplement to the 321 standard provides changes to sections describing acceptable launch COLA approaches, catastrophic risk analysis, some general house cleaning and acronym updates.

This document represents the collective efforts of both government and contractor personnel and is the result of an extensive cooperative effort.

NOTE	Herein, the use of the word “supplement” or the phrase “this supplement” refers to this document. This supplemental document makes many references to the basic 321 standard. For clarity, the basic document is often referred to as the “standard.” For example, “Chapter 3 of the standard” refers to Chapter 3 of RCC 321-23.

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Preface

The RCC 321 standard is the foundational document that defines consensus standards for the range risk management process and risk criteria. This supplement provides additional detailed information to assist in implementation of the standards.

The supplement is intended to:

a. promote a uniform process among the ranges;

b. promote valid, repeatable risk assessments;

c. foster innovation to support challenging missions;

d. nurture openness and trustworthiness among the ranges, range users and the public;

e. simplify the scheduling process;

f. present common risk criteria that can reduce cost for users of multiple test ranges.

Acknowledgements for preparation of this document go to the many participating members of the RSG Risk Committee.

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Acronyms

SLD 30	Space Launch Delta 30
SLD 45	Space Launch Delta 45
ABS	American Bureau of Shipping
A_C	casualty area
ACSR	aluminum conductor steel reinforced
AFB	Air Force Base
AIS	Abbreviated Injury Scale
APA	Administrative Procedures Act
AST	Associate Administrator for Space Transportation (FAA)
AuIS	Automated Identification System
AVM	aircraft vulnerability model
BJ	Business Jet
BRL	Ballistics Research Laboratory
CA	conjunction assessment
CCAS	Cape Canaveral Air Station
CCD	complementary cumulative distribution
CFR	Code of Federal Regulations
COLA	collision avoidance
CSLA	Commercial Launch Space Act
CSLAA	Commercial Launch Space Amendments Act
CSpOC	Combined Space Operations Center
CT	Commercial Transport
DDESB	Department of Defense Explosives Safety Board
DFO	distant focusing overpressure
DoD	Department of Defense
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DOT	Department of Transportation
DSL	damage severity level
E/A	energy to area ratio
E_C	expected casualties
E_F	expected fatalities
ELV	expendable launch vehicle
ER	Eastern Range
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
FRP	fiber-reinforced polymer
FSA	flight safety analysis
FSS	flight safety system
FTCA	Federal Tort Claims Act
FTS	flight termination system
GP	general public
GPa	Refers to: annual general public risk

HEL	high-energy laser
HSE	Health and Safety Executive (UK)
ICV	intercept control volume
IIP	instantaneous impact point
ILL	impact limit line
IMO	International Maritime Organization (United Nations)
ISDS	inadvertent separation destruct system
ISS	International Space Station
JCT	Jumbo Commercial Transport
LEO	low earth orbit
LNG	liquid natural gas
LOC	level of concern
LOR	level of rigor
LSP	Launch Services Program
MDA	Missile Defense Agency
MEa	Refers to: Annual Mission Essential Risk
MEP	mission-essential personnel
MIL-HDBK	Military Handbook
MRTFB	Major Range and Test Facility Base
MSL	mean sea level
NASA	National Aeronautics and Space Administration
NAWCWD PM	Naval Air Warfare Center Weapons Division Point Mugu
NL	Netherlands
nm	nautical miles
NOHD	nominal ocular hazard distance
NOP	neighboring operations personnel
NOTAM	Notice to Airmen
NOTMAR	Notice to Mariners
NPRM	Notice of Proposed Rulemaking
NRC	Nuclear Regulatory Commission
NTSB	National Transportation Safety Board
OPAREA	operating area
OP-I	overpressure-impulse
OSHA	Occupational Safety and Health Administration
P_C	probability of casualty
P_{CF}	fragment probability of casualty
PD/NSC	Presidential Directive/National Security Council Memorandum
PDF	probability density function
P_F	probability of fatality
P_{fail}	probability of failure
PIRAT	Propellant Impact Risk Assessment Team
PoC	probability of collision
PRA	Probabilistic Risk Analysis
psi	pounds per square inch
RALCT	Risk and Lethality Commonality Team
RC	Risk Committee

RCC	Range Commanders Council
RLV	reusable launch vehicle
RSG	Range Safety Group
RSO	range safety officer
RSS	range safety system
SRI	Stanford Research Institute
STIL	Short Term Interval Launch
SUA	special use airspace
TCCR	Transparency, Clarity, Consistency, & Reasonableness
TNT	trinitrotoluene
TVC	Thrust Vector Controller
UAV	unmanned aerial vehicle
UK	United Kingdom
URS	Universal Risk Scales
USAF	United States Air Force
USC	United States Code
VAFB	Vandenberg Air Force Base
V&V	verification and validation
WR	Western Range

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CHAPTER 1

Introduction

1.1 Purpose

This document supplements the policies, criteria, and risk management process established by RCC Standard 321. It also provides supporting rationale and guidance on models and analyses to assist safety professionals in implementing the policies and criteria.

1.2 Scope

This supplement is for use by DoD national ranges and the Major Range and Test Facility Base (MRTFB) members. The information provided applies to launch and reentry hazards generated by endoatmospheric and exoatmospheric range activities, including both guided and unguided missiles and missile intercepts, space launches, artillery, and reentry vehicles. This document does not include aviation operations or unmanned aerial vehicle (UAV) operations (see Section 1.2 of the standard). The RCC document 323[1] provides criteria for UAVs.

1.3 Application

Range safety authorities are expected to use the criteria, analysis principles, and processes defined by the standard and this supplement document; however, the range commander or a designated representative is the final decision authority for accepting risk and proceeding with a mission.

The intent of the safety criteria and guidelines is to provide definitive and quantifiable measures to protect mission-essential personnel (MEP), the general public (GP), and critical assets. The analysis principles and processes defined in this supplement can be used to characterize the operational risk for a mission. Definitive criteria provide a standard by which the range commander's actions can be compared to those of any reasonable person in similar circumstances. All of the criteria have been evaluated from various perspectives and are considered reasonable. A discussion of the supporting rationale for the risk criteria is presented in Chapter 5.

The risk management and safety assessment processes presented in this supplement should be used to consistently characterize and assess the hazards associated with a specific scenario to support an informed risk acceptance decision. Results obtained by applying these analytical methods, or other methods based on the principles endorsed here, are the product of a disciplined process to establish objective safety recommendations. Therefore, the risk estimates should not be subjectively altered at the end of the process. Such changes could invalidate the informed decision process that helps protect the government from liability.

1.4 Organization

The following are the major chapters of the supplement.

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[1] Range Commanders Council. *Range Safety Criteria for Unmanned Air Vehicles*. RCC 323-18. June 2018. May be superseded by update. Retrieved 17 October 2023. Available at https://www.trmc.osd.mil/wiki/x/AYy8Bg.

- Chapter 2*: Risk Management Process Level II*: This is an extended discussion of the risk management process presented in Chapter 2 of the standard.
- Chapter 3*: General Risk Model Requirements*: This chapter describes general model requirements that should be applied to computational tools used to analyze the flight safety risks in support of decisions governing safety.
- Chapter 4*: Risk Criteria Implementation Guidelines*: This is one of the most important chapters of the supplement. This chapter has nine major sections.
    - Section 4.1 outlines the chapter and introduces different measures of risk.
    - Section 4.2 provides guidelines for the application of the criteria. Some of the important concepts presented include risk accrual, different consequence metrics, the relevance of time frame over which risk is computed and how these time frames are defined, and guidance for treatment of different classes of related multiple launches constituting a single mission. It then provides guidance for assessing the level of rigor (LOR) required to support different classes of missions and mission segments. The underlying principle expressed is that the closer the risk is to the tolerable limit the higher the fidelity and the lower the uncertainty that can be accepted in the calculations.
    - Section 4.3 introduces the topic of catastrophic risk and limits for risks in which a single incident can produce injuries or fatalities to a large number of people.
    - The next group of sections provides guidelines for protecting people and critical assets in various locations.
        - Section 4.4 details implementation guidelines for protecting people on-board airplanes.
        - Section 4.5 provides implementation guidelines for protecting people in ships.
        - Section 4.6 provides implementation guidelines for protecting spacecraft.
        - Section 4.7 provides guidelines for protecting critical assets at a launch complex and its surrounding areas.
        - Section 4.8 provides guidance for protecting infrastructure.
    - The final section of this chapter presents a tutorial of uncertainty in risk analysis and risk-based decisions; these concepts are relevant to the decision process as well as the determination of the required LOR.
- Chapter 5*: Risk Criteria Rationale*: Chapter 5 is designed to provide the reasoning for adopting the various risk measures and the levels of tolerable risk. This chapter is structured into the following sections.
    - Rationale for Risk Metrics
    - Criteria Rationale Overview
    - Rational for Casualty Limits
    - Rationale for Fatality Guideline Limits

  - Rationale for Catastrophic Risk Criteria
  - Rationale for Aircraft Risk Management Requirements
  - Rationale for Ship Risk Management Requirements
  - Rationale for Spacecraft Protection Requirements
  - Rationale for Infrastructure Tier 1 Maximum Severity Classes and Protection Acceptance Criteria
  - Using Aviation as a Benchmark for Launch Risk
- Chapter 6: *Hazard Thresholds*: The material in this chapter is organized as follows. The first section clarifies the meaning and intended use of hazard thresholds. The second section presents hazard thresholds for unsheltered persons. The third section provides hazard thresholds for people inside of buildings, ships, and aircraft. The fourth section provides information for establishing hazard thresholds for damage to critical assets. As applicable, separate subsections are devoted to fragment hazards and explosive overpressure hazards. In each subsection, terms are defined and hazard thresholds are cited. Each subsection also includes an explanation of how thresholds were determined with appropriate references for methodology, supporting data, and/or supporting practices.
- Chapter 7: *Approaches and Considerations for Debris Risk Assessment Models*: This chapter is designed to provide guidance to the modeler in developing good models to support debris risk analysis model development. The chapter identifies key submodels that may be needed and characteristics of good models for each function. In many sections, it also addresses the type of data that may be available as input to the model. Major sections of the chapter have subsections providing a deeper insight to relevant thought processes for different aspects of the modeling area.
- Chapter 8: *Other Hazards*: This chapter provides screening criteria and analysis considerations for hazard and risk assessments for toxics, glass breakage from far-field overpressure, and exposure to radiation.

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CHAPTER 2

Risk Management Process Level II

Chapter 2 of the standard presents a risk management process that provides a systematic and logical approach for identifying hazards and controlling risks. Risk assessment is not a single, fixed methodology; rather, it is a systematic approach to organizing and analyzing scientific knowledge and information about potentially hazardous activities. Therefore, the risk management process steps presented here should not be considered as binding rules. These process steps provide a strong foundation from which the responsible safety office may depart consistent with DoD policy when considering the unique situation posed by a range activity. A risk management policy can legitimately contain only those elements that are relevant and significant based on the specific requirements of the missions performed at the range in question. Each range must perform a careful review to ensure that all needed considerations and analyses are included in its risk assessment process. In addition, assessment of unique or unusual hazards may require a range to expand on the considerations included in this chapter.

Most test ranges have developed integrated tools to automate this process. Desirable characteristics for these tools are identified in Chapter 3 and Chapter 7. It is incumbent on the ranges to ensure that the tools adequately incorporate these characteristics and accurately convey the risk estimate and the uncertainties inherent in the methods and data used.

2.1 Historical Background

The original RCC Document 321 included a top-level approach to risk analysis to aid safety professionals in implementing the policies and criteria of the standard. The approach, known as the 8-Step Process, provided a description of activities included in the analysis of inert debris risk. This approach was expanded to include the major activities required to conduct the entire risk management process and includes considerations to address hazards beyond just inert debris.

The current approach is an adaptation of the risk management process accepted as standard by the system safety community and provides a more comprehensive picture of overall risk management. The approach highlights the iterative aspects and critical reviews commonly found in successful risk management programs and in existing range practices. While providing insight, this approach neither is an “approved” methodology nor inclusive of all considerations required to properly assess the risks encountered by every range or mission. The remainder of this chapter describes the risk management process developed for this standard.

2.2 Risk Management Process - Level II: Overview

This chapter expands the process defined in Chapter 2 of the standard to the next level of detail. The flowchart presented in Figure 2-1 provides an overview of the major analysis tasks required to perform risk management from the flight safety perspective. Tasks are grouped into the four phases of Risk Management described in Chapter 2 of the standard. This section describes each of these four phases. Section 2.3 gives a brief description of the steps within each phase. Subsequent sections provide checklists of analytical considerations for each step that might be included in the specific analysis approach adopted by a test range.

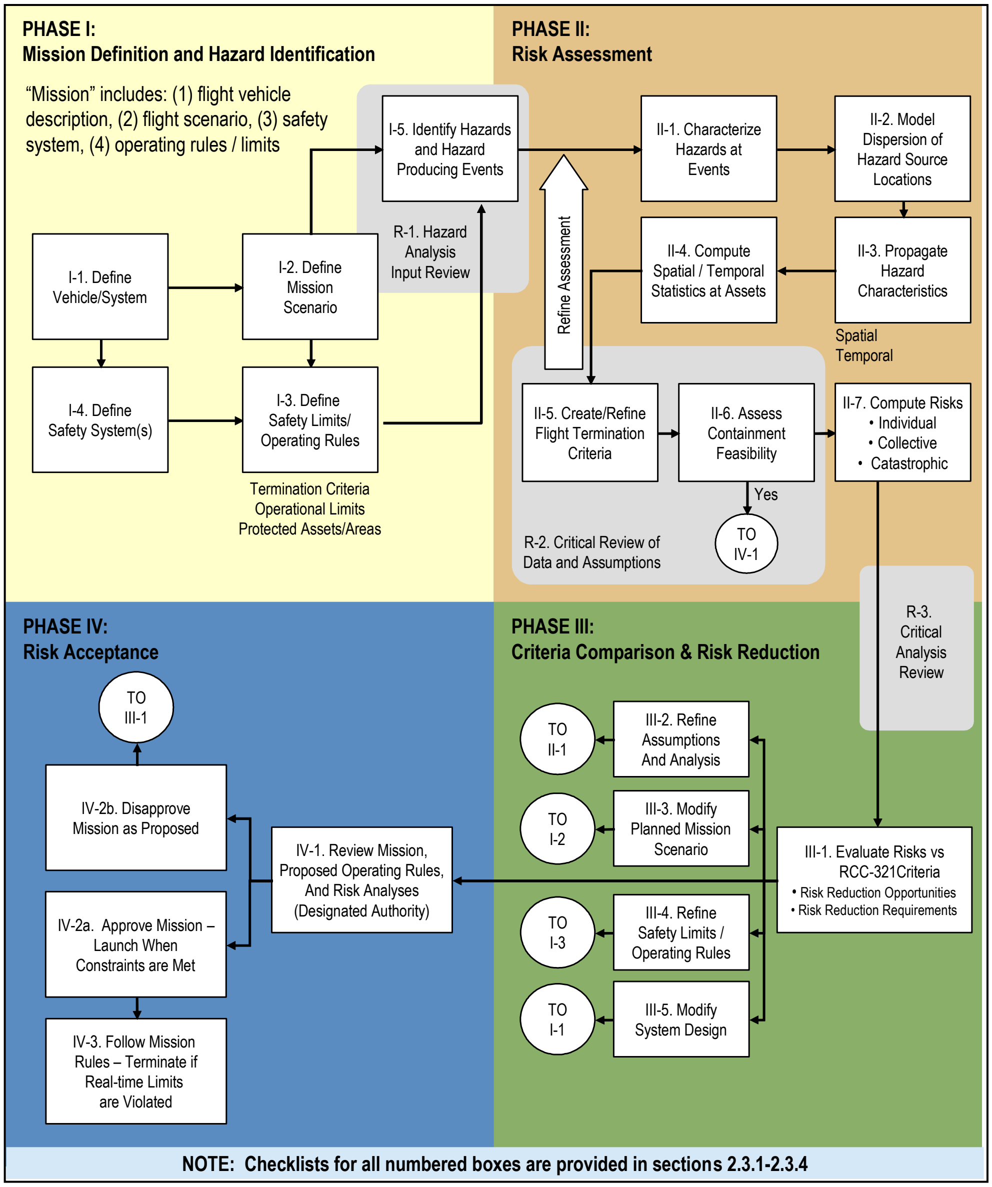

Figure 2-1. Level 2 Risk Management Process Flowchart

2.2.1 Mission Definition and Hazard Identification

Definition of the vehicle, safety control systems, and planned manner of flight are required to support identification of the hazards associated with the mission. Potential hazard sources are then examined by evaluating the system being flown and the range safety constraints. Information sources include range safety data packages, system description documents, MEP locations, surrounding population data, locations of facilities or properties to be protected, the range safety system (RSS) used, and lessons learned from similar missions. The hazards associated with launch or test operations typically result from inert and explosive debris, chemical toxicity of propellants or other toxicants, and the distant focusing of an overpressure blast wave under certain meteorological conditions. These hazards may be the result of a launch vehicle or test article malfunction and subsequent breakup or intact impact, or the combustion and release of chemical constituents during normal operations.

2.2.2 Risk Assessment

The initial approach in the risk management process is to contain the hazards and isolate them from populated areas wherever practical or to define hazard containment areas to minimize the population exposed and/or evacuate persons not associated with the hazard-generating event. This is in accordance with the primary policy that no hazardous condition is acceptable if mission objectives can be attained from a safer approach, methodology, or position (i.e., minimizing the hazards and conducting the mission as safely as reasonably possible). If hazards cannot be contained or minimized to an insignificant level, then more-detailed assessments should be performed to determine if the remaining risk is acceptable.

The risks are determined using quantitative methods that take into consideration the probability of failure (P_{fail}), failure response modes, the actions of the range safety officer (RSO) and RSS to contain the failing vehicle, winds, distribution of the debris, and the location and vulnerability of the exposed population or other assets. This assessment produces risk measures such as individual probability of casualty (P_C) or fatality (P_F), expected casualties (E_C) or fatalities (E_F), etc. These measures are compared with the risk acceptability criteria to determine whether the mission can be allowed to proceed as planned. If the collective risk criteria is greater than 1/3 of the acceptability criteria, further steps should be taken before the launch is permitted to proceed. Either mitigations are introduced to reduce the computed risk to the 1/3 level of the criteria, or an uncertainty analysis of the quantification process is performed to determine whether the refined risk estimates, which account for model and parameter uncertainty, are less than the risk acceptability criteria. If the uncertainty analysis shows that the acceptability criteria are still not satisfied, it will be necessary to introduce risk mitigations until the risk acceptability criteria are no longer exceeded or waived by proper the authority.

2.2.3 Criteria Comparison and Risk Reduction

If the risk is unacceptable when initially compared to the criteria, then various protective measures should be considered to eliminate, mitigate, or control the risks. Elimination is achieved by design or system changes that remove the hazard source. Mitigation is achieved by reducing the hazard level or the effect of the hazard. Control is achieved by using flight termination systems (FTSs), containment approaches, evacuation, sheltering, or other measures to protect assets from the hazards. Risk reduction should include confirmation of the resolution of anomalies and failures of all safety-critical systems during previous tests or flights. Implementation of these measures may warrant a reassessment of the risk using revised assumptions and inputs.

2.2.4 Risk Acceptance

Each organization should establish and use procedures that assure that risk levels are reviewed at the proper level of authority. This review should compare the operational risk to the criteria defined in this document and other applicable mission documents. In general, higher-risk operations require a higher level of approval. This final and necessary step in risk management is the acceptance of operational risks by a properly designated and informed authority. In general, this acceptance should be documented using existing procedures. These procedures should include the means of ensuring that planned standards and controls are being implemented.

2.3 Detailed Checklists for Phases of the Risk Analysis Process

Figure 2-1 provides only a top-level flow of the types of activities required to identify, assess, mitigate, and accept the risks resulting from a flight operation. The checklists below provide additional insight into those factors that should be considered for incorporation into a range's analysis process. Considerations are provided for the steps in the four phases of the Level 2 risk management process shown at Figure 2-1. The checklists for each phase are contained in the following sections as follows:

Phase	Title	Section
I	Mission Definition and Hazard Identification	2.4
II	Risk Assessment	2.5
III	Criteria Comparison and Risk Reduction	2.6
IV	Risk Acceptance	2.7

These checklists are not exhaustive and may not contain all parameters that should be considered in a given analysis. Each range is responsible for determining the level of analysis required to assess the risks of a given mission. Some examples of factors that should be considered in the range's process can be found in Chapter 3 and Chapter 7.

2.4 Phase I: Mission Definition and Hazard Identification

For the purpose of the flight safety analysis (FSA) discussions the term "mission" is defined to include a flight vehicle description, the flight scenario, the FTS on-board the vehicle, the RSS from where the vehicle will be controlled, and the rules and safety limits under which the operation must be conducted.

Phase I of the risk management process is the information-gathering phase. This is often accomplished through technical reviews and meetings between the range users and the range operations and safety personnel. This phase identifies credible scenarios that can either intentionally or unintentionally produce hazards and define the scope of the risk assessment to be performed. The outcome of this phase will be a list of hazards and hazardous events to be analyzed in the risk assessment phase. Key steps of this phase and items that should be considered are described below.

2.4.1 Step I-1: Define Vehicle/System

Identify characteristics of the vehicle and vehicle behavior that can create potential hazards, represent a means of controlling hazards, or affect the magnitude of the hazard. See the checklist at Table 2-1.

Table 2-1. Define the Vehicle/System (Step I-1)

	A. Vehicle characteristics
☐	Configuration
	• Booster stack – motors/stages (liquid/solid, strap-ons), interstages, skirt(s), payload fairings
	• Payload(s) and reentry bodies

	Mass properties as a function of time
☐	• Dry weight
☐	• Propellant (to include ambient and pressurized conditions)
☐	Structural limits
☐	Thrust history/capability
☐	Turn capability (velocity turn data, malfunction turn trajectories, or lateral acceleration)
☐	Guidance/control systems (thrust vector controller, fins, jets/thrusters, etc.)
☐	On-board data/tracking instrumentation (telemetry, Global Positioning System units, transponders)
	• Data rates
	• Tracking uncertainties
	B. Vehicle failure modes and responses
☐	Failure Mode Effects and Criticality Analysis/Failure Modes and Effects Analysis
☐	Event Tree Analysis
	C. Vehicle failure probabilities – derived from:
☐	Historical data
☐	Similar vehicles
☐	Reliability analysis or demonstration
☐	Bayesian analysis
☐	Relevancy of aging data (e.g., fading memory filter)

2.4.2 Step I-2: Define Mission Scenario

Define where and how the vehicle is intended to fly to identify potential hazardous events or pre-determined bounds that may be dictated by mission/program requirements. See the checklist at Table 2-2.

Table 2-2. Define Mission Scenario (Step I-2)

	A. Mission objectives
	Type of mission
	• Payload launch
☐	○ Orbital (including type of orbit)
☐	○ Suborbital
☐	• Demo/experiment
☐	• Intercept
	Data collection/performance requirements
☐	• Altitude requirements
☐	• Range requirements
☐	• Velocity requirements
☐	• Vehicle attitude requirements
☐	• Event/timing requirements
☐	• Program instrumentation requirements

☐	Other program auxiliary requirements (e.g., sun angle, distance from land target flies, etc.)
	B. Nominal flight trajectory/scenario
☐	Flight path (including target area for suborbital launches)
☐	Event timing (staging; other hardware jettisons; guidance, navigation, and control maneuvers; energy management; payload deployments)
☐	Intercept geometry
	C. Flight performance envelope
☐	Trajectory dispersions derived from guidance, navigation, and control performance and motor performance
☐	Allowable or permitted intercept control volume (ICV)

2.4.3 Step I-3: Define Safety Limits/Operating Rules

Identify known or pre-defined safety limits and operating rules to serve as a baseline for beginning the analysis. These are typically revised and refined based on analysis results (See Step II-5). See the checklist at Table 2-3.

Table 2-3. Define Safety Limits/Operating Rules (Step I-3)

	A. First-cut flight termination criteria
☐	Credible RSO and system reaction time
☐	Pre-defined flight corridors (azimuth fans, impact limit lines [ILLs], etc.)
☐	Destruct or flight termination limit lines, vertical plane limits, vehicle attitude criteria, protection circles, gates, etc.
☐	Rules for “No Data” destruct
	B. General safety and operating rules
☐	Instantaneous impact point (IIP) overflight
	Protected assets/areas - “assets”(also called receptors) includes people
☐	• Regions to be protected
☐	• High-value assets (facilities, property or other)
☐	• Population centers
☐	• Staffed personnel locations
☐	Pre-defined personnel sheltering and evacuation requirements
☐	Minimum number of tracking data sources and other applicable requirements such as capability of failing gracefully, etc.
☐	Initial launch commit criteria and launch constraints
☐	Special mission rules identified by the range user or flight analysts

2.4.4 Step I-4: Define Safety System(s)

Identify planned and available means of controlling, containing, or mitigating the hazards and the characteristics of the safety system(s) that define/bound the scope of the assessment. See the checklist at Table 2-4.

Table 2-4. Define Safety Systems (Step I-4)	
	A. Vehicle FTS characteristics
☐	Determine need for FTS - dependent on type of vehicle (some do not require FTS) and capability of a vehicle to hazard a protected area.
	Type(s) of system(s)
☐	1. Commanded
☐	2. Automatic (such as triggered by a premature separation)
☐	3. Autonomous (such as vehicle system determining violation of some predetermined criteria)
	Termination method(s)
☐	• Linear shaped charge - longitudinal, circumferential
☐	• Conical shaped charge
☐	• Thrust termination - ports, fuel line cuts
☐	FTS reliability
☐	System delays – the time to receive and execute the termination command
☐	Antenna type/patterns
	B. RSS characteristics
	Identify system(s) to be used
☐	• Fixed, land-based system
☐	• Mobile (land, sea, air platform)
	Mode(s) of operation
☐	• Manual destruct
☐	• Automatic destruct
☐	Antenna type(s) - directional (dish or helix) or omni-directional.
☐	Antenna location(s) (for plume shadow assessment)
☐	Transmit range (for link margin analysis)
	System delays
☐	• Time to receive and process time-space-position information data
☐	• Time to transmit after destruct button push
☐	Method of handover, if applicable (transfer of command and control)
☐	C. Tracking instrumentation feeds (accuracy, frequency of data, data latency)

2.4.5 Step I-5: Identify Hazards and Hazard Producing Events

Given the inputs of the previous four steps, define the hazards and hazardous events that will be evaluated in the risk analysis and assessment. See the checklist at Table 2-5.

Table 2-5. Identify Hazards and Hazard Producing Events (Step I-5)	
☐	A. Inert debris impact
☐	B. Explosive debris (near-range effects)
☐	C. Explosive debris (far-range effects) i.e., distant focusing overpressure (DFO)
☐	D. Toxics
	E. Typical hazard-producing scenarios:

☐	Malfunctioning vehicle terminated at destruct line or due to other criteria such as potential loss of FTS link or tracking data or obviously erratic flight
☐	Malfunctioning vehicle exceeding structural limits
☐	Motor case rupture (overpressure, burn-through – explosion while following nominal trajectory)
☐	Inadvertent separation of strap-on motors during either normal flight or a vehicle malfunction
☐	Scheduled jettisons
☐	Planned intercept event (whether kinetic, explosive, or directed energy)
☐	Planned destruct (post-mission prevention of recovery)
☐	Planned payload deployments and activations

2.4.6 Review R-1: Hazard Analysis Input Review

Review at this point provides an opportunity to reconfirm the scope of the analysis to be performed and verify that all of the hazards to be assessed are reasonable and feasible. See the checklist at Table 2-6.

Table 2-6. Hazard Analysis Input Review (Review: R-1)

☐	A. Has a sanity check been performed that all potential/feasible hazards have been addressed?
	Have common-cause failures been addressed?
	Have multiple simultaneous or sequential failures (stacked failures) been included that are not realistic or feasible?
☐	B. Have the failure modes and responses been adequately identified, supported, justified, and rationalized?
☐	C. Do the failure probabilities make sense?
	Consider similarities and differences between similar vehicles and similar subsystems
	Are the failure probabilities justified by the vehicle’s flight experience?
☐	D. Have there been any new design changes to the systems (vehicle or other) since the risk management process was started?

2.5 Phase II: Risk Assessment

Phase II consists of conducting qualitative and quantitative risk analyses and assessments to determine the level of risk posed by the mission. The output of Phase II will be the measures of risk to be evaluated against the acceptable risk criteria. The risk assessment phase may be an iterative process where portions of the analyses are conducted more than once as data inputs and assumptions are refined and finalized. All assumptions and the uncertainties associated with these assumptions should be noted at each step for consideration in the critical reviews and decision-making phases. If the analysis shows that containment is achieved then the analyst can finalize the assessment at that point, document the results, and proceed directly into the reviews of the risk acceptance phase (Phase IV).

Risk assessments should be conducted using tools that are both validated (fulfills the requirements of the task) and verified (correctly executes the function). Assessments can either be industry-accepted tools or custom tools developed by the range to meet their specific analysis needs. The tools used should be documented to include a statement identifying the means of verification and validation (V&V). Example statements include commercially produced; industry accepted; compared to available empirical data either from launch accident, planned event or from lab tests/experiments; compared to other accepted or validated tools; and demonstrated to match theoretical models. Additional information on recommended tool/model requirements is provided in Chapter 3.

2.5.1 Step II-1: Characterize Hazards at Events

Identify specific, detailed characteristics of the hazards to be evaluated. Hazards other than those listed here may need to be included as described in Chapter 8. See the checklist at Table 2-7.

Table 2-7. Characterize Hazards at Events[1] (Step II-1)

	A. Debris lists - includes size, shape, material, ballistic coefficient, and fragment imparted velocity information (see Section 7.1 for additional guidance on the development of debris lists).
☐	FTS event - either commanded, auto, or premature separation system - including time variance
☐	Breakup – aerodynamic/inertial, motor pressure (explosion), structural failure
☐	Intercept – relevant mechanisms considered, e.g., direct hit vs. glancing blow, explosive, directed energy; special characteristics of the target or intercept mechanism
☐	Payload deployment activities (explosive and dispersal payloads)
	Credibility of debris list
☐	• Accounts for total mass of vehicle hardware and propellants
☐	• Consistent with launch accident debris data
☐	• Debris pieces adequately defined in terms of weight, size, shape, ballistic characteristics, imparted velocity, propellant content (type, weight)
☐	B. Initial source clouds for toxics
☐	C. Explosives quantities, yields, and geometries
☐	D. Residual thrust dispersion of prematurely separated strap-on motors

[1] This list is not all encompassing and should be supplemented/changed as appropriate to the particular vehicle and/or mission.

2.5.2 Step II-2: Model Dispersion of Hazard Source Locations

Define the origination points of the hazard sources (whether they be debris, toxics, or explosives) taking into account wind dispersions and the uncertainties in vehicle performance and in the hazardous event models. See the checklist at Table 2-8.

Table 2-8. Model Dispersion of Hazard Source Locations (Step II-2)

	A. Identify conditions at breakup, including:
☐	State vector(s) (at a minimum position and velocity; other parameters, such as attitude, are sometimes relevant)

☐	Imparted velocity to each debris class and its probability distribution
☐	Type of breakup (e.g., overpressure/burst, aerodynamic, inertial, destructive flight termination action, thrust termination, intact vehicle, etc.)
☐	Data required to characterize debris resulting from an intercept event
	B. Failure turns - some modeling options are:
☐	Credible malfunction trajectories
☐	Velocity turn data (turn angle and velocity magnitude histories)
☐	Maximum energy footprint
☐	90-degree turn
☐	Maximum rate turn
☐	Credible malfunction turns/tumbles
	C. Address significant sources of uncertainty that may include:
☐	Probability distribution of performance and/or event model
☐	Monte Carlo of trajectories and/or performance and event model data
☐	Tracking instrumentation uncertainties. (Uncertainty in measuring the state vector. This largely affects real-time displays but should be accounted for in analysis when defining/refining flight termination criteria.)
	D. Winds
☐	Measured
☐	Statistical

2.5.3 Step II-3: Propagate Hazard Characteristics (Spatial and Temporal)

Propagate the results of the hazardous events to the points and times of interest. This could be debris propagated to the ground, to aircraft altitudes, or to orbital demise; or explosive or toxic hazards characterized as a function of time and distance from the hazard origination or at specific asset/receptor locations. The outcome of this step is defined hazard characteristics at the points and times of interest. Items that may affect propagation and post-propagation characteristics of the hazards are listed. See the checklist at Table 2-9.

Table 2-9. Propagate Hazard Characteristics (Spatial and Temporal) (Step II-3)	
☐	A. Drag – tumbling or trim (consider applicable flow regime)
☐	B. Aerodynamic lift
☐	C. Gravity (appropriate degree of refinement)
☐	D. Meteorological profile
	E. Winds
☐	Measured
☐	Statistical
☐	F. Aero-thermal demise and propellant burn
☐	G. Vapor cloud dispersion rate
☐	H. Vapor cloud travel rate
☐	I. Time for debris to pass through aircraft altitude
☐	J. Blast wave propagation

2.5.4 Step II-4: Compute Spatial/Temporal Statistics at Protected Assets Exposed to Hazard

Identify the assets (also called receptors) for which risk is to be assessed and determine the level of the hazard exposure for each identified asset. Levels of hazard exposure are often expressed in the form of density statistics or as function of time. See the checklist at Table 2-10.

Table 2-10. Compute Spatial/Temporal Statistics at Protected Assets Exposed to Hazard (Step II-4)

	A. Asset identification
☐	Personnel – category, location, and number (includes distribution by shelter types)
	• What is at risk? (unsheltered people, people in cars, people in structures, - are the people in locations where the safety organization can restrict their presence?)
☐	Aircraft – category, size, engines, # passengers, location (including altitude), flight path, and speed
☐	Surface craft – category, size, # personnel, material (metal, fiberglass, wood, etc.), location, speed
☐	Spacecraft – type, location (ephemeris)
☐	Valuable structures/equipment (control centers, instrumentation sites, radars, etc.)
☐	Protected natural spaces
	B. Debris density (or probability density function [PDF]) by hazard level at location (accounting for flight termination action once flight termination criteria are defined)
☐	At altitude (as a function of time)
☐	At surface
	C. Toxic cloud concentration as function of time at location
☐	Peak at location
☐	Time of exposure
☐	D. Explosive pressure and impulse at assets

NOTE: These next two steps are often performed as an iterative process.

2.5.5 Step II-5: Create/Refine Flight Termination Criteria

Determine whether to define flight termination criteria after debris characteristics are approved or after assessing containment feasibility as a means of achieving containment. Flight termination criteria must not induce an excessive conditional risk. See the checklist at Table 2-11.

Table 2-11. Create/Refine Flight Termination Criteria (Step II-5)

☐	A. Define/refine flight termination boundaries.
☐	B. Define exclusion areas (often referred to as caution or hazard areas).
☐	C. Refine/revise the launch commit criteria and launch constraints as necessary.
☐	D. Return to Step II-1 and recompute the debris statistics once flight termination criteria and launch criteria are finalized.

2.5.6 Step II-6: Assess Containment Feasibility

Identify the ability to contain hazards and thus not put any personnel or property at risk. Containment may be achievable by implementing flight termination criteria and launch constraints; thus this step is performed in close coordination with Step II-5 above. See the checklist at Table 2-12.

Table 2-12. Assess Containment Feasibility (Step II-6)

☐	A. Are any assets at risk?
☐	B. Does debris, explosive, or toxic hazard reach any protected area or defined boundary?

2.5.7 Review R-2: Critical Review of Data and Assumptions

Double-check inputs and assumptions and make any necessary or available adjustments to the analysis before going on to computing the risk numbers, which can be a time-consuming process. See the checklist at Table 2-13.

Table 2-13. Critical Review of Data and Assumptions (Review: R-2)

☐	A. Sanity check of assumptions[1]
☐	B. Update/refine inputs as available
☐	C. Replace assumptions with better data if/when provided
☐	D. Return to Step II-1 and refine analyses with revised/new data as necessary
[1] See Conditional Risk Management Discussion (Section 2.8)	

NOTE	If containment is achieved and the analyst has conducted the critical review of data and assumptions, the assessment may be ended here and the analyst may proceed to documenting the results, conditions, and assumptions for review with the decision authority in Step IV-1 (Subsection 2.7.1). The steps of the risk reduction phase are no longer required.

2.5.8 Step II-7: Compute Risks

Calculate the various measures of risk that are to be evaluated against the acceptable risk criteria. This includes individual, collective, and catastrophic risk for the people exposed. Measures of risk are commonly expressed as probability of impact, P_C/P_F, E_C/E_F, and probability of n or more casualties or fatalities. See the checklist at Table 2-14.

Table 2-14. Compute Risks (Step II-7)

☐	A. Probability of modeled event
	B. “Lethal Hazard Area” and “Casualty Area” (measured as function of asset size and/or debris size and shape, terminal trajectory characteristics such as angle of impact and impact velocity, nature of debris [inert, burning, explosive], and impact phenomenon such as cratering, sliding, and bouncing). Defined for:
☐	Person
☐	Aircraft
☐	Ship
☐	Structure
☐	C. Probabilities of impact on asset(s)

	D. Assess post-impact hazards at receptors (assets)
☐	Explosion (overpressure/impulse and secondary fragmentation)
☐	Cratering
☐	Bounce/slide
☐	Heat/fire
☐	Asphyxiation
	E. Modification of hazard by structures as applicable
☐	Type of structure
	• Structure category (reinforced concrete, steel frame, tilt-up, corrugated metal, wood frame, etc.)
	• Material makeup (wood, steel, concrete, glass, brick, etc.)
	• Construction method
	• Number of stories
	• Wall/Roof thickness
	• Number and types of windows
☐	Protection provided
☐	Spalling
☐	Penetration
☐	Collapse
☐	Window breakage (flying glass shards)
☐	Ventilation, air exchange rate
	F. Probability of casualty/fatality from inert debris
	G. Probability of casualty/fatality from toxics
	H. Probability of casualty/fatality versus overpressure and impulse for explosive debris
☐	Person
☐	Aircraft
☐	Ship
☐	Structure
	I. Expected fatalities/casualties (aggregate risk from the various scenarios, hazards, and assets [receptors])
☐	Individual
☐	Collective
☐	Catastrophic
☐	Risk profile (a plot of the probability of the N or more casualties from an accident vs. N, i.e. P[≥N] vs. N)

2.5.9 Perform Review R-3: Critical Analysis Review

This is a final sanity check and “all bases covered” review to assure that the risk numbers to be evaluated in the risk reduction phase and to be presented to the decision authority are as accurate as possible. See the checklist at Table 2-15.

Table 2-15. Critical Analysis Review (Review: R-3)

☐	A. Sanity check of assumptions and processes

	B. Update/refine inputs as they are made available. Examples:
☐	Revised trajectories
☐	Updated aero/thrust models
☐	Updated mass properties
☐	Refined wind data
☐	Refined debris lists
☐	Updated population counts
☐	C. Return to Step II-1 and refine risk analysis and assessment with revised/new data if necessary.

2.6 Phase III: Criteria Comparison and Risk Reduction

During Phase III, the risk measures computed by the analyst are evaluated to determine if there is a need or desire for risk reduction measures to be taken to eliminate, mitigate, or control risks. Not all the steps of the risk reduction phase are required to be performed – only those that are found applicable. Frequently, risk reduction is accomplished through modification of the mission definition and requires coordination with the range user to determine reasonable, appropriate measures since some modifications can severely impact cost and schedule. Risk reduction should also include confirmation of the resolution of anomalies or failures of all safety-critical systems during previous tests or flights. Once risk reduction measures are taken, the hazards are reassessed to compute the revised levels of risk. The result of this phase is a comparative summary of the measures of risk against the appropriate criteria and a recommendation for the decision authority to either approve or disapprove the mission.

2.6.1 Step III-1: Evaluate Risks vs. Criteria

Compare risk measures with established criteria to determine if risk reduction is required or desired. Identify areas where risk reduction may be achievable. See the checklist at Table 2-16.

Table 2-16. Evaluate Risks vs. Criteria (Step III-1)	
☐	A. Compare computed risks to acceptable risk criteria for all categories of assets.
	B. Evaluate risks for common-sense checks even if criteria are not exceeded.
☐	Does the scenario make sense?
☐	Can minor modifications be made to achieve containment or to reduce risk?
	C. Identify risk reduction requirements.
☐	What area of risk is exceeded – personnel, aircraft, etc.?
☐	By how much are the criteria exceeded?
	D. Identify risk reduction opportunities.
☐	Have assumptions been made that are very conservative and could be revised so as to justifiably reduce the predicted risk?
☐	What area(s) of the mission definition can affect risk reduction?
☐	What area(s) of the mission definition provide the greatest risk reduction?
☐	What area(s) of the mission definition can be altered most easily?
☐	What area(s) of the mission definition can be altered with the least schedule/cost impact?

☐	What evacuations and sheltering of people can be realistically accomplished?
☐	Prioritize areas of focus.
☐	E. Evaluate the uncertainties and conservative biases in the data, model parameter, and analysis process and, if necessary, compute the casualty/fatality expectation considering uncertainty.

2.6.2 Step III-2: Refine Assumptions and Analysis (returning to Step II-1)

Reevaluate the analysis methodology to determine if any assumptions should be adjusted or if any steps or processes should be refined with further detail. See the checklist at Table 2-17.

Table 2-17. Refine Assumptions and Analysis (returning to Step II) (Step III-2)

☐	A. Remove any excess conservatism in assumptions (so long as the reduction is supportable).
	B. Adjust level of depth of the analysis.
☐	Was any part of the process initially deemed unnecessary that should be reconsidered? (example: initially looked at only worst cases or bounding cases now refine to assess Monte Carlos or 3-sigma performance)

2.6.3 Step III-3: Modify Planned Mission Scenario (returning to Step I-2)

Reevaluate the scenario and determine if any changes can be made to move the hazards further away from endangered areas while still meeting mission requirements. See the checklist at Table 2-18.

Table 2-18. Modify Planned Mission Scenario (returning to Step I-2) (Step III-3)

☐	A. Shift trajectory azimuth.
☐	B. Increase or decrease quadrant elevation.
☐	C. Modify flight profile - doglegs, Generalized Energy Management Steering maneuvers, pitch up, pitch down, lofting, etc.

2.6.4 Step III-4: Refine Safety Limits/Operating Rules (returning to Step I-3)

Reevaluate the safety and mission rules to determine any changes that can eliminate or control the hazards or can reduce the severity and/or probability of the hazard. Again, flight termination criteria should be optimized by balancing the risk given a failure and flight termination against the risk given a failure and no flight termination. See the checklist at Table 2-19.

Table 2-19. Refine Safety Limits/Operating Rules (returning to Step I-3) (Step III-4)

☐	A. Adjust destruct lines, ILLs, and/or protection boundaries.[1]
☐	B. Adjust allowable RSO response time (so long as the adjustment is supportable).
☐	C. Evacuate or shelter personnel.

☐	D. Implement hands-off gates or critical-event markers.
☐	E. Implement gates or critical-event markers for staging, ignition, or performance.
☐	F. Utilize automatic destruct system if available.
[1]See Conditional Risk Management Discussion (Section 2.8)	

2.6.5 Step III-5: Modify System Design (returning to Step I-1)

Reevaluate the vehicle and safety system(s) designs to determine if any modifications can be made that will eliminate hazards or significantly reduce the hazardous effect. See the checklist at Table 2-20.

Table 2-20. Modify System Design (Returning to Step I-1) (Step III-5)

☐	A. Remove or add ballast.
☐	B. Impose hardware or software steering limits.
☐	C. Implement inhibit logic.
☐	D. Increase tracking instrumentation reliability/accuracy.
☐	E. Refine system delay times.
	F. Modify vehicle FTS.
☐	Type of system – automatic or autonomous vs. commanded
	Modify post-termination states – terminate thrust, deploy chutes, disperse fuel, change debris fragmentation, etc.
☐	• Change termination method – linear shaped charge > conical shaped charge > thrust termination > line cut.
☐	• Change location of charge – raceway vs. aft dome vs. forward dome.

2.7 Phase IV: Risk Acceptance

Once the risk assessment is complete and all necessary risk reduction measures are taken, final results and recommendations (including proposed operating/mission rules) are presented to the appropriate decision authority. The result of this phase can be one of the following outcomes:

a. An approved mission;

b. An approved or disapproved mission with further instructions; or

c. A decision to reject the mission.

To ensure that the decision authority is fully informed, the analysis/assessment should be fully documented to include the assumptions made and justifications, results, recommendations of the analysis team, models used for the analysis, and uncertainties associated with the assumptions and models. Information on models used should include version numbers and a brief description of certification and/or heritage. (Examples: industry-accepted model XX version #.#, Debris generator X, custom developed by Organization Y and verified using available empirical (or test) data or via comparative analysis against Tool Z.)

After reviewing the information, the decision authority may either approve the mission with the noted risks or disapprove the mission. If the mission is disapproved, the safety organization and the range user may elect to continue efforts to reduce risks to an acceptable level. If no further risk reduction is possible and the predicted risks are still too high, the appropriate decision authority may reject the mission as unsafe and determine that it should not be pursued. If the risks are acceptable and the mission is approved, the authority is issued to proceed with a countdown and subsequent launch once all of the defined commit criteria launch constraints are met. Once the vehicle is launched the defined flight termination criteria are in effect and the flight will be terminated if those criteria are violated in order to ensure the approved level of risk is not exceeded.

2.7.1 Step IV-1: Review Mission, Operating Rules, and Risk Analyses (Designated Authority)

Present analysis results, conditions, and recommendations to the decision authority. These should include the elements shown at Table 2-21.

Table 2-21. Review Mission, Operating Rules, and Risk Analyses (Designated Authority) (Step IV-1)

☐	A. Measures of risk that are presented
	B. Risk level or loss potential
☐	Maximum risk in event of a flight termination action
☐	Maximum risk should flight termination fail
☐	Risk profiles, if used
☐	Sensitivity analyses
☐	C. Key analysis assumptions
☐	D. Population centers potentially at risk
	E. Facilities, property, or other assets at risk
☐	F. Protective measures
☐	G. Operating rules
☐	H. Launch constraints and launch commit criteria
☐	I. Flight termination criteria

2.7.2 Step IV-2a: Approve Mission – Launch When Constraints are Met

The decision authority accepts the mission risk and approves operating/mission rules and launch constraints. The countdown proceeds and liftoff is allowed if launch constraints are met. A "Hold" is issued if launch constraints are not met; however, the appropriate designated decision authority is allowed to implement a real-time waiver if deemed necessary. Some of the significant constraints considered are shown at Table 2-22.

Table 2-22. Approve Mission – Launch When Constraints are Met (Step IV-2A)

☐	A. Hazard area cleared
☐	B. Personnel in approved shelters
☐	C. Vehicle FTS operating properly (battery levels good, signal strength, etc.)
☐	D. RSS operating properly (receiving good data, transmit-power good, etc.)
☐	E. Casualty expectation under current meteorological conditions within approved limits

2.7.3 Step IV-2b: Disapprove Mission as Proposed (returning to Step III-1)

If the risks remain too high or the operating rules are too severe or restrictive, the decision authority may disapprove the mission thus requiring the analyst and range user to return to the risk reduction phase in an attempt to identify and implement any further risk reduction measures. If all measures have been exhausted and the risks still exceed established criteria then a waiver may be requested by the range user and granted by the appropriate authority if the need is justified or the mission may be rejected.

2.7.4 Step IV-3: Follow Mission Rules

Terminate the mission if real-time limits are violated. During execution of an approved mission, the defined flight termination criteria are in effect and the flight will be terminated if those criteria are violated in order to ensure the approved level of risk is not exceeded.

2.8 Conditional Risk Management Process

As shown in Figure 2-2, the conditional risk management supplements the current risk management requirements of the standard. After assuring that the mission risks have been adequately addressed, the conditional risk management process provides assurance that the proposed risk mitigations address unacceptable levels of "high-consequence" conditional risk and introduce reasonable conditional risks when the mitigation actions are taken.

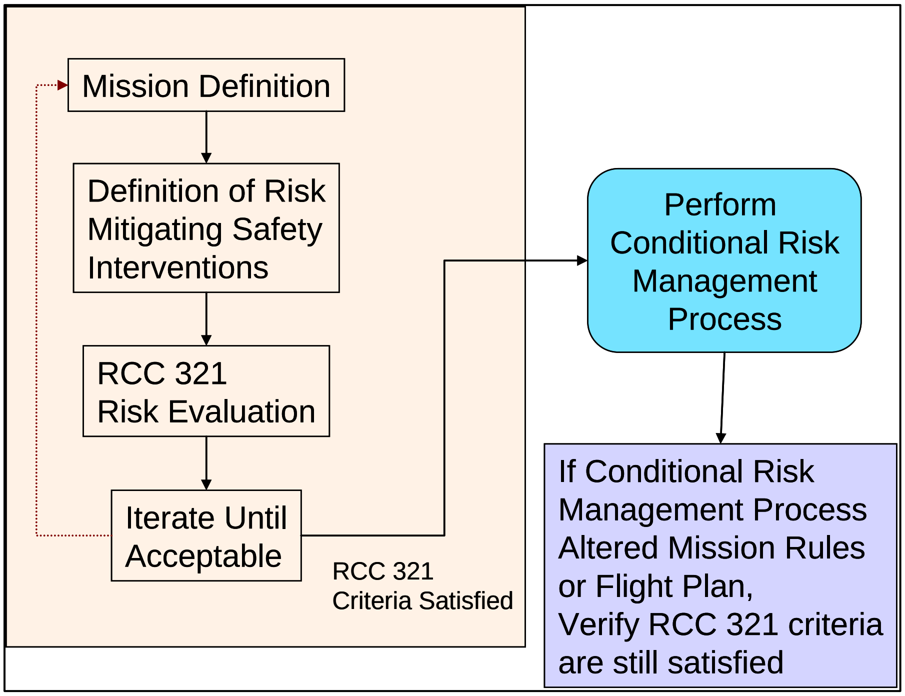

Figure 2-2. Overview of the Relationship Between RCC 321 Requirements and Conditional Risk Management

The phrase "risk-mitigating safety interventions" is intended to encompass the entire range of risk-mitigating actions that may be proposed for either expendable launch vehicles (ELVs) or reusable launch vehicles (RLVs). For example, flight termination is a common risk-mitigating safety intervention for ELVs and a contingency abort to an alternative landing site could be a useful risk-mitigating safety intervention for an RLV. Figure 2-3 outlines a systematic approach to managing the risks induced by such interventions.

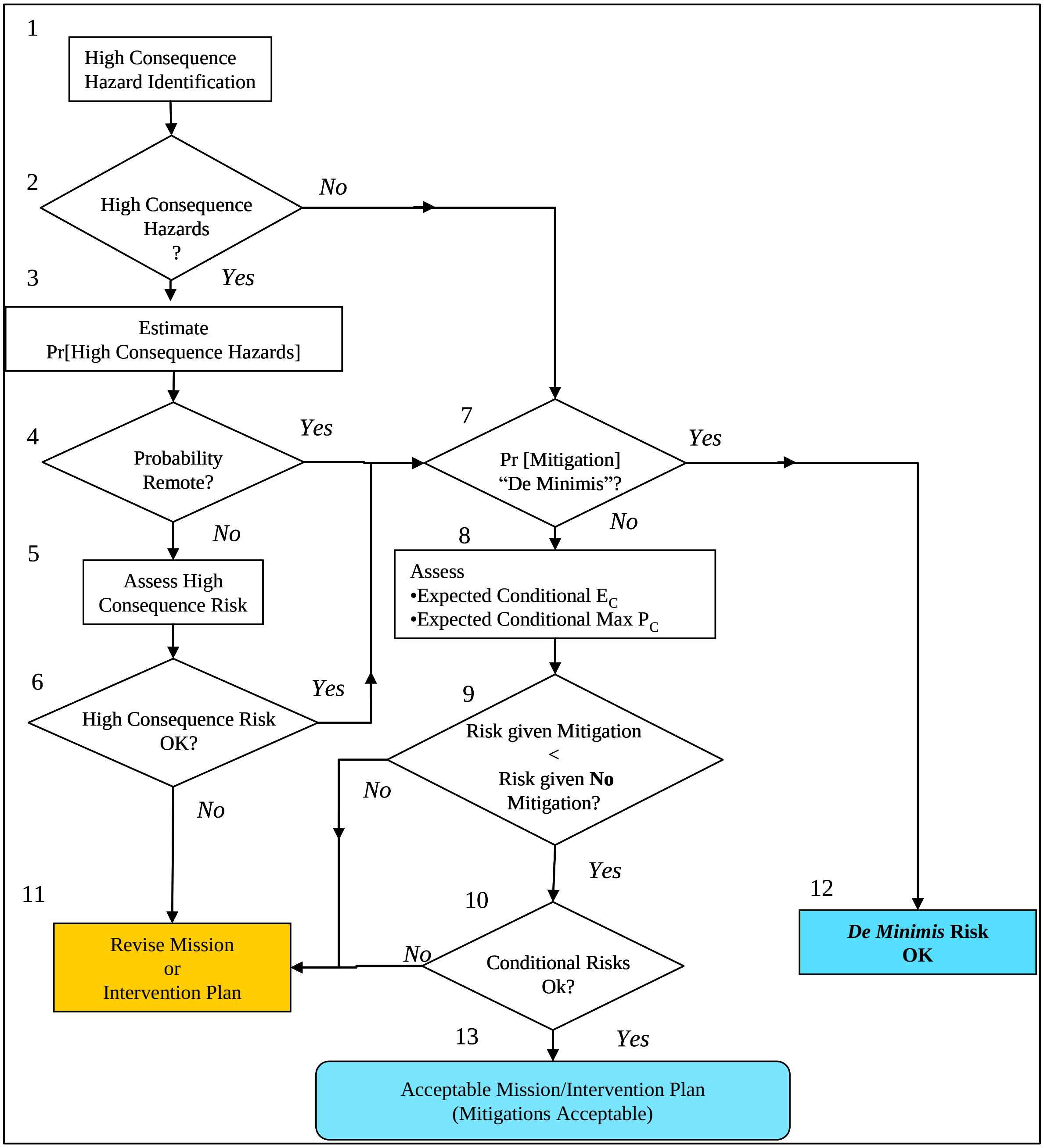

Figure 2-3. Conditional Risk Management Approach

The steps in this process are numbered for easy reference in the following discussion. The order of the steps has been designed to assure completeness and avoid unnecessary efforts whenever possible. The figure has two termination points. Step 12 is the final step when it has been demonstrated that the risks are *de minimis;* Step 13 is the last step of a complete analysis that demonstrates the conditional risks from the defined mitigating actions are acceptable.

1. The Environmental Protection Agency (EPA) and systems safety use the term "hazard identification" for the initial step in a risk assessment in which hazards and possible consequences are identified. This process first seeks to rule out the introduction of high-consequence hazards. "High-consequence hazards" may include outcomes that have a significant impact on continued range or launch operations, significant environmental impacts, impacts on relationships with other countries, and other long-term or irreversible consequences. Signal events have a major impact on society as a result of a combination of **dread** and **lack of visibility and understanding** by the GP. Catastrophes as defined in Section 3.8 of the standard are also high-consequence events. Some examples of potential high-consequence events include:

    a. Events that may produce significant dollar damage or large numbers of casualties (See, for example, Section 3.8 of the standard);

    b. Events that damage critical assets or cultural treasures or natural wonders;

    c. Events that create a public perception of irresponsible action on the part of the range – whether or not any damage or injuries resulted;

    d. Events that damage the local economy, such as creating an atmosphere of fear in a tourist-dependent community;

    e. Events that violate or appear to violate the rights of foreign nationals.

2. If there are no identifiable high-consequence hazards the process flow skips to Step 7.

3. When-high consequence hazards are a concern, an assessment must be performed of the chance of the high-consequence result occurring given that the risk mitigation being reviewed is invoked. In the context of flight termination this would be the conditional probability of high consequence given flight termination. Evaluation approaches applied would depend on the type of high-consequence event. Events that may produce large number of casualties, for example, might result from impacting explosive fragments with a sufficiently large yield to affect many people or a fragment hitting a transportation system (an airplane, ship, bus, or train) that results in loss of the transportation system and all of its passengers.

4. If it can be shown that the conditional probability of a high consequence given the risk mitigation is remote[2], the process flow skips to Step 7

5. **Quantitative** or **qualitative** methods may be used to assess the high-consequence risk potential. Safety personnel must be prepared to show that the assessment procedure has a traceable, defensible rationale such as a conditional risk analysis that uses accurate data and scientific principles and is statistically valid.

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[2] ACTA Report 09-696/WR-18 (Haber, 2009) discusses some precedents that may be the basis for assessing when the event probabilities are negligible.

6. Evaluation of the acceptability of the high-consequence risk must consider severity of the consequences and probability of occurrence. These must be assessed in the context of federal and state laws and regulations and local agreements. (Section 2.3.4 of the standard). If the high-consequence risks are not acceptable modify the intervention or the mission (Step 11) and repeat the process. Otherwise continue with Step 7.

7. Having ruled out significant high-consequence-hazard induced risks, the next step is to assess whether the probability of using the risk mitigation during the mission is negligibly small. When that can be established, the conditional risks are *de minimis*.

8. To assure that the risk induced by the intervention is reasonable, two conditional risk measures must be calculated:

    a. expected value of collective risk given the mitigation; and

    b. expected value of the individual risk to the maximally exposed individual given the mitigation.

    Expected values of the two risk measures are used as the risk measure rather than the peak values to produce more stable, consistent measures as the basis for decision making. The set of events over which averaging occurs will depend on the nature of the safety intervention. The general principles for grouping for averaging are:

    c. Events in a group result from different instances of the same safety intervention.

    d. Events hazard substantially the same population centers.

9. Acceptable safety mitigations should normally be expected to reduce the risk relative to no mitigation. While extenuating circumstances, such as national security or foreign policy interests, might warrant accepting higher safety risks from applying a risk mitigating action than from no mitigation, this is the standard reasoning employed in decision theory. With that caveat, compare the risk induced by the mitigation with what would occur without the mitigation. If the mitigation does not reduce the risk, modify the intervention or the mission (Step 11) and repeat the process.

10. The conditional risks are reviewed for acceptability. If they are not acceptable, modify the intervention or the mission (Step 11) and repeat the process.

11. When some set of conditional risks has been determined to be unacceptable, the mission or the risk mitigations must be revised and the revised mission/risk mitigations must be reassessed to assure that it is now acceptable. Candidate revisions to mission design and mission rules will consider range architecture and range user objectives.

12. When it has been shown that the conditional risks are *de minimis,* no further evaluation is required.

13. When the conditional risks given the mitigation are shown to be acceptable, the original risk analysis should be reviewed and, if necessary, revised to assure that mission risks are acceptable.

CHAPTER 3

General Risk Model Requirements

Computer models and simulations are typically used to estimate the risk involved in an activity. This chapter describes general model requirements that should be applied to computational tools used to analyze the flight safety risks in support of decisions governing safety. In general, a model is a technical representation of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics. For the purposes of this chapter, in range safety usage models are defined as those tools developed for the specific task of analyzing flight risks.

3.1 Specific to Policy

Models must provide results that support decisions based on risk policy. Compliance with risk policy is assessed using established criteria that consist of two components: a well-defined measure of risk, and a threshold of acceptability. Models must produce a valid estimate of one or more of the measures of risk stipulated by applicable criteria.

3.2 Transparency, Clarity, Consistency, and Reasonableness (TCCR)

Models must uphold standards of TCCR accepted by the scientific community. Specifically, models must reflect the following.

a. Transparency. Provide decision-makers a clear understanding of the technical approach used. This understanding must include key supporting assumptions as well as the limitations of the model and the results it produces.

b. Clarity. Produce results that can be clearly displayed and communicated.

c. Consistency. Use processes and approaches that are consistent with (similar to or accepted by) those used by scientific communities involved in studying similar problems. This requirement is intended to ensure scientific accountability rather than to stifle innovation.

d. Reasonableness. Use appropriate technical procedures and input data that, if subjected to scrutiny, would be accepted by the scientific community, government agencies, and to the degree possible, the GP. Available resources may limit the approaches used.

3.3 Verification and Validation

Models should provide a formally documented basis of confidence in the results produced. Numerous methods can be used to build confidence in a model, including:

a. Comparison to real-world results;

b. Comparison to other models that have been independently developed and possess an accepted basis of confidence;

c. Formally documented V&V;

d. Peer reviews/expert elicitations.

3.4 Configuration Control

Model development should follow processes that are formally managed and controlled. A documented process should be used to request, implement, and test changes to the model. In unusual circumstances, an abbreviated review of model changes may be necessary to support near-term mission requirements. The full requirements of the documented process should be met prior to repeated use of results from the upgraded model to make safety decisions. The development of computer codes implementing models should adhere to industry standards such as the Software Engineering Institute's Capability Maturity Model Integration.[3] The use of that standard's Level 2 is recommended as a minimum requirement. Each range should develop and implement an accreditation process that is applied to all models used for FSA and support. This accreditation process should identify V&V requirements for safety-critical software and safety analysis software. The results of V&V efforts for safety-critical software should be formally documented, including the source and nature of any external data used to conduct validation. Requirements for accreditation of safety-critical software should be greater than requirements for safety analysis software.

3.5 Liability Protection

Models must produce results that meet the "best available" information-test affording the decision-maker the opportunity to make a fully informed decision that qualifies for liability protection under the Discretionary Function Exclusion of the Federal Tort Claims Act (FTCA)[4].

3.6 Best Estimate of Expected Value

Models should produce the best estimate of the risk based on available inputs and require the use of best engineering estimates. A conservative estimate can be developed by using slightly conservative inputs when data are uncertain or are unavailable and need to be estimated. An analysis of the uncertainties and sensitivities of results is highly desirable and necessary if the impact of uncertainty in the mean of the E_C considering uncertainty could conceivably exceed the risk acceptability criterion.

3.7 Balance of Accuracy, Simplicity, and Fidelity

Models must produce the most accurate results possible considering real-world limitations (such as computer run time, computational resources, cost, and time to develop input data) and the diminishing return on further investment. Compliance with this standard requires a balance between modeling fidelity, uncertainties in input data, and the ability to communicate understanding of both the analysis process and the results.

3.8 Conservatism and Uncertainty

Model development must consider the dangers of excessive conservatism. Where possible, developers should avoid compounding conservatism in analytical results by using best-estimate approaches for developing input data and modeling algorithms. Potential variation in the input data and inaccuracies in the modeling results should be addressed by the

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[3] Information on CMMI standards can be found at http://www.sei.cmu.edu/cmmi/models/

[4] Exceptions. 28 U.S.C. § 2680

acknowledgement and documentation of uncertainties as discussed in Section 2.4 of the standard rather than by introducing bias in the risk estimate.

3.9 Balance of Element Fidelity

Models should clarify the accuracy of analytical results based on assessment of the accuracy of each element of the risk model. Assessments of models should focus on the accuracy of the risk estimation rather than the fidelity of a single element.

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CHAPTER 4

Risk Criteria Implementation Guidelines

4.1 Introduction

This chapter provides guidelines for implementation of the acceptable risk criteria presented in Chapter 3 of the standard. The guidelines are presented to help:

a. determine the start and end of a flight in terms of application of the per-mission risk criteria;

b. establish appropriate risk criteria for complex missions, such as those that involve multiple launches;

c. facilitate the proper management of annual risk.

4.1.1 Context and Purpose of this Chapter

The general policy and goals of the standard, expressed in Chapter 2 of the standard, assert that all ranges should strive to achieve complete containment of hazards resulting from both normal and malfunctioning flights; however, many range missions cannot be accomplished using a containment approach. If a planned mission cannot be reasonably accomplished using a containment approach, a risk management approach should be authorized by the range commander or designated representative. The risk management approach should conform to the guidelines presented in this document or otherwise demonstrate compliance with the policy objectives presented in Chapter 2 of the standard. The guidelines and rationale presented in this chapter are intended to help the range commander understand and balance the factors that affect mission acceptability. These factors include criticality of mission objectives, protection of life and property, the potential for high-consequence mishaps, local political factors, and governing range or programmatic environmental requirements.

Range commanders should not accept adverse consequences (such as any casualty) as being routine or permissible; however, some range missions cannot be accomplished without a finite probability of producing adverse consequences. “Acceptable” risks as discussed here should be interpreted as “tolerable” risks. By implementing the guidelines presented here, the range commander may tolerate these risks to secure certain benefits from a range activity with the confidence that the risks are properly managed within prescribed limits.

This chapter has nine major sections.

- This section outlines the chapter and introduces different measures of risk.
- Section 4.2 provides guidelines for the application of the criteria. Some of the important concepts presented include risk accrual, different consequence metrics, the relevance of time frame over which risk is computed and how these time frames are defined, and guidance for treatment of different classes of related multiple launches constituting a single mission. It then provides guidance for assessing the LOR required to support different classes of missions and segment of the missions. The underlying principle expressed is that the closer the risk is to the tolerable limit the higher the fidelity and the lower the uncertainty that can be accepted in the calculations.

- Section 4.3 introduces the topic of catastrophic risk and limits for risks in which a single incident can produce injuries or fatalities to a large number of people.
- The next group of sections provide guidelines for protecting people and critical assets in various locations.
  - Section 4.4 details implementation guidelines for protecting people on-board airplanes.
  - Section 4.5 provides implementation guidelines for protecting people in ships.
  - Section 4.6 provides implementation guidelines for protecting spacecraft.
  - Section 4.7 provides guidelines for protecting critical assets at a launch complex and its surrounding areas.
  - Section 4.8 provides guidance for protecting infrastructure.
- The final section of this chapter presents a tutorial of uncertainty in risk analysis and risk-based decisions; these concepts are relevant to the decision process as well as the determination of the required LOR.

4.1.2 Different Measures of Risk

4.1.2.1 Individual and Collective Risk

Risk is a measure that accounts for both the consequence of an event and the probability of occurrence over a specified exposure interval. Individual risk and collective risk are two important measures of risk, both of which can be expressed on an annual or per-mission basis. For example, collective risk on an annual basis is analogous to an estimate of the average number of people hit by lightning each year, while individual annual risk would be an individual's likelihood of being hit by lightning in any given year. Collective risk on a per-mission basis is analogous to an estimate of the average number of people injured by an earthquake, while individual risk would be the likelihood of an individual in a given location being injured by the earthquake. Collective risk is often expressed in terms of expected values; the average (mean) consequences that can occur as a result of an event if the event were to be repeated many times.

Mean risk estimates do not convey important information about the uncertainties associated with limited accident experience, incomplete knowledge of accident phenomenology, and an inherent randomness in certain accident phenomena. Therefore, sensitivity studies should be performed to determine those uncertainties most important to the risk estimates. The results of sensitivity studies should show, for example, the range of variation together with the underlying assumptions that dominate this variation.

4.1.2.2 Risk Profile

A risk profile provides more information about the nature of the risks posed by an event than mean individual and collective risk values. A risk profile is a plot that shows the probability of exceeding various outcomes (e.g. numbers of deaths, number of casualties, or amount of monetary damages) resulting from a future event. Specifically, the abscissa of a casualty risk profile is the number of casualties (N) and the ordinate is the probability of N or more casualties. It is treated discretely, i.e., only integers. The formal probabilistic definition is that it is the complementary cumulative distributions (CCDs) of the integer number of casualties (or fatalities).

Consider an example launch where the vehicle has a 5% chance of failure. Most of the failures do not result in any casualties; range safety action at an abort boundary or aerodynamic breakup before reaching the abort boundaries causes the debris to impact in unpopulated regions. In this hypothetical example there are exactly five failure scenarios where casualties result. The probabilities and consequences for this example are shown in Table 4-1. The data for abscissa and ordinate of the risk profile are listed in the last two columns of Table 4-1. The data for the ordinate of the risk profile are the sum of all of the probabilities for scenarios that produce N or more casualties.

Table 4-1. Example Risk Profile Data

Scenario Index (*i*)	Scenario Probability	Number of Casualties (N) for Scenario ***i***	Total Probability of N or More Casualties
1	0.0499874	0	
2	0.0000100	1	0.0000126
3	0.0000010	8	0.0000026
4	0.0000010	24	0.0000016
5	0.0000005	32	0.0000006
6	0.0000001	40	0.0000001
Total =	**0.05**		

Figure 4-1 illustrates the risk profile for this simplified example launch. The E_C and probability of a casualty-producing accident for this particular case are described following Figure 4-1.

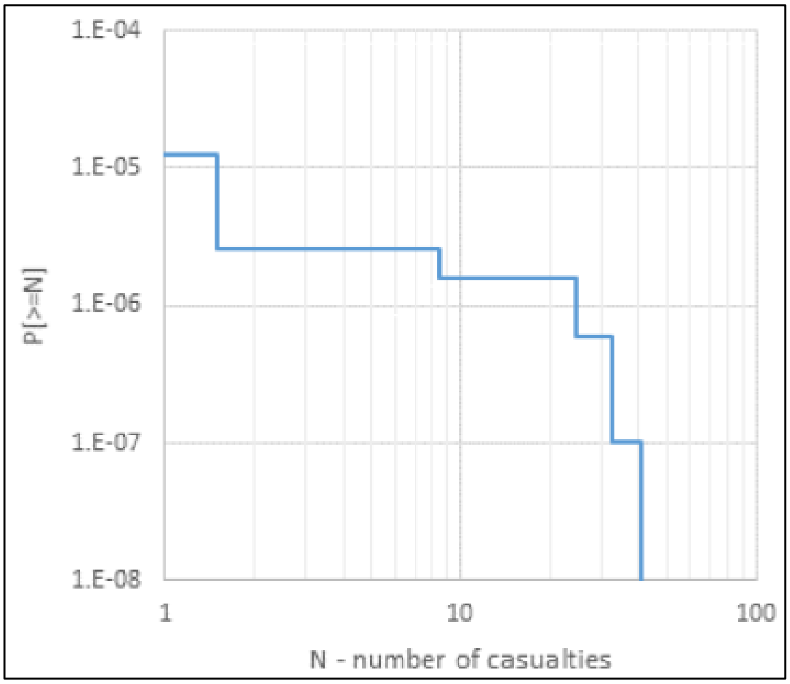

Figure 4-1. Risk Profile from Example Problem

Unlike the single valued E_C, risk profiles illustrate the combination of consequences contributing to collective risk. Thus, the decision-maker can quickly see whether the risk is from a very rare large-consequence outcome or from more frequent, smaller consequence outcomes. This standard uses risk profiles to define limits on catastrophic risks. Section 4.3 shows how a risk profile or a simplified approach may be used to evaluate compliance with the catastrophic risk criteria presented in Chapter 3 of the standard.

One of the conveniences of using a risk profile (i.e., a discrete representation of the more common F-N curve) is that the area under a discrete risk profile equals the collective risk.[5] The following equations prove this point.

$$\begin{aligned} P(\geq 1) &= p(1) + p(2) + p(3) + \ldots \\ P(\geq 2) &= \phantom{p(1) + {}} p(2) + p(3) + \ldots \\ P(\geq 3) &= \phantom{p(1) + p(2) + {}} p(3) + \ldots \\ &\;\;\vdots \\ \sum_{k=1}^{N\max} P(\geq k) &= p(1) + 2p(2) + 3p(3) + \ldots + N_{\max} p(N_{\max}) \\ \sum_{k=1}^{N\max} P(\geq k) &= \sum_{k=1}^{N\max} k \times p(k) \end{aligned} \tag{4-1}$$

The right side of this equation is recognizable as the classical definition of E_C:

$$E_C = \sum_{k=1}^{N\max} k \times p(k) \tag{4-2}$$

The E_C for this particular case is 62×10^{-6} and the probability of a casualty-producing accident $P(\geq1)$ is 12.6×10^{-6}. More information on this example is available in Section 4.3.

4.2 Guidelines for Application of the Criteria

4.2.1 Risk Accrual

- Total Risk. The individual and collective risk criteria prescribed in Chapter 3 of the standard, use the total risks, which account for all hazards to all people, including those in all transportation systems, throughout the flight portion of the entire mission. Subsequent paragraphs provide guidelines for circumstances where separate risk budgets may be justified if multiple vehicles are involved. Unless those special circumstances exist, each criterion should be compared to the total risk estimate - the combined risk due to all hazards throughout the launch or reentry mission. Subsequent paragraphs also provide guidelines for implementation of probability of impact limits to define hazard areas for ships and aircraft.

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[5] Collins, J., J. Chrostowski, and P. Wilde. "Measures and Techniques for Inserting Catastrophe Aversion into the Explosives Safety Risk Management Process." Paper presented during the 32nd DoD Explosives Safety Seminar, Philadelphia, PA. 22-24 August 2006.

- Accumulated and Aggregated Risk. This standard uses the terms "accumulated risk" and "aggregated risk." The accumulated risk refers to the risk from a *single* hazard throughout all phases of a mission. The aggregated risk refers to the accumulated risk due to *all* hazards associated with a mission, which includes, but is not limited to, the risk due to any debris impact, toxic release, and DFO.

  When multiple hazards exist, the aggregated risks (individual and collective) can always be estimated as the sum of the accumulated risk from each hazard. More sophisticated methods to compute the aggregated risks may be used to eliminate double counting, which can occur if a mission simultaneously poses multiple hazards to certain exposed populations. If multiple hazards exist, the decision authority should be briefed on the risks due to each hazard in order to make a fully informed decision.

  Unless special circumstances exist (such as those described in this chapter), the total risk for the mission of an orbital ELV should be the aggregated risk that is accumulated from liftoff through orbital insertion, including any planned debris releases.[6] Similarly, for the mission of a suborbital launch vehicle, the total risk should be the aggregated risk that is accumulated from liftoff through the impact of all pieces of the launch vehicle, including the payload.

4.2.2 Consequence Metrics

Section 3.1 of the standard requires a range to "estimate the expected casualties associated with each activity that falls within the scope of this document," and states that "additional measures of risk may be useful for range operations that are dominated by fatality to ensure fatality risks do not exceed acceptable limits." In this context, "estimate" refers to a point estimate, while the overall process is called the risk assessment. Thus, the intent of this requirement is to ensure that an estimate of the E_C is documented for each range activity that intends to comply with this standard; however, there may be certain circumstances where the decision authority should be informed of the estimated fatality risks as well.

Computation of fatality risks (both individual and collective) in addition to E_C are performed at the discretion of the safety office. Fatality risks should be computed in addition to casualty risks for those missions where: (1) any one hazard (e.g., inert debris, toxic, DFO, etc.) produces E_C for the GP greater than 50E−6 (50% of tolerable general population limit) AND; (2) the nature of the hazards posed suggests fatality risks may be of significance. For example, consider a hypothetical inert debris hazard with E_C = 60E−6. If an examination of the debris distribution indicates that potentially fatal debris (e.g., kinetic energy > 58 ft-lbs) falls within defined containment or evacuated hazard areas, no further action is necessary; but if potentially fatal debris falls outside of the containment zone onto populated areas, then fatality risks should also be calculated. These should not be interpreted as limiting the discretion of the safety office to compute fatality risks under other circumstances.

4.2.3 Annual Risks and Per-mission Risks

Annual risk acceptability criteria serve an important role in the implementation of a robust risk management system. First, a range should periodically conduct a formal review to ensure that its activities in recent years and its mission risk acceptability policy are consistent with its annual risk acceptability criteria. This review is intended to ensure that the level of

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[6] Planned debris releases include intercept debris, jettisons stages, nozzle covers, fairings, inter-stage hardware, etc.

activity at a range and the risks accepted on a per-mission basis do not equate to inordinate annual risks. Specifically, if this review finds that the sum of the mission risks accepted annually on average, for the past or the future, exceeds the annual risk criteria in this standard, then the range should revise its mission risk acceptability policy to ensure that the annual risk in the foreseeable future comply with the criteria presented here.

This standard contains primary risk management criteria on a per-mission basis for several reasons. First, the decision to authorize a flight is typically made in consideration of the safety and importance of a mission. Since the goal of risk management is to facilitate fully informed decisions, the risk acceptability criteria should be directly correlated to the risk acceptance decision. In some cases, it may be difficult to estimate the risk from a single mission since it may be difficult to delineate what constitutes a single mission. Therefore, this standard also endorses the use of annual risk management in lieu of per-mission risk management in certain circumstances. Specifically, risk management using only an annual measure of collective risk is only justified for range operations that occur frequently and pose low risk on a per-mission basis. In this context, "low risk" means about two orders of magnitude below the per-mission criteria for collective and individual risks. For example, empirical data from a range's past activities (where many missions of a similar nature have been safely executed) may be used to demonstrate that the annual risks comply with the limits prescribed in Chapter 3 of the standard, and that the per-mission risks comply with this guideline. In those cases, the risk analyst should evaluate the similarity of the empirical data by comparing the probability of any hazardous events, the magnitude of the potential hazards presented, and the exposure to any hazardous events.

4.2.4 Defining "Per-mission"

This standard presents criteria for acceptable risks on a per-mission basis. The RCC intends for the standard risk acceptability criteria to apply separately to launch and reentry missions as defined below.

a. Launch Mission. For the purposes of flight safety analyses, a launch mission begins with lift-off, ends at orbital insertion, and includes impacts from all planned debris released prior to orbital insertion. A launch mission includes any flight of a suborbital or orbital rocket, guided or unguided missile, and missile intercepts. A launch mission includes space launch, suborbital launch, and the rocket flight portion of hybrid launch missions as described in more detail below.

b. Reentry Mission. For the purposes of flight safety analyses, a reentry mission begins when an orbiting vehicle (or object) is committed to enter a perigee below 70 nautical miles (nm), either by command or natural decay, resulting in atmospheric reentry and impact on the surface of the Earth. A reentry mission ends when all vehicle components associated with the reentry come to rest on the Earth. Reentry missions include both controlled and uncontrolled reentries as described in more detail below. The reentry of upper stages and payloads are separate reentry missions per the US Government Orbital Debris Mitigation Standard Practices[7] and Department of Defense Instruction (DoDI)

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[7] United States Government. "U.S. Government Orbital Debris Mitigation Standard Practices, November 2019 Update." November 2019. Available at https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf.

3100.12.[8] In this context, reentry missions do not occur during suborbital flights because a reentry mission separate from the launch mission can only occur subsequent to orbital insertion.

4.2.5 Per-mission Guidelines Defining the Beginning and End of a Mission

There are precedents in federal law for establishing launch risk criteria that apply strictly to the risk from flight[9] for an ELV and RLV[10] mission. The RCC intends for the standard criteria to be implemented in a manner consistent with these precedents, except when past precedent is in direct conflict with these guidelines. Guidelines to help discern the beginning and end of flight are important to establish appropriate risk budgets for complex range activities. The following paragraphs present guidelines to help define "per-mission," to understand the precedents for defining the beginning and end of a mission, and to establish appropriate risk budgets for complex range activities. These guidelines are consistent with current practices, the direction given to range commanders in Subsection 4.h.(5).(e) of enclosure 2 of DoDI 3200.18[11], and the current federal law governing commercial launches.[12]

4.2.5.1 Space Launch Mission

A space launch mission typically involves the flight of an ELV that is injected into a pre-determined and sustainable orbit for an indefinite period of time prior to reentry or disposal. Unless special circumstances exist (such as those described in Subsection 4.2.5.11 and Subsection 4.2.6), a space launch mission begins at liftoff and ends at orbital insertion. Therefore, the per-mission risk criteria specified in Chapter 3 of the standard should be compared to the total risks posed from liftoff until orbital insertion, including the risks from all hazards due to all foreseeable malfunctions and from any planned debris releases, with the exceptions noted in Subsection 4.2.5.11 and Subsection 4.2.6.

4.2.5.2 Suborbital Launch Mission

For the purposes of the standard, a suborbital launch mission is any flight of a launch vehicle, rocket, or missile that does not achieve orbital insertion as defined in the glossary of the standard. A flight that has a perigee above 70 nm, but is only intended to re-establish an IIP on the surface of the Earth, may be treated as suborbital launch mission depending on specifics that would need to be evaluated on a case-by-case basis. All of the per-mission requirements specified in the standard apply to a suborbital launch mission from lift-off until landing or final impact, including all planned debris impacts. Specifically, risk should be accumulated from

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[8] Department of Defense. "Subject: Space Support." DoDI 3100.12. 14 September 2000. May be superseded by update. Retrieved 16 October 2023. Available at https://www.esd.whs.mil/Directives/issuances/dodi/.

[9] In 1999, the FAA promulgated limits on ELV "acceptable flight risk through orbital insertion." (See 14 CFR 415.35(a)) The FAA's most recent regulation to govern expendable launches allows "the flight of a launch vehicle only if the risk associated with the total flight" satisfy certain criteria (See 14 CFR 417.107b in Docket No. FAA-2000-7953).

[10] 14 CFR 401.5 defines *Reusable launch vehicle* (RLV) as "a launch vehicle that is designed to return to Earth substantially intact and therefore may be launched more than one time or that contains vehicle stages that may be recovered by a launch operator for future use in the operation of a substantially similar launch vehicle." The Space Shuttle Orbiter and *SpaceShipOne* are examples that meet the definition of an RLV.

[11] Department of Defense. "Management and Operation of the Major Range and Test Facility Base (MRTFB)". DoDI 3200.18. 1 February 2010. May be superseded by update. Retrieved 16 October 2023. Available at https://www.esd.whs.mil/Directives/issuances/dodi/.

[12] Flight risk through orbital insertion or impact. 14 CFR § 415.35a.

liftoff through impact of all pieces of the launch vehicle, including the payload, for the flight of a suborbital launch vehicle. The ship and aircraft protection requirements specified in the standard are also intended to apply to a suborbital launch mission.

4.2.5.3 Hybrid Launch Mission

Suborbital flights of missiles and rockets are relatively well-understood; however, the opening of space to commercial enterprises introduces "hybrid" missions. A hybrid mission involves a vehicle that has some aircraft and launch vehicle characteristics. In 2004, Congress found that opening space to the American people and to their private commercial enterprises was a worthy goal, and that the creation of a clear legal and regulatory regime for commercial human space flight would advance that goal. Those findings accompanied passage of the Commercial Space Launch Amendments Act (CSLAA) of 2004.[13] Prior to passage of the CSLAA, the absence of definitions for the terms "suborbital rocket" and "suborbital trajectory" created confusion as to the appropriate regulatory regime for hybrid vehicles. The CSLAA provided definitions for suborbital rocket and suborbital trajectory:

- Suborbital rocket means a rocket-propelled vehicle intended for flight on a suborbital trajectory whose thrust is greater than its lift for the majority of the powered portion of its flight.
- Suborbital trajectory means the intentional flight path of a launch vehicle, reentry vehicle, or any portion thereof, whose vacuum IIP does not leave the surface of the Earth.

These definitions should be used as guidelines to determine if a particular hybrid vehicle should be treated like aircraft or like a launch vehicle for the purposes of risk management. Congress recognized that hybrid vehicles with certain flight plans may be subject to dual regulation as both aircraft and launch vehicles. All of the per-mission requirements specified in the standard should be applied to the non-aircraft portion flight of a hybrid mission. For example, if a hybrid mission includes a suborbital (or orbital) rocket, then the risk criteria should be applied to the flight of the rocket from lift-off until landing or final impact (or orbital insertion), including all planned debris impacts for the rocket. Specifically, risk should be accumulated from liftoff through impact of all pieces of the rocket, including the payload. The ship and aircraft protection requirements specified in the standard are also intended to apply to the rocket flight portion of a hybrid mission.

4.2.5.4 Controlled and Uncontrolled Re-entries

A reentry mission includes both controlled and uncontrolled reentries. Guidance from Air Force Instruction 91-202[14] provides additional information that is helpful in understanding controlled and uncontrolled reentries.

- Controlled reentry. A planned reentry for which the final atmospheric penetration time is chosen through spacecraft maneuvering so as to either maximize the amount of spacecraft material that burns up in the atmosphere, limiting the potential for endangering the

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[13] Commercial Space Launch Amendments Act of 2004. Pub. L. No. 108-492, 118 Stat. 3974 (2005).

[14] Secretary of the Air Force. "The US Air Force Mishap Prevention Program." AFI91-202. 13 April 2023. May be superseded by update. Retrieved 17 October 2023. Available at https://static.e-publishing.af.mil/production/1/af_se/publication/dafi91-202/dafi91-202.pdf.

public, or to bring down a recoverable reentry vehicle (e.g., capsule) in a manner that does not endanger the public. This typically controls the time and place of the disposal of space objects that are at the end of their mission life or for reentry capsules.

- Uncontrolled reentry. A random reentry in which the spacecraft/object reenters the atmosphere where an operator cannot sufficiently determine or influence the surface impact point prior to reentry. This is the typical reentry method for debris and spacecraft in decay orbits where the final reentry point and time is underdetermined due to uncertainty in atmospheric density conditions due to the extended time period between disposal and reentry

The collective risks from a reentry mission, excluding the risks to people in aircraft and water-borne vessels, should be compared to the per-mission risk criteria specified in Chapter 3 of the standard for each returning element. In addition, for controlled reentries, hazard areas should be established to satisfy the individual risk limits set in Subsection 3.2.1 of the standard and to comply with the aircraft and ship protection requirements in Sections 3.3. and 3.4 of the standard. The risks from a reentry must account for all the hazards and foreseeable outcomes of the reentry mission. A reentry risk analysis will ideally quantify (1) the P_{fail} prior to the final commitment to enter the atmosphere from orbit (or otherwise from outer space) that would lead to uncontrolled reentry; (2) the P_{fail} after the final commitment to enter the atmosphere that would lead to uncontrolled reentry; (3) the P_{fail} after the final commitment to enter the atmosphere that would lead to impacts outside the planned impact area; (4) the collective and maximum individual risks given an uncontrolled reentry; (5) the collective and maximum individual risks given impacts within the planned impact area; and (6) the collective and maximum individual risks given failures after the final commitment to enter the atmosphere that would lead to impacts outside the planned impact area. If a controlled reentry allows for more than one reentry opportunity (e.g., multiple trajectories under nominal or non-nominal conditions, or a nominal trajectory at different times of day), then the reentry risk analysis should quantify the highest individual and collective risks associated with any reentry opportunity. If the reentry is predicted to occur more than 25 years in the future, the risk estimates should assume reentry 25 years in the future even if the 25-year orbital mitigation requirement is waived.

4.2.5.5 Beginning of Flight – Launch Mission

The plain language definition of flight is “the motion of an object in or through a medium, especially through the Earth’s atmosphere or through space.”[15] Thus, the flight of a launch mission typically begins with the first motion of the object that poses risk. Therefore, the per-mission risk criteria specified in Chapter 3 of the standard should be compared to the total risks posed by a mission starting with the first motion of the object, which is often liftoff. Subsection 4.4.2.1 gives guidance on the treatment and discernment of pre-flight risks from a mission.

The use of carrier aircraft can complicate the definition of the beginning of flight for a launch vehicle. The Federal Aviation Administration (FAA) requires:

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[15] See Webster’s II New Riverside University Dictionary, 1984.

> For flight analysis purposes, flight begins at a time in which a launch vehicle normally or inadvertently lifts off from a launch platform. Liftoff occurs with any motion of the launch vehicle with respect to the launch platform.[16]

Recent FAA guidelines clarify that:

> the term 'liftoff' is often used in the context of motion with respect to a fixed asset, such as a launch pad or sea platform, but here liftoff also includes separation from a carrier aircraft. For other types of launch platforms, the determination of liftoff will be on a case-by-case basis and may need to consider the threat to the GP before separation of the launch vehicle, such as when a balloon-launching craft is airborne. [17]

The FAA's guidelines for the beginning of flight have been incorporated into the RCC's definition of liftoff with the further clarification that liftoff applies to vehicle motion during the launch countdown. This was done to exclude other times when the vehicle might be in motion, such as during ground processing or captive carry tests done in preparation for a carrier aircraft launch.

4.2.5.6 Beginning of the Mission Risks

In a sense, the per-mission risk limits in this standard equate in practice to risk limits for the flight phase of a mission, consistent with past precedents. Specifically, the RCC does not intend the standard criteria given in Chapter 3 of the standard to apply to pre-flight range activities; however, there are often significant risks posed prior to flight about which the range commander should make informed decisions. The need for a range commander to manage mission risks, including those posed by pre-flight hazards, means that the beginning of the mission or launch for the purposes of evaluating the overall mission safety should not always be liftoff for a vertically launched vehicle or separation from a carrier aircraft. Even so, the RCC's Risk Committee (RC) recommends that pre-flight safety decisions be based on other methods and criteria.[18]

As an example, the FAA determined that the initiation of the launch phase of flight for the *SpaceShipOne* (i.e., the starting point for an RLV risk estimate per 14 CFR 431.35[19]) was at ignition, subsequent to separation from the carrier aircraft (called the *White Knight*). For *SpaceShipOne*, the FAA found that pre-flight operations posed negligible risks due to its small size and selected propellants.[20] The FAA determined that separation from the carrier aircraft (i.e., independent motion of the launch vehicle from the carrier aircraft) defined the point where risk from *SpaceShipOne* increased; however, the FAA had issued an experimental airworthiness certificate that covered the gliding portion of flight prior to ignition. Therefore, the FAA treated the *SpaceShipOne* as an aircraft unless it was operated as a suborbital rocket.

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[16] 71 Fed. Reg. 165 (25 August 2006), p. 50555.

[17] FAA. *Guide to Probability of Failure Analysis for New Expendable Launch Vehicles*. Version 1.0. November 2005. Retrieved 16 October 2023. Available at https://www.faa.gov/about/office_org/headquarters_offices/ast/licenses_permits/media/Guide_Probability_Failure_110205.pdf.

[18] Pre-flight risks are typically subject to ground safety, system safety, and explosives safety criteria.

[19] Acceptable reusable launch vehicle mission risk. 14 CFR § 431.35.

[20] Because it uses a hybrid rocket motor and N_2O oxidizer, there are comparatively small risks due to solid rocket motor handling and processing such as fire, explosion, debris, or unintended motor stage flight. Nor are there any liquid propellant hazards such as toxicity or vapor cloud explosions.

The FAA guidelines state that “preflight anomalies exist that should be accounted for by launch risk analyses even though liftoff did not occur.” For example, an anomaly that could occur without liftoff and pose a hazard “should be accounted for by risk analyses as an on-pad failure.”[21] The RCC does not intend that the risks from any such preflight anomalies be compared to the per-mission risk criteria given in Chapter 3 of the standard.

4.2.5.7 End of Flight – Launch Mission

As discussed above for a typical space launch mission, the per-mission risk criteria specified in Chapter 3 of the standard should be compared to the total risk posed from liftoff until orbital insertion, which occurs when a launch vehicle achieves a minimum 70 nm perigee based on a computation that accounts for drag. Similarly, for the flight of a suborbital launch vehicle, the per-mission risk criteria specified in Chapter 3 of the standard should be compared to the total risk posed from liftoff until the impact of all pieces of the launch vehicle, including the payload.

4.2.5.8 Safety Concerns Beyond Orbital Insertion

The RC recognizes that missions that involve vehicles, objects, or debris at altitudes above 150 km (81 nm) may create legitimate post-orbital insertion safety concerns, just as there may be important pre-flight risks. However, there are several reasons that only the criteria in Section 3.5 of the standard, which address the protection of manned spacecraft, apply to the management of risks posed beyond orbital insertion.

a. Using the definition of orbital insertion adopted here, the launch risks posed beyond orbital insertion are insignificant for people on Earth or in aircraft.
b. Establishment of separate flight risk acceptability criteria that set limits on the risk from liftoff to orbital insertion is consistent with the direction provided in DoDI 3200.18 and current federal law for ELVs.
c. Ending the collective and individual risk assessment for flight of a typical ELV at orbital insertion also makes sense from a flight termination perspective, the exercise of positive control, and the hazards resulting from that process.

Nevertheless, the appropriate authorities must address legitimate safety concerns associated with launch beyond orbital insertion. Under the Space Liability Convention[22], the U.S. Government accepts absolute liability for damage on the ground or to aircraft in flight, outside of the United States, when the United States is deemed a launching State under the terms of Article I. Liability for damage caused elsewhere, such as on-orbit damage, is also accepted by the government as a launching State under the Liability Convention but only if the damage is the fault of persons for whom the launching State is responsible. Under Article VI of the Outer Space Treaty, the U.S. Government bears responsibility for national activities in outer space, including those carried on by non-governmental entities.[23]

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[21] Note, however, such on-pad failures without liftoff should not be included in the “flight” history of a subject vehicle for the purposes of estimating the probability of an in-flight failure.

[22] Convention on International Liability for Damage Caused by Space Objects, Multilateral, 29 March 1972, 961 U.N.T.S. 13810 at 187.

[23] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, Multilateral, 27 January 1967, 610 U.N.T.S. 8843 at 205.

For these reasons, the range commander should address legitimate safety concerns associated with launch beyond orbital insertion. For example, damage involving other orbiting assets (manned or active) may still occur after orbital insertion. Without taking appropriate measures, there is a potentially serious risk from the collision of a launch vehicle or its components with other objects in space. Dangerous orbital debris might also be generated unless appropriate measures are taken after orbital insertion. The DoDI 3100.12 policy states that "the creation of space debris shall be minimized." Specifically, "the probability of collision [PoC] with known objects during launch and orbital lifetime shall be estimated and limited in the development of the design and mission profile for spacecraft or upper stages." The following measures should be implemented to address the concerns beyond orbital insertion.

a. Prevention of unplanned physical contact between the vehicle and its components.
b. Minimization of debris generation from the conversion of energy sources into energy that fragments the vehicle or its components. Energy sources include chemical, pressure, and kinetic energy.
c. Development of reentry procedures to ensure safety of personnel is maintained as required by international space law and consistent with mission requirements.
d. Performance of conjunction assessments (CAs) and development of collision avoidance (COLA) procedures to avoid contact with other spacecraft from the launch vehicle, jettisoned components, and payload through a sufficient number of revolutions after orbital insertion to account for the type of orbit injected into or operating in, the altitude of the manned spacecraft, and the time until the vehicle or component can be properly catalogued.
e. Proper disposal of orbiting objects.

Department of Defense Directive (DoDD) 3100.10[24] directs that all DoD activities to, in, through, or from space, or aimed above the horizon with the potential to inadvertently and adversely affect satellites or humans in space, shall be conducted in a safe and responsible manner that protects space systems, their mission effectiveness, and humans in space, consistent with national security requirements. The DoDD 3100.10 guidance also directs that all such activities shall be coordinated with U.S. Space Command (or its successor).[25] The responsibility for risk management during flight phases subsequent to payload separation typically lies with the spacecraft operator, except for planned reentry missions that terminate on a test range. In the latter case, reentry risk is the responsibility of the test range conducting the reentry operation and/or the lead range initiating the launch in accordance with direction in DoDI 3200.18. For these final flight phases, the range commander should coordinate with the spacecraft operator and United States Strategic Command Combined Space Operations Center (CSpOC) to ensure that safety issues beyond orbital insertion are addressed to the extent necessary to reduce the U.S. Government's absolute liability under international treaties.

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[24] Department of Defense. "Space Policy." DoDD 3100.10. 30 August 2022. May be superseded by update. Retrieved 16 October 2023. Available at https://www.esd.whs.mil/Directives/issuances/dodd/.

[25] DoDI 3100.10, July 9, 1999, paragraph 4.11.7 states that these activities shall be coordinated with U.S. Space Command (succeeded by AF Space Command), as appropriate, for predictive avoidance or de-confliction with U.S., friendly, and other space operations.

The DoDI 3100.12 regulation sets limits on the risk from disposal of a spacecraft or an upper stage at the end of mission life. The regulation also specifically requires programs involving on-orbit operations plan to dispose of a spacecraft or upper stage using atmospheric reentry, maneuvering to an appropriate storage orbit, or direct retrieval. Atmospheric reentry is only allowed if atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission. If atmospheric reentry is used, "either the risk of injury from the total debris casualty area for components and structural fragments surviving reentry shall not exceed 1 in 10,000 (based upon an evenly distributed human population density across the Earth), or it shall be confined to a broad ocean or essentially unpopulated area."[26]

The criteria in Chapter 3 of the standard that apply beyond orbital insertion are concerned with the protection of manned spacecraft from collision with those injected vehicles, objects, or debris. This can be accomplished by delaying initiation of the launch mission or defining avoidance volumes as described in Section 4.6, which provides specific guidance for the range commander to implement the spacecraft protection criteria presented in Chapter 3 of the standard.

4.2.5.9 Beginning of Flight – Reentry Mission

As discussed above, a controlled reentry mission begins with the initiation of the final command or decision that commits a vehicle (or object) to a perigee below 70 nm. Similarly, an uncontrolled reentry mission begins when an object naturally decays to a perigee below 70 nm.

4.2.5.10 End of Flight – Reentry Mission

Using the plain language definition of "flight," a flight involving reentry ends when the vehicle discontinues motion through Earth's atmosphere or through space. See the standard's glossary for the definition for reentry mission.

4.2.5.11 Separate Risk Budgets for RLV Missions

The RCC intends for the standard risk acceptability criteria to also apply separately to the launch and reentry phases of an RLV mission. Because of differences in organizational responsibilities, the RC recognizes that the FAA's definition for the end of the launch phase and beginning of the reentry phase for an RLV mission may be different from the launch range; however, the following review of a current federal regulation shows that they have used decision points to divide RLV flights into distinct phases, which is consistent with the RC's guidelines.

The Federal Register states that, for an orbital RLV launch, but not the mission, "flight ends after deployment of a payload for an RLV having payload deployment as a mission objective." However, the Register states that, "for other orbital RLVs, flight ends upon completion of the first sustained, steady-state orbit of an RLV at its intended location."[27] Statutory mandates have strongly influenced the FAA's decision to make a regulatory distinction between the end of the flight of an ELV and RLV. Using the end of flight definition for an ELV[28] was not considered appropriate for an RLV because doing so would suggest that launch continues through vehicle reentry and landing. This would have been illogical in light of direction from Congress that reentry of an RLV is subject to, and in fact requires, a separate

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[26] See DoDI 3100.12 paragraph 6.4.1

[27] 68 Fed. Reg. 59676 (16 October 2003).

[28] 14 CFR 401.5: "For purposes of an ELV launch, flight ends after the licensee's last exercise of control over its launch vehicle."

reentry license by the FAA. Instead, the FAA proposed to use payload deployment as the point to end the flight of an RLV, and thus end the launch phase of an RLV mission. Therefore, the current FAA regulations hold that reentry[29] commences upon initiation of operations necessary to assure reentry readiness and safety, that are uniquely associated with reentry, and that are critical to ensuring public health and safety and the safety of property during reentry.

For *SpaceShipOne*, the FAA determined that the end of flight (i.e., the ending point for an RLV risk estimate) corresponded to the point of the last motion of the launch vehicle. This was because the FAA determined that *SpaceShipOne* no longer posed any hazards after landing. The FAA found that ending the risk assessment for *SpaceShipOne* at any earlier point (such as an altitude of 60,000 feet when it resumed gliding flight) was not appropriate. At any earlier point, *SpaceShipOne* was still flying, and it had been exposed to unique space launch environments (i.e., accelerations, reentry loading, and thermal heating of vehicle). The fact that it may have resumed gliding flight does not necessarily mean that it has returned to a flight-proven (i.e., inherently safe) glider configuration.

4.2.6 Separate Risk Budgets for Multiple Launches

This subsection provides guidelines for circumstances where the per-mission risk criteria specified in Chapter 3 of the standard may be applied separately to multiple flights. In all cases, the risk acceptance decision maker for the lead range (e.g., the range commander) should be presented with the best estimate of the total risk that accounts for all aspects of an activity the range is involved with, including multiple flights from different locations. The risk acceptance decision maker should also be presented with the best estimate of the risks due to each flight. In all cases, the mission rules should clearly define the conditions necessary for each launch to proceed in the most comprehensive manner possible.

The per-mission risk criteria specified in Chapter 3 of the standard should be compared to the total risk posed by multiple flights (i.e., the aggregated risk from all flights) unless there is a decision point between each flight where the following separate flight phase test is satisfied:

a. The initiation of each flight has sufficient controllability to allow operational options that could reduce the risk posed by a flight significantly; AND
b. The decisions as to whether or how to initiate a subsequent flight is based on a risk assessment that is conducted or validated just prior to each flight; AND
c. The risk assessment for each subsequent flight is made or validated using updated vehicle status and updated predictions of flight conditions; AND
d. The decision to initiate any subsequent flight is made with the knowledge that there is no current risk from the previous flight(s); OR
e. The P_{fail}, and other critical input data, for the risk estimate of the subsequent flight accounts for the failure of the previous flight(s).

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[29] In plain language, reentry is defined as the event occurring when a spacecraft or other object comes back into the sensible atmosphere after going to higher altitudes, or the actions involved in this event. A regulatory definition is given in 14 CFR 401.5 and cited below.

> **NOTE** The separate flight phase test is passed if the first four conditions are passed, or if the first three and the fifth condition are passed; *not all five conditions need to be satisfied.*

The Short-Term Interval Launch (STIL) operations conducted from Vandenberg Air Force Base (VAFB) illustrate how the separate flight phase test should be evaluated. The STIL range activity involves two Minuteman III vehicles launched within about two hours of each other. Each vehicle is launched from a separate facility on the northern part of VAFB, and is targeted for the same general area. Complete risk analyses are done for both vehicles prior to the first launch using the latest vehicle status and predicted flight conditions. The risk estimates for the second launch are updated after the first launch using the latest vehicle status and predicted flight conditions. The per-mission risk criteria specified in Chapter 3 of the standard should be compared to the total risk posed by each STIL launch because four of the above five decision conditions are satisfied. Both launches are independently initiated: the second launch could be held if the first launch fails. Holding the second launch is an operational option that could reduce the risk posed by a flight significantly. Therefore, the first condition is met. The decision to initiate the second flight is based on a risk assessment that is conducted or validated just prior to each flight, so the second condition is met. The risk assessment for the second flight is made or validated using updated vehicle status and updated predictions of flight conditions, so the third condition is met. The decision to initiate the second flight is made with the knowledge that there is no current risk from the previous flight, so the fourth condition is met. If the first launch was a failure, the risk assessment for the second flight would account for failure of the first (in terms of P_{fail}, etc.), so the fifth condition is also met. As a secondary consideration, if the subsequent launch would result in distinctly different population groups being hazarded, then there is additional justification to apply the per-mission risk criteria specified in Chapter 3 of the standard independently to the subsequent launch.

White Sands Missile Range does “ripple fire” tests where two missiles are in thrust-controlled flight at the same time, under a single risk budget; however, if thrust and substantial control are complete for a flight (such that the IIP cannot change significantly), any subsequent missile launch gets a separate risk budget because the outcome of the first launch is known from a safety perspective. These “shoot look shoot” and “ripple fire” approaches to risk management are consistent with these guidelines.

A typical “salvo” mission where two vehicles are launched from the same range nearly simultaneously would not satisfy the separate flight phase test. A typical salvo mission does not allow separate decisions between launches that would reduce the total risk from the mission. Also, risks cannot be re-evaluated using updated conditions between launches for a typical salvo mission. Therefore, the total risk from all launches involved in a typical salvo mission should be compared to the per-mission criteria specified in Chapter 3 of the standard.

4.2.7 Levels of Rigor

Risk to the public is a function of both (1) how likely an accident is; and (2) the severity of the consequences of an accident if one were to occur. Different approaches are required for events that are highly likely but not dangerous, likely and dangerous, or unlikely and dangerous.

Figure 4-2 shows a generalized risk matrix. If an event (e.g., vehicle failure) could result in a high level of danger to the public, there needs to be more safeguards against it occurring to lower the probability that it will occur (orange box – lower left). Conversely, if a given event is likely to occur, there need to be safeguards against it being dangerous (orange box – upper right). Events that are likely to occur and likely to be dangerous if they do occur should be avoided entirely (red box – upper left). Ideally, vehicle failures should be unlikely to cause harm and unlikely to happen at all (green box – lower right).

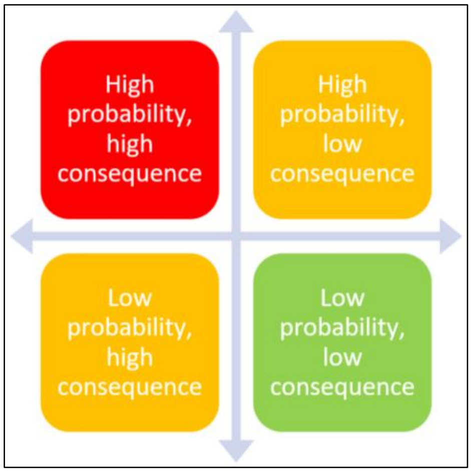

Figure 4-2. Generalized Risk Matrix

Based on the failure probability and consequences, some missions will be judged acceptable and some will be unacceptable due to excessive risk of failure and/or consequences. Figure 4-3 notionally shows how increasing the P_{fail} and/or the consequence of failure leads to unacceptable missions (red, upper left).

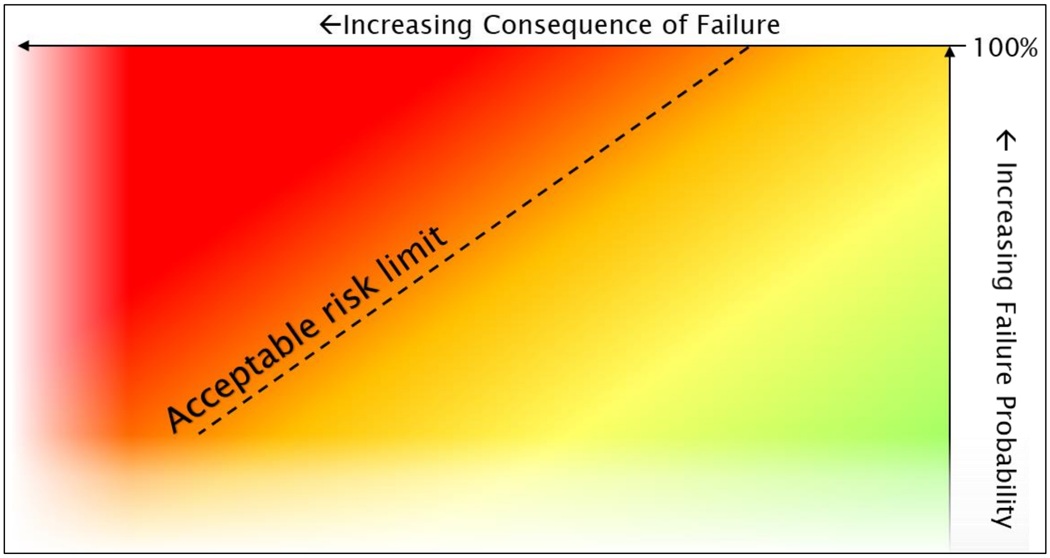

Figure 4-3. Acceptable Risk Limit as a Function of Failure Probability and Consequence

Some examples of high- and low-consequence events are the following.

- Low consequence: Failure of a vehicle for which the kinematic range is limited to an area cleared of people.

  - Test flights on closed ranges
  - Launches isolated in broad ocean areas
- High consequence: Failure of a large or high-fuel-load vehicle flying over a densely populated area.
  - Large commercial aircraft
  - Returning space shuttle

Examples of events with high and low P_{fail} include:

- Low P_{fail}: Well-tested vehicle with very large history, such as commercial aircraft
- High P_{fail}: First-time launch of a new vehicle or a vehicle with many past failures, such as new ELVs developed and launched by inexperienced operators.

4.2.7.1 Uncertainty

Every estimation of accident probability or the consequences of an accident comes with an associated level of uncertainty in the value of that estimate. This value is seldom explicitly stated but is often (though not always) included in the answer by modeling unknown effects as conservatively as possible. The uncertainty is a function of the method used for the risk analysis. Lowering the uncertainty in an analysis is typically associated with an increase in effort. Understanding the uncertainty is important because there needs to be confidence that the risk assessment is accurately predicting when the risk will be lower than the acceptable limit.

Missions with risk that is well below the acceptable limit can use more approximate methods to show their compliance with risk levels, since the uncertainty in the answer is unlikely to affect whether the mission is in compliance with the accepted risk levels. For example, if an event is very unlikely to cause harm, it is not as critical to understand exactly how likely the event is to occur. This is illustrated in Figure 4-4, where the mission with the smaller risk (purple) is allowed to have a larger risk uncertainty (purple circle) than the mission with the larger risk (green).

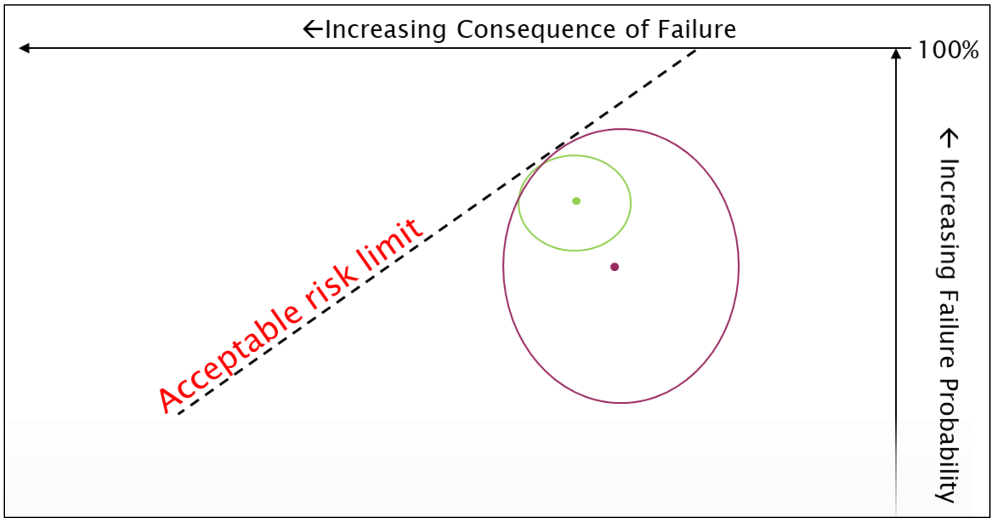

Figure 4-4. Results Closer to the Acceptable Risk Limit Should Have Smaller Uncertainty

If a mission is near the allowed limit of risk, it is important that the risk be well understood. Here, the fidelity of the answer is critical in assuring that the risk is within allowed limits. In Figure 4-5, both nominal results (dots) are below the acceptable risk limit; however, the analysis represented by the orange dot has a large associated uncertainty (orange circle) indicating that the true value of the risk may lie above the acceptable risk limit. Although the orange analysis has a lower nominal value than the green analysis, the lower uncertainty associated with the green analysis (green circle) makes it acceptable, while the orange analysis is unacceptable.

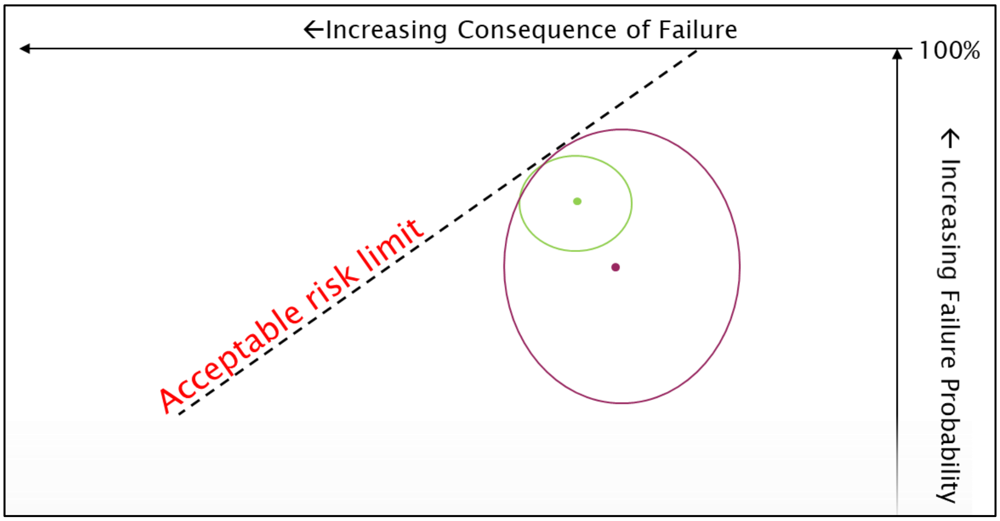

Figure 4-5. Lower Mean Risk Estimates do not Always Improve Acceptability

In most cases, the uncertainty can generally be reduced by improving the analysis methods. Better models of the vehicle reliability or of the at-risk populations can improve confidence in the predicted outcomes.

4.2.7.2 Level of Rigor

More rigorous analyses take more resources but should result in greater confidence in the results. If a low-fidelity analysis shows a sufficiently low risk, a higher-fidelity analysis is not required; however, if the lower fidelity analysis shows a risk close to (or above) the allowable risk, a more rigorous analysis should be performed to ensure the allowable risk will not be exceeded. If the risk is above the allowable risk limit, a higher-fidelity analysis should help identify potential additional mitigations.

The LOR applies to not just the risk analysis, but the whole safety analysis. For example, a better system safety process provides more confidence that the previous flight history is an accurate representation of the future reliability of the vehicle. Additional fault tolerance of a safety-critical system helps to ensure confidence that mechanisms are in place to reduce the likelihood of consequences in highly populated areas. Better population data provides more confidence in consequence analyses.

Simple, low-effort approaches can be used to get an initial estimate of the total P_{fail} and maximum consequence. It is possible to then get an initial estimate of the required LOR for the analysis using these estimates for failure probability and failure consequence.

4.2.7.3 Assessing the Required Level of Rigor

What is needed is a simple, practical framework to assess the initial LOR required for an analysis and a method to adjust the LOR as the analysis proceeds. The initial estimate of the needed rigor of the safety analysis should be based on mission parameters that are available *without* first requiring a high-fidelity analysis. Simple, low-effort approaches can be used to get an initial estimate of the total P_{fail} and maximum consequence. It is possible to then get an initial estimate of the required LOR for the analysis using the estimates for failure probability and failure consequence.

Much of the required information for a LOR assessment will be a natural result of a preliminary safety assessment. It is relatively easy to get first-order estimates of maximum casualty area and total mission failure probability.

It is more difficult to assess impact probability as a function of locations; population density at specific locations; and allocation of P_{fail}.

Figure 4-6 shows the general process to be used to determine the LOR for the flight safety processes. Readily available data will be used to obtain an initial estimate of the LOR. This can be used to evaluate the system safety program and perform the FSA, or refinements can be made to the mission or analysis until the LOR is acceptable to the operator.

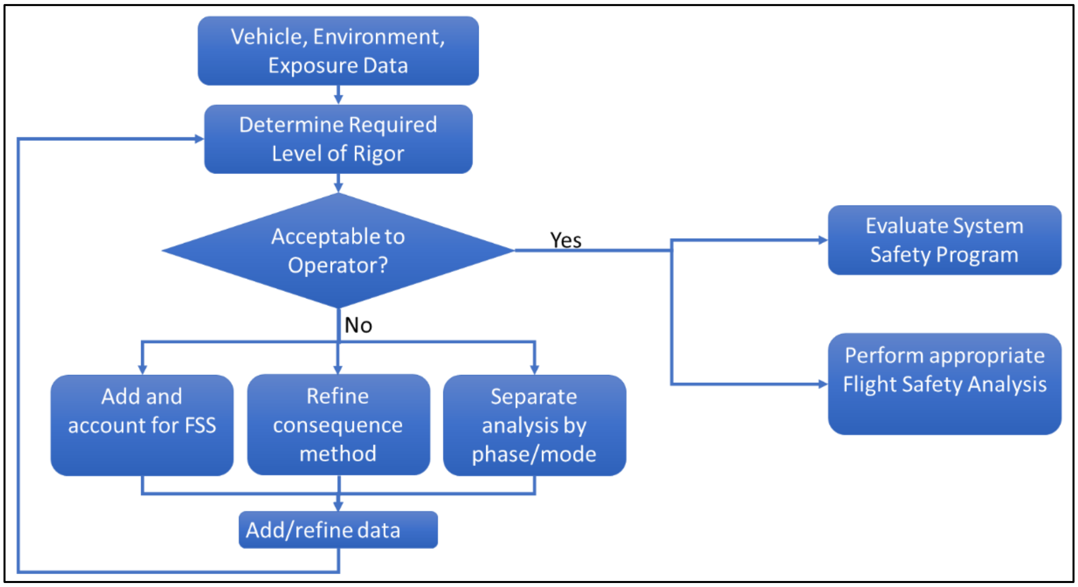

Figure 4-6. General Process to Determine the Required Level of Rigor

4.2.7.4 Integer Level of Rigor Method

The first approach considered to estimate the LOR assigns integer scores to the various aspects of risk.[30] This approach does not compute a true conditional risk, but only a very rough

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[30] The importance of failure probability and consequence are essentially logarithmic, so it can be represented by an integer scale that changes by one for each order of magnitude change in the actual value (e.g., the metric for failure probability has a difference of two between a reliability of 99% compared to 99.99%). A simple model for consequence is the maximum consequence area multiplied by the maximum credible population density. Since logarithms are additive instead of multiplicative, a consequence metric can be given as log(consequence area) + log(population density).

approximation. The objective is to determine the credible upper bounds of the consequence and probability, which are then used to determine the LOR required.

Define the LOR required, L, as:

$$L = C_1 + C_2 - R_1 - A \tag{4-3}$$

where the contributions to consequence are C_1 (casualty area) and C_2 (population density), the vehicle reliability is R_1, and the acceptable risk is A. If the consequence (C_1 or C_2) increases, then the required LOR increases. If the P_{fail} is lower (R_1 becomes larger), then the required level or rigor decreases. If the acceptable risk is higher (larger A) then the required LOR is lower. This does not yet consider the flight safety system (FSS), which will be discussed later.

- Consequence variables
  - Casualty area: $C_1=\log_{10}$(Maximum casualty area, in square feet) – *round up to integer*
  - Population density within the maximum physical extent of the vehicle: C_2=range 0 to 6, where 0 is evacuated and 6 represents a major metropolitan area (see Table 4-2).
- Reliability of failure probability factor: $R_1=-\log_{10}(P_{fail}$ of vehicle), based on demonstrated history – *round down to integer*.

  $P_f \le 1$ → $R_1=0$
  $P_f \le 0.1$ → $R_1=1$
  $P_f \le 0.01$ → $R_1=2$ etc.

- Acceptable risk. A is the limit for acceptable risk, (value discussed below), where larger values of A indicate higher allowable risk.

Table 4-2. Relationship between Category of Occupancy and "Log (Population Density)"

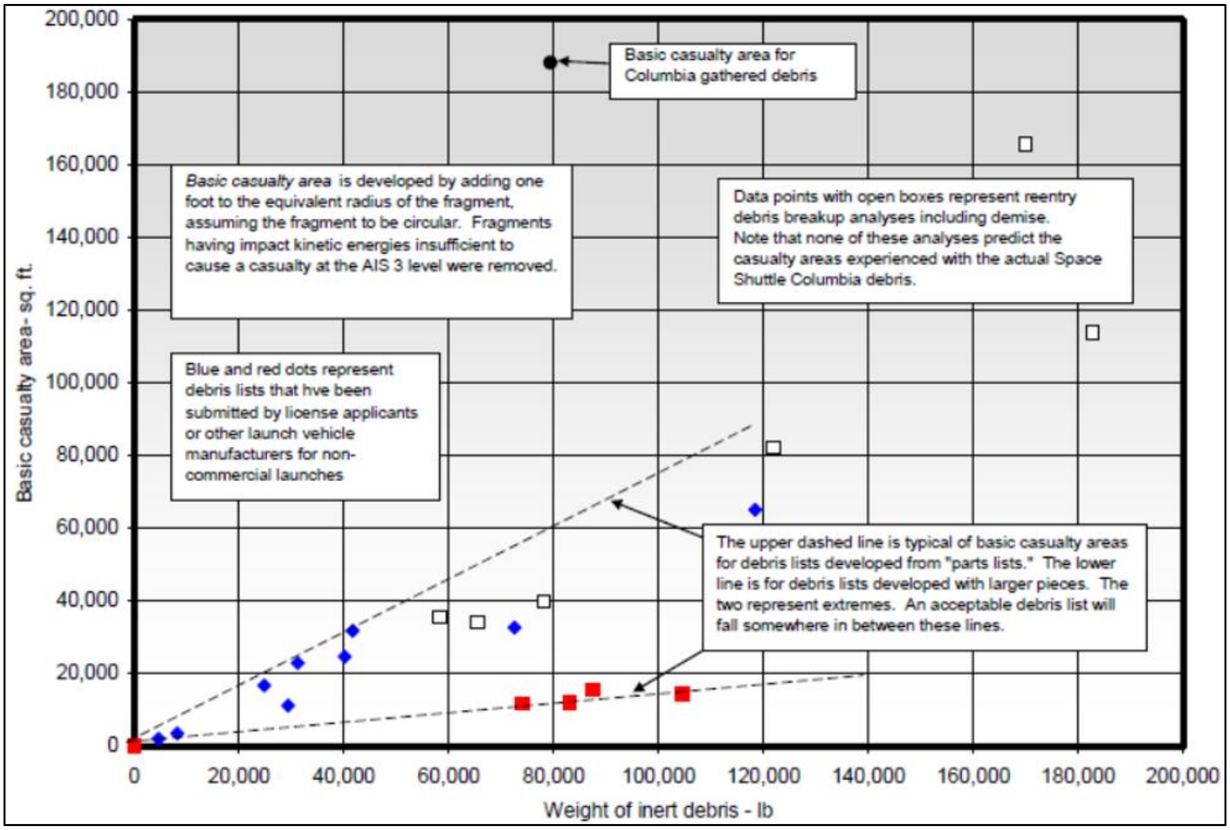
C_1	Categories
6	Major metropolitan area
5	Small City
4	Suburban or Small Towns
3	Rural
2	Scattered Mountain or Desert Occupancies
1	Notice to keep out only
0	Notice to keep out and either access controlled or surveillance

These integer assignments are conservative values, designed to be a reasonable upper limit (thus the reason that items are rounded in a specific direction). For this approach, the impact probability distribution is not required; the maximum casualty area is applied to the area of maximum population density.

The first part of the consequence analysis is population density, $C_1 = \log_{10}$ "(Maximum Population Density)". This term should be interpreted as a category rather than a directly measurable quantity, particularly for an initial assessment of the required LOR. The label "log (Maximum Population Density)" is placed in quotes to indicate that this is NOT literally the logarithm of the population density but a notional representation of the maximum population density in the region overflown on a logarithmic scale. Example values of C_1 are shown in Table 4-2. The categories listed were developed to reflect easily identifiable population characteristics.

The upper portion of the table includes categories that will be most relevant for most evaluations of full-ascent or reentry missions. The lower portion of the table contains categories that are useful in the context of decomposing a mission into segments, each of which may be treated at a different LOR.

The second part of the conditional consequence analysis is the casualty area term, C_2. This term is defined as $C_2 = \log_{10}$ (maximum basic casualty area). Figure 4-7 depicts trends in basic casualty areas from manufacturers of ELVs and evolved ELVs resulting from a launch accident as well as estimates of basic casualty areas for a handful of reentries. The basic casualty accounts for all hazardous debris resulting from vehicle breakup. The figure also shows the estimated basic casualty area for the debris gathered from the Columbia reentry breakup. This figure may be used as a basis for a preliminary estimate for the term C_2. Estimates should err on the high side to provide conservative results.



Basic casualty area for Columbia gathered debris

Basic casualty area is developed by adding one foot to the equivalent radius of the fragment, assuming the fragment to be circular. Fragments having impact kinetic energies insufficient to cause a casualty at the AIS 3 level were removed.

Data points with open boxes represent reentry debris breakup analyses including demise. Note that none of these analyses predict the casualty areas experienced with the actual Space Shuttle Columbia debris.

Blue and red dots represent debris lists that hve been submitted by license applicants or other launch vehicle manufacturers for non-commercial launches

The upper dashed line is typical of basic casualty areas for debris lists developed from "parts lists." The lower line is for debris lists developed with larger pieces. The two represent extremes. An acceptable debris list will fall somewhere in between these lines.

Figure 4-7. Trends in the Relationships between Basic Casualty Area and Dry Weight of a Vehicle

The value for acceptable risk, A, should be set at 2 (or lower). This value is comparable to acceptable risks for existing commercial and general aviation, experimental aircraft, and active (non-testing) UAVs.[31]

Launch operations cannot currently achieve a value of $A \leq 2$ without an FSS, as the LOR required would be higher than the maximum value possible. The FSS, however, can be included by separating the analysis into two parts: inside the operating areas (OPAREAs) and outside the OPAREAs. This is addressed by adding two more variables.

- Population density *within* the operating area, C_3, which has the same 0 to 6 range as C_2. For launch operations, the operating area is considered the area inside the fight safety limit boundaries.
- Reliability of the *FSS*, $R_2 = -\log_{10}$ (P_{fail} of the FSS to contain debris to the operating area), which is the same as the "number of nines" in the FSS reliability, i.e. for 99.99% reliability, R_2=4.

Now separate Equation (4-3) into two parts. Considering the risk inside the operating area, the population is now different, so C_3 replaces C_2, as

$$L_{in} = C_1 + C_3 - A - R_1 \qquad (4\text{-}4)$$

For the area outside the operating area, the addition of the FSS adds another term to the equation, as

$$L_{out} = C_1 + C_2 - A - R_1 - R_2 \qquad (4\text{-}5)$$

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[31] To justify this, rearrange Equation (4-3) to solve for the accepted risk as follows:

$$A = C_1 + C_2 - R_1 - L$$

Now, assign values for the variables using four types of example aircraft.

- A commercial transport aircraft has a large casualty area (up to approximately one million ft^2), can fly over cities, and has a demonstrated reliability of better than 1 failure per million missions. The system safety program is very high (level 5) and there is high redundancy of all safety-critical systems, so we will assign a level of rigor of 5.
- For general aviation (including business jets), the casualty area is smaller, likely up to around 10,000 ft^2, can fly over cities, and the demonstrated reliability is better than one failure per 100,000 operations. The system safety program is quite high, although the lack of redundancy in safety-critical systems is not as high as for commercial transport aircraft, so we will assign a level of rigor of 4.
- For experimental aircraft, the casualty area is also likely up to 10,000 ft^2, but they are not allowed to fly in densely populated areas, and the reliability is less than one failure in 1000 operations. The analysis rigor can be quite low, with little oversight of the design and build process, so we will assign a level of rigor of 2.
- Active (non-testing) UAVs typically have a casualty area less than 100 ft^2, are allowed to operate in cities, and have a probability of failure on the order of 1 per 10,000 operations. The level of rigor is fairly low (production is fairly high, but training of operators is quite low), so we will assign an analysis rigor of 2.

These values are summarized in the table below; the effective risk acceptance level is consistently a value of 1 or 2. As might be expected, the accepted risk is somewhat lower for commercial aircraft and general aviation, which have passengers on board as well. Based on this analysis, the recommended value for the acceptable level of risk, *A*, is 2.

Level of Rigor and Acceptable Risk for Aircraft

	Commercial aircraft	General Aviation	Experimental aircraft	Active UAV
C1, Maximum casualty area	6	4	4	2
C2, Maximum population density	6	6	3	6
R1, Reliability	6	5	3	4
L1, Level of rigor	5	4	2	2
A, Effective risk acceptance	1	1	2	2

For example, apply this to some common launch operations, with the calculation summarized in Table 4-3.

Table 4-3. Example Level of Rigor Determination for Example Launches

	Orbital Launch	Experimental Vehicle	Sounding rocket
C_1, Maximum casualty area	6	4	4
C_2, Maximum population density	6	5	3
C_3, Population inside OA	-	2	-
R_1, Vehicle reliability	1	1	2
R_2, FSS reliability	-	1	-
A, Acceptable Risk	2	2	2
L_{out}, Rigor required outside OA	9	5	3
L_{in}, Rigor required inside OA	-	3	-

- Orbital Launch Vehicle. For a typical orbital launch vehicle, the maximum casualty area might be approximately one million square feet, so C_1=6. The population within the maximum physical extent could include a metropolitan area (i.e., cities during overflight), in which case C_2=6. During overflight, there is no FSS, so there is no operating area. Current typical vehicles have between 1% and 10% P_{fail}, so they have a reliability score of 1. Assuming an acceptable risk value of A=2, this leads to an impossibly high LOR, 9, discussed following these bullets.
- Experimental Vehicle. Consider an experimental vehicle with a much smaller maximum casualty area, perhaps about 10,000 ft^2, so C_1=4. Assume the population within the maximum extent includes a midsize city, which would have a C_2 score of 5, and the population inside the operating area includes a few very small towns, resulting in a score of C_3=2 (however, a large crowd of spectators would increase this). The reliability might reasonably be between 1% and 10%, so R_1 is 1. The FSS on this example vehicle has not been previously demonstrated, so a maximum score of R_2=1. With an acceptable risk value of A=2, the LOR inside the operating area is L=3, but outside the operating area is L=5.
- Sounding Rocket. For a large sounding rocket, the casualty area is again in the neighborhood of 10,000 ft^2, so C_1=4. In an isolated setting, the population density within the range of the vehicle is relatively low, perhaps a few small towns, so it could be assigned C_2=3. The sounding rocket has no FSS. With an acceptable risk value of A=2, this results in a required LOR of L=3.

By this simple approach, it is impossible to reach required LOR for the orbital launch. So as a first step, the analysis would be separated into the phase where there is an FSS, and the phase without it. For the experimental vehicle, increasing the reliability of the FSS is the most obvious approach, but another alternative would be to move testing to a location where there are no significant population centers within range, since the LOR is driven by the potential impact the midsized cities nearby.

This approach can also be used to separate flight into phases or failure modes. For example, consider the orbital launch, and separate the flight into that before the orbital gate (when there is an FSS) and after the orbital gate (where there is no FSS). The population inside the operating area and/or the flight safety limit boundaries is small, but not completely evacuated for a typical launch, so assign C_3=2. The FSS is certified to RCC 319[32] or equivalent, which is assigned a reliability of 99.99% or a score of 4. When considering only downrange overflight, the casualty area is much smaller (moving from a 6 to a 4). Additionally, the reliability is increased; typically, overflight is less than 5% of the time of the overall mission, and thus the likelihood of a failure during overflight is much smaller. Beginning with a 2% P_{fail}, the P_{fail} for overflight is 0.1% (i.e., a score of 3). With an acceptable risk value of A=1, the LOR both inside and outside the operating area is 6 - still one level higher than the maximum on the scale, but much closer. This means that a determination with a more sophisticated approach is necessary. Table 4-4 summarizes the values of the parameters in the LOR calculation just described and the computed LOR by phase of flight and, for pre-orbital gate, by region. Note that to keep the total allowable acceptable risk to a level of 2, each phase is allowed a value of 1.)

Table 4-4. Level of Rigor Determination for Orbital Launch by Phase

	Pre-orbital gate	Overflight
C_1, Maximum casualty area	6	4
C_2, Maximum population density	6	6
C_3, Population inside OA	2	-
R_1, Vehicle reliability	1	3
R_2, FSS reliability	4	-
A, Acceptable Risk	1	1
L_{out}, Rigor required outside OA	6	6
L_{in}, Rigor required inside OA	6	-

4.2.7.5 Lower Fidelity Risk Evaluations to Assess Required LOR

Figure 4-8 shows the margin for compliance resulting from the gap between the acceptable risk limits and the estimated risk level and its associated uncertainty. The figure illustrates the roles of conditional consequences, vehicle reliability (safety system reliability), and uncertainties in the quantities in determining the required LOR for a proposed mission. Consequences in the figure are characterized by two terms: the maximum casualty area of the vehicle, C_1; and the population density, C_2, within the maximum physical range of the vehicle. Reliability is characterized by the demonstrated reliability of the vehicle, R_1, and when an FSS is employed the reliability of the FSS, R_2.

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[32] Range Commanders Council. *Flight Termination Systems Commonality Standard*. RCC 319-19. June 2019. May be superseded by update. Retrieved 17 October 2023. Available at https://www.trmc.osd.mil/wiki/x/AYy8Bg.

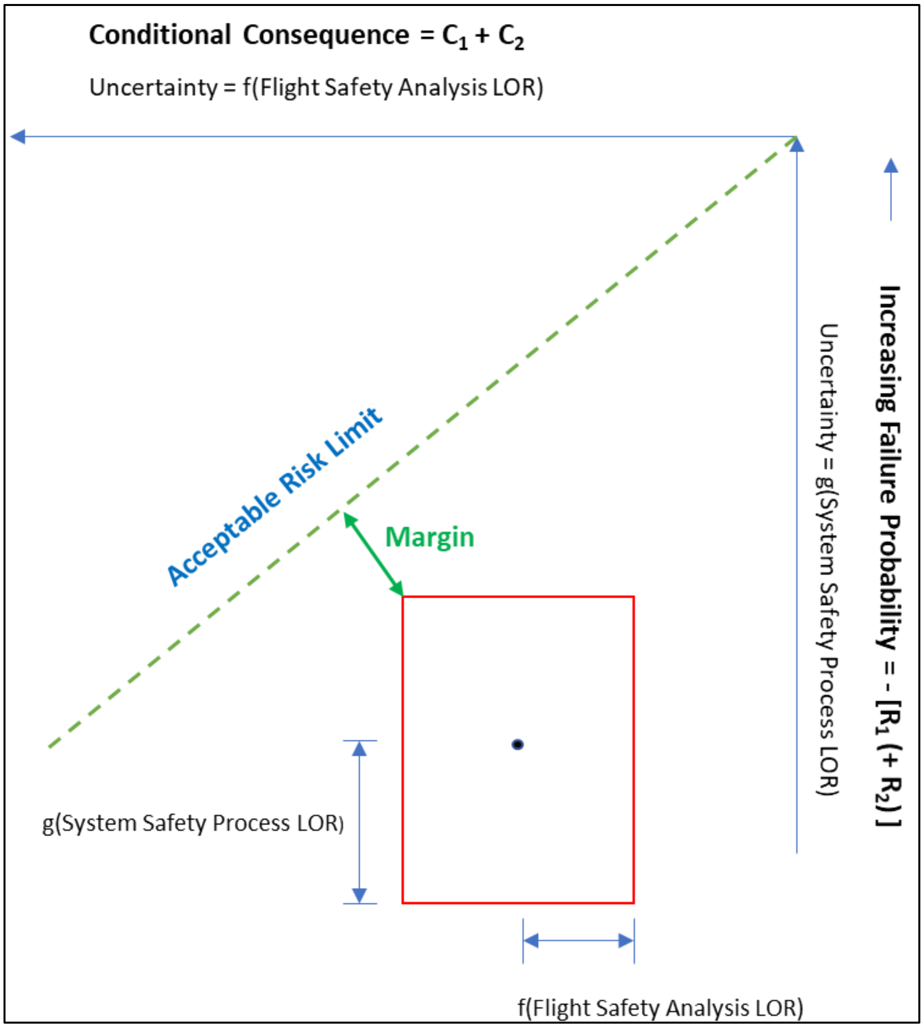

Figure 4-8. Assessing the Required Level of Rigor

The dot at the center of the diagram indicates the point estimate of the reliability and the conditional consequences of a failure (for the purpose of this figure, biases in estimates are ignored[33]). Uncertainties in conditional risk are depicted simplistically as being uncorrelated; hence the resulting rectangular uncertainty region. The acceptable risk limit is depicted as the dashed line. Thus, in the diagram, a mission with acceptable risk will have the entire rectangle below the acceptable risk boundary. Both conditional consequences and reliability are expressed in logarithmic units. Assessing the required LOR (fidelity) requires an operator to develop an initial estimate of the risk level and its associated uncertainty.

There are many factors that will influence the level of risk that will be posed by a given mission. These include the characteristics of the launch or reentry vehicle, the potential hazards that the vehicle poses to people and property, the design of the mission trajectory, the geographical region within which the mission will be conducted, and the meteorological conditions in the launch area. A range user will need to assess all of these factors to determine the feasibility of meeting acceptable risk criteria. The following is a list of key factors (risk

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[33] Ignoring biases is an unrealistic assumption, made here for simplicity. This assumption will be reconsidered subsequently.

drivers) that will affect the level of debris risk for a mission. Since at this point the objective is to qualitatively assess how close the risk is to the tolerable levels, the list of risk drivers should be used as a tool to assess what population centers or segments of the planned trajectory will be the largest contributors to the risk.

a. The following are characteristics of the launch or reentry vehicle that determine the types of hazardous debris (potentially including an intact vehicle or vehicle stages) and the casualty area that can result from a failure.

    (1) The size and weight of the vehicle affects the amount of debris that can be generated.

    (2) The types of stages (liquid or solid propellant) and their propellants determine the potential for explosive debris and for in-flight explosions causing breakup with velocities imparted to fragments.

    (3) The structural capacities of the vehicle will determine whether the vehicle, or its stages, will stay intact to impact or break up during free fall (due to aerodynamic and inertial loads).

b. The geographical region in which the mission is to be conducted will determine the potential exposure of people and property to the launch hazards.

    (1) The locations of public populated areas in the launch area often lead to high risks or significant limits on the launch profile; this includes industrial areas and housing areas on a federal range or near a launch site. Overflight or near overflight of regions of high population density can likewise lead to high risks or limits on the launch profile.

    (2) The types of buildings that house people (shelter categories) will significantly affect the consequences of impacting debris; often people inside of a structure are at *greater* risk from debris and explosions than those that are outside.

    (3) The locations of other launch facilities or high-value structures can impose strict limits on flight profiles and potentially add significantly to the risk; these may include structures that contain hazardous materials.

c. The design of the mission trajectory will significantly affect the areas that are hazarded and the potential spread of the debris from an accident.

    (1) Steep-ascent trajectory profiles lead to longer flight time intervals during which debris from a malfunctioning vehicle can hazard the launch area.

    (2) Slow vehicle ascent also results in longer flight time intervals during which debris hazards can threaten the launch area.

    (3) The velocity and altitude of the vehicle as it moves downrange strongly affects the size of the region that can be hazarded by a debris-generating event.

    (4) The uncertainties in the trajectory position and velocity due to vehicle guidance and performance variations have a strong influence on the size of the region that can be hazarded by a debris-generating event.

d. The meteorological conditions in the launch area are a key factor in the potential spread of the debris from an accident.

  (1) Prevailing wind conditions can carry debris towards populated areas.

  (2) The likelihood of high wind magnitudes can lead to high risk for surrounding populations or result in significant constraints on when a launch can occur.

Given the point estimate of the risk, some quantification of the uncertainty in the risk estimate is needed to assess the required LOR. Unfortunately, limited information is available to assist in this determination.

It is useful to understand what typical uncertainties in risk estimates are. Table 4-5 *postulates* uncertainty bounds for mission E_C for five different LORs. **Actual values have not been established**; however, it is generally, although not universally, accepted that a high-fidelity analysis produces risk estimates that are good to within ± a half order of magnitude. Each lower-fidelity analysis is *asserted* to be one half order of magnitude more uncertain than the adjacent higher-fidelity method.

Table 4-5. Uncertainty Bounds in E_C for Different Levels of Rigor

LOR	Level	Uncertainty in Risk Estimate	Lower Bound[1]	Upper Bound[1]
Low Fidelity	1	± 2.5 orders of magnitude	3E−7	3E−2
	2	± two orders of magnitude	1E−6	1E−2
Medium Fidelity	3	± 1.5 orders of magnitude	3E−6	3E−3
	4	± one order of magnitude	1E−5	1E−3
High Fidelity	5	± 0.5 order of magnitude	3E−5	3E−4

[1] Upper and lower bounds to "true" risks when calculate risk is 1×10^{-4}

Uncertainty bounds for computed risks for each LOR have been computed and listed in Table 4-6 based on the assumption that the uncertainties in Table 4-5 are valid. Thus, for example, if the preliminary calculation provides an estimated mission collective risk of 1E−6, this table would suggest that a Level 4 FSA would be required.

Table 4-6. Inferred Allowable Calculated Risk

LOR	Level	Allowable Calculated Risk (Based on Table 4-5) to Ensure E_C is Acceptable[1]	Tolerable Computed E_C Based on Single-Digit Precision[2]
Low Fidelity	1	3E−7	5E−7
	2	1E−6	1.5E−6
Medium Fidelity	3	3E−6	5E−6
	4	1E−5	1.5E−5
High Fidelity	5	3E−5	5E−5

[1] Tolerable risk limit of 100E−6

[2] Tolerable risk limit of 150E−6 (FAA Regulations E_C should be treated as containing one significant figure)

The uncertainty in risk estimates is a combination of the uncertainty in reliability (failure probability) and the uncertainty in FSA consequence assessment. The uncertainty in FSA consequence assessment is, in turn, composed of the uncertainty induced by the models used in the FSA and the uncertainty in the data items used in the analysis. When determining the uncertainty bounds on consequence assessment both of these sources must be addressed.

The tolerable values for collective risk tabulated in Table 4-6 as derived from the uncertainty bounds in Table 4-5 should be taken as notional. The lower-fidelity methods are designed to include a conservative bias. To use the method in this section a range user should verify if the tabulated uncertainty bounds apply to their mission, assess the level of bias in any lower-fidelity method considered, and develop an upper bound to their risk estimate based on those factors.

There are four fundamental strategies to shifting an unacceptable value from the risk assessment to an acceptable value.

a. Reduce the conditional consequences; no other changes.

b. Reduce the *uncertainty* in the calculated conditional consequences; no other changes.

c. Increase the reliability; no other changes.

d. Decrease the reliability *uncertainty*; no other changes.

Obviously, favorable combinations of these strategies will also move toward an acceptable result. Table 4-7 provides an overview of the factors contributing to risk in an FSA. Inspection of this table shows some of the challenges in performing an analysis with uncertainty bounds no greater than shown for a Level 5 analysis. Once an analysis process is adopted, the uncertainty induced by the models tends to remain stable. The uncertainty in launch vehicle-related parameters tends to be highest for the first several flights and decrease with maturity of the vehicle. As a consequence of these data-driven uncertainties the uncertainty bounds listed above for a high-fidelity analysis are NOT likely to be achievable for the first several flights of a vehicle unless the planned mission is inherently very low risk.

Table 4-7. Uncertainty Sources in Flight Safety Analysis

Uncertainty Source	Parameters	Effect on E_C Uncertainty
Failure probability	Overall vehicle failure probability Allocation of P_{fail} versus time and vehicle response mode	Dominant for new vehicles, less so as vehicle matures Can have big effect on E_C; particularly allocation to malfunction turns
Breakup list	Number of fragments Allocation between inert and explosive fragments	Normally, biggest effect is allocation between inert and explosive fragments

Debris dispersion	Demise	Most important for reentry; neglecting this can overstate risk
	Winds	Can have large effects on individual receptors
	Ballistic coefficients	Typically, small. May be large for particular receptors
	Imparted velocity	Can be significant. Magnitude and direction important
	Vehicle performance	Usually small effect in downrange direction
	Vehicle guidance	If flying the “nominal trajectory”, this cross-range effect typically is small unless near particular population centers. May be very significant when flying a trajectory significantly different from nominal
	Malfunction maneuvers	Large effect on risk from both selection of malfunctions and models
	Mission rules	Variable, situation and rule specific
	Form of impact probability distribution	Can be large; effect on protected area boundaries not well understood
Vulnerability	Human vulnerability to inert debris	Age, posture, size, robustness can have significant impact; magnitude depends on mix at population centers
	Casualty areas from inert debris	Greatest uncertainties associated with fragments that can roll or bounce
	Human vulnerability to blast waves	Moderate uncertainty, may be high based on definition of injury associated with casualty
	Human (and structural) vulnerability to sheltered people from inert debris	Moderate effect when considered over large number of typical structures; significant when dominated by a few specialized structures
Exposure	Exposed population	Effect proportional to uncertainty in populations

With a sufficiently large number of flights, the flight history is deemed the best indicator of the vehicle reliability or, equivalently, the failure probability. The flight history may be used to estimate the statistical uncertainty in the failure probability estimate.

This assumes that the operator and manufacturer continue to implement a system safety program that ensures the long flight history is predictive of the future of the program. While it is not uncommon for an established program to pass from a company’s subject matter experts to less-experienced personnel, a well-designed, properly managed system safety program provides procedures and knowledge transfer that allows high reliability levels to be maintained. A high LOR in system safety will ensure that the dimensions of the uncertainty box may be assessed using the point estimate of the failure probability and a standard confidence interval calculator. Lower LORs will require increasing the uncertainty in the failure probability to account for possible degradation of processes and consequential degradation of vehicle reliability.

A new vehicle provides additional challenges. With a new launch vehicle, historical data supports the assertion that experienced developers may be expected to have lower expected P_{fail}

on the first two launches than new developers. Based on a limited data sample, experienced developers have an expected failure probability of approximately one-third of that of new developers. On an absolute basis there are significant uncertainties in these failure probabilities as a result of the relatively small sample sizes. The 90% confidence bounds for experienced developers are on the order of ±50%; the bounds for new developers span a range of approximately 30%.

It is generally believed that use of proven designs; high-reliability components that are tested at the component, subsystem, and system level; and avoided complexity lead to more-reliable vehicles. Paradoxically, one of the design approaches used to achieve reliability generates complexity by employing redundancy at the subsystem and system level to rule out the possibility of single-point failures causing a flight safety failure. Redundancy also provides reduced uncertainty in the achievable reliability. Other design-based approaches should also be considered for enhancing reliability and reducing the uncertainty in reliability characterization.

As mentioned earlier, system safety plays a key role in ensuring that design reliability is achieved operationally. The current state of the art is limited in quantifying that result. Research is currently in progress to develop methodologies to rate system safety programs. A possible by-product of this research is the ability to begin to quantify their impact on uncertainty in achievable reliability.

4.2.7.6 Partitioning Analyses

Once the minimum LOR is determined, it can be used for the entire analysis. If a high LOR is required, in some cases it might be advantageous to break the analysis into parts to determine whether for some portions of the analysis, a lower LOR would be sufficient. The analysis can be separated into sub-sections to make it easier to determine where to focus efforts of decreasing risk or risk uncertainty.

There are at least three methods to split up an analysis (any or all of these can be done):

a. separate by failure response mode (e.g., on-trajectory/near on-trajectory vs. guidance failure);
b. separate by flight phase (e.g., launch area vs. downrange/overflight);
c. separate by physical boundary imposed by FSS (e.g., inside flight safety boundaries vs. outside)

Risk is divided up amongst portions of the analysis. The acceptable risk level will be reduced for each portion; otherwise, it would be possible to split any analysis up enough times to end up with all portions below the initial acceptable risk level, but the total risk from all segments in excess of the allowable level. Though more sophisticated partitioning is possible, in general the risk level needs to be divided by the number of partitions. For example, if the analysis is broken into two response modes, the allowed risk limit for each portion is reduced by a factor of two.

4.2.7.7 Separate Analysis by Failure Response Mode

Depending on the type of failure, a vehicle can respond in different ways. For example, a failure that causes loss of thrust would probably lead to the vehicle falling in an unpowered ballistic trajectory, while a guidance failure could cause the vehicle to veer off in an unexpected direction under full power. A loss of control failure could cause the vehicle to change course and exceed structural limits.

Figure 4-9 shows how this can impact the required LOR. Assume the original analysis (green) has a high LOR. The loss-of-thrust case alone might have a similar failure probability, but a lower consequence of failure than the combined results (pink/dotted) lowers the required LOR. The guidance failures would have the maximum consequences but be significantly less likely (orange/dashed), again lowering the LOR.

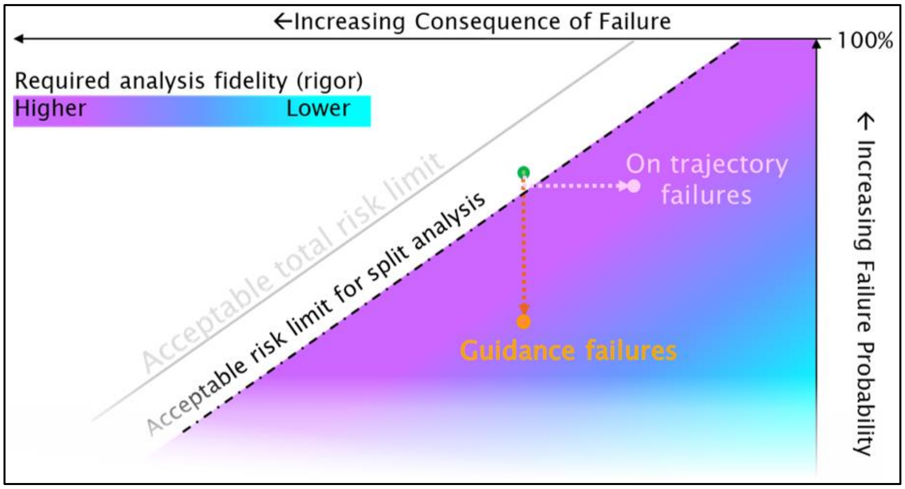

Figure 4-9. Effect of Splitting Analysis into Parts (Notional)

Some other examples: For a vehicle launched over the ocean, there might be very little expected population directly under the flight path, thus requiring only a low-fidelity analysis for on-trajectory failures. Conversely, if the probability of an on-trajectory failure is significant, but off-trajectory failures are rare, it might be the on-trajectory analysis that requires higher fidelity, while a lower-fidelity analysis will suffice for the off-trajectory failures.

4.2.7.8 Separate Analysis by Flight Phase

A vehicle might fly over areas of widely differing population density. During a phase where the population density is low (e.g., over an ocean) the lower population density will lower the consequence of a failure.

One phase of flight could have more flight experience than another part; for example, using a second-stage motor that has been extensively flown on top of a brand-new first-stage motor. In this case, the longer flight history can lower the estimate of failure probability, thus allowing a lower LOR for that portion of the flight.

Innovations mean that new vehicles could have flight phases that are currently unanticipated. For example, feathered flight, vertical rocket landing, etc., pose unique analysis challenges that had not been seen before. A given flight phase might require more or less analysis than average.

4.2.7.9 Separate Analysis by FSS Response

If a failure occurs, the FSS will be implemented to destroy the vehicle or prevent a hazard outside the operating area. In some cases, the area inside the operating area can be cleared or mostly cleared of people, thus bringing the possible consequences of a failure to very low levels.

However, if the FSS itself fails, the vehicle or its debris could potentially land outside the operating area, an area that is typically not cleared of people, since the vehicle is not expected to go there. If the area surrounding the operating area is, for example, densely populated, it could have a high potential consequence in the event of vehicle failure. In this scenario, it is important to know the probability of the FSS failing. The probability of the vehicle exiting the operating area depends on the overall P_{fail} for the vehicle combined with the probability that the FSS will also fail. To assess this, the reliability of the FSS should be evaluated.

Thus, inside the operating area, the P_{fail} is the vehicle's P_{fail}, which might be high, but the consequence will typically be low. In Figure 4-10, this would correspond to the pink/dotted analysis segment.

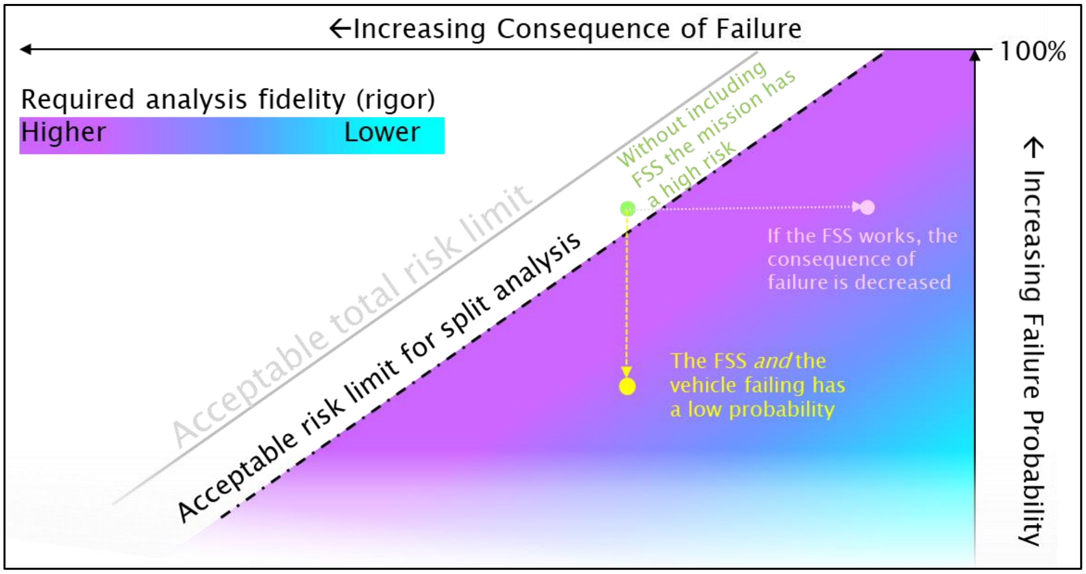

Figure 4-10. The Effects of Adding an FSS on Risk

Outside the operating area, the consequence might be much higher than inside, but the P_{fail} is now $P_{Fvehicle} \times P_{FFSS}$, which could be considerably lower if the FSS reliability is high. In Figure 4-10, this would correspond to the yellow/dashed portion of the analysis.

4.2.7.10 Iterative Re-evaluation of the Level of Rigor

After the LOR is initially determined, this LOR is applied to the FSA, system safety process, and FSSs as described in Section 4.2.8. The results of the subsequent analysis may be different than those initially used to estimate the LOR. These improved estimates of risk and consequence should be used to verify that the initial estimate of the LOR is still valid.

If the revised LOR is lower, this lower LOR can be applied to sections of the FSA, systems safety process, or FSSs that have not yet been performed/ implemented. If the revised LOR is higher than the initial estimate, the analysis must be adjusted accordingly. This can result in an iterative process until the results of the safety process at the required LOR confirm that the LOR is appropriate to the proposed flight operation.

4.2.8 Defining the Implications of Level of Rigor

4.2.8.1 Flight Safety Analysis

Four products derive from an FSA:

a. Aircraft hazard areas.
b. Ship and boat hazard areas.
c. Ground exclusions areas.
d. Casualty expectation assessment.

For the highest LOR (level 5), a high-fidelity FSA, including trajectory analysis, failure response analysis, breakup analysis, population/sheltering modeling, hazard propagation, and consequence modeling is necessary. Six-degree-of-freedom modeling should be used to model failure trajectories (at least to ensure that lower-fidelity models are adequate representations) and the FSS should be explicitly modeled in the failure response. A vehicle-specific breakup analysis should be performed for each breakup mode. This process provides explicit calculation of the risk to aircraft, ships, and people on the ground. The casualty expectation should be updated with the latest wind forecast and real-time population data for nearby facilities and spectators during the launch countdown (i.e., within 24 hours). Observation of ships and aircraft that are potentially hazarded should be performed in real time and launch commit based on computed risk.

Level 4 FSA uses the same models as Level 5, but in many cases, data can be substituted from prior work from similar vehicles rather than assessing for the specific vehicle or vehicle configuration. For example, six-degree-of-freedom failure trajectory simulations would not be necessary. If the failure modes are common and the validity has been established for similar previous vehicles, lower-fidelity simulations are acceptable. Debris lists would not have to be developed specifically for the vehicle but using a maximum-risk list from similar vehicles and FTSs would be acceptable. Risk-based approaches would be used to determine exclusion and keep-out areas. With using a more-restrictive risk level and the most vulnerable ships, issuing of notices would be sufficient to protect ships and aircraft. The outcome of the pre-mission launch risk analysis would guide the need for real-time population data, although large gatherings of spectators in the vicinity should always be considered.

Level 3 FSA, also described as medium-fidelity analysis, utilizes limited mission-specific data and some vehicle characterizations in conjunction with a baseline population model to provide a quick analysis with a minimal amount of data. Required data types are limited to the nominal trajectory and a breakup list for the vehicle in question or for a similar vehicle and a population library with a resolution proportional to the size of the debris dispersions.

Impact probability distributions are highly simplified. In the launch area each representative ballistic coefficient has an associated bivariate normal impact distribution with the same variance in each direction. In the downrange area the impact probability distribution is based on the corridor method[34] employing a normal cross-range impact probability distribution and a downrange distribution developed from the vehicle failure probability and the rate of

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[34] Jerry Haber. “Launch Operations Safety.” In *Safety Design for Space Operations*. San Diego: Elsevier, 2013. pp. 162-164.

advance of the fragment IIP rate. Sensitivity studies should be performed for credible ranges of parameters for the probability distributions; based on these the maximum risks or exclusion area should be selected.

The method includes the typical vehicle response modes (see Table 4-8). Impact probability distributions are simplified by only considering the dominant uncertainty sources.

Table 4-8. Vehicle Response Modes for Level 3 FSA
On-trajectory aerodynamic breakup
On-trajectory explosion
Incorrect azimuth
Loss of thrust
Turn failure

For level 2, the results of previous level 3 or higher analysis could be translated/rotated from previous similar vehicles/operations without the need for specific analysis. An example of this is the safety template approach commonly used for common range operations without major potential consequences. However, if no previous operations were similar, a higher LOR would be necessary to account for those, at least with the initial operations, until enough experience could be gained to make templates.

The low LOR corresponds to a very safe operation where there is minimal risk. This requires high reliability and very small casualty area together with isolation of the hazard from any people. It is difficult to see how such a small casualty area is possible with a launch or reentry, though other types of operations may qualify.

It is expected that this LOR means that the hazard is contained to an isolated area. This minimum LOR would likely only be acceptable if it is possible to clear the entire operating area, and, if there is an FSS, that the FSS is extremely reliable—and likely with sufficiently low consequences even if it fails.

Thus, the first three objectives can be obtained by clearing the entire operating area of people on the ground, of ships and boats, and of aircraft for the duration of the mission until all potential hazards are known to be contained. This would require identification of whether there are toxic, fire, or debris/blast hazards and a strategy for identification of when each hazard no longer exists (e.g., all debris has impacted, or fire has been contained).

4.3 Catastrophic Risk Evaluation

NOTE

This standard recommends catastrophic risk aversion[35] to protect against incidents involving multiple casualties or multiple fatalities, for example loss of a bus, ship, or aircraft. Catastrophic risk assessments are especially useful for pre-flight analyses intended to evaluate and mitigate potentially catastrophic outcomes. There

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[35] In academic literature (see for example, Vrijling, J. and Van Gelder, P. "Societal Risk and the Concept of Risk Aversion" in *Advances in Safety and Reliability*, Vol. 1. Oxford: Elsevier, 1997, pp.45-52), the term *risk averse* is almost equivalent to the term *catastrophe averse*. In both cases resistance to accepting multiple casualties grows non-linearly with the number of potential casualties. The difference between the two is that risk averse is for all N for N≥2 and catastrophe averse is for all N above a higher starting number such as 5 or 10. Catastrophe averse is a subset of risk averse. The background for the selected criteria is provided in Section 5.5.

	are several approaches to characterize the potential for catastrophic risk when identifying the need for mitigations. The flight safety community has employed a conservative screening formula for managing catastrophic risks from transportation systems. It is rarely applicable to land-based fixed population centers. When the potential catastrophe is expected to involve serious injuries and no fatalities, the criterion to be applied is the tolerable mission E_C for casualties. When two or more fatalities is a potential outcome, screening should be performed using both the tolerable mission E_C and the tolerable mission E_F as the criteria. If these screening tests cannot be satisfied, the alternatives are to mitigate the risk or to perform additional analyses in compliance with FAA regulations on high-consequence event protection or assessing the catastrophic risk using risk profiles. Another alternative for managing the potential for catastrophic risk is a practice employed by the ground safety community. That community has identified the decision maker frequently wants to be briefed on the worst possible consequences. This corresponds to maximum conditional risk from any single possible failure.

Formula 4-6 has been used for transportation systems and provides a reasonable triage method to assess Catastrophic risk limits for the GP.

$$P[\geq N] \times N^{1.5} \leq \text{Criterion} \qquad (4\text{-}6)$$

where

P[≥N]	is the cumulative probability of all events capable of causing *N* or more casualties or N or more fatalities with the respectively appropriate criteria.
N	is number of casualties[36] based on the occupant load.
Criterion	is the maximum allowable collective risk for the event with various scenarios as feasible outcomes as defined in Subsection 3.2.1b of the standard.

If the 4-6 formula test fails then additional analysis is needed such as demonstrating compliance with FAA regulations on high consequence event protection given in 14 CFR 450.101(c) or calculating a risk profile for the populations of concern.

Consider again the hypothetical example presented in Subsection 4.1.2.2. Figure 4-11 compares the risk profile computed for this example and the catastrophic risk criteria established in the standard for the GP. The fact that the example launch risk profile has points above the acceptable risk profile (the straight line) indicates that this example launch presents an excessive catastrophic risk.

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[36] OSHA promulgated a formal definition of catastrophe in 29 CFR 1960.2: “An accident resulting in five or more agency and/or non-agency people being hospitalized for inpatient care.” Santa Barbara County, CA uses a minimum number of 10 people to define a catastrophe.

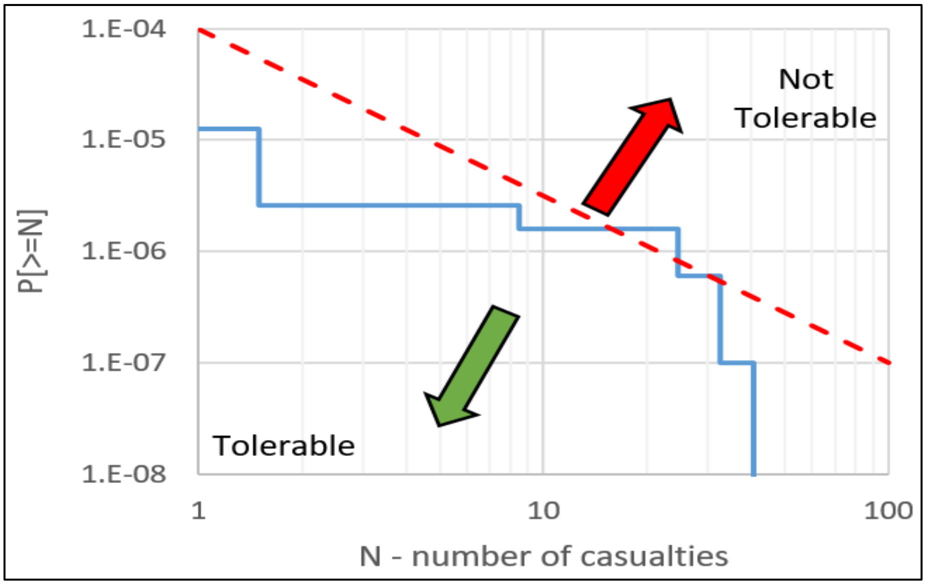

Figure 4-11. Example Risk Profile Compared with the General Public Catastrophic Risk Criteria

Due to the limited number of scenarios that can produce casualties in this example, computation of the risk profile is straightforward; however, computing the risk profile for actual flights often requires a considerable effort. Therefore, the RC devised a simplified and conservative method to screen for excessive catastrophic risk for **transportation systems** only, which are typically the only significant sources of potentially excessive catastrophic risks. This simplified method entails replacing the number of casualties contributed by the occupant load of each transportation system from each failure scenario, *N*, everywhere in an otherwise standard E_C computation with $N^{1.5}$. Specifically, the catastrophic risk averse pseudo-E_C for transportation systems may be computed using a standard E_C computation but replacing the number of casualties contributed by each transportation system from each failure scenario, *N*, which equals the occupancy load for a transportation system as given in Table 4-9, with $N^{1.5}$. A similar computation should be performed for potential fatalities when this is a credible outcome, such as downing an airplane. For fatalities, the criterion is the tolerable mission E_F.

Table 4-9. Definitions Used to Define Tolerable Catastrophic Risks

Population Type	Catastrophic Outcome	Casualty/Fatality Potential (*N*)
Public Aircraft	An occurrence resulting in multiple fatalities[37], usually with the loss of the airplane[38]	Maximum occupancy

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[37] The FAA also has a formal definition for "severe consequence:" forced landing (which is also formally defined), loss of aircraft while occupants are on board, serious injuries (as formally defined), or fatalities.

[38] FAA. "Subject: Continued Airworthiness Assessments of Powerplant and Auxiliary Power Unit Installations of Transport Category Airplanes." AC 39-8. 8 September 2003. Retrieved 17 October 2023. Available at http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC39-8.pdf.

Mission-Essential Aircraft	An occurrence resulting in multiple fatalities, usually with the loss of the airplane	Expected occupancy
Public Ship	An occurrence resulting in multiple casualties, usually with loss of the ship	Maximum occupancy
Mission-Essential Ship	An occurrence resulting in multiple casualties, usually with loss of the ship	Expected occupancy
Public Land Vehicle	An occurrence resulting in multiple casualties, usually with loss of the vehicle	Maximum occupancy
Mission-Essential Land Vehicle	An occurrence resulting in multiple casualties, usually with loss of the vehicle	Expected occupancy
Public Train	An occurrence resulting in multiple casualties, usually with loss of the train	Maximum occupancy
Mission-Essential Train	An occurrence resulting in multiple casualties, usually with loss of the train	Expected occupancy
Public Gatherings[39]	An occurrence resulting in multiple casualties or fatalities.	credible occupancy within the maximum effective casualty/fatality area for any fragment
Mission-Essential Personnel Gathering	An occurrence resulting in multiple casualties or fatalities	Expected occupancy within the maximum effective casualty/fatality area for any fragment

If the resulting catastrophic risk averse pseudo-E_C is less than 1E−4 for the GP, then the catastrophic risk is generally acceptable.[40] If the catastrophic risk averse pseudo-E_C is greater than 1E−4 for the GP, then a risk profile should be computed to determine if the catastrophic risk complies with the standard criteria. Similarly, for fatality-producing events, the catastrophic risk averse pseudo-E_F must be less than 30E−6, to pass the screening test for catastrophic risk. Otherwise, a risk profile should be computed to determine if the catastrophic risk complies with the standard criteria.

In general, a risk profile can be computed based on a complete set of credible and mutually exclusive scenarios, where each scenario has a finite probability and a consequence in terms of casualties. A formal definition of "scenario" is provided in Chapter 7. Based on a complete set of scenarios, a histogram can be generated where the abscissa is the number of casualties/fatalities (N) and the ordinate is the probability of N casualties/fatalities. The risk profile is a complementary cumulative probability distribution diagram that can be computed based on this histogram, which gives the total probability of at least N casualties/fatalities for each value of N. The ordinate of the resulting risk profile is the probability of N or more casualties/fatalities.

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[39] Public gathering places subject to catastrophic accidents include any locations where population concentrations may occur, such as schools, hospitals, stadiums, beaches, etc.

[40] There are exceptions, involving cases where a scenario threatens multiple transportation systems (such as two aircraft), where the pseudo-E_C is not a conservative indicator of the catastrophe potential.

Even without computation of a complete risk profile, the catastrophe aversion criteria may be used to identify individual scenarios or failure modes that present elevated catastrophe potential and practical mitigations. For example, the analyst could show that a malfunction turn during a particular period of flight combined with the absence of an FTS on a vehicle, or the presence of a large concentration of spectators in a particular location, corresponds to a point above the solid line shown in Figure 4-2. Any single scenario that corresponds to a point above the solid line shown in Figure 4-2 conclusively demonstrates that the launch exceeds the recommended catastrophe aversion criteria.

4.3.1 Catastrophic Risk – Risk Table Example

In 2022 the commander of Camp Bull Simons identified the need for a child development center on base. The Army's Camp Bull Simons Special Operations Cantonment Area is located on the Eglin Airforce Base. The Air Force conducted a safety assessment[41] of that child development center given past and planned events to identify the risks that Eglin operations would pose. In that study the Air Force extrapolated the formulas presented in this section and integrated them with the criteria from Table 3-3 in the standard. A modified version of that information is provided in Table 4-10.

Table 4-10. Eglin AFB Proposed Casualty Criteria with Catastrophic Risk Triage Equations

		General Public	**ME and NOP**
Per Mission	**Undesired Event**	**Thresholds**	**Thresholds**
	Individual Probability of Casualty	1E−6[b]	10E−6
	Expected Casualties	100E−6 [b]	300E−6
	Catastrophic Risk Casualty Triage Formula	P[N] <=100E^{-6}/N^1.5[c]	P[N] <=300E^{-6}/N^1.5[c]
Annual	Expected Casualties	3000E−6 [a]	30000E−6 [a]
	Catastrophic Risk Casualty Triage Formula	P[N] <=3000E^{-6}/N^1.5[c]	P[N] <=30000E^{-6}/N^1.5[c]

[a] Advisory Requirements.

[b] If a flight operation creates a toxic risk, then the range must separately ensure the allowable level of risk enforced by them does not exceed other standards for toxic exposure limits for the GP when appropriate mitigations are in place. Chapter 8 provides an approach for implementing this requirement.

[c] These equations do not constitute an absolute criterion but serve as an initial indications of whether additional effort is needed. If these screening tests cannot be satisfied, the alternatives are to mitigate the risk or to perform additional analyses in compliance with FAA regulations on high-consequence event protection or assessing the catastrophic risk using risk profiles.

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[41] Col Vincent Chioma, Chief of Safety. "Risk of Catastrophic Casualty Event on Eglin Land Range – CDC Inherent Risk Analysis." Version 2022-11-24b. Retrieved 16 October 2023. Available to RCC members with private page access at https://www.trmc.osd.mil/wiki/x/b4hyBQ.

The decision was made not to add this to the standard for two reasons. First, this table incorporates formulas instead of discrete criteria. Second, the formulas do not constitute an absolute criteria but rather a triage approach used to determine if a more in-depth study is required.

4.3.2 Catastrophic Risk: Kennedy Space Center Approach

NASA's Kennedy Space Center uses an alternative approach for annual catastrophic risks, which is described in Equation (4-7).

$$\begin{gathered} individual\ event: P[\geq N] \ \leq \ \frac{3 \times 10^{-4}}{N^{1.5}} \\ \text{annual risk: } \mathrm{A}R[\geq N] \ \leq \ 1 - (1 - P[\geq N])\hat{}\left(t \cdot \frac{3\times10^{-4}}{N^{1.5}}\right) \end{gathered} \tag{4-7}$$

where t is the time in number of operations (e.g., t = (ops per day)x(# of days)).

If the goal were to turn this into a variable failure rate, then it would need to be treated with conditional probability.

4.4 Aircraft Protection

This section provides guidelines for proper implementation of the requirements regarding aircraft hazard regions:

a. for planned debris releases;

b. in response to a mishap;

c. based on probability of impact limits; and

d. that demonstrate compliance with the individual, collective, and catastrophic risk limits.

4.4.1 Planned Debris Impacts

This subsection provides guidance to facilitate proper implementation of the requirement given in Subsection 3.3.3 of the standard, which reads as follows.

> The range must confirm that appropriate SUAs are reserved or Noticed to Airmen are issued that encompass the volume and duration necessary to protect aircraft from debris capable of causing an aircraft accident due to all planned events.

Planned debris releases include any solid object planned to fall uncontrolled through the navigable airspace as the result of a range activity, such as intercept debris, jettisoned stages, nozzle covers, fairings, and inter-stage hardware. To satisfy the requirement in Subsection 3.3.3 of the standard, a range must confirm that NOTAMs are issued for each area hazarded by a planned debris release capable of causing an aircraft accident. To determine if a planned debris release is capable of causing an aircraft accident, a range should:

a. use the aircraft vulnerability models (AVMs) for commercial aircraft or hazard threshold for other aircraft presented in Chapter 6; or

b. Use other valid[42] methods to evaluate debris impacts capable of causing an aircraft accident as defined in 49 CFR 830.2.[43]

To determine the volume and duration necessary to protect from each planned debris release a range should define a finite region(s) and demonstrate compliance with subsections 3.3.1a of the standard for non-mission aircraft and 3.3.2a for mission aircraft. If the area is under active surveillance and air traffic control, and if probability of impact levels do not exceed the limitations set in the standard, then the planned impact hazard volume and duration should encompass the two-sigma impact dispersion area[44] from the ground level up to an altitude of 60,000 feet.[45]

If the area is not under active surveillance and air traffic control, and there is no region that exceeds the probability of impact levels specified in subsections 3.3.1a for non-mission aircraft and 3.3.2a for mission aircraft, then the planned impact hazard volume and duration should encompass the three-sigma impact dispersion area[46] from the ground level up to an altitude of 60,000 feet.

4.4.2 Mishap Response Hazard Areas for Aircraft

This section provides guidance to facilitate proper implementation of the standard requirements given in Subsection 3.3.4 of the standard, which states:

> The range must coordinate with the FAA to ensure timely notification of any expected air traffic hazard associated with range activities. In the event of a mishap, the range must immediately inform the FAA of the volume and duration of airspace where an aircraft hazard is predicted.

4.4.2.1 Pre-flight Analyses, Timely Notification, and FAA Coordination

Pre-flight analyses and coordination with the FAA should be performed "to ensure timely notification of any expected air traffic hazard associated with range activities." To demonstrate compliance with this requirement, a range should (at a minimum):

a. Identify the volume and duration of airspace necessary to protect from each planned debris release capable of causing an aircraft accident as described in Subsection 4.4.1.

b. Identify all regions of airspace where debris that poses an aircraft hazard could be predicted in the event of a mishap.[47]

c. Develop and implement a standard procedure, in coordination with the FAA, to ensure timely notification of any air traffic hazards that could occur from range activities.

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[42] i.e., methods that comply with the guidelines specified in this supplement, which may include aircraft specific models that account for the known trajectories of aircraft.

[43] Definitions. 49 CFR § 830.2.

[44] i.e., 95 percent confidence of containment of the planned debris impacts capable of causing an aircraft accident.

[45] 60,000 feet, used here, is typically the maximum altitude under active control by the FAA.

[46] i.e., 99.7 percent confidence of containment of the planned debris impacts capable of causing an aircraft accident.

[47] Debris that poses an aircraft hazard should be defined by the range in coordination with the FAA depending on the type of aircraft in the vicinity, the debris characteristics, etc. The intention here is to provide more protection than the "debris capable of causing an accident" as a means of compensating for the larger uncertainties inherent in an unplanned event. Adding a substantial buffer to any calculated hazard area is recommended.

Example: Current practice at the Eastern Range (ER) provides an example of how a range can "coordinate with the FAA to ensure timely notification of any expected air traffic hazard associated with range activities." The ER protects non-essential and mission-essential aircraft from the hazards associated with ELV debris using a combination of exclusionary and risk analysis methods. To protect aircraft from potential launch vehicle hazards, Space Launch Delta (SLD) 45 develops three types of hazard areas for aircraft.

For the launch area, SLD 45 defines two types of airspace. First, the range operates multiple FAA-assigned special use airspaces (SUAs). The range has been assigned SUAs in the form of three restricted areas and two warning areas. When the range requests through SLD 45 that these areas be considered "hot," control of the airspace is transferred to the range and a NOTAM is published to that effect. The range does not necessarily hold a launch if an aircraft is within an SUA because the SUAs encompass more airspace than is needed to protect aircraft from the potential effects of a launch vehicle.

Within the SUAs, the range calculates the potential three-sigma dispersion (based on a conservative estimate of potential wind effects) from a launch vehicle destructing on the nominal trajectory for every point in time where the vehicle's dispersion is wholly or partially contained within the vicinity of the launch site. The potential three-sigma dispersion is based on explosive forces acting only perpendicularly to the nominal trajectory, three-sigma monthly winds acting only perpendicularly to the nominal trajectory, and vehicle debris divided into nine classes with the smallest element considered having a ballistic coefficient of three. This calculated dispersion footprint at sea level is extended to infinity and is defined as the aircraft corridor. Due to logistical limitations for surveillance, the aircraft corridor extends downrange to the outer limit of the "hot" SUAs. A launch will be held if an aircraft either is observed or is calculated to be in the aircraft corridor at the time of launch. Therefore, the aircraft corridor is an absolute exclusion area for non-mission-essential aircraft.

The vicinity of the ER launch site depends on vehicle performance and the limitations of the range's surveillance assets. The vicinity of the ER launch site bounds the first group of scheduled impacting vehicle components if they impact within the range surveillance assets' effective range of between 70 and 100 nm from the launch point. While the entire vicinity of the ER launch site does not have to be evacuated of aircraft, the entire vicinity of the ER launch site is under surveillance up through the launch.

Although there is no formal definition, impact locations more than 100 nm downrange have been treated as downrange impact locations. For downrange impact locations where components or debris from a staging action impact the earth, SLD 45 issues a NOTAM for each impact location in accordance with International Civil Aviation Organization procedures. The NOTAM area is requested to enclose both the three-sigma dispersion of the impacting components and a five-nm buffer added to the three-sigma dispersion envelope in the downrange, up-range, and cross-range directions. The range does not typically survey downrange impact locations unless mission-related resources are available for other reasons.

The mission-essential airborne assets that survey the launch area are protected to the one-in-one-million probability of impact level. 45 SLD calculates the probability of impact for mission-essential aircraft with a reasonable level of confidence because the vulnerability area and the asset locations are known. While every effort is made to station a support aircraft outside the mission's ILLs, if the aircraft must be within the ILLs, a worst-case scenario is analyzed to assess the asset's safety. As a worst case, the analysis assumes the rocket travels directly at the aircraft's support location. An aircraft's support location within the ILLs may be acceptable if the aircraft is capable of reaching safety under such a worst-case scenario.

In other situations, it may be appropriate to account for the density of air traffic and demonstrate compliance with the long-term acceptable risk guidelines. For example, in areas where only a malfunction can threaten aircraft, a reasonable level of aircraft safety might be provided using statistical air traffic density data and compliance with the long-term acceptable risk guidelines described in this subsection.

4.4.2.2 Defining Mishap Hazard Areas

Subsection 3.3.4 of the standard states that, "in the event of a mishap, the range must immediately inform the FAA of the volume and duration of airspace where an aircraft hazard is predicted." In the event of a space launch malfunction, there may be enough time to activate a real-time system that would effectively mitigate the risk to aircraft by redirecting aircraft near the expected space vehicle debris hazard area before debris reaches aircraft altitudes.[48] In all cases, a range should implement the fastest available method to inform the FAA of air traffic hazards in the event of a range mishap. The RCC is aware of several acceptable methods to demonstrate overall compliance with this requirement as described below.

A range should select the most appropriate method to define the volume and duration of airspace where an aircraft hazard is predicted based on the specific situation and the discretion of the range commander. In all cases, a range commander should implement all measures necessary to protect aircraft from unreasonable risks generated by a range mishap. This subsection provides guidelines to help a range define:

a. where an aircraft hazard is predicted in the event of a mishap;
b. reasonable risks generated by a range mishap.

An approach to comply with Subsection 3.3.4 of the standard is to implement aircraft hazard volumes based on pre-flight analyses. For example, a range may:

a. compute three-sigma impact dispersion areas on the ground that provide 99.7% confidence of containment of the debris impacts that could be hazardous to aircraft for predefined failure times or state vectors;
b. compute the maximum time for any debris that could be hazardous to aircraft to reach the ground for the same predefined failure times or state vectors;
c. define an aircraft hazard volume to encompass the three-sigma impact dispersion area for each predefined failure time or state vector, inclusive of the airspace from ground level to an altitude of 60,000 ft;
d. inform the FAA of the appropriate aircraft hazard volume and duration based on the mishap failure time or the best estimated state vector for the mishap.

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[48] Larson, E., P. Wilde, and A. Linn. "Determination of Risk to Aircraft from Space Vehicle Debris." In *Proceedings of the First IAASS Conference*. Noordwijk: European Space Agency, 2005.

Another approach to comply with Subsection 3.3.4 of the standard is to implement aircraft hazard volumes that encompass all regions of airspace where aircraft would be exposed to debris capable of causing an aircraft accident with a probability of impact exceeding 1E−7 for a single aircraft. This probability of impact calculation should account for the fact that the mishap has occurred and assume that aircraft are present at the hazard volume boundary. Protection against potential catastrophes based on the provisional criteria should also be provided in the event of a mishap.

4.4.3 Hazard Areas for Aircraft Using Probability of Impact Limits

Three risk metrics have been defined to protect occupants of aircraft: individual risk; collective risk; and catastrophic risk. Meeting the acceptability criteria requires a combination of hazard containment and evaluation of residual risk. The approach outlined in this subsection is to first develop exclusion criteria (hazard areas) to protect against catastrophic risks and assure that individual risks are acceptable. The second part of the approach is to assess the residual total collective risks to all people (unsheltered, land-based sheltered, and people in ships and aircraft) to assure compliance with the collective risk standard.

The standard provides requirements to define aircraft hazard areas. For example, Subsection 3.3.1a of the standard requires that “All non-mission aircraft will be restricted from hazard volumes of airspace where the cumulative probability of debris impact capable of causing a casualty on an aircraft exceeds 1E−6. The restriction limit increases to 0.1E−6 (1E−7) for the cumulative probability of debris impact capable of causing a fatality.” The aircraft hazard area requirements in the standard can be satisfied using the vulnerability thresholds given in Chapter 6. Specifically, Section 6.4 defines vulnerability models for several types of aircraft and a hazard threshold for other aircraft for debris potentially injurious to personnel and catastrophe-producing debris. For example, the probability of impact requirement given in Subsection 3.3.1a of the standard should be satisfied based on the size of the largest aircraft potentially exposed and the probability of impact computed for all debris capable of producing a casualty to a person in an aircraft. In all cases, the final hazard areas should be the union of the areas required to comply with the individual, collective, and catastrophic risk criteria.

As shown in Figure 4-12, a practical implementation of defining the hazard areas involves the following steps:

a. determining the debris that has the potential for producing serious injuries to occupants of an aircraft;

b. determining impact probability contours at the allowable individual casualty risk;

c. determining the debris that has the potential for producing a catastrophic accident;

d. determining impact probability contours at the allowable catastrophic risk probability;

e. computing a preliminary hazard area as the envelope of the contours developed in step b and step d.

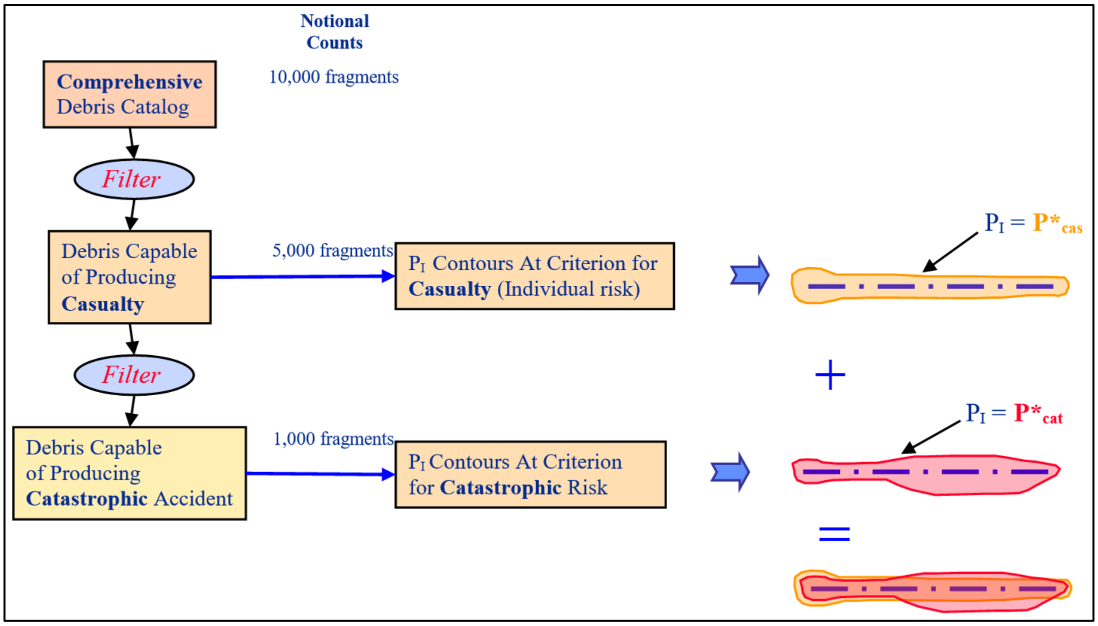

Figure 4-12. Process for Developing Hazard Areas

The preliminary hazard area should then be evaluated to assess the feasibility of controlling access to the area as well as the feasibility and need to monitor traffic in the area. This latter evaluation will consider factors such as traffic density and distance of the preliminary hazard area to land. Surveillance regions are typically functions of need (traffic density in a hazard region) and technical feasibility of monitoring. Thus, surveillance may be limited to the vicinity of the launch site and selected downrange regions where assets are already deployed. Based on these feasibility evaluations, the hazard area boundaries may be adjusted to produce a final hazard area. These results also become part of the basis for day-of-launch preparations and launch-commit decisions. Typically, the FAA adds a buffer to the hazard area(s) to develop NOTAMs. These formal notices should be disseminated through the appropriate government channels to all potentially affected parties.

4.4.4 Compliance with Individual, Collective, and Catastrophic Risk Limits

Proper implementation of the probability of impact limits for aircraft hazard areas and use of the vulnerability thresholds and models in Section 6.4 can be used to demonstrate compliance with the individual and catastrophic risk criteria established in Figure 3-1 of the standard. Subsection 3.3.1a of the standard requires that non-mission aircraft be “restricted[49] from hazard volumes of airspace where the cumulative probability of debris impact capable of causing a casualty on an aircraft exceeds 1E−6.” Section 6.4 defines AVMs for two levels of adverse consequences (i.e., fragment characteristics): casualty producing and catastrophic.

Compliance with this probability of impact requirement, based on all potential casualty- and catastrophe-producing debris, demonstrates compliance with the individual risk limits established in Subsection 3.2.1a of the standard. In other words, the P_C is below 1E−6 for a single mission and below 1E−7 P_F if fatality risks are computed, regardless of the number of

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[49] In this context restricted from means that the range will: (1) ensure that appropriate warnings/restrictions are issued through the FAA; and (2) not proceed with the hazardous activity if the range has knowledge that any aircraft hazard volume is violated.

people in potentially threatened aircraft. Consider a commercial aircraft with a maximum occupancy of 400 people. To comply with the catastrophic risk criteria given in Subsection 3.8.3 of the standard, hazard areas should be designed to limit the probability of impact with potentially casualty-producing debris to 1E−7 and limit the probability of impact with potentially catastrophic debris to 1E−8. In such a case, the catastrophic risk-averse pseudo-E_C defined in Section 4.3 equals 8E−5, which is below 1E−4, and thus complies with the catastrophic risk criteria.

To demonstrate compliance with the collective risk criteria established in Subsection 3.2.1b of the standard, the analysis must account for the collective risk to people in each type of vehicle. This requires estimates of the number of vehicles exposed, probabilities of impact to exposed vehicles, and the potential consequences of an impact to exposed vehicles. For planned impact areas, the analysis should assume at least one vehicle is present continuously at the boundary of each hazard area. If the available traffic data indicates that more than one aircraft may reasonably be expected to typically occupy a hazard area (i.e., empirical traffic data indicates more than a 10% chance that more than one vehicle would normally transit through the hazard area throughout the time period when the mission could pose a threat), then the analysis should assume that the maximum number of vehicles reasonably expected to typically occupy a hazard area are continuously at the boundary of each hazard area. Based on these exposure levels, conservative estimates of the collective risks for people in vehicles can be made using the probability of impact levels at the boundary of each hazard area. The total collective risk estimate should assume that each casualty-producing debris impact produces one casualty, and each catastrophic impact produces a number of casualties equal to the maximum occupancy of the vehicle not associated with the mission, and equal to the actual occupancy of any vehicle related to the mission. In areas where only a malfunction can threaten aircraft, a reasonable collective risk estimate can be based on statistical traffic density data.

4.5 Ship Protection

This section provides guidelines for proper implementation of the requirements regarding ship protection (Section 3.4 of the standard), including both planned debris impacts and debris resulting from unplanned events. Ship protection includes both issuing warnings and assessing residual risk. Most of this section focuses on protecting the GP (non-MEP), but the application to MEP is straightforward. There are two main differences: 1) the values of acceptable risk limits are different; and 2) the location, vessel size and type, and crew size are often known better for mission-related ships.

Modeling of risk to ships is complicated because there are several significantly different hazard mechanisms, each with very different vulnerable areas. The first mechanism, a direct hit to a person (or even penetration through a roof followed by direct hit). has a relatively small casualty area. The second, impact of a sufficiently large fragment causing extensive damage to and potential loss of the ship, may cause casualties to most or all persons on-board, depending on emergency response. This one is particularly challenging to model because size of the debris capable of causing such an accident is inversely correlated with the size of the ship (smaller ships are harder to hit but more easily damaged), and there is also the special case here of an inert fragment igniting on-board fuels. The third mechanism is a nearby explosion, the consequences of which depend on the yield, water depth, and ship size. Personnel risk estimates should account for the potential for injury from all three mechanisms using the vulnerability information provided in this supplement. A fourth mechanism is the release of toxic gases from an impacting fragment. Because this fourth type of hazard is very rare, this supplement does not currently provide a means to account for it.

The event tree shown in Figure 4-13 provides a summary of the hazards to a vessel.

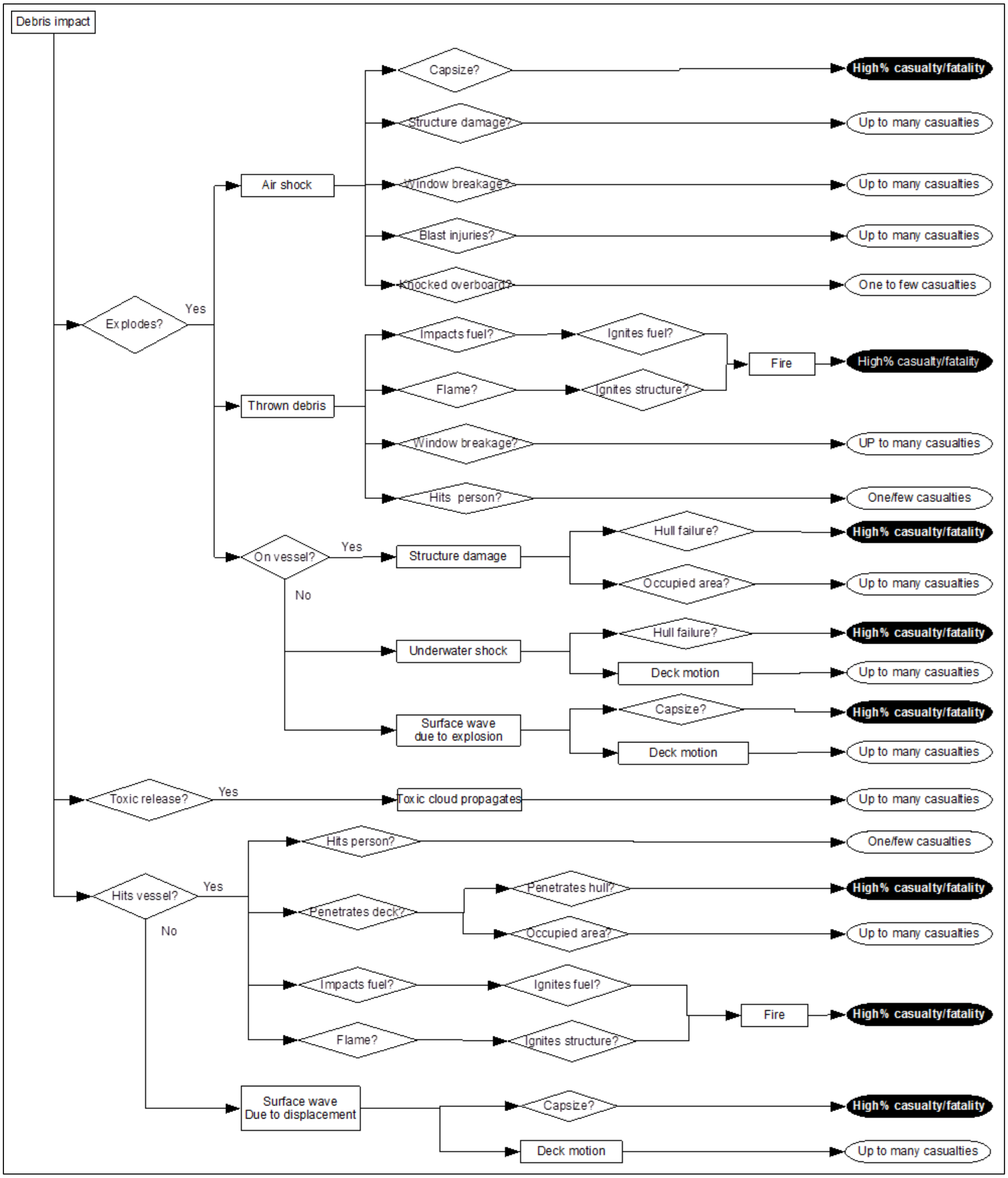

Figure 4-13. Debris Impact Fault Tree for Ships

The severity of effects of debris upon ships is provided by the vulnerability models and thresholds given in Chapter 6. Specifically, Section 6.5 defines ship vulnerability models for debris potentially hazardous to personnel. The standard defines three risk metrics to protect people in general, including occupants of ships: individual, collective, and catastrophic risk. Meeting the acceptability criteria for these three risk metrics typically involves a combination of hazard containment, reducing exposure, and evaluation of residual risk. For missions with small potential hazards, simple, conservative approaches are sufficient to ensure that risk criteria are met; however, for missions with a larger potential hazard, a higher-fidelity approach may be necessary for risk management and mitigation. This discussion provides a general approach for both cases, and (conservative) simplifying assumptions can be used when the hazard is small.

The approach outlined in this section is to **first** develop warning areas to mitigate the risk. These warning areas are designed to meet ship protection criteria provided in the standard using the three primary risk metrics identified above. Experience indicates that warnings may not be completely effective (especially outside of the launch area). The ineffectiveness of warnings is assumed to be due to two causes: the communication system for warnings has limited reliability; and ships (especially smaller vessels, such as fishing boats) have little regard for the warnings even if they received them.

Thus, the **second** part of the approach is to assess the residual risk based on actual ship traffic during the mission in regions where ship surveillance is warranted. In this second phase, techniques are used to locate ships and residual risk is computed for the ships that are observed. This section provides discussion of suitable approaches for determining the regions where observation should occur, as well as the various types of observation methods. The region where observation is performed is determine both by the probability of the hazard and by the likelihood of ships being present. Other mission requirements may necessitate observation areas larger than those needed to protect the public.

For mission-essential ships, this process is simplified because the location, type/size, and crew size of the ships are generally known. The warning areas developed above can be used to help determine allowable positions for these ships during the mission. Since their location is known, the risk to each mission-essential ship can be computed and compared to the risk criteria in the standard.

4.5.1 Computation of Risk Measures

The standard specifies three measures of risks to be evaluated to protect ships: 1) the individual probability of a casualty to a person on-board a vessel; 2) the contribution to collective risk; and 3) the probability of a catastrophe. All three of these risks are generally a function of location (e.g., latitude/longitude) based on the impact density distribution of debris.

Determining the probability of a casualty to a person on-board a vessel is challenging because of the many different mechanisms, as discussed above. For this discussion, it will be assumed that these complexities are accounted for in the effective casualty and catastrophe areas[50] for each fragment impact.

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[50] An effective casualty area is the two-dimensional integration of the probability of casualty, e.g. $A_{Casualty} = \iint P_{Casualty}(\mathbf{r})dA$, over all space, where $P_{Casualty}(\mathbf{r})$) is the probability of casualty to a person at some location **r.** The integration is limited to the region around the fragment impact, because $P_{Casualty}(\mathbf{r})$ goes to zero as the distance from the impact location increases.

Given these areas (see Chapter 6), then the risk measures can be computed with Equation (4-8).

$$P_{consequence}(\mathbf{r}) = \sum_{events} P_{Event}\left\{1 - \prod_{fragments}\left[1 - \rho_{FragImpact}(\mathbf{r})\, A_{consequence,frag}\right]\right\} \tag{4-8}$$

Where:

$P_{consequence}(\mathbf{r})$ is the probability of a particular consequence (casualty, catastrophe) at a particular ship location **r**.

P_{Event} is the probability of particular debris-generating event (e.g., a simulation of a breakup)

$\rho_{FragImpact}(\mathbf{r})$ is the probability density of a particular fragment from an event at location **r**

$A_{consequence,frag}$ is the effective consequence area for the particular fragment

The use of effective consequence areas to compute risk measures assumes that the impact probability density of the fragment impact is roughly uniform in the vicinity of the ship.

The collective risk (expectation of casualty, or E_C) can be computed as:

$$E_{Casualty}(\mathbf{r}) = N_{Shelt}(\mathbf{r})P_{CasShelt}(\mathbf{r}) + N_{Unshelt}(\mathbf{r})\, P_{CasUnshelt}(\mathbf{r}) \tag{4-9}$$

Where:

N_{Shelt} is the number of people on-board the ship who are inside

$N_{Unshelt}$ is the number of people on-board the ship who are on the deck

$P_{CasShelt}(\mathbf{r})$ and $P_{CasUnshelt}(\mathbf{r})$ are the P_C to a sheltered person and unsheltered person, respectively, computed with the equation above using the appropriate effective areas.

A complexity in computing hazards for a general region of the ocean is that it is necessary to compute these probabilities for different types of ships. In many cases, the relevant parameters of ships are known only generally (e.g., construction type and number of people on-board). Due to the inverse relationship between the ship area and the probability of penetration (smaller vessels are more vulnerable, but less likely to be impacted), it is often not known which ship type will have the highest risk for a particular mission. Likewise, the ship size has a strong effect on the effective casualty area. In addition, when computing collective values, small ships are most common in near-shore regions, but may have the smallest individual probabilities. Therefore, the appropriate solution is to compute these values for different ship categories using conservative choices within each category (e.g., the largest area and largest probability). Then maximum individual risk probabilities can be determined across all ship categories at a location by taking the maximum value. Though accounting for different ship types adds a small amount of complexity to the calculation, typically only a limited number of ship types (5-10) are used for these calculations, and the application of the above equations to the various ship types is straightforward and not onerous. Example calculations are shown in Subsection 4.5.4.

4.5.2 Warning and Observation Areas for Ships

A warning area is the region over which mitigation of risk to ships is performed by reducing the exposure. A warning area should encompass at least the region over which *any single ship* (except unusual vessels, see below) exceeds the individual, catastrophic, or collective risk criteria. In most cases it is helpful to expand the warning area beyond this minimum in order to reduce the likelihood of exceeding risk criteria on launch day. Warning areas are generated for non-mission-essential ships, but can be used as a first approximation when determining where to locate mission-essential ships as well.

The warning areas become part of the basis for day-of-launch preparations and launch-commit decisions. Typically, when developing Notices to Mariners (NOTMARs), a buffer is added to the initial hazard areas and the complex polygons (e.g., contours) resulting from computations are simplified to shapes with fewer vertices. These formal notices should be disseminated through the appropriate government channels to all potentially affected parties. On mission day, traffic in the observation area(s) is inventoried. In many cases, the warning area is equivalent to the observation area, but this is not necessarily the case. The relationship between the observation area and the warning area will be discussed in more detail below. Observation can be performed through a variety of methods, as required to mitigate risk, which are further discussed in Subsection 4.5.3. As feasible and necessary, communications with observed "foulers" (i.e., ships in the restricted area) should advise them the most expeditious way to move to lower risk areas and depart the region. If an observed individual ship exceeds an acceptable criterion, the mission should be held until the ship has relocated to an acceptable area.

The methodology below is an acceptable approach (there may be others) for determining the warning and observation areas to ensure risk measures are below acceptable criteria for individual ships. The actual warning and observation areas may be extended to ensure that collective risk measures are met. One key concept is the mitigation effectiveness. A mitigation reduces, but does not necessarily eliminate, the risk at a particular location by reducing the number of vessels present at that location from what it would be without the mitigation. Examples of mitigations include not only warning areas such as NOTMARs, but also patrolling near-shore regions by guard boats to keep traffic away.

The basic procedure for the determination of warning and observation areas to protect individual ships is as follows.

a. **Develop the warning area**. The sections in this step that specify limits are found in the standard. Warning areas (i.e., issued through NOTMAR) encompass the region(s) where the individual P_C to a person on any vessel is higher than the limit in 3.2.1a, where the collective casualty expectation for an individual ship (computed for at least all of the common ship types) is greater than the limit in 3.2.1.b, or where the catastrophic risk measure is higher than the limit in 3.2.1c for at least all common ship types. In addition, the warning area must include regions where planned debris is predicted (per 3.4.3).

b. **Calculate the mitigated risk.** The mitigated risk is the original risk calculation multiplied by the mitigation ineffectiveness (one minus the effectiveness).

c. **Determine the observation area.** The observation area should include (at a minimum) the region where the mitigated individual risk still exceeds the acceptable limit. This may be less than the warning area (and may not include the planned debris impact area).

d. **Determine the observation method**. The observation method used must have effectiveness high enough to reduce the individual risk to the acceptable level everywhere for ALL ship types.

4.5.2.1 Develop the Warning Area

It is generally necessary to assess risk measures for different classes of ships based on size and population. A typical set of ship classes (correlated with the vulnerability models in Chapter 6) are as follows: cargo vessels, passenger vessels, fishing vessels, tankers, other. Additional classes may be desired, e.g., small vs. large fishing vessels, flammable tankers. The debris hazard analysis should determine the probability of impact for debris as a function of location. This is the impact density of debris. Then, the probability of individual casualty, collective risk, and probability of catastrophe should be computed for each ship class as a function of location using the equations in the section above. These three contributions to the warning area should account for risk to all common ships. In order to avoid excessively large warning areas, it may be necessary that large passenger vessels and fuel tankers be excluded from consideration and instead be protected via observation methods.

4.5.2.1.1 individual risk criterion

For each ship category the region where the probability of individual casualty exceeds the limit (1E−6) and the region where the probability of individual fatality exceeds the limit (1E−7), both specified in Subsection 3.2.1.a of the standard, must be computed. The union of these regions must be computed. The resulting area must be in the warning area. Note that the individual risk does not depend on the expected number of ships present, since it defines the region where any person, if present, is exposed to risk exceeding acceptable limits.

4.5.2.1.2 Collective risk

The standard limits the total collective risk to non-mission personnel. The minimum warning area size must be sufficient to encompass the area where the collective risk contribution from a single ship would be larger than the total collective risk limit. In practice, the warning area will typically be larger because 1) there may be multiple ships in the region and 2) there are other contributions to total collective risk from persons on land that must be included in the allowable collective risk budget. This is discussed in more detail in Subsection 4.5.3.

4.5.2.1.3 Catastrophic risk

When assessing catastrophic criterion the following calculation must be performed for each ship category. The maximum occupancy of the ship should be raised to the power 1.5 and multiplied by the probability of catastrophe at each location. For each ship category the region where this quantity exceeds 100E−6 (1E−4) should be determined. The union of the areas calculated this way for all ship categories should be calculated. The resulting areas must be included in the warning area.

Additionally, the warning areas must encompass regions where planned debris is likely to fall. Subsection 3.4.3 of the standard states “The range must confirm that appropriate SUS [special use surface] areas are reserved or NOTMARs are issued for each planned debris release event that encompass the areas and duration necessary to… contain, with 97% probability of containment, all resulting debris impacts capable of causing a casualty.” Since various distributions are possible, this is given as a probability of containment. In the case of a two-dimensional Gaussian distribution, this is essentially equal to a 3-sigma confidence level (98.889%) for a single fragment. For multiple fragments, Equation (4-10) permits the computation of a given sigma level, z, from the number of fragments, N, assuming all fragments have the same impact distribution.

$$z = \sqrt{-2\, ln\left(1 - 0.99^{\frac{1}{N}}\right)} \tag{4-10}$$

4.5.2.2 Calculate the Mitigated Risk

The mitigated risk is determined by applying the effectiveness of the warning areas (or other mitigation) at reducing ship traffic ($\mathrm{E_{mitigation}}$) to the probability of adverse events at each location. The mitigated P_C is the mitigation ineffectiveness multiplied by the unmitigated P_C,

$$P(Casualty)_{mitigated} = (1 - \mathrm{E_{mitigation}})P(Casualty) \tag{4-11}$$

(A similar calculation should be performed for collective risk and for catastrophe).

For example, it might be assumed that a properly issued NOTMAR in a location has an effectiveness of 90%, i.e., it reduces the probability that a ship is present at any location within the region to 10% of the value that it would have had if there were no NOTMAR issued. Therefore in this example, the mitigated P_C may be considered in this region to be (0.1)*P(casualty).* Note that the effectiveness of warnings could vary with the type of ship (e.g., a fishing boat is generally less likely to heed a warning than a cruise ship.)

While mitigated collective and catastrophic risk make intuitive sense, since they depend on the number of ships present, the mitigated probability of individual casualty needs a word of explanation since the probability of individual casualty does *not* depend on whether a person (or ship) is present. It is used here in determining whether an area should be observed or not.

Areas subject to observation are those areas in which: (a) a person present is subject to an unacceptable level of risk; and (b) a person has not been reasonably warned to avoid. For example, on land, a region of high risk might have access restricted by gates or guards and be deemed to not require direct observation since reasonable measures have been taken to protect individuals. However, at sea, it is not generally possible to restrict access to a specific ocean area (especially away from shore), as everyone has an equal right to the use of international waters. Scaling the individual P_C by the effectiveness of the warning gives an empirical basis for how to determine whether an area requires surveillance. Regions of very high risk will be likely to need observation, while regions that are just barely above the threshold risk can be adequately served by the warning area.

4.5.2.3 Determine the Observation Area

To determine the minimum observation area, the mitigated risk is calculated as above. The observation area should include any regions where the risks (individual, collective, or catastrophic) to a single ship would still exceed the acceptable risk criteria. The observation area may differ by vessel class: for example, in a stage drop region, only large vessels may need to be observed because the mitigated risk to small vessels is below the threshold. Although one or two ship types may be the drivers in setting the size of the warning areas, observation regions should be determined for ALL ship classes (but again, inexpensive observation is quite reliable and readily obtainable for some vessel types such as large cargo ships).

In addition, the observation area should include regions where the risk to multiple ships, as estimated from average ship traffic (with mitigations), would cause the collective or catastrophic risk criteria to exceed acceptable limits.

The following outlines a general methodology for determining the observation area: First, use ship traffic estimates and warning effectiveness estimates to determine residual ship traffic for the region where debris might fall. Combine the ship data with the predicted debris data (which includes the probability of the event, predicted number of fragments, and casualty and/or catastrophe areas for the fragments) to estimate the collective risk. This should be done for each category of ship. If the total resulting risk estimate is significant compared to the criteria for acceptable risk, observation for the types of ships that most contribute should be performed over a sufficient region that the residual risk outside the observed area is small compared to the criteria.

Estimates of ship traffic will vary with ship category and the type of ocean region. An examination of the PASTA MARE database[51] suggests that ship traffic can be well-categorized considering only five types of ocean regions.

a. *Coastal areas*: these include ocean areas within 60 miles of shore (excluding Antarctica coastal areas).
b. *Seas and Shipping lanes*: specific high-traffic shipping (e.g., from the Cape of Good Hope to the East Indies), and smaller open regions, such as the Sea of Japan, the Arabian Sea, the Mediterranean Sea, etc.
c. *Busy open ocean*: includes the Atlantic and North Pacific.
d. *Empty open ocean*: includes the South Pacific and Indian Ocean.
e. *Southern ocean*: areas below 40 degrees south (except non-Antarctic coastal areas).

Definition of these regions facilitates ship risk estimates without regard to precise location where debris is predicted to fall. To estimate risk, it is sufficient to predict probability of hazardous debris in each type of ocean area and use estimated ship traffic data for the region as a whole for the various ship categories.

Ship traffic estimates are useful to anticipate the likelihood of the presence of a ship or ships leading to violation of risk acceptability criteria during a launch. During a pre-mission analysis, the collective risk from ships can be estimated from the sum over all areas of the mitigated estimated ship traffic multiplied by the E_C for a single vessel in Subsection 4.5.1. The mitigated ship traffic is obtained by using data on typical average ship traffic (see Subsection 4.5.4) reduced by the warning and surveillance effectiveness. The number of people on-board must be estimated by the type or length of vessel. If this estimated collective risk, combined with collective risk from people on land, exceeds the acceptable limit, then the additional mitigations may be needed to reduce the risk either by reducing risks to ships or reducing risks to land-based populations. A sample calculation of this type is performed in Subsection 4.5.4.

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[51] https://webgate.ec.europa.eu/maritimeforum/en/node/1473

4.5.2.4 Determine the Observation Method

The reliability (probability of detection) of the observation method must be sufficient to further reduce the mitigated risks to below the acceptable limits. For example, if the mitigated P_C is 1E−5, a factor of 10 above the allowed level, the observation method should have at least a 90% probability of detection to reduce the risk to below 1E−6.

The type of observation method chosen may depend on the vessel class to be observed. For example, consider a planned jettison of a small number of objects that remain intact to impact (such as a stage drop) in an open-ocean region. In this scenario, the collective risk to small vessels might be well below acceptable risk levels, and thus sufficiently low that no observation of small vessels is indicated; however, because of their greater probability of being hit (due to their larger size) and greater adverse consequences if hit (due to a larger occupancy), the risk to large cargo vessels and passenger vehicles might in this case be above accepted limits. In such a case, it would be necessary to monitor only for large cargo and passenger vessels. Thus, it would be reasonable to use less-expensive methods that have a low probability of detecting small vessels but are sufficiently reliable for detecting large vessels. Subsection 4.5.3 discusses various types of observation methods in greater detail.

4.5.2.5 Day-of-Launch Calculations

Even when risk criteria are met for individual ships through the hazard area approach above, this does not ensure that the collective risk will be below acceptable levels during the launch (or re-entry) operation, as ships that are observed during launch preparation also contribute to total mission risk. The warning areas defined above are designed to reduce the likelihood of ships causing risk limits to be violated. When any risk level computed using the best available data during the countdown exceeds a criterion, the mission should be held until the risk can be reduced to acceptable levels, such as through mitigation.

During the launch countdown, the collective risk from vessels observed within the defined observation region[52] is added to the total collective risk from other exposed sites (i.e., on land). If the total collective risk exceeds acceptable limits, the mission should be held until the collective risk falls below acceptable limits. This may be accomplished by assuring observed ships in the hazarded area have moved to areas of lower risk in order to reduce the total collective risk from the mission.

The catastrophic risk profile from ships can be computed following the methodology in Subsection 4.1.2.2 using the probability of catastrophe equation from Subsection 4.5.1 with the same input data on the number of people on-board used in the collective risk calculation.

4.5.3 Ship Observation Methods

While active surveillance by manned aircraft has been a popular approach for determining whether ships are present at a specific location, there are many other options available. These include land-based methods, satellites, and UAVs.

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[52] While estimates of ship density could be used to estimate collective and catastrophic risk, actual ship traffic is highly variable and currently available ship density data does not appear sufficiently accurate to use for risk estimation.

4.5.3.1 Surveillance aircraft

Aircraft provide a thorough means of active range management where monitoring and clearance of range-fouling ships must be conducted over ocean areas. Dedicated range surveillance aircraft are often employed by the national ranges to ensure clearance of ships at varying distances from the launch facility. Aircraft used are range assets (such as Navy P-3, C-130) and U.S. Coast Guard assets. Signal relay aircraft are also employed in vessel detection during their inbound and outbound transits. Aircraft can employ radar to efficiently cover large areas and largely overcome weather-related visibility limitations such as cloud cover and rain.

Traditionally, surveillance has been performed by manned aircraft, both military and commercial. As unmanned systems with extended range, endurance, and operating cost advantages become more prevalent, there is an increasing opportunity to use unmanned aerial systems to perform ship surveillance.

4.5.3.2 Radar Surveillance Technology

Shore-based radar systems are capable of line-of-sight detection of marine traffic, with elevated locations capable of detection in the 10-to-30 mile range depending on power and height above sea level. Due to their short range, these systems are used near fixed assets such as launch facilities and within ports. Various marine radars are used by the coastal ranges to detect ships and small power boats in and near restricted zones. This is often sufficient for small vessels because the risk to these vessels is often insignificant outside of the launch area.

Various other types of radar surveillance technology could potentially be used for ship surveillance but are not in common use at the present time. These include satellite-based synthetic aperture radar, land-based high-frequency radar, or airborne maritime surveillance radar.

4.5.3.3 Automatic Identification System (AuIS[53])

All vessels over 300 tonnes on an international voyage, all domestic vessels over 500 tonnes, and all passenger carriers are required to operate Class A AuIS transponders that broadcast continually updated data such as identity, position, course, speed, ship characteristics, cargo, and voyage information to and from other vessels and the shore.

The AuIS data is monitored by shipping and fishing fleets, port authorities, and coast guards to track maritime ship traffic and moored ship locations. Monitoring of AuIS transmission is performed by coastal authorities within areas of interest and by commercial tracking services, with both terrestrial and satellite networks employed to effect world-wide tracking capability. Since the required system transmits via very high frequency radio signals with a horizontal range of 20 to 40 nm (37-74 km), it most reliably tracks ship location within coastal zones and between closely situated ships. Skyward directed transmissions can travel much greater distances than transmissions along Earth’s surface. Space-based AuIS signal reception is so effective that satellites reach the limit of the number of ships that can be simultaneously tracked and must be augmented by terrestrial receivers in congested regions.

Recent studies of satellite AuIS data have examined detection metrics of existing first-generation satellite networks. The PASTA MARE study compared AuIS detection and

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[53] AIS is the commonly accepted acronym for this term. AuIS is used in this document to avoid confusion with the acronym for Abbreviated Injury Scale.

processing by Orbcomm, Pathfinder2, NTS1, and AprizeSat satellites. Congested areas present the most challenging environment for identifying vessels. The probability of detection is often well below 80-90% of the transmitting ships at any given time. However, in low-density areas, probability of detection can be very good, especially with multiple overlapping passes of the satellite over an area to overcome congestion and high satellite elevation angle issues.

Notwithstanding detection challenges, AuIS data monitoring does not guarantee ship detection. The requirement to transmit AuIS data does not include small non-passenger vessels, which include a significant percentage of near-shore fishing and pleasure craft that are not mandated to use AuIS equipment. The detection of such vessels is almost exclusively accomplished by fixed ground-based and ship-board radar as well as surveillance aircraft, all with line-of-sight detection limitations.

Non-compliance is also an issue. Fishing vessels have been observed to turn off AuIS to avoid detection, perhaps to avoid knowledge of their location by competing fishing vessels and authorities. Other examples of private vessel non-compliance have also been noted. Military ships do not commonly broadcast AuIS, instead relying on secure military locator technology to track ships and aircraft.

Even with its shortcomings, the near-real-time database provided by the AuIS vendors that incorporates satellite AuIS, terrestrial AuIS, and custom location services provides a viable solution for global maritime traffic monitoring that is unmatched by any other tracking technology. The AuIS data is available from both government and private tracking services.

The AuIS tracking data can be obtained from a number of service providers, most of which offer premium subscription services for a fee and free access for limited data. Below is a list of service companies that have developed their own AuIS reception hardware and systems (terrestrial and/or satellite AuIS).

- http://www.exactearth.com – ExactEarth operates a constellation of five AuIS satellites and provides AuIS message data service and AuIS software integration services. ExactEarth maintains a historical database, providing customized historical reports and statistical analyses.
- http://www.fleetmon.com – FleetMon operates a land-based AuIS receiver station network and partners to provide satellite AuIS service from LuxSpace.
- http://www.luxspace.lu/ - LuxSpace is a European AuIS data provider, partnered with Orbcomm.
- http://www.orbcomm.com - Orbcomm operates a constellation of communications/AuIS satellites to collect ship location data. Orbcomm deployed 17 next-generation satellites (OG2) in 2014 and 2015 with improved detection capabilities, higher update frequency and, reduced latency.
- http://www.spacequest.com/ - SpaceQuest is a satellite technology company that operates the AprizeSat-3 AuIS microsatellite. They show an interesting animation of AprizeSat-3 detection on their website. SpaceQuest launched AprizeSat 5 & 6, 2nd-generation AuIS satellites that are part of the ExactEarth constellation.

There is a number of service companies that bundle data from other sources. Examples of these are:

- http://www.marinetraffic.com/ais/home
- http://shipfinder.com/
- http://www.terramarnetworks.com
- http://www.vesseltracker.com/app

4.5.3.4 US Navy SeaWatch

The US Navy operates the Global Maritime Information and Data Analysis Branch that manages a global maritime database and provides analysis of the global maritime environment. The database utilizes AuIS and other sources of ship movement data and compares this to a merchant ship characteristics database that includes physical and functional attributes garnered from ship photographs and blueprints. Customers can access this data through the SeaWatch program, which provides a near-real-time and historical operational database of merchant and fishing vessel movement and also contains data on naval ship movements.

SeaWatch is a service-oriented Navy program that can assist in provisioning custom ship location data for a given area, participate in range clearance by providing tailored ship and vessel monitoring over an area, and produce custom historical studies such as ship density plots and statistics for bounded areas and points of interest. The SeaWatch service has access to a number of data sources and databases. Larger ships (over 300-tonne displacement) and some compliant smaller ships can be tracked via AuIS. Other smaller vessels can frequently be identified by cross-referencing with its ship characteristics databases. Data types in these databases that are potentially useful for identification, contacting the crew, and risk assessment include ship name, owners, markings, and call sign; ship type, hull, and propulsion type; cargo types, load state, and draft.

Comprehensive real-time vessel tracking is classified at the SECRET level; however, nearly all merchant ship information is unclassified, while historical statistical density studies may be available at the unclassified level depending on the information included. Access to comprehensive data sets requires the use of a SIPRnet or JWICS terminal.[54]

4.5.4 Sample Calculations

A simplified methodology that uses the total number of casualty- and catastrophe-producing fragments, the casualty area per fragment, the warning and surveillance effectiveness, and an estimate of the average ship traffic and size for each ship class can be used to determine whether the collective risk or catastrophe criteria are violated for each ship class.

For each ship class (i), the collective risk (E_C) can be calculated as follows:

$$EC_i = P(Event)N_{total_i}\rho_{ship_i}(A_{cas}N_{fragCas} + A_{ship_i}N_{fragCat}) \tag{4-12}$$

and the catastrophe contribution (using $PN^{1.5}$) as:

$$(PN^{1.5})_i = P(Event)N^{1.5}_{total_i}\rho_{ship_i}(A_{ship_i}N_{fragCat}) \tag{4-13}$$

Here, $N_{fragCas}$ and $N_{fragCat}$ are the number of casualty-producing and catastrophe-producing fragments, respectively, and the other variables are as defined in Subsection 4.5.1.

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[54] For access and information, contact Brian Roberts, SeaWatch Team Lead: broberts@nmic.navy.mil 301-669-3166.

The typical ship traffic can be estimated for the various vessel classes for different regions of the ocean using AuIS satellite data or other sources. Table 4-11 shows an example of typical ship traffic values for coastal areas, shipping lanes, and seas; busy and empty open ocean areas; and the southern oceans. The values in the first five columns were estimated from samples taken from the PASTA MARE database. Note that the category 'other' is a catch-all category that refers to a wide range of vessels, from sailboats to aircraft carriers. Thus, although it is shown here as an example, it is not clear how useful it is as a practical category. The values in the last two columns are not derived from AuIS data but are merely expert judgments (flammable tankers are assumed to be 5% of all tankers, and small fishing boats are estimated based on the number of larger fishing vessels). For the various vessel types the average population per vessel and ship size can be estimated, as in Table 4-12.

Table 4-11. Average Ship Traffic for Different Ocean Regions by Ship Class

Values are Ships per 1000 square nm[55]	**Cargo**	**Fishing**	**Other**	**Passenger**	**Tanker**	**Flammable Tanker**	**Small Fishing**
Data source	Satellite AuIS Avg	Satellite AuIS Avg	Satellite AuIS Avg	Satellite AuIS Avg	Satellite AuIS Avg	Estimate	Estimate
Coastal areas	25	3.2	20	6	13	0.65	200
Shipping Lanes & Seas	13	2.2	21	4	3	0.15	100
Busy open ocean	3	0.7	0.6	0.2	0.28	0.014	20
Empty open ocean	0.18	0.09	0.05	0.02	0.06	0.003	0
Southern Ocean	0.02	0.01	0.04	0.02	0.01	0.0005	0

Table 4-12. Sample Vessel Populations and Sizes

	Cargo	**Fishing**	**Other**	**Passenger**	**Tanker**	**Flammable Tanker**	**Small Fishing**
Population	30	20	40	1000	30	15	5
Length (ft)	700	100	500	700	1000	1000	40
Area (ft^2) ($A = L*L/5$)	98000	2000	50000	98000	200000	200000	320

As a sample calculation, consider an intact stage drop event. Such an event often occurs in a tightly defined region (as opposed to spanning several types of ocean areas). It is conventional to assign Pr(Event) = 1 for planned debris impacts (to ensure that planned debris events are safe assuming they do occur). For this example, assume that there is one resulting object that is capable of producing a catastrophe to any ship. Assume further that NOTMARs have been issued, which are 90% effective for cargo, tanker, and large fishing ships, 98%

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[55] The units of ships per 1000 square nautical miles was chosen just as convenient units; any reference area could have been used. These units were chosen only to make the values in the table readable and intuitive, and is not meant to be indicative of the size or scale of any of the various ocean regions.

effective for passenger vessels, but only 80% for ‘other’ and 50% for small fishing vessels. Using the average ship traffic and vessel category sizes and populations from the tables above, the collective risk (E_C) and catastrophe criteria can be computed for each ship type, for each ocean region type. For example, in coastal areas for cargo ships, we have (with values from the tables above):

$$E_C = \rho_{ship} N_{people} A_{Cat} (1 - E_{mit}) = \left(\frac{25 \text{ ships}}{1000 \text{ NM}^2}\right)\left(30 \frac{\text{people}}{\text{ship}}\right)(98000 \text{ ft}^2)(1 - 90\%) = 199 \times 10^{-6} \qquad (4\text{-}14)$$

Table 4-13 shows the E_C values for all ship types in all ocean areas. The collective risk criterion requires a total E_C of less than 100 in a million per mission from all sources. Colored E_C values show the combination of ocean area and ship types for which the criterion is exceeded without regard to risk to land-based populations. High values are red, moderate values are yellow, and black values are below risk criterion. The criterion is violated for large ships in coastal areas and shipping lanes, but not in relatively empty ocean areas (even after accounting for the effectiveness of warnings).

Table 4-13. Example Calculation 1: E_C Values Per Ship Type Per Ocean Type

Total E_C (Value shown is per million)	**Cargo**	**Fishing**	**Other**	**Passenger**	**Tanker**	**Flammable Tanker**	**Small Fishing**
Coastal areas	***199***	0.3	***217***	***319***	***211***	5.3	4.3
Shipping Lanes & “Seas”	***104***	0.2	***228***	***212***	***49***	1.2	2.2
Busy open ocean	***24***	0.1	6.5	11	4.6	0.1	0.4
Empty open ocean	1.4	0	0.5	1.1	1	0	0
Southern Ocean	0.2	0	0.4	1.1	0.2	0	0

In addition, since the resulting debris is assumed to be catastrophic to all ships, the catastrophic measure is also relevant. Table 4-14 shows the measures of this value for each ocean area and ship category (assuming that all ships of the same type have the same population). By this measure, observation (which can likely be performed by passive tracking) is also necessary for a stage drop in busy open ocean areas, but only for large vessels.

Table 4-14. Example Calculation 1: Catastrophe Values per Ship Type per Ocean Type

Catastrophe Measure ($PN^{1.5}$) (value shown is per million)	**Cargo**	**Fishing**	**Other**	**Passenger**	**Tanker**	**Flammable Tanker**	**Small Fishing**
Coastal areas	***1090***	1.6	***1371***	***10073***	***1157***	21	19
Shipping Lanes & “Seas”	***567***	1.1	***1440***	***6716***	***267***	4.7	9.7
Busy open ocean	***131***	0.3	41	***336***	25	0.4	1.9
Empty open ocean	7.9	0.0	3.4	34	5.3	0.1	0.0
Southern Ocean	0.9	0.0	2.7	34	0.9	0.0	0.0

As a second example, consider an analysis of failures of a vehicle in the downrange region (see Table 4-15). For this example, assume the probability of a failure event is different in each region (the second column). For simplicity, assume that a failure event results in 15 fragments capable of producing a catastrophe to small ships, but only 1 for large vessels, and further that there are 300 additional fragments that do not lead to a catastrophe, but have an average casualty area of 4 square feet.

Table 4-15. Example Calculation 2: E_C Values per Ship Type per Ocean Area Type

Total E_C (Value shown is per million)	Debris Event Probability	Cargo	Fishing	Other	Passenger	Tanker	Flammable Tanker	Small Fishing
Coastal areas	0.02%	0.4	0.0	3.3	3.2	0.4	3.3	0.0
Shipping Lanes & “Seas”	0.10%	0.1	0.0	17	1.1	0.0	0.4	0.1
Busy open ocean	0.50%	1.2	0.1	2.4	2.7	0.2	1.8	0.1
Empty open ocean	0.20%	0.0	0.0	0.1	0.1	0.0	0.2	0.0
Southern Ocean	0.10%	0.0	0.0	0.0	0.1	0.0	0.0	0.0

Using the average ship traffic and vessel category sizes and populations from the tables above, the collective risk (E_C) can be computed for each ship type, for each ocean region type, assuming no warnings or other mitigations have been issued. In this case, the total E_C is 38 per million; about half of this arises from other vessels in shipping lanes and seas. Depending on the contributions to E_C from other sources, no mitigation may be needed, but it may be advisable to monitor the shipping lanes and seas that are traversed to ensure that there is not an unusually high number of ships at the time of the mission.

4.5.5 Potential Simplifications

The approach outlined in Subsection 4.5.2 can be simplified through additional observation when the cost to doing so is reasonable, such as when the area involved is small and easily surveyed. In the simplest case,

a. the warning area is determined by considering all ships, including passenger ships and fuel tankers, perhaps with the simplified equations for P(casualty) and P(catastrophe); and

b. the entire warning area is surveyed by a method with nearly 100% probability of detection (e.g. aircraft).

This simple approach is practical for missions that hazard only a small coastal region, but becomes less practical as the area affected by a mission grows.

An alternative simplified approach is to restrict only the impact probability for ships, as was specified in prior versions of the standard, which read,

> Non-mission ships will be restricted from hazard areas where the probability of impact of debris capable of causing a casualty exceeds 10E−6 (1E−5) for non-mission ships. Non-mission ships should also be restricted from hazard areas where the cumulative probability of impact of debris capable of causing a catastrophic accident exceeds 1E−6 for all non-mission ships.

For breakup events resulting in many fragments, this method is typically sufficient when the entire ship area is used in the calculation of impact probability. Since the area of a ship is significantly greater than the casualty area for a person, this method will usually provide much more protection than the direct measures of P_C. However, this approach does not account for explosive events, and is not conservative for events that produce only a few fragments with catastrophic potential, especially for passenger vessels. Note that this approach is extremely conservative for scenarios that generate large numbers of small fragments capable of causing a casualty, but not catastrophe.

4.6 Spacecraft Protection Guidelines for Implementation

The launch range is responsible for selecting launch times that afford a level of spacecraft protection in accordance with the criteria outlined in the standard. Launch ranges satisfy that responsibility by performing CAs for launch times throughout the planned launch window. The CAs identify launch times that would violate those criteria. The launch ranges use those times that violate the risk criteria (Section 3.6 of the standard) as launch holds or blackout times throughout the launch window.

4.6.1 Applicable Launch Range Space Protection Phase

The flight phase, during which the launch range is responsible to have CAs performed, begins with vehicle launch and extends until three hours after launch. Another definition of the first phase of flight is that phase governed by CSpOC Orbital Data Request, Form 22 and R-15 Form. Additional information is provided on the following website: https://www.space-track.org/documentation#/odr-examples_forms.

The next phase of flight is either defined as Cataloged Orbit or Project/Spacecraft Initiated Orbit transfer burns, which are addressed by the CSpOC Early Orbit Maneuver Plan. Often this phase of flight is addressed by the program and generally by launch vehicle or space vehicle personnel.

The final phase of flight is addressed by the CSpOC On-Orbit Maneuver Plan, which provides information about station keeping and the de-orbit or disposal orbit plan. Generally, the final phase of flight is addressed by the satellite owner.

4.6.2 Sources of Conjunction Assessment

The launch ranges often rely on the Space Force CSpOC to provide miss distance/ probabilities of collision during which launch times would lead to a violation of the criteria. The CSpOC currently provides this service to national and international launch ranges. When information required for some aspect of the launch COLA is unavailable to CSpOC, the launch range or the program may need to perform some aspect of the launch COLA. For example, when an intercept engagement is planned, the CSpOC's CA may be augmented with or replaced by an independent COLA analysis. In a planned engagement mission, the debris cloud is a function of the engagement parameters, which are not available to CSpOC. Another example of when an independent or additional CA is performed is as defined in the study[56] by Beaver et al.

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[56] Beaver, B., M. Hametz, J. Ollivierre, L. Hewman, and M. Hejduk. "Recommended Screening Practices for Launch Collision Avoidance." NASA/TM-2015-219270. March 2015. Retrieved 16 October 2023. Available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150015575.pdf.

The CSpOC is the primary source for COLA or CAs for the U.S. and international launch ranges.

4.6.3 Protection Criteria

Spacecraft protection criteria take three basic forms in the standard: 1) collision risk analysis; 2) ellipsoidal miss distance elongated in the direction of the nominal velocity vector; and 3) spherical miss distance. These are listed in the order preferred.

NASA published guidance in a technical manual (Beaver et al 2015) for screening for launch COLA; the following is an extract of the key points from this document.

> This discussion is based on the premise that technically sound analytical techniques, tools, and supporting data exist that can be brought to bear on the launch COLA problem. …Conclusions include:
>
> 1) The necessary input data to support probability-based screening is available; most significantly, existing methods of characterizing launch vehicle state uncertainty in flight are technically sound and consistent with flight data.
> 2) It is reasonable to use either the Special Perturbation propagator or General Perturbation propagator catalog for probability-based screening, with the lower-fidelity GP catalog producing results that are slightly more conservative in general.
> 3) Miss distance based screening does not correlate with risk in any direct, practical way, and should not be used as a substitute for probability-based screening.

Computation of collision probability should be used whenever practical in order to account for spatial and temporal dispersions in CA and COLA.

To conduct a collision probability COLA, the CSpOC requires a covariance matrix for the objects launched into or through orbital altitudes. The CSpOC debris catalog has a format that supports covariance data for each cataloged item.

For manned spacecraft CA the use of ellipsoidal (200 km in-track x 50 km cross-track and radial) or spherical (200 km) miss distances is customary when covariance data is not available. As a practical matter, many analysts choose to use spherical miss distance volumes when they are dealing with large launch windows.

During a NASA Launch Services Program (LSP) study[57] it was determined and stated in the summary (item 6) that miss distance launch COLAs are "cripplingly heavy-handed and thus this procedure is not recommended".

NOTE	When covariance data is not practical to develop or obtain, or the quality of the data is questionable, an acceptable alternative would include using the tightest covariance parameters of any comparable vehicle. This will still allow collision probability to be estimated but will provide results that are more conservative since larger covariances generally lead to fewer launch window closures.

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[57] Hejduk, M.D. et al. "Launch COLA Operations: an Examination of Data Products, Procedures, and Thresholds Revision A." NASA/TP-2015-000000. March 2015. Retrieved 17 October 2023. Available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150015576.pdf.

As part of the COLA process, the launch wait period should be equivalently adjusted to account for arrival time dispersions associated with the launch vehicle or its jettisoned components. The CSpOC analyst performs three tasks: considers whether the manned spacecraft has maneuvered since the time its last ephemeris was established; determines the cumulative time based on the orbital period change per revolution and the number of revolutions prior to launch; and accounts for this arrival time dispersion in the launch wait period. For example, the International Space Station (ISS) operates in a near-circular orbit with an average altitude of 407 km (350 km to 460 km)[58]and in an inclination of 51.6°. If the ISS were to perform a maneuver after the epoch time (the date and time at which the Keplerian element set defining the ephemeris of its orbit was established and valid), uncertainty in the arrival time would have been introduced into a subsequent CA using that element set. Assuming the apogee and perigee of the station spread about its average altitude, i.e., 415 km to 400 km, the orbital period change (per revolution), ΔP, or arrival time uncertainty per revolution can be calculated and is shown in Table 4-16, where ΔR represents the expected incremental change in the orbital radius, or altitude, of the ISS after the maneuver. Thus, a typical maneuver of the ISS resulting in an altitude change of 7 km would result in approximately 8.6 sec change in the orbital period and the analyst would multiply this value by the number of revolutions expected before liftoff of the launch vehicle to determine the temporal dispersion to add to the launch wait period. These values will not change appreciably for the range of operational altitudes of the ISS.

Table 4-16. Orbital Period Change (per Revolution) of the ISS

ΔR (km)	1	2	3	4	5	7	10	15	20	25
ΔP (sec)	1.23	2.46	3.69	4.92	6.15	8.61	12.30	18.45	24.59	30.74

The individual range has the responsibility to incorporate the dispersions into the CA/COLA process, but the CSpOC is generally involved in the process, when practicable, to improve the dispersion estimates. Thus, the range would obtain and provide covariance data to the CSpOC for CA and the estimated collision probability. As an alternative, and part of the COLA process, the range could utilize a simplified model for estimating maximum collision probability as based on actual separation distance, conjunction geometry, and maximum or capped spatial and temporal dispersions.

4.6.4 Launch COLA Duration and COLA Gap

The length of the trajectory provided to CSpOC should ideally be long enough to account for the time necessary to:

- enter the new objects into the orbital COLA (as long as 3 hours and 45 minutes for the Antares mission that inserted in a low earth orbit [LEO]);
- perform the orbital COLA with those new objects;
- plan a COLA maneuver for those new objects should it be needed;

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[58] European Space Agency. *The International Space Station: A Guide for European Users*. Noordwijk: European Space Agency, 1999.

- execute a COLA maneuver for those new objects.

The challenge is that these four steps can take up to 36 hours for the ISS; however, for established vehicles and launches to the ISS this time is much shorter.

Recognizing these long COLA gaps exist, the launch ranges have agreed to specify a trajectory time no less than 3 hours after launch. NASA LSP is often asked to perform a geometric COLA gap analysis to determine whether the orbiting manned objects are potentially endangered at any point in the launch window from the newly launched objects during the COLA gap period if the orbit of the newly launched object intersects the ISS orbit. (Note: NASA LSP will attempt to select orbits that will not initially intersect the ISS if possible, thus avoiding COLA gap concerns. Example: CubeSats released from LSP missions are typically above or below the ISS orbit.)

Not only can it be cumbersome to provide launch COLA input trajectories for 3 hours, but because of the large uncertainty of the position of the launched objects after 3 hours such trajectories are considered to be of diminishing value.[59]

4.6.5 Active Satellite Advisory Requirements

Active satellite launch COLA advisory requirements in the standard are set at a level of 1E−4, which is two orders of magnitude less constraining than the requirement for PoC to manned spacecraft. The rationale for making this criteria advisory is as follows. The NASA LSP study cited in Subsection 4.6.3 found that launch COLAs against active satellites protected to the level of P_C 1E−4 are not necessary due to large trajectory uncertainties in the current state-of-the-art inertial measurement units and navigation controls. In fact, there are only a few cases in that study, when the risks slightly exceeded 1E−5 such that a cumulative PoC would not be expected to be exceeded either.

4.6.6 Other Protection Strategies

The RC discussions regarding space objects on the high and low end of value (from National Security Agency/NASA satellites down to micro satellites) and threat capability (large space debris with smaller covariances down to small debris with large positional uncertainty) were considered. Initial discussions led to identification of intermediary thresholds for each proposed grouping of space objects. In the end, however, consensus could not be reached on the specific categories, risk thresholds, or keep out volumes. Challenges associated with reaching consensus included who would determine what should be considered a high-valued asset as well as what size of debris would warrant a smaller risk threshold.

4.6.7 Strategies for Multiple Object Deployments

Ideally the range provides launch COLA trajectories for each object, however that approach can be redundant, inaccurate, computationally intensive or cumbersome for the following reasons:

- Objects deployment delta velocity is very small (spent stages, inter-stages, fairings, etc.) such that the result conjunctions will be the same for all objects

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[59] Hametz, M. and B. Beaver. "A Geometric Analysis to Protect Manned Assets from Newly Launched Objects – COLA Gap Analysis." Paper presented during the 23rd AAS/AIAA Space Flight Mechanics Meeting, Kauai, HI, 10-14 February 2013.

- Deployment angle is uncertain due to a lack of design to determine roll angle at deployment pre-mission or to control the roll angle at deployment
- Deployment velocities are unpredictable depending on the deployment mechanism.
- When the number of objects deployed is too high the launch COLA can overwhelm the computational capability of the 19 SDS or the output is too cumbersome for the range to work with.
- Wide range of object delta velocity, size and numbers - as is the case with a planned engagement

4.6.7.1 Approaches for Multiple Objects Deployed Close Together

In these cases ranges have chosen to approach launch COLA based on a central object or the locus of trajectories while accounting for the number of objects in several ways:

- Account for the total area of all the objects using a representative radar cross-section for input into the launch COLA in Form 22 (item 5). For example, the separation distance for SLD 45 Starlink launches is below 10 km between satellites in each cloud. Note: For Starlink FAA/SLD 45 found that the objects were 7 km apart (over L+3 hrs) – which was small as compared to the dispersions.
- Compute PoC downstream of the 19 SDS analysis using debris cloud density estimates and debris object size - until the density becomes a small fraction of the background flux.
- Decrease the Input PoC threshold to the launch COLA proportionally to account for all the objects in Form 22 (item 7). SLD 30 uses this approach.
- Increase the Output PoC value provided by 19 SDS proportionally to account for all the objects and comparing those values to the standard PoC threshold (as contained in APL/JPL raw .res [.result] files) prior to the all sorted file and produce their own all sorted file. The Missile Defense Agency (MDA) uses this approach.

4.6.7.2 Launch COLA Approaches for the Deployment of Many Satellites

In these cases ranges have elected to package the satellites into smaller groupings each with its own total radar cross-section and covariances.

- Similar payload types
- Representative extreme trajectories
- Separate clouds such as top, middle and bottom satellites on the ‘bus’ as is done for SpaceX’s Starlink launches.
    - In the Starlink deployments the tumbling stage (bus) provides additional delta velocity to the top and bottom as compared to the middle satellites. Therefore the top and the bottom are the extremes of the cloud. All in plane deployments delta V comes from tumbling. When using this approach the radar cross-section values of each object should be combined and the total should be used on Form 22.
    - Time separation of Starlink launches focuses on distinct 60-satellite, 30-satellite, and single-satellite clouds, which represent the extremes. With a 10-km limit (each) between 60-satellite and 30 satellite clouds of 7.5 km and between 30-satellite and

single-satellite clouds of 7.4 km, SpaceX identifies a remote chance (perhaps 1 in 200) of recontact.The limit of 10 km was determined based on results of conjunctions.

4.6.7.3 Launch COLA Approaches for the Deployment of Parent (unstable) & then Child Satellites

In these cases ranges have elected to:

- identify unique trajectories for each parent satellite and handle child satellites by methods described in the two earlier charts;
- handle the parent by methods described in the two earlier charts and employ standoff approaches for the child satellites;
- add to the standoff distance a distance equivalent to the delta velocity of the parent and the child after L+3 hours.

4.7 Critical Asset Protection

Launch operations can present hazards to life as well as the property (facilities, support equipment, etc.) used to accomplish range activities. In general, the requirements for managing risk to the public and workforce (i.e., MEP and neighboring operations personnel [NOP]) also provide appropriate protection for property; however, in accordance with Subsection 2.2.6 of the standard, a higher level of protection may be necessary for property needed for emergency response and continued operations. This section provides guidelines for implementing this policy objective and examples of criteria that can be used to protect these assets.

It may not be possible to fully protect existing critical assets and still accomplish the mission. In this case it is important to have a complete understanding of the launch risks and that the risks are accepted by a properly designated and informed authority. Information quantifying the expected level of damage from a launch mishap can still be useful in determining how the mission is accomplished. For example, if there is a high probability of a launch mishap that could cause significant damage to critical assets, then the decision authority may require the risks be minimized by implementing changes in the vehicle design or flight plan during the planning phase for the mission.

The design and siting of critical assets should consider the potential hazards and threat envelopes to ensure their exposure to launch hazards is limited to acceptable levels. During the design phase, the range should evaluate the site to assess the potential debris hazards in the area. If possible, the asset should be placed outside of launch hazard areas so that debris from a launch mishap cannot affect it. The objective should be to reduce the launch risks to the extent practicable in keeping with operational objectives.

4.7.1 Critical Assets Requiring Protection

The hazard analysis for the protection of property should begin with the development of a list of critical assets.[60] The list of assets should only include the critical items that if damaged, present a risk to surrounding population centers or items needed to successfully accomplish the range's mission. Four types of assets should be considered based on mission requirements and whether a secondary hazard to surrounding personnel can be created if the asset is impacted by a fragment. They are:

a. hazardous facilities;
b. emergency response facilities;
c. range assets; and
d. range user assets.

The first two types of assets include property that would increase the risk to surrounding population centers if they were damaged or not available in the event of an emergency, while the second two include the range and range user property essential to maintaining range operations. Examples of each type include: (a) structures housing sufficient quantities of explosive substances to be dangerous to the safety of personnel if released; (b) a tank or other structure containing, housing, or supporting water or fire-suppression materials or equipment needed to successfully respond to a mishap; (c) mandatory instrumentation sites that would preclude the successful initiation of a mission; and (d) ground support equipment deemed essential to continued operations.

Normally, the list of critical assets should be limited to those that when impaired significantly degrade the capability to respond to an emergency, generates a substantial secondary hazard, or are needed for national security. In addition, the list should be limited to assets that would be very difficult, time-consuming, or expensive to replace; however, a range may also include high-value or unique assets that may not necessarily be essential to their operational mission.

When assessing critical assets, only the area of the asset vulnerable to an impact should be assessed. In general, assuming impact anywhere, on a building, that houses the asset should be carefully considered as this can unnecessarily drive the risk; though this may make the analysis more simple. Scrutiny on the support assets (e.g. electrical and air conditioning) should also be performed to determine if these support assets are actually critical or just strongly desired.

4.7.2 Potential Hazard Sources

The hazard sources that should be considered when evaluating the risk to critical assets are described below.

a. Debris. The primary hazard that may pose a threat to critical assets from a launch operation is debris resulting from a vehicle breakup or nominal jettison of flight

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[60] NASA's policy for protection of property requires "the vehicle program, the range safety organizations(s), and the authority responsible for the range, launch site, or landing site" coordinate on the identification of any property in the vicinity of the flight that requires protection from potential debris impact, identification of the potential damage of concern and the mitigation of the associated risk.

hardware. Debris can damage a structure and its contents by either a direct impact or nearby impact of explosive debris. Inert debris can damage the roof, floor, interior partitions, and frame of the structure depending on its weight and velocity at impact. These items can also be damaged by the blast loads resulting from the impact of explosive debris.

b. Fire. A fire is also likely to occur with the impact of explosive propellants. A fire can cause a significant amount of damage. The Minuteman I failure in 1993 at the Western Range (WR) ignited a 500-acre brush fire that burned within 1,000 yards of a small coastal town. Private property damage resulting from the Delta II failure at the ER came to approximately $429,000. The risk of fire is greatest in the up-range area prior to the consumption of the vehicle propellants. It is normally managed by having a firefighting crew in place during the operation to ensure immediate response and rapid control in the event of a mishap.

c. Toxic Gases. The toxic propellants used by some launch vehicles can also pose a threat to critical assets. Some propellants, such as nitric acid, are very corrosive and can damage or contaminate critical assets located in a facility. The risks due to toxic propellants can be minimized by taking mitigation actions such as shutting off the ventilation system for facilities containing critical assets prior to the operation.

Table 4-17 provides a summary of the hazards. It identifies the hazards that are normally applicable to a type of asset and the consequences associated with their degradation or failure.

Table 4-17. Threats and Consequences For Critical Assets

Critical Asset Type	Applicable Hazards			Potential Consequences
	Debris	Fire	Toxics	
Hazardous Facilities	✓			Casualties in surrounding population centers
Emergency Response Facilities	✓	✓		Casualties in surrounding population centers
Range Assets	✓	✓		Unable to conduct essential range capabilities
Range User Assets	✓	✓	✓	Unable to conduct essential range capabilities

The implementation guidelines will focus on debris since it is the dominant hazard to critical assets and because the capability to model other secondary hazards to assets (fire and toxics) is limited; however, secondary hazards should be considered in the risk management process and controlled through implementation of operational procedures, such as those identified above.

4.7.3 Sample Protection Criteria

The primary hazard to an asset can be measured by determining the probability of impacting it with a piece of inert debris or exposing it to the blast loads from the impact of a piece of explosive debris. The impact probability only defines the likelihood of a potential threat to critical assets. If the probability of debris hazarding an asset is high, then the expected level of damage to the asset may also need to be measured to identify the probability of significant adverse consequences.

Based on the policy objective for protection of critical assets, the criteria for the impact probability needs to be set such that it does not increase the risk to surrounding population centers or degrade the range's or range user's capability to conduct their mission. The first part of the objective implies that the level of risk to members of the GP and workforce needs to be considered when setting the criteria. The second part of the objective implies that the degree to which an asset is available to support the mission also needs to be considered when setting the criteria. These points will be discussed separately in the examples in the following paragraphs since the protection criteria depends on the type of asset being protected. Since the example criteria also depend on the operational availability of the asset, the individual ranges need to establish the protection criteria to meet the policy objective for their particular situation.

4.7.3.1 Impact Probability Criteria for Hazardous and Emergency Response Facilities

The first part of the policy objective requires that the consequences of the impacts on hazardous and emergency response facilities not exceed the individual risk criteria for members of the GP or workforce.[61] Per Subsection 3.2.1.a of the standard, the risk of casualty to any individual member of the public must be no greater than 1E−6. This can be met by limiting the probability of impacting a hazardous or emergency response facility to less than 1E−6. A probability of impact of less than 1E−5 could be used if only workforce personnel are hazarded since, per Subsection 3.2.2.a of the standard, the workforce can be exposed to a higher level of individual risk.[62]

4.7.3.2 Impact Probability Criteria for Range and Range User Assets

The main factor that determines the level of protection for range and range user assets is their operational availability (A_o), which is a measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called for at an unknown (random) time.[63] To meet the policy objective, the probability of a launch mishap that could damage critical infrastructure should be significantly less than the probability that a launch would be scrubbed due to unavailability of critical launch support assets for other reasons.

The standard equation for A_o is:

$$A_o = \mathrm{MTBDE}/(\mathrm{MTBDE} + \mathrm{MTTRS}) \tag{4-15}$$

where:

MTBDE = mean time between downing events
MTTRS = mean time to restore system

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[61] A mishap that affects a large number of people could also cause a situation that exceeds the collective risk criterion.

[62] The launch safety criteria for protection of hazardous and emergency response facilities are similar to the performance goals used by the Department of Energy (DOE) to develop the design and evaluation criteria for DOE facilities (DOE-STD-1020-2002). The DOE uses an annual probability of exceedance of 1E−5 to establish the seismic loads used in the design of facilities that handle hazardous material or could potentially endanger workers or the public or interrupt a significant mission if they are damaged. Assuming a launch rate of 33 launches per year and that each launch generates the maximum allowable risk of 1E−6, the annual risk to critical assets could be as high as 0.3E−4, which compares favorably to the value used by the DOE to protect workers and the general public from the impact of earthquake hazards on their facilities.

[63] Department of Defense. "Definition of Terms for Reliability & Maintainability." MIL-STD-721C. 12 June 1981. Cancelled, no replacement.

Since MTBDE and MTTRS are range-dependent, there is no single P_I criterion for all range and range user assets. The following is an example of how the standard could be applied to critical assets at the ER and WR.

4.7.3.2.1 Range assets

These ranges require an A_o of 89.29% for range systems.[64] Assuming it takes 2 years to restore an asset and there are 33 launches per year, the likelihood of a scrub due to the unavailability of a critical range asset can be computed as follows.

$$\begin{aligned} MTBDE &= \frac{(A_O\ x\ MTTRS)}{(1-\ A_O)} = 16.67 = 0.05997\ downing\ events/year \\ \frac{downing\ events}{launch} &= 0.05977\,\frac{downing\ events}{year} \div 33\,\frac{launches}{year} \\ &= 0.00182 \end{aligned} \tag{4-15}$$

So, a P_I of 1E−3 would maintain the range's operational availability of 89.29%

An MTTRS of 2 years and launch rate of 33 launches per year are conservative for the WR. An MTTRS of 1 year is more in line with the 5 months it took to relocate their telemetry processing system to their operations control center and a launch rate of 16 launches per year is more in line with what they have done over the last few years. If these values were used to calculate downing events per launch, then the likelihood of having a critical range asset down at the time of a launch is 0.0075, which is within an order of magnitude of 0.00182. Using a P_I limit of 1E−3 allows for uncertainty in ensuring the range's operational availability.

4.7.3.2.2 Range user assets

Launch scrubs for spacelift launches (CY2000 – 2018) due to range user problems with their vehicle or launch equipment was 11% for the most dependable launch vehicle (Atlas V), or an A_o of 89%.[65] This is consistent with a MTBDE of 0.377 years or 2.654 events per year based on the longest scrub duration of 17 days. With 33 launches per year, the allowable probability of downing events per launch is 8E−2. Using a P_I limit of 1E−3 protects for debris impacts that can cause a moderate level of damage, which are expected to have a longer MTTRS.

A review of the level of hazard that range users have exposed their launch support equipment to can also help establish an acceptable probability of impact limit for range user assets. For WR launches, the probability of damaging launch support equipment due to the impact of one or more fragments capable of penetrating them is typically between 0.001E−3 and 6E−3. A P_I limit of 1E−3 is less than the maximum hit probability that range users have accepted in the past.

The impact probability does not account for the level of damage to protected assets. It is useful for defining an area of concern for critical assets; however, an assessment based on impact

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[64] Draft Systems Safety Specification for the Launch Test Range System (LTRS), Revision K, Document # SS-010010, 19 December 2008

[65] Aerospace Briefing, 18 May 18, Launch Scrub Data for Launch Service Providers & Spacecraft

probability alone may be too conservative and unnecessarily restrict range activities. If the P_I criteria for an asset is exceeded, then the expected level of damage may also need to be evaluated. The percentage of damage for the impact probability limit should not cause a degree of structural failure that would damage critical equipment within the facility or require an extended amount of time to repair the facility assuming the hazard impinges on the asset's most vulnerable structural component.

4.7.4 Evaluation of Hazards

An impact probability analysis should be done to evaluate the hazards to critical assets in the vicinity of the flight that require protection from potential debris impact. The analysis should be done according to the steps in the risk management process described in Chapter 2. The procedure can be summarized as follows.

a. Identify hazards. Identify the critical assets and the hazards that could threaten them.

b. Assess the risks. Calculate the risk to the critical assets by determining impact probabilities for the direct impact of an intact vehicle or hazardous fragments.[66] In addition, determine impact probabilities for a threshold overpressure for the nearby impact of explosive fragments. Table 4-18 provides estimates of the incident pressures at which different types of damage occur for typical structures.[67] If the impact probability is high, do a more detailed analysis to determine the potential level of damage for the critical assets using structural vulnerability models developed specifically for these assets (see Chapter 6 for damage levels that could make a building unusable).

Table 4-18. Damage Approximations From Overpressure

Damage	Incident Overpressure (psi)[68,69,70]
Typical window glass breakage	0.15 – 0.22
Minor damage to some buildings	0.5 – 1.1
Panels of sheet metal buckled	1.1 – 1.8
Failure of concrete block walls	1.8 – 2.9
Collapse of wood framed buildings	Over 5.0
Serious damage to steel framed buildings	4 – 7
Severe damage to reinforced concrete structures	6 – 9
Probable total destruction of most buildings	10 – 12

A probability of percent damage analysis can be done to evaluate whether the level of damage to critical assets is acceptable. The level of damage depends on the structural

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[66] The probability of impact analysis could be done twice: the first time with all the fragments and, if the P_I exceeds the acceptance criterion, a second time with only the fragments that are assets to the critical assets. For example, if a critical asset is contained in a facility, then the hazard thresholds for buildings could be used to filter out fragments that are not capable of penetrating different building classes.

[67] FEMA. "Primer to Design Safe School Projects in Case of Terrorist Attacks." Report 428. December 2003. Retrieved 17 October 2023. Available at https://permanent.fdlp.gov/lps44537/fema428.pdf.

[68] Kinney, G. and K. Graham. *Explosive Shocks in Air*. 2nd edition. Berlin: Springer, 1985.

[69] Montgomery, R. and J. Ward. "Facility Damage and Personnel Injury from Explosive Blast." Research Triangle Institute Technical Report RT/5180/26-08F. April 1993.

[70] Glasstone, S. and P. Dolan. *The effects of nuclear weapons*. Washington, DC: Headquarters, Department of the Army. 1977.

characteristics of the assets and their response to a blast wave or fragment landing on the roof structure. Building and facility damage models have been developed for generic building types found at the ER and WR. These models can be used to determine the percentage of damage to an asset. The relationship between percent damage and impact probability is based on the impact distribution of the falling debris.

c. Analyze risk and control measures. Determine if the impact probability exceeds the probability of impact criteria for any protected assets. If it does, then determine the percentage of damage to these assets. If the risks are not acceptable, then work with the range user and/or range safety personnel to determine the feasibility of the control measures. Potential control measures include modifying the vehicle abort/destruct system, modifying the mission, modifying the ILL, or modifying the abort/destruct criteria. The analyst should also consider whether the hazard is mitigated by the protective measures designed to protect personnel from hazardous facilities. For example, personnel may be located outside the safety clear zone required for hazardous facilities containing explosives.

d. Make risk control decisions. Present the results of the analysis to the decision authority. It may need to be presented to both the range commander and the asset owner. The decision authority should make a go/no-go decision based on the probability of damaging the critical assets. If the cost of repairing the assets was determined, then the decision authority should also consider the cost of repairing them versus the cost of holding the operation until the probability of damaging them is acceptable.

Note that this table correlates damage to overpressure only. In fact, impulse plays a very large role in damage to substantive structures and, in contrast, a very small role in the breakage of glass. More comprehensive damage models are based on a combination of both overpressure and impulse. This table is useful in indicating the damage trend based on a single measure, overpressure.

4.8 Infrastructure Protection

Infrastructure as discussed in this standard and supplement encompasses equipment and facilities that are intended to function as sub-subsystems of a larger whole, regardless of any direct relationship to the mission planning, execution, or response to mishaps. Therefore, protection of this type of infrastructure needs to protect not only the equipment itself but the functionality of the system to which it contributes.

4.8.1 Infrastructure Requiring Protection

As with critical assets, hazard analysis for the protection of infrastructure begins with an enumeration of infrastructure that is placed at risk by threats from the mission. This enumeration can begin at the Tier 1 stage. Infrastructure that is not a critical asset is identified by comparison with the examples in Table 4-19, which groups infrastructure at the unit component level into three major categories.

Table 4-19. Infrastructure Examples and Categories

Category	Representative Infrastructure Type	Typical Functionality and Distinguishing Characteristics

Type I	Motors/pumps and transformers	Infrastructure components whose function is to generate or transform energy. Typically heavy and compact unit components.
	Wind turbines	
	Backup generators	
Type II	Load centers, photovoltaic panels, and solar thermal collectors	Infrastructure components used in the temporary storage or consumption of material or energy. Typically bulky (may be heavy), with usually large hazard areas to generic mission debris.
	Electrical substations	
	Water heaters, containers, and tanks for bulk storage (water, fuel, chemicals)	
Type III	Transmission lines	Infrastructure components whose functionality is primarily focused on the distribution/transmission of energy and material over long distances.
	Heating, ventilation, and cooling ducting and plumbing	
	Information networks	

The Tier 1 analysis involves two stes: 1) performing a qualitative assessment to identify those items of infrastructure that may be threatened by the mission; 2) assessing each class (and potentially sub-class) of infrastructure to rank the level of impairment to functionality at the unit component level and at the system level into one of the four maximum damage severity classes (Table 4-20).

Table 4-20. Tier 1 Mandatory Acceptability Criteria: Maximum Severity versus Vulnerability for Mission-specific Hazards.

		Maximum Severity and Duration of Consequences 🟥 Exclusion area acceptance criteria 🟨 Risk-informed acceptance criteria			
		Severe System Consequences: mandatory repair with significant $ cost and/or accompanied by potential derivative exposure, and involvement of extra-local authorities. Potential for cascading consequences.	Mandatory Repair to infrastructure required with minimal social/political/ economic consequences and only local authority involvement. All consequences confined.	Elective Repair to infrastructure required with minimal social/ political/economic consequences (no accident/ environmental assessments). All consequences confined.	Nuisance to infrastructure, people, and range operations. Consequences acceptable to government and developer/operators.
Type of Vulnerability from Event	**Prompt and easily assessed damage to unoccupied infrastructure and/or early derivative exposure to people**(1)	Hazard areas will not encroach upon a facility (of N_{uc} unit components) that would permit the probability of incurring DSL 2(2) or greater on any *individual* unit component to exceed 10^{-6}, that is: $\Pr(UC_i \geq DSL\ 2) \leq 1 \times 10^{-6}$. *Or*—hazard areas (HA) will not encroach a facility that otherwise would permit a *cumulative* probability to exceed 10^{-6} for the *critical number* of unit components of incurring causing DSL 2(2) or greater.	Any single unit component must not be exposed to a hazard resulting in DSL 2(2) or greater with a probability greater than 1 in 100000, that is: $\Pr(UC_i \geq DSL\ 2) \leq 1 \times 10^{-5}$. *Or*—HAs will not encroach a facility that otherwise would permit a *cumulative* probability to exceed 10^{-5} for the *critical number* of unit components of incurring causing DSL 2(2) or greater.	Any single unit component must not be exposed to a hazard resulting in DSL 2(2) or greater with a probability greater than 1 in 10000, that is: $\Pr(UC_i \geq DSL\ 2) \leq 1 \times 10^{-4}$. *Or*—HAs will not encroach a facility that otherwise would permit a *cumulative* probability to exceed 10^{-4} for the *critical number* of unit components of incurring causing DSL 2[2] or greater.	Any single unit component must not be exposed to a hazard resulting in DSL 2(2) or greater with a probability greater than 1 in 1000, that is: $\Pr(UC_i \geq DSL\ 2) \leq 1 \times 10^{-3}$. *Or*—HAs will not encroach a facility that otherwise would permit a *cumulative* probability to exceed 10^{-3} for the *critical number* of unit components of incurring causing DSL 2(2) or greater.

(1) Debris hazards and/or air blast.
(2) See Table 4-21 for definition of DSL (damage severity level).

Table 4-21. Severity Level Definitions

Damage Level	Definitions	Associated Damage Index
No Damage	Component functions without repair	**0**
Regular Repair	Item can be repaired by reasonable competent mechanic working with basic set of tools	**1** Onset of regular repair **2** Regular repair damage assured (significant repair time required)
Special Repair Damage	Item can be repaired by specially trained mechanic working with special set of tools	**3** Onset of specialized repair damage **4** Specialized repair damage assured
Total Damage	Item is beyond repair	**5** Total Damage

4.8.2 Potential Hazard Sources

The hazard sources that should be considered when evaluating the risk to infrastructure are debris impacts, overpressure, fire, and toxic threats.

The term infrastructure, as used here, represents equipment and facilities that are typically physically further removed from launch areas than mission-critical assets. For this reason, the likelihood of fire and toxic threats and to some extent overpressure from explosions to infrastructure will be smaller than for critical infrastructure simply as a result of separation. Hence, risk to infrastructure will generally be dominated by damage caused by inert debris impacts except in cases where explosive debris may dominate the debris list.

4.8.3 Evaluation of Hazards at Tier 1 and Tier 2

The Tier 1 analysis is intended to simplify and expedite the risk management process by allowing risk modeling and acceptance decisions that can be framed and answered in a qualitative way to be evaluated first. The Tier 1 step addresses the qualitative consequences of high-level system functionality impairment and low-level unit component damage. It is also the step in which semi-quantitative and important questions can be addressed with stakeholders and subject matter experts. For example, an infrastructure system may be composed of many unit components, such as a wind turbine farm is composed of many individual wind turbines. The Tier 1 step is where a question is asked such as “what is the critical number of wind turbines that could sustain mandatory repair damage without system-level impairment or the need for mitigation through operation or stakeholder involvement?” Another relevant question would be “what would be the possible derivative consequences if damage to a rotating blade occurs and the blade is ejected a considerable distance?”

Answering these questions leads to the selection of the appropriate protection criteria (neither too lax nor over-conservative) for use after Tier 2 vulnerability assessment.

After the initial scrub of Tier 1 maximum severity consequences, a Tier 2 analysis is performed. The Tier 2 analysis mirrors the recommendations in Subsection 4.7.4 for the evaluation of hazards for critical assets. An impact probability analysis should be done using recommended vulnerability flowcharts and damage thresholds for damage at DSL 2 and DSL 5. Note that acceptance criteria at Tier 1 are framed in terms of the probability of incurring DSL 2 or greater; however, the relative probability of DSL 5 occurring is necessary to justify the initial assessment of maximum consequence severity at Tier 1, especially should functionality of the critical number of unit components be an issue.

The Tier 2 analysis should address hazards from the nominal mission and the outcomes from all plausible malfunctions, with a specific recommendation to contemplate maximum severity for mandatory repair and severe system damage.

The quantitative result (or results) from the Tier 2 step will be probabilities of DSL 2 or greater for the infrastructure classes that are at risk. These damage severity probabilities are then compared against the acceptance criteria identified during the Tier 1 step.

4.8.4 Vulnerability Flowcharts

This section currently contains vulnerability flowcharts that have been developed for protection of wind turbines and transmission lines. These flowcharts are used to diagram the mapping between mission threats, likely unit component damage modes, and failure mechanisms, and through to damage severity assessment. The current flowcharts presume the mission threats are predominately from debris.

Figure 4-14 shows the vulnerability flowchart for wind turbines, and Figure 4-15 shows the vulnerability flowchart for transmission lines.

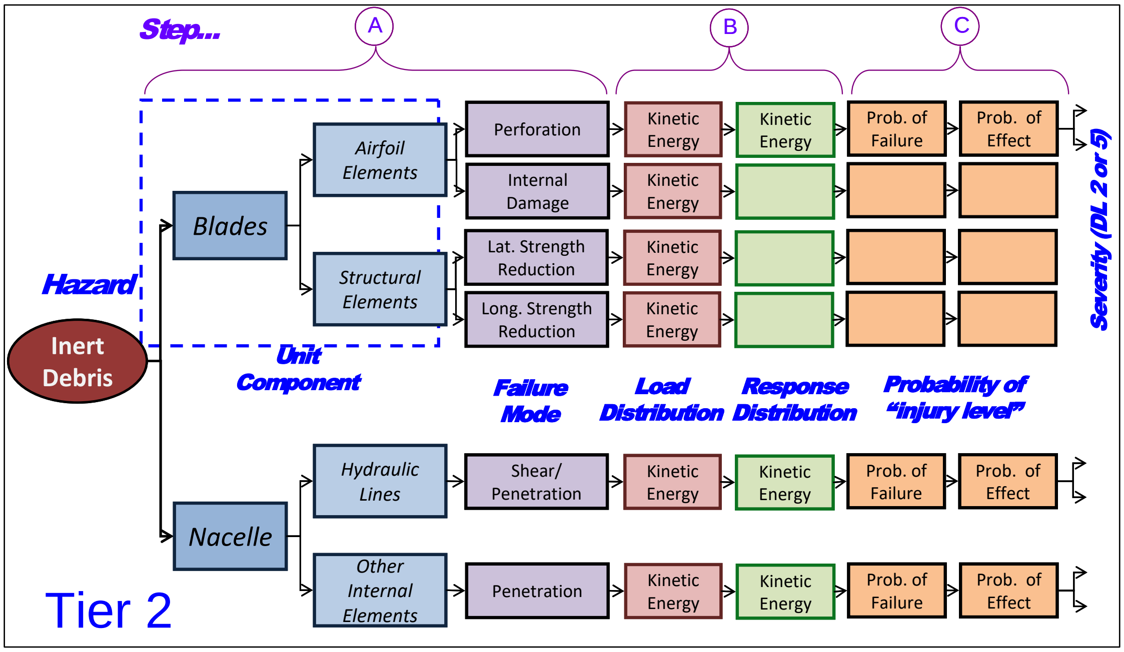

Figure 4-14. Wind Turbine Vulnerability Flowchart

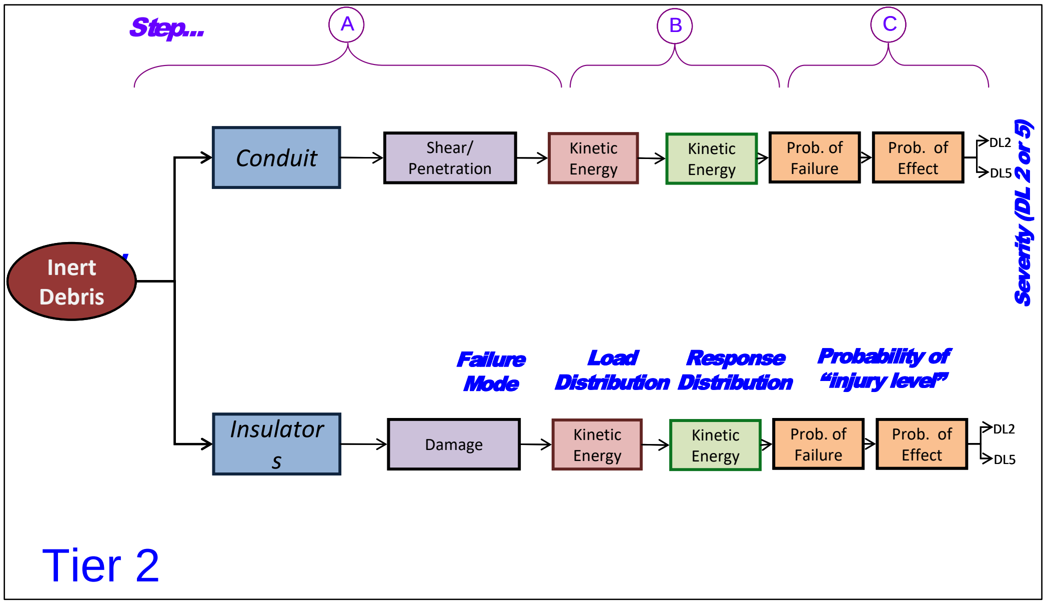

Figure 4-15. Transmission Lines Vulnerability Flowchart

4.8.5 Scaling Relationships

Implementation of the consequence assessment process diagrammed in the vulnerability flowcharts in Subsection 4.8.4 requires reasonably accurate knowledge of the hazard areas. The scaling relationships presented in this section allow these hazards areas to be estimated from basic knowledge of the ratings or name-plate capacities of the impacted infrastructure. This type of information is generally public information, whereas detailed knowledge of individual unit components is proprietary and/or difficult or expensive to obtain separately.

Figure 4-16 shows a notional layout of a wind turbine indicating the regions at risk to vertically falling debris.

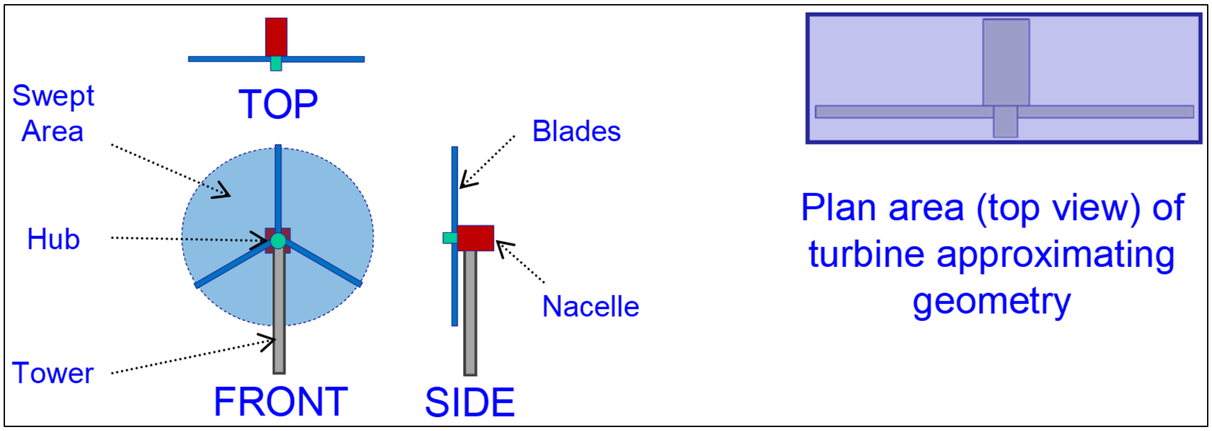

Figure 4-16. Wind Turbine Hazard Area Geometry

Figure 4-17 depicts the relationship between the turbine's exposed areas to vertically falling debris and the wind turbines' power capacity (based on manufacturers' data).

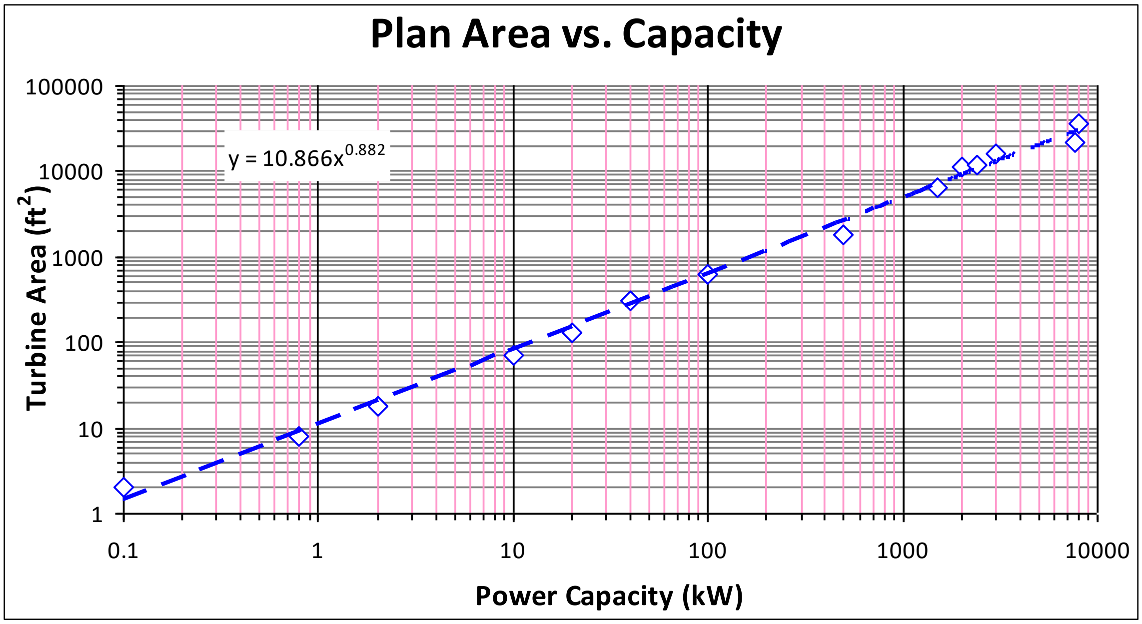

Figure 4-17. Scaling Relationship for Exposed Area for Wind Turbines

Figure 4-18 is a plot of manufacturers' data gathered from the literature showing the empirical relationship between blade lengths and power capacity.

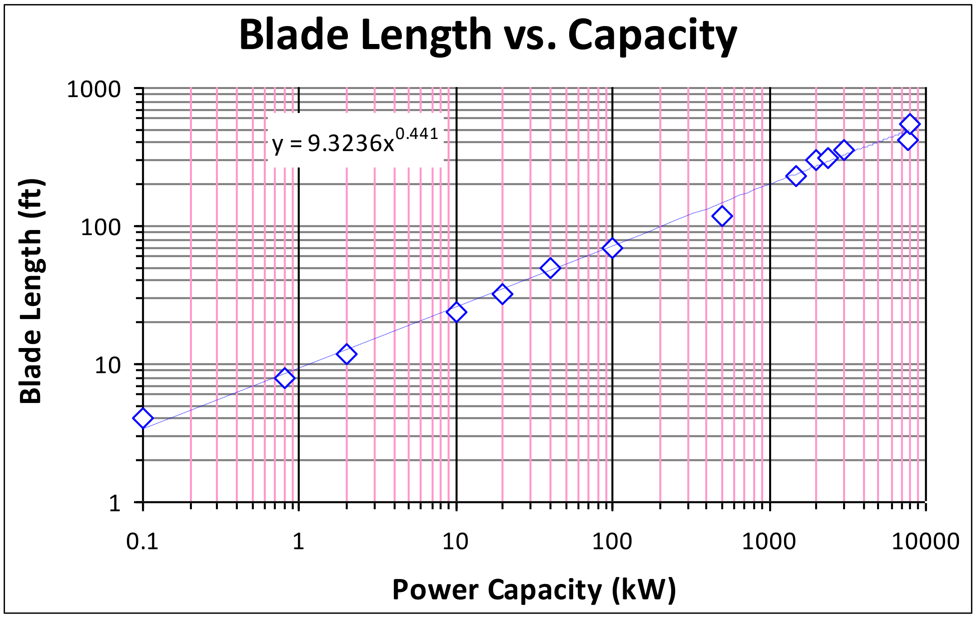

Figure 4-18. Scaling Relationship for Wind Turbine Blade Length

These plots illustrate how publically available data can be used to relate geometry of infrastructure to more widely available information about the systems, in this case the power capacity of wind turbine generators.

4.9 Uncertainty in Risk Determination

4.9.1 Introduction

Risk analysis is a process that is dependent upon mathematical models with many parameters that are used to simulate the consequences of vehicle failures and the resulting hazardous events. The models are approximations at various levels of sophistication and the model parameters are frequently difficult to quantify accurately. Consequently, the results of these studies can have considerable uncertainty. There have been a few comparisons of launch risk analysis models (from simplistic to detailed models) that have shown differences in risk predictions of up to three orders of magnitude.[71] Even among the most proven models there can be significant differences when still using common input data. Thus, results from risk analysis programs have uncertainty coming from both the model designs and the model parameters.

There are two categories of uncertainty that occur in a risk analysis: aleatory and epistemic.

Aleatory uncertainty, i.e., the uncontrollable **variability** of events, is typified by the distribution of debris impacts from one accident to another (the same initial conditions will not produce exactly the same consequences in sequential trials). In launch risk analysis models, the effect of aleatory uncertainty is most frequently averaged in the process of determining impact probability or E_C, which is the average number of casualties when considering all of the aleatory uncertainties as explained in Subsection 4.9.2.

Epistemic uncertainty, i.e., the **uncertainty** in the model and the model parameters, is expressed as probability distributions for risk measures, such as E_C; when *epistemic* uncertainty is accounted for, then the computed E_C is no longer a point value. The epistemic uncertainty derives from the model and parameter inadequacies that introduce model or systematic uncertainty. Epistemic (or model) uncertainty must account for any bias or conservatism in the model.

Thus, from a launch risk analysis point of view, aleatory uncertainty is the randomness in the occurrence and consequences of a launch accident, and epistemic uncertainty represents the uncertainty in the ability of the model to compute the true risk.

4.9.2 The Role of Aleatory Uncertainty in a Launch Risk Analysis

An example of the aleatory uncertainty is shown in Figure 4-19. The four frames in the figure represent four different samples of randomly generated debris impact points resulting from a Space Shuttle vehicle failure and breakup scenario. Here, a vehicle failure and breakup scenario is defined by a specific mode of failure occurring at a specific time of flight and resulting in a vehicle breakup and scatter of debris, with every fragment having a unique impact point.

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[71] In 2003, the MDA-sponsored Hazard Modeling and Simulation Committee initiated an activity to compare the performance of the different ranges' risk analysis programs. Several ranges offered sample launch risk analysis scenarios and risk analyses were performed using each range's tools. In the one case where all the participants produced a P_I or E_C for the same scenario, the range of E_C values was three orders of magnitude. This is the only known occasion where the performance of different risk analysis programs has been systematically compared.

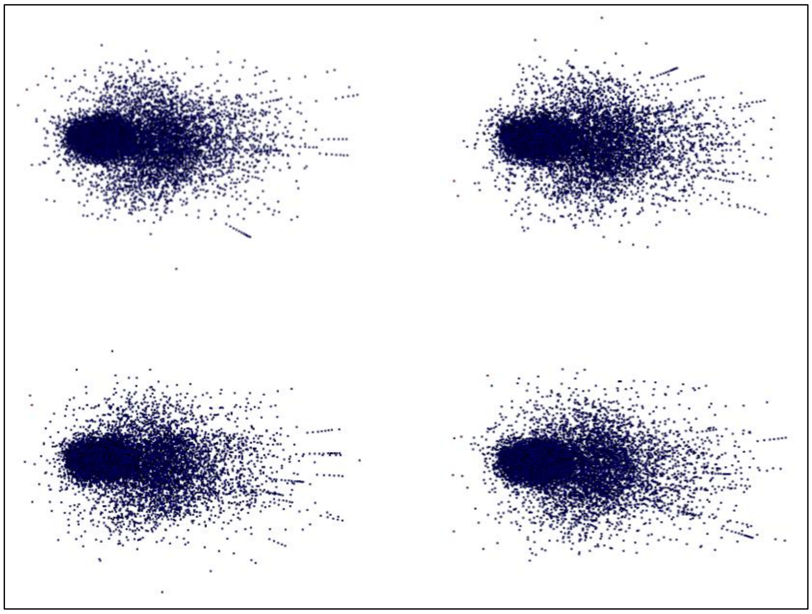

Figure 4-19. An Example of Aleatory Uncertainty: Four Scatter Plots for Debris Impact Based on the Same Dispersion Model

This is a Monte Carlo process. Once the impact points and impact conditions have been determined, the impacts are evaluated one by one to count the number of casualties. Each cycle of the Monte Carlo process will produce a single total number of casualties. Each cycle will also have a probability based on the likelihood of the event and the total number of cycles in the simulation. The result of each cycle (a number of casualties and a probability) is entered into a histogram of probability as a function of the number of casualties. Each entry adds to the probability in the column associated with the number of casualties resulting from the particular cycle. The histogram is shown in Figure 4-20.

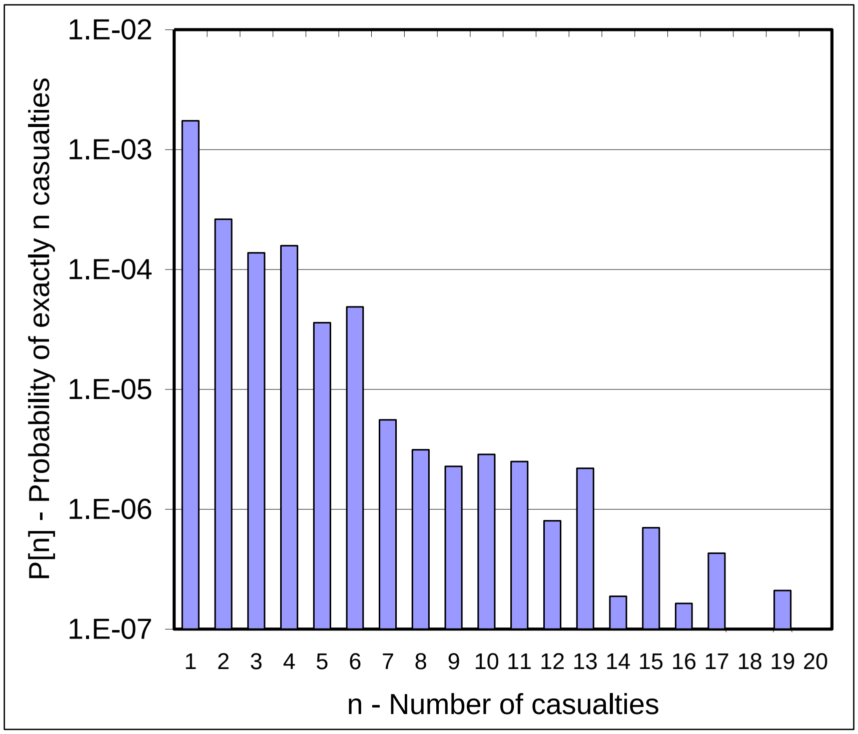

Figure 4-20. Discrete Probability Density Function for Number of Casualties Representing the Aleatory Uncertainty in the Risk Analysis

The average number of casualties from the histogram is the E_C, i.e., $E_C = \sum_{i=1}^{n_{max}} \left(i * P[i] \right)$ where *i* is an integer and *P[i]* is the corresponding probability of *i* casualties. The variability in the results defined in the histogram describes the uncertainty in the number of casualties due to the aleatory uncertainties in the problem (e.g., wind, explosive debris scatter, etc.). If the aleatory uncertainties were to be set to zero, there would be only one column in the histogram representing the deterministic result for the number of casualties predicted with the probability of the vehicle failure scenario. The histogram can also be used to compute a standard deviation, σ_C, of the number of casualties. This standard deviation represents the uncertainty in the estimate of the number of casualties due to aleatory uncertainty.

$$\sigma_C^2 = \sum_{i=1}^{n_{max}} \left(i - \mu_i \right)^2 * P[i] = \sum_{i=1}^{n_{max}} \left(i - E_C \right)^2 * P[i] = \sum_{i=1}^{n_{max}} \left(i^2 * P[i] \right) - E_C^2 \tag{4-16}$$

σ_C is a measure of the breadth of the distribution. It is related to the risk profile. If σ_C is large, the risk profile will have a shallower slope and have a higher likelihood of catastrophic consequences. If σ_C is small, the risk profile will be steep.

The CCD of the histogram in Figure 4-20 provides the probability of exceedance of any particular number of casualties. The CCD is commonly known as the risk profile and is represented by the equation $P[\geq n] = \sum_{i=n}^{n_{max}} P[i]$. It is a discrete distribution, having only integer values. Figure 4-21 shows the risk profile associated with the discrete PDF (histogram) illustrated in Figure 4-20.

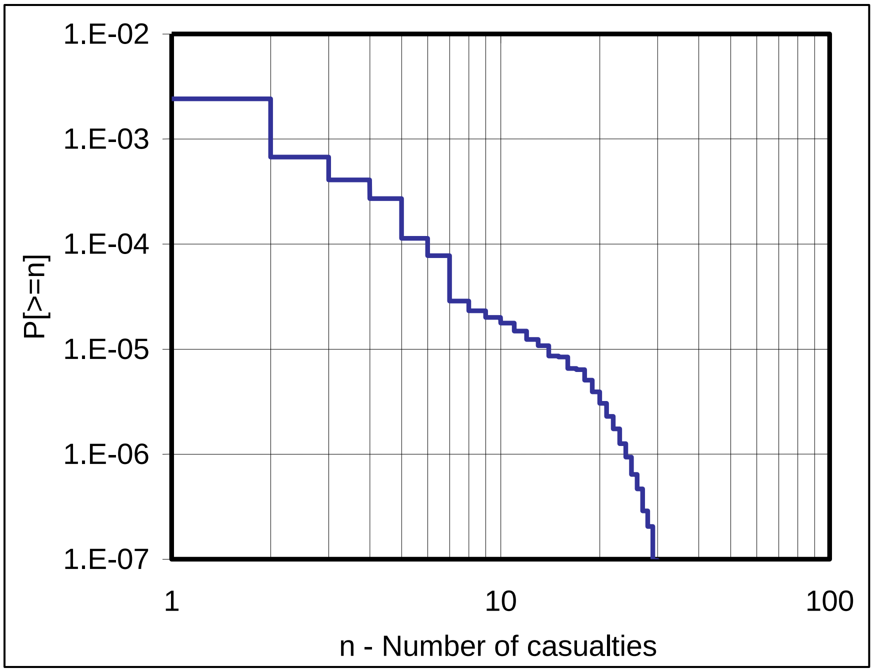

Figure 4-21. The Discrete Risk Profile - the Complementary Cumulative Distribution of the Aleatory Uncertainty in the Number of Casualties

Note that if the risk profile is based only upon aleatory uncertainty, then the information that is used to evaluate catastrophic risk is also based on aleatory uncertainty and that is the way it should be – the catastrophic potential of a launch is due to the mission, vehicle, and exposure variations, and not due to the ability of the analyst to accurately model/simulate the event. Thus E_C, σ_c, and the risk profile are functions of aleatory uncertainty. The ability to accurately model/compute them is measured by the epistemic uncertainty.

Figure 4-22 describes the major elements of a debris risk analysis program. The basic risk analysis processes as shown in the figure are dealing with aleatory uncertainties, and the uncertainty in the ability of the model and parameters to produce the true E_C is epistemic.

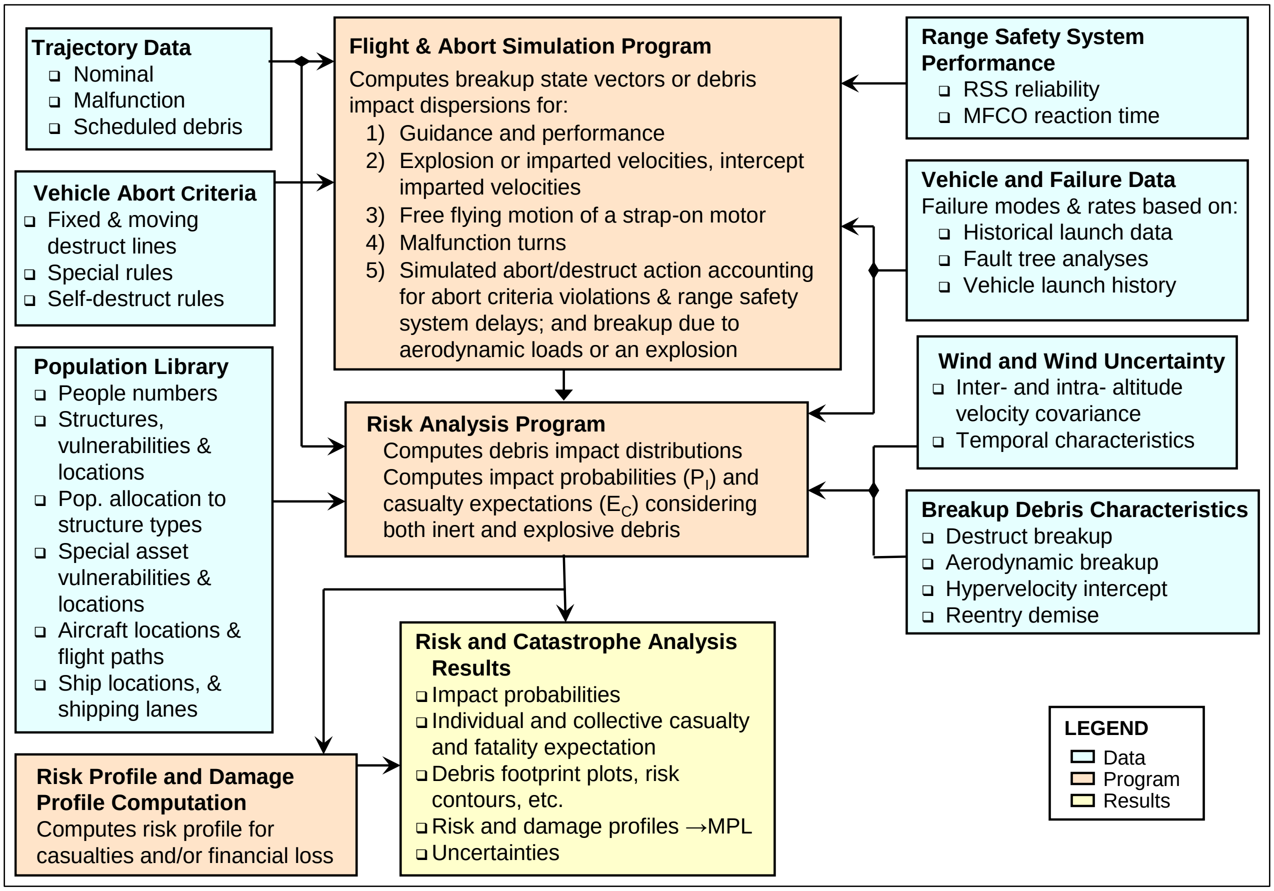

Figure 4-22. Generic Flow of a Debris Risk Analysis Program using Aleatory Uncertainties to Determine the E_C and the Risk Profile

4.9.3 Risk Analysis Computational Schemes

There are three general computational schemes for launch risk analysis programs for accomplishing the tasks typified in Figure 4-22. One is to use a Monte Carlo approach, where values are sampled from statistical distributions used to characterize aleatory uncertainties. A Monte Carlo approach will sample accidents, each of which has its own set of randomly computed impacts for every piece of debris based on these aleatory uncertainty distributions. This process, containing detailed simulations of each fragment's velocity perturbation and trajectory, simulation of all possible motions of the failing vehicle, operation of the RSS, etc., must be repeated over all times in flight and for all vehicle failure modes with sufficient frequency to produce a stable answer. Monte Carlo simulations such as these are generally very long running and not very flexible for doing mission planning or launch support. Consequently most developers have shied away from that approach, have developed programs using assumed analytical impact distributions, and have integrated the distributions over the areas at risk to determine impact probabilities. The accuracy of this second class of programs is dependent on (1) the applicability and parametric uncertainty of the assumed distributions representing the impact distributions; (2) the ability to properly model vehicle behavior during a malfunction; and (3) the simulation of the RSS, the abort criteria, and RSO response. There are also other considerations such as proper modeling of the meteorology and the vulnerability issues associated with inert debris impacts and explosive debris detonations or deflagrations.

Presumably these could be modeled more accurately with a Monte Carlo simulation but at much greater cost and use of computer time. One would assume that the Monte Carlo approach would have a smaller epistemic uncertainty in determining E_C than the second but faster approach that relies on distributions. A third approach is a hybrid of the first two; it contains features of both producing more accuracy and being more efficient in terms of cost and computer time.

4.9.4 Procedures to Compute Epistemic Uncertainty of Risk

The most accurate method of computing epistemic uncertainty is to use a Monte Carlo approach that can be completely general from the standpoint of the probability distributions used for sampling model parameter uncertainties. If part of the epistemic uncertainty is sampling between different sub-models (such as alternative breakup models and debris lists), this may be accomplished best by the Monte Carlo method. Figure 4-23 and Figure 4-24 describe the epistemic uncertainty computational procedures for the two general risk analysis approaches (with and without Monte Carlo) discussed in the previous section. The procedure in Figure 4-23 includes a full Monte Carlo risk analysis in the inner loop (aleatory) and this procedure is overlaid with a Monte Carlo procedure in the outer loop to determine the average E_C given the epistemic uncertainty. This is a very long running computational process. A convergence criterion is included in both loops to establish a requirement for accuracy of the final result.[72]

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[72] A typical convergence testing is as follows. During the cycling of computations, both the sampled mean and standard deviation through the current cycle 'n' are computed and a standard error of the mean is determined by dividing the sample standard deviation by the square root of the number of cycles, i.e., $SE_{\bar{E}_C} = \frac{s}{\sqrt{n}}$ where 's' is the sample standard deviation and 'n' is the size of the sample (number of Monte Carlo cycles). The convergence criterion can require that the uncertainty in the final result be no more than X% of the sampled result ($\overline{E_C}$) with Y% confidence. The confidence limits, in this case, are computed using the T distribution and thus, for Y% confidence (two-sided), the convergence criterion becomes $t_{(n-1),\alpha/2} \times \frac{s}{\sqrt{n-1}} \le \left(\frac{X\%}{100}\right) \times \overline{E_C}$ where $t_{(n-1),\alpha/2}$ is a variate of the T distribution with n−1 degrees of freedom and $\alpha = \left(1 - \frac{Y\%}{100}\right)$.

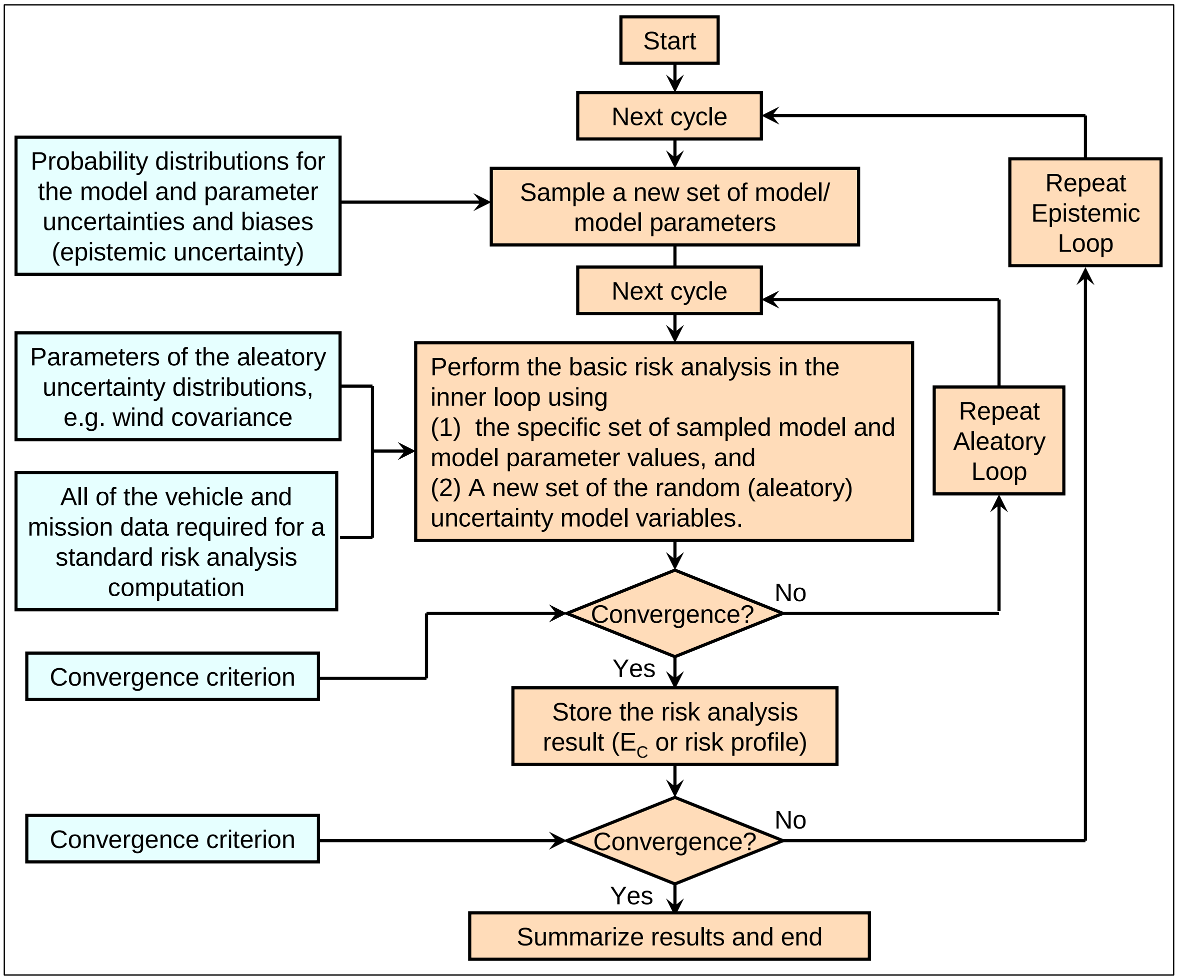

Figure 4-23. General Flow Diagram for Determining Epistemic Uncertainty of E_C Including the Monte Carlo Aleatory Inner Loop

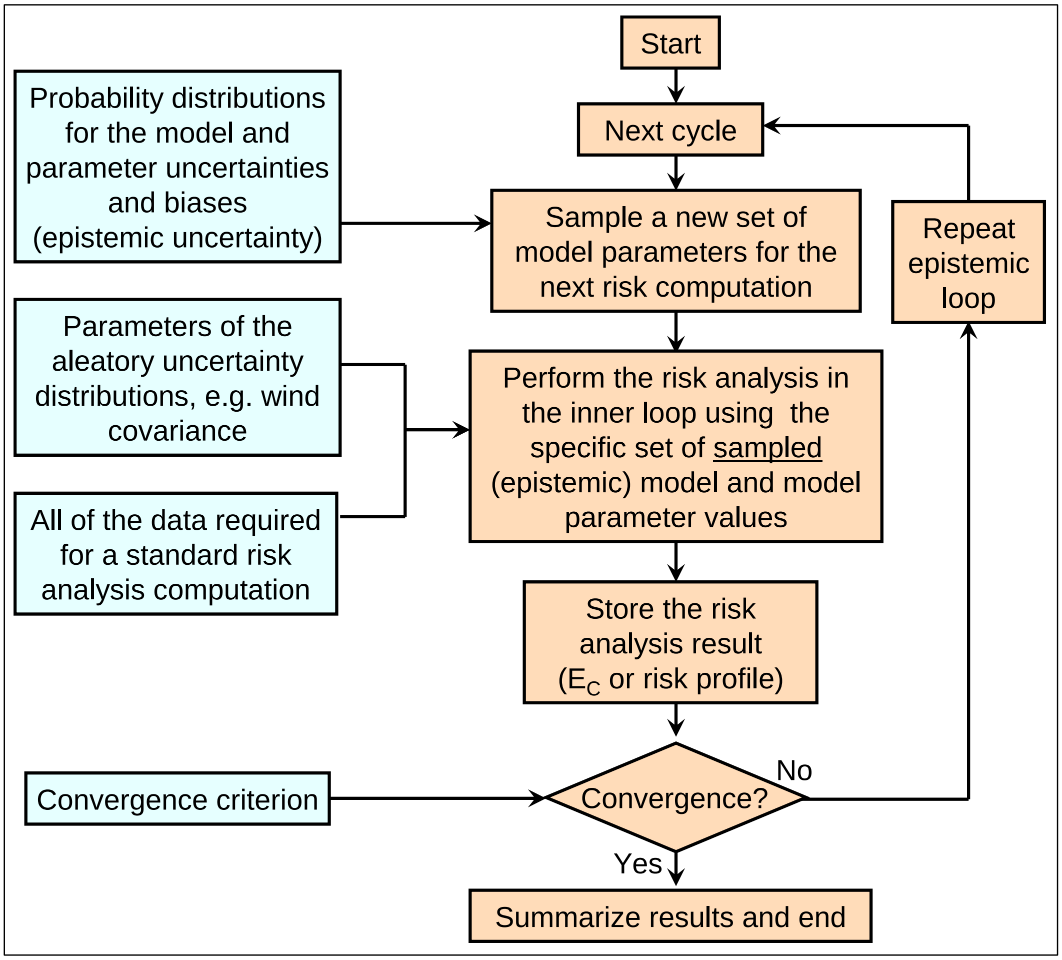

Figure 4-24. General Flow Diagram for Determining Epistemic Uncertainty of E_C Using a Program that Uses Integration Over Aleatory Distributions to Obtain E_C

Figure 4-24 replaces the Monte Carlo risk analysis inner loop with either of the other two distribution-based risk analysis methods described in Subsection 4.9.3. This approach is obviously much faster and more easily implemented.

Figure 4-24 applies to those risk analysis models that compute E_C by using impact probabilities determined by integrating over aleatory impact distributions. The inner aleatory loop has been eliminated. The outer epistemic loop will still need the convergence criterion to establish a satisfactory number of Monte Carlo cycles to achieve the desired accuracy in the estimate of the average E_C. If the risk analysis program is a hybrid containing some Monte Carlo features, the uncertainty computation time is increased.

The number of sampled uncertainty parameters does not have a large influence on computing time (the sample standard deviation of E_C and the number of cycles do effect computing time); however, some parameters play significant or dominating roles. These include failure probability (which has a very large uncertainty, particularly for new vehicles), the debris list, and the fidelity and accuracy of the impact dispersion models. The sources of uncertainty are covered in the following section.

4.9.5 An Alternative Approximate Model for Determining the Average E_C Due to Epistemic Uncertainty

The epistemic uncertainty discussion to this point has focused on a Monte Carlo approach with complete generality with regard to how competing sub-models (such as for debris lists) and model parameter uncertainties are treated. There is a less-accurate method where uncertainty factors are applied to the overall model. Assume that E_C is a function of a set of model parameters p_1, p_2, p_3, etc. Since E_C can take on very large variations it is usually more appropriate to use logarithms, i.e., $ln\,E_C = f(ln\,p_1, ln\,p_2, \ldots)$. Taking the partial derivatives of $ln\,E_C$ with respect to each of the logarithms of the parameters, we get $\frac{\partial lnE_C}{\partial ln\,p_1}, \frac{\partial lnE_C}{\partial ln\,p_2}, \frac{\partial lnE_C}{\partial ln\,p_3}, etc.$ These partial derivatives can be used to form a linear equation showing the dependency of changes in $ln\,E_C$ on the logarithms of the parameters.

$$\Delta lnE_C = \frac{\partial lnE_C}{\partial ln\,p_1}\Delta ln\,p_1 + \frac{\partial lnE_C}{\partial ln\,p_2}\Delta ln\,p_2 + \frac{\partial lnE_C}{\partial ln\,p_3}\Delta ln\,p_3 + \ldots = \sum_{i=1}^{n}\frac{\partial lnE_C}{\partial ln\,p_i}\Delta ln\,p_i \qquad (4\text{-}17)$$

If we assume statistical independency between the parameters, with the uncertainty of each being represented as $\sigma_{ln\,p_i}$ (i.e., with the parameters being log-normally distributed) with i = 1, 2, 3, …, then the variance of the uncertainty in $ln\,E_C$ can be expressed as

$$\sigma^2_{ln\,E_C} = \sum_{i=1}^{n}\left(\frac{\partial\,ln\,E_C}{\partial\,ln\,p_i}\sigma_{ln\,p_i}\right)^2 \qquad (4\text{-}18)$$

The variance is about the mean estimate of $ln\,E_C$. If the distributions of each of the logarithms of the parameters are statistically independent of each other and the products $\left(\frac{\partial\,ln\,E_C}{\partial\,ln\,p_i}\sigma_{ln\,p_i}\right)$ are similar in size with the other products, then the distribution of $ln\,E_C$ tends toward a normal distribution per the Central Limit Theorem. Hence the distribution of E_C tends toward being lognormally distributed.

This is a very simple and convenient way of obtaining the epistemic uncertainty distribution of E_C and may be all that is necessary in trying to make a point with regard to the uncertainty of the risk estimate. In effect, it replaces the outer Monte Carlo loop in Figure 4-23. It has a number of shortcomings that need to be noted before automatically adopting the procedure. First, failure probability can be very dominant and that can weaken the validity of the Central Limit Theorem assumption. In addition, the parameters that are varied are assumed to have a universal effect on the determination of E_C; however, they may not; their variation may only affect part of the solution. For instance, the uncertainty in yield of exploding fragments will only apply to those parts of the problem or time when people can be affected by an explosion. Similarly uncertainty in roof vulnerability only applies to cases where pieces of inert debris are impacting structures sheltering people.

4.9.6 Model and Parameter Uncertainties and Biases to be Considered in a Risk Analysis

Failure probability uncertainty usually dominates the total uncertainty in a risk analysis for new vehicles. Uncertainty in the failure probability decreases as the vehicle matures, so the number of launches is an important factor. The occurrence of a failure is aleatory. The probability distribution describing the uncertainty in P_{fail} is epistemic.

Debris characterization is also a significant factor, although it varies with the location and sheltering of population. There is very limited real data to validate vehicle breakup models. Uncertainty in the debris characterization is both aleatory and epistemic, but in the past has not been treated as aleatory. No one knows exactly how a vehicle will break up. Frequently the debris list resembles a parts list, although some may try to logically follow the sequence of vehicle break up. One way to model the epistemic uncertainty is to develop alternate debris lists that seem to cover the possibilities and then assign probabilities of occurrence to each of the lists.

Characterization of debris dispersion is very difficult considering all of the influences, such as vehicle behavior, the effect of destruct action, wind effects, imparted velocity, and aerodynamic characteristics. It is in this category where weaker risk analysis models can produce very poor predictions of impact dispersions and the resulting impact distribution, resulting in large errors in the predictions of risk. For instance, the assumption of a large standard deviation in an impact distribution is not necessarily conservative – it depends upon where the population centers are located relative to the center of the distribution. Once again, there is very limited data to validate models.

A good risk analysis model must be able to model the effects of the RSS: accounting for destruct criteria, RSO reaction, and system delays.

All of the vulnerability models have fairly large uncertainties but are not as dominating because the effect may be randomly higher or lower going from structure to structure and thus diminish the overall effect. On the other hand, if the models are deliberately conservative they may introduce a bias into the estimate of E_C.

Another area of uncertainty and bias is in the explosive yield models. Actual data is limited and not always applicable to the situations occurring in launch accidents. Thus safety analysts usually take a conservative position as to the predicted yield, introducing a bias into the analysis. Both liquid and solid propellant yield models are based on very limited data and, consequently, the uncertainties are quite large.

Population models are affected by sheltering and allocation of people between different sheltering categories.

Table 4-22 provides a summary of most of the uncertainties and biases that could be encountered in a launch debris risk analysis. It categorizes the sources, defines the uncertainty type and its bias, and gives a general indication of the relative importance to the uncertainty in the computed risk.

Table 4-22. Uncertainties and Biases to be Considered in a Launch Risk Analysis

Uncertainty Description		General Model Category	Type of Uncertainty	Uncertainty distr. currently or commonly used (A-aleatory, E-epistemic)	Bias	Effect on E_C Uncertainty	Comment
1	Failure probability	Failure probability	Failure probability is aleatory, its uncertainty is epistemic	(E) Beta distribution most straightforward, changes with the launch number	Most predictions are deliberately conservative	Dominant for new vehicles, less so as the vehicle matures	Must be evaluated by stage
2	Weighting of relative importance of previous flight success/failure experience (refers to "fading memory" or "learning" models)		Epistemic	Currently not modeled	No intended bias	Probably not a major effect on E_C uncertainty	
3	Failure rate vs. time		Failure rate is aleatory, its uncertainty is epistemic	Currently not modeled	A bias vs. time is created if the failure rate vs. time is not modeled properly	Highest with stages having high failure probability.	
4	Vehicle failure response mode (VFRM) allocation		Epistemic	Currently not modeled	No intended bias	Can have a big effect on E_C uncertainty	Manufacturer predictions of VFRM allocations seem to underestimate actual malfunction turn probability history
5	Discrete event failure probabilities		Aleatory	Currently not modeled	No bias	Depends upon the case	
6	Debris lists for different breakup conditions	Debris generation	Epistemic	Modeled using separate debris lists	No intended bias	Varies, can have a large affect when going from all inert debris to all explosive debris	
7	Debris characterization		Both aleatory and epistemic (E)	(E) Modeled using separate debris lists and probability of each option	No intended bias	Varies, can have a large affect when going from all inert debris to all explosion	
8	Modification of debris due to demise in the hypersonic velocity regime	Debris demise	Both aleatory and epistemic	Currently not modeled	Desire not to overestimate demise		Demise can contribute to 50% reduction in surviving debris mass
9	Scheduled debris (stages, fairings, etc.) impact dispersions	Debris dispersion	Aleatory and epistemic	(A) Frequently modeled as bivariate normal, but the downrange part becomes increasingly skewed with range. Best to use something like a skew-normal distribution	No intended bias	Usually no effect since missions try to keep scheduled debris away from population centers	
10	Meteorology - wind		Aleatory. Also epistemic in how the ranges actually use wind profiles for risks and destruct criteria	Multivariate normal distributions as a function of altitude	No bias unless introduced deliberately for conservatism	Can have a large effect on the point estimate of risk depending upon the particular wind conditions and exposed population.	There is also a large uncertainty in wind due to errors in measurement and variations with location
11	Meteorology - atmospheric density		Aleatory	Normal as a function of altitude	No bias	No measurable effect	
12	Impact dispersions due to ballistic coefficient (β)		Both aleatory (A) and epistemic	(A) β modeled as lognormal and impact distribution either lognormal in the ground intersection with the trajectory plane or with Monte Carlo simulations	Dependent upon the style of grouping of debris in categories	Small except in special cases with small βs in the launch area and with scheduled debris near population centers	
13	Impact dispersions due to lift		Both aleatory (A) and epistemic	(A) Bivariate normal impact distributions	Modeled as symmetric, no bias	Very small effect on average risk	The symmetry breaks down as the descent angle decreases

Table 4-22. Uncertainties and Biases to be Considered in a Launch Risk Analysis

Uncertainty Description		General Model Category	Type of Uncertainty	Uncertainty distr. currently or commonly used (A-aleatory, E-epistemic)	Bias	Effect on E_C Uncertainty	Comment
14	Impact dispersions due to imparted velocity		Both aleatory and epistemic	(A) Can be trivariate normal or have special distributions for destruct breakups or for hypersonic impacts. (E) can be a lognormal multiplier	No bias	Can be very significant	
15	Vehicle performance (I_{sp})		Aleatory	Currently modeled as Gaussian in up-range/ downrange only or simulated-impact distribution should be more skewed with range	No bias	Usually small	Biggest effect is downrange
16	Vehicle guidance (cross-range effect)		Aleatory	Gaussian	No bias	Could be slight or significant depending on the location of the population cross range of the flight track	A factor here is that the nominal trajectory provided by vendors is often NOT a good representation of the mean trajectory
17	Malfunction turn		Both aleatory and epistemic	(A) Complicated, best simulated	No bias assumed	Has a large effect on the risk	
18	Effect of range safety actions/controls		Aleatory	Complicated, best simulated	No bias assumed	Varies depending on the situation.	
19	Debris impact distribution type, size and shifts or biases		Both aleatory (A) and epistemic (E)	(A) Impact: bivariate normal or skew-normal. (E) Lognormally distributed multiplier on aleatory distr. parameters	Bias is the shift in the mean and is very hard to model	Obviously the aleatory uncertainty has a big impact. The model effect (epistemic) can also be large.	Debris distribution uncertainties are very difficult to model.
20	Model and parameters for casualty area for people in the open due to inert debris	Vulnerability	Both aleatory and epistemic	(E) Lognormal	The bias appears in the way different organizations model the debris lists (2)	Can affect the point estimate of E_C by a factor of 3 under certain conditions	
21	Model and parameters for casualty prob. for people in the open exposed to blast waves		Both aleatory and epistemic	Currently not modeled	Under evaluation, the criteria for casualty can have a large effect	Depends upon the casualty criteria	
22	Model and parameters for structure vulnerability and people vulnerability in the structures impacted by inert debris		Both aleatory and epistemic	Lognormal for epistemic. The aleatory effects tend to average out from building to building and have a very small effect.	Under evaluation	Moderate effect depending upon the sheltering of the population	
23	Model & parameters for yield from exploding propellant or propellant tanks		Both aleatory and epistemic	(E) Lognormal	Not intended, but the database is poor - better for solids than liquids	Can have a fairly large effect	The liquid propellant explosion models suffer from limited test data and tend to be conservative
24	Model and parameters for window vulnerability and people vulnerability due to the glass shards from the breaking windows in structures affected by blast waves resulting from explosive debris landing nearby		Both aleatory and epistemic (E)	(E) Log-uniform	Depends upon how drapes behind windows are considered	Moderate effect	
25	Model and parameters for structure vulnerability and people vulnerability in the structures affected by blast waves resulting from explosive debris landing nearby		Both aleatory and epistemic	Currently uniform	Current bias is modeled as a function of probability of casualty	Moderate effect	

Table 4-22. Uncertainties and Biases to be Considered in a Launch Risk Analysis

Uncertainty Description		General Model Category	Type of Uncertainty	Uncertainty distr. currently or commonly used (A-aleatory, E-epistemic)	Bias	Effect on E_C Uncertainty	Comment
26	Variations in human vulnerability		Both, simulated as aleatory	Not specific	Depends upon model assumptions. The bias has a bigger effect than the uncertainty	No measurable effect	
27	Variations in actual structure vulnerability relative to standard models in the program		Aleatory	Lognormal	None assumed, but a bias could exist relative to model and actual building construction practice	Moderate effect	
28	Variation in the vulnerability to aircraft catastrophic accident	Vulnerability (ships and aircraft)	Both aleatory and epistemic	Currently not modeled	Modeled to the conservative side in almost every assumption	While most underlying assumptions are conservative, there are a number of areas regarded as unconservative. Most notably as the use of composite material for aircraft construction increases, the modeling of aircraft based on aluminum construction becomes more obsolete. Investigations in process under funding by MDA and FAA/AST are addressing this issue. Findings sufficient to update these models are anticipated by the end of 2021. Since collective risk criteria in the standard do not address aircraft there is no effect on mission E_C calculations.	
29	Variation in the vulnerability to aircraft casualty producing accident		Both aleatory and epistemic	Currently not modeled	Modeled to the conservative side in almost every assumption	While most underlying assumptions are conservative, there are a number of areas regarded as unconservative. Most notably as the use of composite material for aircraft construction increases, the modeling of aircraft based on aluminum construction becomes more obsolete. Investigations in process under funding by MDA and FAA/AST are addressing this issue. Findings sufficient to update these models are anticipated by the end of 2021. Since collective risk criteria in the standard do not address aircraft there is no effect on mission E_C calculations.	

Table 4-22. Uncertainties and Biases to be Considered in a Launch Risk Analysis

Uncertainty Description		General Model Category	Type of Uncertainty	Uncertainty distr. currently or commonly used (A-aleatory, E-epistemic)	Bias	Effect on E_C Uncertainty	Comment
30	Vulnerability of people on/in ships		Both aleatory and epistemic	Currently not modeled	Modeled to the conservative side in almost every assumption	Biases in ship models are significant. Ships are best protected using NOTMARS which are semi-effective exclusion zones. When NOTMARS are properly constructed and enforced the ship contribution to E_C is negligible. The bigger issue is detection and enforcement	
31	Assignment of population to shelter categories	Exposed population	Epistemic	Currently not modeled	No intended bias	When the appropriate level of attention to resolving vulnerability based on number of people exposed, debris pattern size, and proximity to the center of debris patterns is exercised, the effect on E_C uncertainty should be minimal. The cost of so doing can be considerable. Guidelines to relate impact on E_C uncertainty of different levels of quantification of sheltering have not been developed in a structured fashion as of late 2019.	
32	Allocation of population within population centers or shelters		Aleatory	Uniform or grouped	No intended bias	Effect on average risk depends upon the scenario	Affects the risk profile
33	Population density		Epistemic	Lognormal applied as a multiplier	No bias	Effect on E_C is directly proportional to the population variation	
34	Ship traffic density	Both scheduled & unscheduled traffic	Both aleatory and epistemic	(E) Lognormal applied as a multiplier	No intended bias	Effect on E_C is directly proportional to the population variation	
35	Aircraft population density		Both aleatory and epistemic	(E) Lognormal applied as a multiplier	No intended bias	Effect on E_C is directly proportional to the population variation	Aircraft are not currently (2020) protected using an E_C criterion. Impact probabilities are computed for casualty- and catastrophe-causing impacts. Some ranges only use the former.

The failure probability directly affects the uncertainty. The failure probability uncertainty model is better if it accounts for uncertainty levels separately in each of the stages or flight phases and for different failure modes. There is also the issue of the probability distribution of failure versus time. Failure probabilities can be biased because of conservative predictions by the safety organization. Although the conservatism is appropriate in an analysis without uncertainty, it should be removed before making the uncertainty determination. The uncertainty analysis should be making an unbiased estimate of the average E_C and the uncertainty distribution of E_C.

The impact distributions have potentially large uncertainties due to the difficulty in modeling the true behavior of the failing vehicle prior to breakup. The best that can be done at this point is to model uncertainties as shifts (epistemic) in the midpoints of the impact distributions (aleatory) and scale sizes (epistemic) of the parameters of the impact distributions.

Some of the uncertainties in the Table 4-22 list can be modeled by uncertainty factors, i.e., the partial derivative approach discussed in Section 4.9.5; however, using uncertainty factors is a top-down approach and has the potential of leading to an inaccurate estimate of the effect of the uncertainty in those parameters on the calculated E_C, since many of the parameters may affect only part of the solution.

4.9.7 An Example

The following example illustrates the launch risk uncertainty analysis process. It is based on a launch risk analysis that used the footprint method to determine impact probabilities. The epistemic uncertainties of most concern were failure probability and the debris list. Other sources of uncertainty that were evaluated were: casualty area for people in shelters that are impacted by debris; impact distribution size; yield from exploding propellant and propellant tanks; probability of injury from a blast wave (sheltered or unsheltered); and population density. The mean failure probability for the first stage had already been established as 0.037. The uncertainty distribution for the failure probability was assumed to be a beta distribution with parameters r = 0.4 and n = 10.8. In establishing these values, consideration was given to the fact that this vehicle's first-stage launch history was no failures in ten launches.

The following equation is for the density function of the beta distribution used to model the epistemic uncertainty in failure probability. The parameters of the beta distribution are the r and n mentioned above.

$$f(p) = \frac{\Gamma(r+n)}{\Gamma(r)\ \Gamma(n-r)}\ p^{r-1}(1-p)^{n-r-1}\quad \mathit{if}\ \ 0 \le p \le 1,$$

$$f(p) = 0 \quad \text{elsewhere} \tag{4-19}$$

$$\text{where } \Gamma(x) = \int_0^\infty e^{-t} t^{x-1} dx \quad \mathit{for}\ x > 0$$

The density function for the failure probability is shown in Figure 4-25.

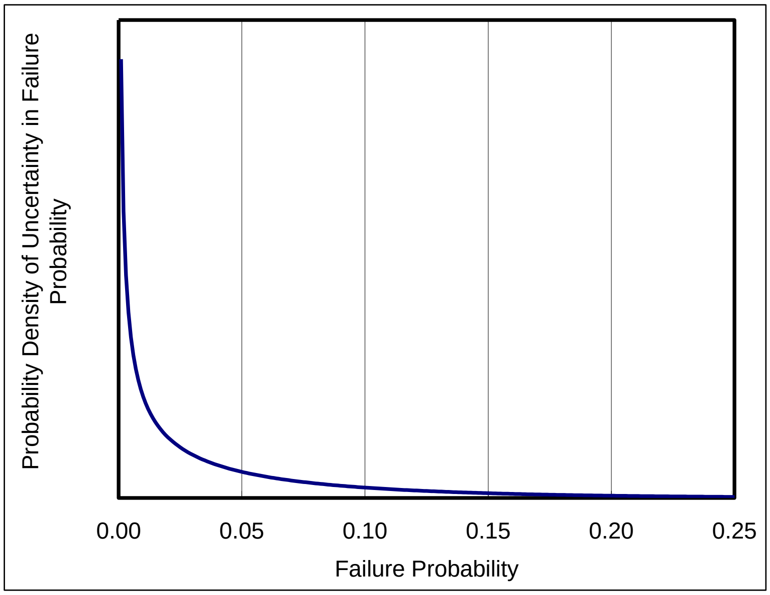

Figure 4-25. Probability Density Function for Failure Probability

As discussed above, this epistemic uncertainty process uses a beta distribution to model failure probability uncertainty and to model debris list uncertainty. Alternative debris lists are modeled by selecting samples from discrete debris list options. Other than failure probability and debris list, the influences of all other uncertainties were modeled as factors times the nominal value of the parameter of interest. Most of the parameters were assumed to have a lognormal distribution. The procedure used is shown in Figure 4-26. Note that it is, in principle, the same procedure that is illustrated in Figure 4-24. Biases were not considered in the analysis.

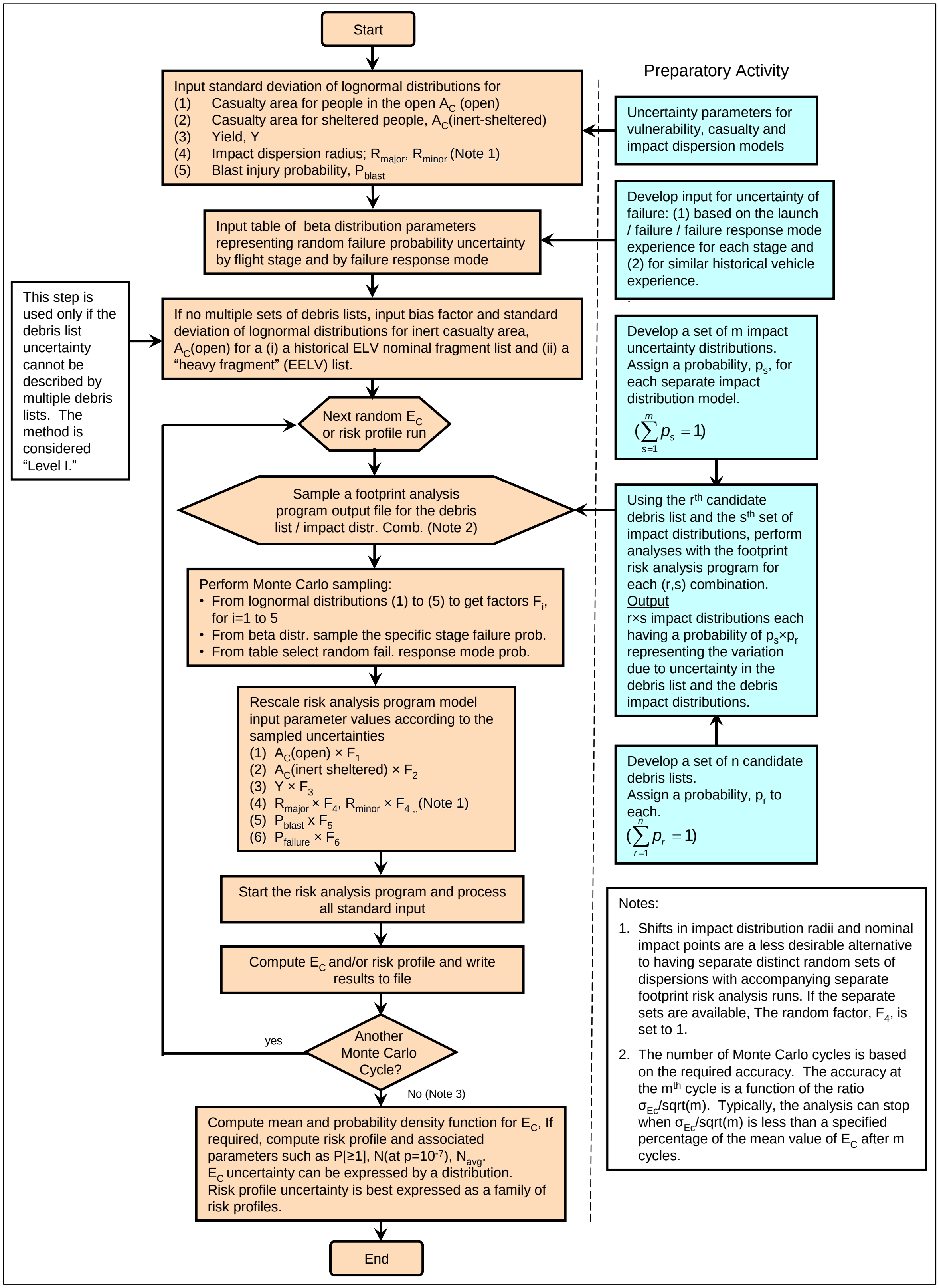

Figure 4-26. Flow Diagram of Computational Procedures to Compute the E_C and Risk Profile Uncertainties for Example Case

A modified version of a footprint risk analysis program was used to perform the uncertainty analysis using impact dispersion data developed by the risk analysis program used for the original analysis. This was performed for each failure time, failure response mode, and candidate debris list. Table 4-23 presents the values of the uncertainties in the model parameters that were used in the calculation. It is important to note that not all of the possible epistemic uncertainties in the models and parameters were used. This means that the final answer underestimates the uncertainty, but probably not significantly, since the major uncertainty factors have been considered. The study did not evaluate the effect of conservative bias. Even though shown in the table, the coefficient of variation for failure probability was not used directly since the failure probabilities were sampled from a beta distribution.

Table 4-23. Uncertainty Parameters Used in the Example Risk Uncertainty Analysis (Not Including Debris List Uncertainty)

Model Parameter	Coefficient of variation (σ/μ)	Logarithmic Standard Deviation
Failure probability (assume the 11th launch with the mean failure probability of 0.037 and previous launch experience of no failures in 10 launches). A beta distribution is used to describe this uncertainty and it uses a Bayesian approach with pseudo data of $r' = 0.4$ and $n' = 10$. See the section on failure probability uncertainty.	1.484	N/A
Casualty area for people in open	0.20	0.20
Solid propellant impact yield	0.20	0.20
Impact distribution size	0.20	0.20
Vulnerability of humans in structures to inert debris	0.36	0.35
Vulnerability of humans in structures to explosive debris	0.84	0.73
Population density and population distribution	0.05	0.05

The analysis produced uncertainties in both the E_C and the risk profile. The cumulative probability distribution for uncertainty in E_C is shown in Figure 4-27.

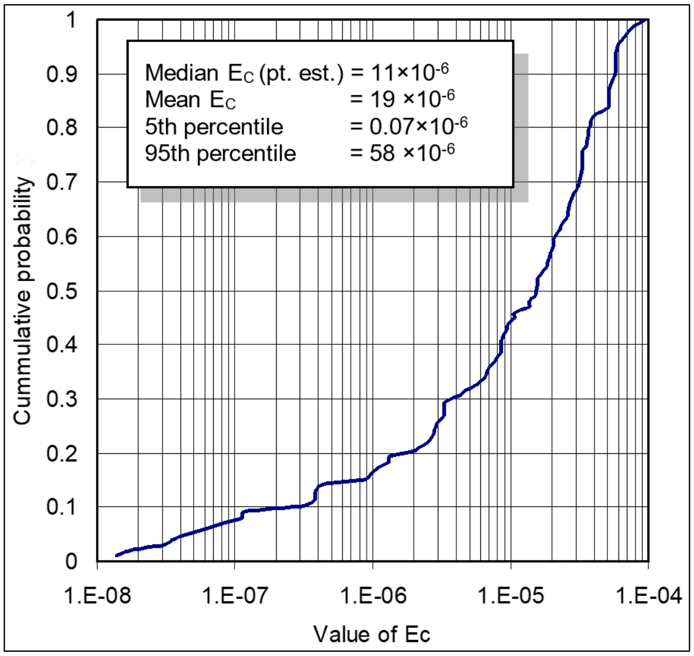

Figure 4-27. Cumulative Probability Distribution of the Epistemic Uncertainty of E_C

The results show that the mean value of E_C, considering epistemic uncertainty, is 19E−6. The point estimate, i.e., the value of E_C not considering epistemic uncertainty, is 11E−6. The shape of the cumulative distribution in Figure 4-27 indicates a long tail to the left on the log plot of the cumulative probability distribution of E_C. This is because the beta distribution for failure probability, which dominated the uncertainty, can have a non-zero value at $P_F = 0$. If the distribution for P_F were lognormally distributed, the cumulative probability distribution of E_C would have taken on more of the shape of the familiar S curve produced by the lognormal distribution.

The ratio of the average E_C[73] to the point estimate of E_C in this case is 19/11 = 1.7[74]. The ratio would be greater if the uncertainty in the E_C had been greater. If additional parameter uncertainties had been introduced, the ratio would have increased. If some of the other epistemic uncertainties in parameters have increased, the ratio would have increased. Thus, no doubt, the ratio could be larger. This example is probably the most detailed uncertainty evaluation to date, but it will take more accumulated uncertainty analysis experience to determine the upper range of the ratio. Since the parameters that should have the largest impacts have been considered, it is doubtful that the ratio of average E_C to point estimate of E_C will exceed 2 in similar cases for this vehicle and mission.

Figure 4-28 shows a risk profile for a hypothetical mission. As noted earlier, the risk profile displays the aleatory uncertainty. The figure also depicts the RCC's recommended criteria for acceptable risk profiles.

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[73] It has been assumed in this example that the estimate of risk is unbiased, i.e., the conservatisms in the models have been removed. Thus, the average E_C is an unbiased estimate of the true E_C.

[74] This factor will vary from vehicle to vehicle, mission to mission, and from one launch to the next. It can also be affected by change in meteorological conditions.

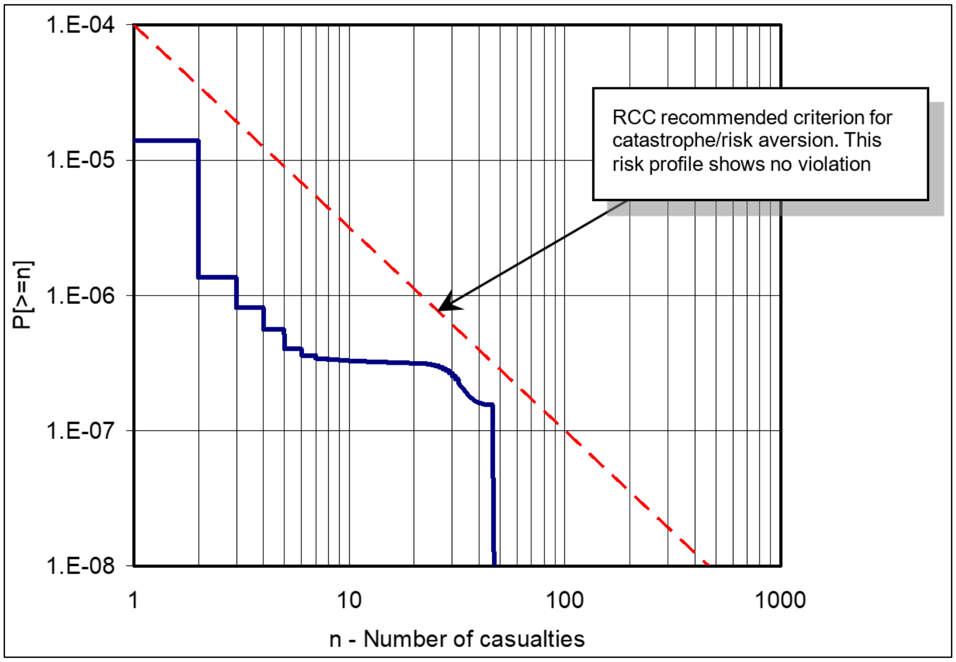

Figure 4-28. Risk Profile for Example Showing Complimentary Cumulative Distribution of Aleatory Uncertainty

The uncertainties in the risk profiles are represented by 100 equally probable risk profiles sampled in the Monte Carlo analysis of epistemic uncertainty. In this case, about 10% of the risk profiles extend into the region beyond the recommended criteria for catastrophe aversion. None of the risk profiles reach the line of indifference to catastrophe. Figure 4-29 depicts these risk profiles resulting from sampling the factors that contribute to epistemic uncertainty.

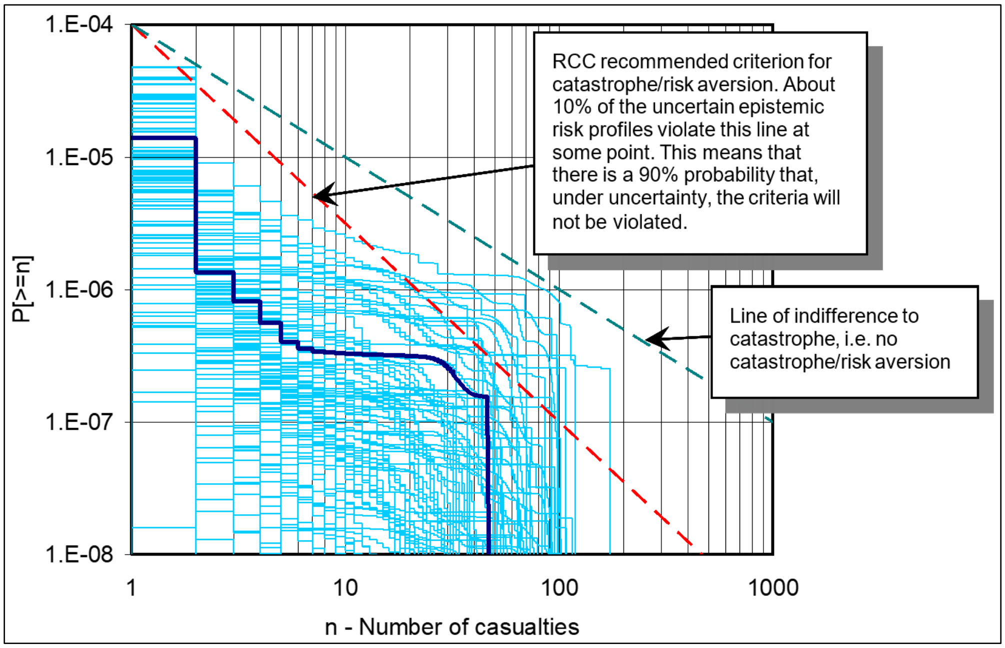

Figure 4-29. Epistemic Uncertainty of the Example Risk Profile

4.9.8 Comparison of the Uncertain Risk Estimate with Criteria

Without consideration of uncertainty, the decision maker has been provided a single value of the E_C. This value was compared to the acceptability criteria and if the E_C satisfied the criteria, the mission was allowed to proceed without further review; however, uncertainty makes the risk value fuzzy and makes the decision point not so clear. The options for presentation of uncertain computed risk involve the probability distribution representing the uncertainty. Options include picking a percentile level, e.g., 90%, where the decision maker is taking a 10% chance that the true risk is actually greater than the risk associated with the percentile level. This approach relies on the somewhat arbitrary choice of probability. The other more common option is to use the mean value of E_C considering uncertainty. Since the decision regarding risk was based on an average, the average of the E_C under uncertainty is simply a better average. This approach has been used in other industries that use risk criteria. The standard recommends the approach using average E_C. Note also that the average E_C, in order to be unbiased, must have been computed with the conservative biases in the analysis process removed.

As mentioned in the previous section, the average E_C in this example is 1.7 times the point estimate of the E_C. This factor is reflective of the particular problem and the distributions used in the problem. It could have been larger (how much is difficult to say) but with additional parametric uncertainties added, it could grow to a factor of about two.

CHAPTER 5

Risk Criteria Rationale

As stated in Section 2.3 of the standard, the initial goal of range risk management should be to isolate the hazards from populated areas whenever practical. This goal is consistent with the primary policy that no hazardous condition is acceptable if mission objectives can be achieved with a safer approach, methodology, or position to minimize the hazards and conduct the mission as safely as reasonably possible. When hazards cannot be contained or minimized to an insignificant level, then more-detailed assessments must be performed to determine if the remaining risk is acceptable.

During the development of this standard, the RC sought criteria that would promote an improved ability to effectively manage risks (and thereby protect everyone) and accommodate a diverse mix of missions without compromising safety. This chapter presents the rationale behind each criterion (the information considered, the connection between the available facts, and the selection of each criterion). The purposes of this chapter are to:

a. establish that the criteria in Chapter 3 of the standard are reasonable and rational;

b. provide insight into the criteria to facilitate proper implementation;

c. help the risk acceptance decision maker understand and balance the factors that affect mission acceptability (e.g., criticality of mission objectives, protection of life and property, the potential for high-consequence mishaps, local political factors, and governing range or programmatic environmental requirements).

This chapter is structured into the following sections.

5.1 Rationale for Risk Metrics

5.1.1 Aggregated Risk Criteria

This standard endorses risk criteria that limit the aggregated mission risk from a range of activities (i.e., the total risks, which account for all hazards throughout flight). For example, Subsection 3.2.1.b of the standard states that the collective risk for the GP must not exceed 100E−6 (1E−4) E_C for any single mission.

While preparing the 321-07 version of this supplement, the RC considered the fact that current practice included both setting limits on the risks posed by separate hazards and limits on the aggregated risk posed by all hazards from launches. Careful consideration was given to the pros and cons of both approaches. This standard endorses the use of aggregated risk limits for the reasons given on subparagraphs a through d below.

a. Although there have been valid reasons[75] given for setting limits on the risks posed by separate hazards, acceptance of higher risk levels simply because there are multiple hazards present does not appear rational. For example, risk acceptability criteria that limit the risk posed by separate hazards (e.g., one limit for the risk from toxic releases, another limit for debris, etc.) theoretically allows a system that incorporates toxic materials to pose greater risks simply because toxics are present.

b. Aggregated risk limits provide the maximum flexibility for management of risk from various hazards, although other sources of requirements may still impose limits on certain hazards (for example immediately dangerous to life and health, for toxics as described in Chapter 8). For example, a mission could be designed to eliminate the risk from certain hazards (such as toxic releases and DFO to comply with the aggregated risk limit 100E−6 E_C due to over-flight of a downrange land mass [such as Europe or Africa]). However, a similar mission that included toxic and DFO hazards could pose virtually the same aggregated risk but fail to meet limits set for the risks posed by separate hazards. Maximum flexibility is attributed to management of the total risk from a mission instead of setting separate limits for each hazard. The aggregated risk management approach treats a single hazard that presents a certain risk level the same as many hazards with the same total risk level. Aggregated risk management is the most flexible, logical, and consistent approach.

c. Aggregated risk limits provide the maximum flexibility for management of risk to various exposed populations, especially those in various transportation modes. The probability of impact limits intended to constrain the risks posed to people on-board ships or aircraft are often convenient and efficient means to define hazard areas as discussed in Chapter 4. However, setting limits on the aggregated risk to all exposed populations allows, for example, more sophisticated methods that provide acceptable risk levels with potentially fewer restrictions on ship or air traffic. For example, this standard now allows using part of the aggregated risk budget for ship or aircraft risks as an alternative to using relatively simple and conservative probability of impact limits to define ship or aircraft hazard areas.

d. Aggregated risk limits quantify the threat from all hazards in the simplest and most logical manner because the total risk is expressed in a single value. To support a fully informed decision to authorize a mission, the decision authority should be advised of the various sources of risk, etc. However, aggregated risk limits provide the most definitive basis to consistently characterize, evaluate, and compare the risks associated with a range activity because the risk acceptability is defined by a single value.

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[75] 67 Fed. Reg. 146 (30 July 2002), pp. 49461, 49462, and 49465.

5.1.2 Casualty and Fatality Risk Limits

Early versions of this standard used fatalities as the consequence metric to define acceptable risks for a variety of reasons. A 1996 survey of national ranges showed that acceptable risk has historically been expressed in terms of casualties. However, until recently the lower injury threshold for defining casualty varied widely among the ranges, and in all cases, the term included fatality. Furthermore, the early versions of this standard applied only to inert debris hazards, where a relatively high percentage of casualties is expected to be fatalities. Thus, fatality was chosen as the measure of risk for early versions of this standard.

In 2006, the RC developed a consensus on the definition of casualty and other issues (such as threshold values) that facilitate risk estimates based on casualty consequences, which are discussed in Chapter 6. A casualty is defined here as serious injury or worse, including death, for a human. For the purposes of this standard, the RC adopted Abbreviated Injury Scale (AIS) level 3 to characterize serious injury.[76] The risk acceptability criteria now apply to all launch vehicle hazards, including those from toxic releases where a relatively low percentage of casualties is expected to be fatalities.

Casualty was chosen as the primary consequence metric for this revised standard because:

a. casualty is consistent with current and past range practices that have produced an excellent public safety record;
b. using casualty as the consequence criterion instead of separate criteria for fatalities and serious injuries avoids the uncertainty associated with promptness and effectiveness of medical treatment that can prevent serious injuries from becoming fatal;[77]
c. casualty measures are necessary to provide a reasonable level of protection from serious injuries due to all launch vehicle hazards;
d. serious injuries are onerous.[78]

This standard endorses the use of fatality as a supplemental consequence metric for several reasons. Evaluation of both casualty and fatality risks can provide a more in-depth understanding of mission risks. Specifically, a range commander may view missions with the same risk of casualties differently depending on the risk of fatalities. For example, a range commander may view a mission that poses only inert debris hazards, with risks of $90\text{E}{-}6\ \text{E}_\text{C}$ and $45\text{E}{-}6\ \text{E}_\text{F}$, differently from a mission that poses only toxic release hazards, with risks of $90\text{E}{-}6\ \text{E}_\text{C}$ and less than $0.1\text{E}{-}6\ \text{E}_\text{F}$. Furthermore, some range operations might pose a very high ratio of potential fatalities to potential casualties. For example, a mission that poses risks only from very

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[76] Serious injuries are formally defined in U.S. law 49 CFR 830.2 for the purpose of reporting the consequences of aviation accidents. However, the FAA has accepted that “the use of AIS level 3 or greater is appropriate for describing a medical condition sufficiently to allow modeling of casualties for purposes of determining whether a launch satisfies the public risk criteria.” (67 Fed. Reg. 146 [30 July 2002], pp. 49455-49521).

[77] Medical treatment can often save a seriously injured individual from dying, but the availability of such medical treatment is highly unpredictable.

[78] A DOT study (Blincoe et al, May 2002) on the economic impact of motor vehicle crashes in 2000 found that, “serious injury can be catastrophic to the victim’s economic well-being in addition to their physical and emotional condition.” Furthermore, motor vehicle crash data and government cost analysis guidelines show that debilitating injuries typically incur more economic damage than fatalities. (See Blincoe et al Table 2 and GRA Inc, 2007.)

large and dense pieces of inert debris could produce virtually equal risks of casualty and fatality. In such a case, a range commander may choose to limit the risk of fatality in addition to the risk of casualty.

5.1.3 Best Estimate Risk Limits and the Role of Uncertainty

The RC intends for the risk criteria in Chapter 3 of the standard to be compared to the best estimate of individual and collective risks. The use of best estimate individual and collective risk estimates is consistent with the FAA's regulations on risks from commercial launch[79] and reentry[80] vehicles, and is the current practice at the national ranges.

The use of best estimates also appears to be reasonable and rational in comparison with the Nuclear Regulatory Commission (NRC) approach: "the Commission has adopted the use of mean estimates for purposes of implementing the quantitative objectives of this safety goal policy".[81] The RCC recognizes, just as the NRC did, that uncertainties are inherent in risk-based decision making. It appears that the current RCC approach to risk limits and uncertainty is the same as the approach initially taken by the NRC some 20 years ago. For example, it appears that NRC references to "mean estimates" equate to the best estimates used in this standard, which presently do not always completely account for all sources of uncertainty; the NRC stated that the "use of mean estimates does not, however, resolve the need to quantify (to the extent reasonable) and understand those important uncertainties involved in…risk predictions."

The RCC recognizes that the following statements regarding uncertainties, which were published with the NRC safety goals, also apply to risk management for range activities.

a. "Uncertainties are not caused by use of quantitative methodology in decision-making but are merely highlighted through the use of the quantification process."

b. "A number of uncertainties arise because of a direct lack of severe accident experience or knowledge of accident phenomenology along with data related to probability distributions."

c. "Through the use of quantitative techniques important uncertainties have been and continue to be brought into better focus and may even be reduced compared to those that would remain with sole reliance on deterministic decision-making."

d. "For this reason, sensitivity studies should be performed to determine those uncertainties most important to the probabilistic estimates. The results of sensitivity studies should be displayed showing, for example, the range of variation together with the underlying science or engineering assumptions that dominate this variation."

e. "Depending on the decision needs, the probabilistic results should also be reasonably balanced and supported through the use of deterministic arguments. In this way, judgments can be made by the decision-maker about the degree of confidence to be given to these estimates and assumptions. This is a key part of the process of determining the

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[79] 14 CFR 415.35a: "Acceptable flight risk through orbital insertion for an orbital launch vehicle, and through impact for a suborbital launch vehicle, is measured in terms of the expected average number of casualties (Ec) to the collective members of the public exposed to debris hazards from any one launch." 64 Fed Reg 19586 (21 April 1999), p. 19618. 71 Fed. Reg. 165 (25 August 2006) p. 50542.

[80] 14 CFR 435.31b: "Acceptable risk for a proposed mission is measured in terms of the expected average number of casualties (Ec)." 65 Fed. Reg. 182 (19 September 2000), page 56660.

[81] 51 Fed. Reg. 29901 (August 21,1986), p. 30031.

degree of conservatism that may be warranted for particular decisions. This defense-in-depth approach is expected to continue to ensure the protection of public health and safety."

5.2 Criteria Rationale Overview

In establishing the standard criteria, the five separate types of logic generally used were:

a. consistency with prior range or closely related safety criteria;
b. similar regulatory experience;
c. comparable accident statistics and background risk levels;
d. internal consistency;
e. legal considerations.

The five types are summarized below, followed by the rationale for each criterion.

5.2.1 Consistency with Prior Safety Criteria

The national ranges have a long history (more than 50 years) of successful protection from falling debris. This excellent safety record was achieved using criteria that have varied over time and among ranges. Therefore, a primary goal of the standard criteria is to build on the foundation of existing criteria while promoting consistency among the ranges.

5.2.2 Similar Regulatory Experience

The criteria consider similar regulatory experiences of local, state, federal, and international organizations. Other regulatory agencies have set numerous precedents to define acceptable risk levels. These precedents vary widely in their relevance and applicability to this standard. In some cases, similar regulatory experience includes federal laws governing commercial space transportation risks.

5.2.3 Comparable Accident Statistics and Background Risk Levels

The standard criteria compare favorably with generic accident experience data for categories that correlate with potential range accidents. The use of accident statistics has a specific and limited purpose. The history of risk from falling rocket launch debris shows no casualties. We are comparing potential accidents from falling debris to actual accident experience in other categories that have a much larger statistical base to ensure that the acceptable risk levels defined here do not exceed those risk levels that have been experienced in the past.

In some cases, the standard criteria are rationalized by comparison to background risk levels. There are two protection philosophies that may be employed based on background risk. The first is to use background risk as a tolerated risk and to demonstrate that the new activity (launch operations) does not significantly perturb the background risk. That approach requires demonstrating that the risk from the new activity is significantly smaller than the background risk (typically, one to two orders of magnitude smaller.) The alternative, employed in this standard, is to treat the background risk as indicating a combination of risk levels and benefits that society finds acceptable. The policy objectives given in Chapter 2 of the standard include that "the general public should not be exposed, individually or collectively, to a risk level greater than the background risk in comparable involuntary activities.” In this context, the RCC considers “comparable involuntary activities” as those where the risk arises from manmade activities that:

a. are subject to government regulations or are otherwise controlled by a government agency;

b. are of vital interest to the U.S.;[82]

c. impose involuntary risk of serious injury or worse on the public.

People ordinarily accept a wide range of risks depending on their perception of the risks and benefits. During the development of risk-related policies, experts have noted that people generally accept higher risks if those risks are perceived to be voluntary, familiar, natural, under their control,[83] fairly distributed, not threatening to children, and devoid of catastrophic potential.[84,85,86] These “outrage factors” suggest that people are likely to be relatively intolerant of accidents/risks from range activities that are typically involuntary, exotic, man-made, beyond individual control, potentially catastrophic, likely to capture a great deal of media attention, etc. The main point here is that people are far less tolerant of risks that are imposed on them without any form of consent (i.e., involuntary risks) or any sense of benefit from the source of risk. (Covello and Sandman 2001, Starr[87])

In establishing a federal law to define acceptable flight risk limits for launches, the FAA noted that “commercial launches should not expose the public to risk greater than normal background risk, which the FAA defined in its Notice of Proposed Rulemaking (NPRM) as those risks voluntarily accepted in the course of normal day-to-day activities.”[88] Other organizations have also used normal background risks, particularly from other types of accidents, as important benchmarks for acceptable risks in a variety of fields.[89,90,91,92]

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[82] In 2004, Congress identified space transportation as “inherently risky.” (see 49 USC Chapter 701, referred to as the Commercial Space Launch Act (CSLA), §70101 (a)(12), 12/2004). At the same time, Congress found that “a robust US space transportation industry is vital to the Nation's economic well-being and national security,” (CSLA §70101, which gives reference Pub. L.106-405, Sec. 2, 11/1/2000, 114 Stat. 1751). The Major Range and Test Facility Bases (MRTFBs) have long been regarded as “national assets,” and thus vital to the interests of the US.

[83] People tend to be more sensitive to risks, even voluntarily accepted risks, when someone else is in control, such as flying in an airplane piloted by someone else, and less concerned about risks when they feel in control, such as driving in an automobile.

[84] Rolf Skjong. “Risk Acceptance Criteria: Current Proposals and IMO Position.” Paper presented during the Surface Transport Technologies for Sustainable Development EU Commission Conference: Valencia, 2002.

[85] Terry Hardy. “Risk Perception and Communication in Commercial Reusable Launch Vehicle Operations.” Paper presented at the 1st IAASS Safety Conference: Nice, 2005.

[86] Covello, Vincent and Peter Sandman. “Risk Communications: Evolution and Revolution.” In *Solutions to an Environment in Peril*. Baltimore: Johns Hopkins University Press, 2001.

[87] Chauncey Starr. “Societal Benefit versus Technological Risk.” *Science*. Vol. 165, Issue 3899: pp. 1232-1238.

[88] 64 Fed. Reg. 19586 (21 April 1999), p. 19605.

[89] Skjong, 2002.

[90] Andrew Evans. *Third Party Risk Near Airports and Public Safety Zone Policy*. Great Britain: Department of the Environment, Transport and the Regions, 1997.

[91] 51 Fed. Reg. 162 (21 August 1986), pp. 30028-30033.

[92] Great Britain Health and Safety Executive. “Reducing Risks, Protecting People: HSE’s Decision-Making Process.” HSE Books, 2001.

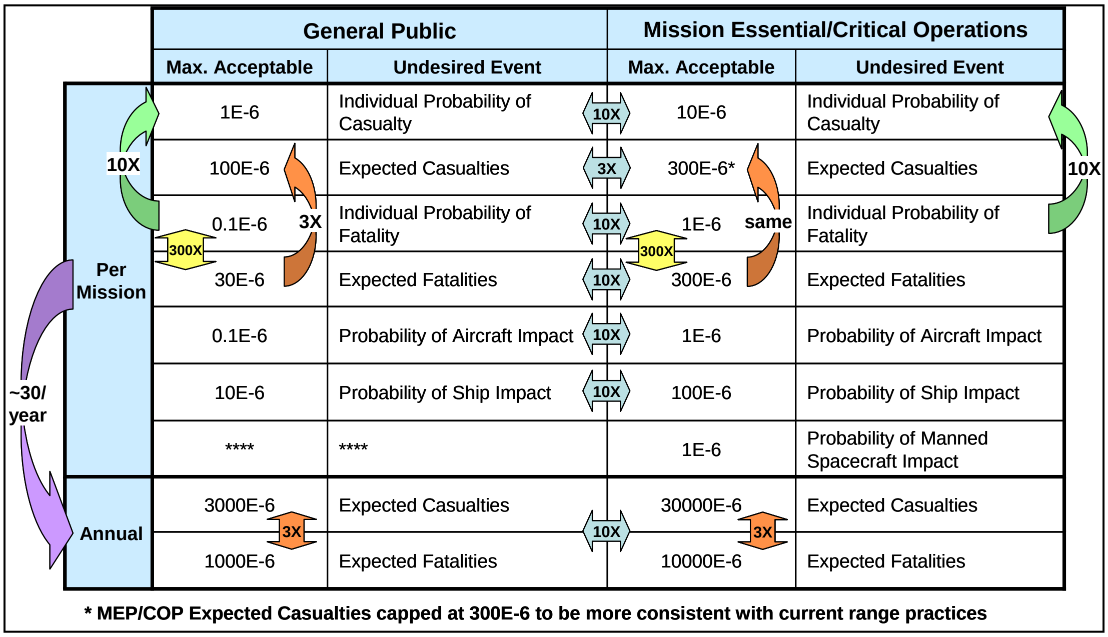
In light of the distinctly different tolerance of voluntary and involuntary risks, and the general principle that acceptable risk levels should be correlated with background risks, the RCC endorses the following qualitative standard as a guideline for the development and implementation of range requirements.

> *For any individual uninvolved in the mission, but participating in a voluntary activity that increases their background risk (such as traveling in an aircraft or waterborne vessel), the chances of casualty resulting from the mission should be less than the background risk associated with the voluntary activity*.

Parts of Section 5.3 and Section 5.4 discuss the use of background risk levels for comparable involuntary and voluntary activities as important benchmarks for risk acceptability standards.

5.2.4 Internal Consistency

Each acceptable risk criterion is supported by rationale founded in the other categories and by their relationship with one another. Each criterion is related to the other criteria by assumptions that reflect a reasonable set of conditions at the U.S. launch ranges. Figure 5-1 shows the inter-relationships between the criteria. Specifics of these are discussed in the applicable sections.



	General Public		Mission Essential/Critical Operations	
	Max. Acceptable	Undesired Event	Max. Acceptable	Undesired Event
Per Mission	1E-6	Individual Probability of Casualty	10E-6	Individual Probability of Casualty
	100E-6	Expected Casualties	300E-6*	Expected Casualties
	0.1E-6	Individual Probability of Fatality	1E-6	Individual Probability of Fatality
	30E-6	Expected Fatalities	300E-6	Expected Fatalities
	0.1E-6	Probability of Aircraft Impact	1E-6	Probability of Aircraft Impact
	10E-6	Probability of Ship Impact	100E-6	Probability of Ship Impact
	****	****	1E-6	Probability of Manned Spacecraft Impact
Annual	3000E-6	Expected Casualties	30000E-6	Expected Casualties
	1000E-6	Expected Fatalities	10000E-6	Expected Fatalities

*** MEP/COP Expected Casualties capped at 300E-6 to be more consistent with current range practices**

Figure 5-1. Criteria Inter-Relationships

5.2.5 Legal Considerations

The standard criteria are supported by five legal principles, described below.

5.2.5.1 Reasonable Risk

Increasingly, decision makers have encountered opposition to acceptable risk decisions based on expert judgments or on risk comparisons that may be deemed inappropriate. The courts, however, have often upheld these decisions on the basis that the decision by the federal agency was *reasonable*. The term *reasonable*, or more commonly *unreasonable*, appears in several federal statutes (such as the Toxic Substances Control Act) and is used as the primary criterion in making difficult decisions. *Reasonableness* is undefined in these laws, leaving the regulatory agencies and courts to determine what constitutes a reasonable decision. In general, all of the commonality criteria are reasonable because they are supported by at least three of the five lines of logic.

5.2.5.2 De Manifestis and De Minimis

Two levels of risk are distinguished by their Latin names: *de manifestis* and *de minimis*. *De manifestis* risk, literally a “manifest” risk of obvious concern, has its roots in the legal definition of an “obvious risk”: a risk that is instantly recognized by a person of ordinary intelligence as inherently unacceptable. *De minimis* risk, on the other hand, defines a level of risk that is below regulatory concern. This term stems from the legal principle, *de minimis non curat lex*: “the law does not concern itself with trifles.”

In recent years, there has been a growing recognition that the perception and acceptability of risks by the GP must be considered. For example, the annual risk of an individual dying in an automobile accident in the United States has been stated as 2E−5.[93] This risk is widely accepted by the public because of the great benefit perceived from automobile transportation. In comparison, other activities require much lower levels of risk in order to be perceived as acceptable. Thus, a single *de minimis* value may not be sufficient.

5.2.5.3 Informed Decision

The “informed decision” principle is used in tort claims against the U.S. Government. The FTCA enjoins the U.S. court system from second-guessing decisions made by properly authorized government officials in determining the acceptability of operational risks. A key test under the FTCA requires that the decision-making official be fully advised and informed of the known risks. Failure to fully advise the decision-making authority of known risks can result in liability of the U.S. Government or its officials.

5.2.5.4 Rationale

Federal law[94] provides the principal statutory authority governing judicial review of actions by a regulatory agency. Section 706 of the Code defines an “arbitrary, capricious… abuse of discretion” standard for the review of a regulatory agency’s judgement and discretion. The case law on the scope of judicial review is extensive and not easily summarized. Using this standard, courts have upheld agency determinations that were rational, based on consideration of the relevant factors, and within the agency’s authority delegated by statute. More specifically, a court is not to overrule the agency’s judgment provided that the agency examines the relevant data and documents a rational connection between the facts and the choices made.[95,96] In essence, the agency must provide a rational explanation of its decision or be subject to injunction by a court under the “arbitrary and capricious” standard.

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[93] Motor Vehicle Manufacturers Association v. State Farm Mutual Auto. Ins. Co. 463 U.S. 29, at 42-57, 103 S. Ct. 2856 (1983)

[94] 5 U.S.C. §701- §706

[95] 103 S. Ct. 2856 (1983)

[96] Illinois Public Telecommunications Association v. FCC, 117 F.3d 555, 564 (D.C. Cir. 1997)

5.3 Rationale for Casualty Limits

Table 5-1 summarizes the casualty criteria for both the GP and MEP/NOP. Rationale for these numbers is presented in the following sections.

Table 5-1. Maximum Acceptable Casualty Risk to People

Per-mission Criteria	**General Public**	**Mission-essential**
Individual Probability of Casualty	1E−6	10E−6
Expected Casualties	100E−6	300E−6
Annual Criteria		
Expected Casualties	3,000E−6	30,000E−6

5.3.1 General Public Collective Risk Per Mission (GP: 100E−6 E_C)

Limiting the collective risk for the GP to 100E−6 (1E−4) E_C per mission is rational and reasonable in light of the following:

a. past RCC launch safety criteria;

b. launch safety criteria used by other organizations;

c. federal law governing launch and reentry risks;

d. risks accepted for “comparable involuntary activities”;

e. internal consistency (correlation with other criteria);

f. legal considerations.

5.3.2 Justification of the 100E−6 Collective Risk Standard

The following subsections describe how the 100E−6 collective risk standard is justified from all of these perspectives.

5.3.2.1 Prior Safety Criteria

In 1997, the RCC established a collective risk limit for the GP equal to 30E−6 (3E−4) E_F due to inert debris for any single mission. Five separate types of logic were used to establish that criteria:

a. consistency with prior safety criteria;

b. legal considerations;

c. similar regulatory experience;

d. comparable accident statistics;

e. correlation to the other criteria.

The rationale behind that previous criterion is still valid and applicable to the current fatality risk criteria because: a) the previous and current criteria use the same numerical limits for fatality risks; and b) the only difference is that the updated criterion applies to all sources of hazards from range activities, not just inert debris.

Limiting the collective risk for the GP to 100E−6 (1E−4) E_C per mission ensures protection that is generally consistent with, or more conservative than, the previous limit of 30E−6 (3E−5) E_F due to inert debris. Specifically, the typical ratio of fatality expectation to casualty expectation for the typical hazards listed in Table 5-2 indicate that the 100E−6 (1E−4) E_C criteria is likely to limit a range activity more than the previous limit unless the range activity presents inert debris hazards only. For example, a launch with inert and explosive debris hazards and a risk estimate of 100E−6 (1E−4) E_C would typically correspond to about 25E−6 E_F. Table 5-2 shows that the other hazards, such as toxic releases and DFO, typically produce even smaller ratios of E_F to E_C. This demonstrates the 100E−6 E_C limit provides more protection than the 30E−6 E_F limit, particularly if toxic or DFO risks are significant. Thus, the current standard for E_C is rational: consistent with the previous E_F criteria from a safety perspective. This same ratio between the E_C and E_F criteria for GP is carried over the MEP/NOP categories and annual criteria.

Table 5-2. Typical Ratio of Expected Fatalities to Casualties

Hazard Scenario	Range of E_F/E_C
Large inert debris impacts	0.6 to 0.8
Explosive and inert debris impacts	0.1 to 0.8, 0.25 typical
Distant focusing overpressure	0.001 to 0.03, 0.01 typical
Solid rocket propellant toxic release	0.001 typical

There are hypothetical circumstances where much larger or smaller fractions of E_C would be E_F. For example, if building impacts are severe enough to cause collapse, the number of E_F might equal the number of casualties. Those circumstances are unusual because areas vulnerable to such severe impacts are typically designated hazard areas and are evacuated. Therefore, where there is the potential for such circumstances, implementation of the supplemental fatality risk criteria in addition to the primary casualty risk criteria is advisable.

5.3.2.2 Similar Regulatory Experience

Limiting the collective risk for the GP to 100E−6 (1E−4) E_C per mission is consistent with the following closely related launch safety criteria set by other organizations. The criteria are explained as follows.

a. DoDI 3100.12: If atmospheric reentry is used for post-mission disposal of a spacecraft or upper stage, “either the risk of injury from the total debris casualty area for components and structural fragments surviving reentry shall not exceed 1 in 10,000 (based upon an evenly distributed human population density across the Earth), or it shall be confined to a broad ocean or essentially unpopulated area.” This DoDI essentially established 100E−6 E_C as a standard for risk acceptability from an uncontrolled reentry; NASA[97] has, and the European Space Agency[98] is considering, the same threshold value.

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[97] NASA. “Process for Limiting Orbital Debris.” NASA-STD-8719.14 Revision C. 5 November 2021. May be superseded by update. Retrieved 17 October 2023. Available at https://standards.nasa.gov/standard/nasa/nasa-std-871914.

[98] Walker, R. et al. “Update of the ESA Space Debris Mitigation Handbook.” July 2002, page 1.9.3. Retrieved 17 October 2023. Available at https://nebula.esa.int/sites/default/files/neb_study/423/C14471ExS.pdf.

b. NASA 8719.25 states “The E_C for the Public shall be less than or equal to (≤) $100X10^{-6}$.” (Subsection 4.3.3.2)[99]

c. The Commonwealth of Australia Space Licensing and Safety Office established 100E−6 as “the maximum third-party collective risk (the sum of casualty risks to all individuals in the general public) on a per-launch basis.”[100]

d. AFSPCMAN 91-710: “The risk associated with the total flight to all members of the general public, excluding persons in waterborne vessels and aircraft, shall not exceed an expected average number of 0.00003 casualties (E_C < 30E−6) from impacting inert and explosive debris, E_C < 30E−6 for toxic release (exposure to rocket propellant effluent), and E_C < 30E−6 for far-field blast overpressure.”[101] This United States Air Force (USAF) E_C criterion for each hazard applies to each launch from liftoff through orbital insertion, including planned impact for an orbital launch, and through final impact for a suborbital launch. Note that the AFSPCMAN 91-710 criteria allows a theoretical maximum of 90E−6 E_C, excluding any risks from hazards other than toxic release, far-field overpressure (DFO), and impacting inert and explosive debris. Given the uncertainty inherent in even the most sophisticated launch risk estimate available today, there is essentially no real difference between a limit of 90E−6 or 100E−6 E_C. If another hazard was presented by a launch, such as from radioactive materials, then more risk might be accepted under AFSPCMAN 91-710.

Therefore, limiting the collective risk for the GP to 100E−6 (1E−4) E_C for any single mission is reasonable and rational compared with closely related safety criteria established by other U.S. and foreign agencies.

5.3.2.3 Federal Law Governing Commercial Launch

In 1999, the FAA promulgated a federal law establishing the following restriction. “To obtain safety approval, an applicant shall demonstrate that the risk level associated with debris from an applicant’s proposed launch shall not exceed an expected average number of 0.00003 casualties per launch (E_C < 30E−6).” The preamble to that law clarified that it was intended to limit “risk from debris, not from toxic releases or blast overpressure, which the federal launch ranges handle through other means”.[102] The preamble stated that the FAA derived that limit “from launch risk guidance employed by the Air Force at its Eastern Range, Cape Canaveral Air Station, and its Western Range, VAFB, to define acceptable risk.” In adopting this acceptable flight risk limit for debris the FAA wrote that it “believes that commercial launches should not

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[99] NASA. “Range Flight Safety Requirements.” NASA-STD-8719.25. 5 February 2018. May be superseded by update. Retrieved 17 October 2023. Available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180001258.pdf.

[100] Australian Space Agency. “Flight Safety Code.” Paragraph 3.1.1. August 2019. May be superseded by update. Retrieved 16 October 2023. Available at https://www.industry.gov.au/sites/default/files/2019-08/space-flight-safety-code.pdf.

[101] Commander, Air Force Space Command. “Range Safety User Requirements Manual Volume 1 – Air Force Space Command Range Safety Policies and Procedures.” AFSPCMAN 91-710. 1 July 2004. Superseded 3 November 2016.

[102] In this context the FAA refers to DFO as “blast overpressure.”

expose the public to risk greater than normal background risk, which the FAA defined in its NPRM as those risks voluntarily accepted in the course of normal day-to-day activities."[103]

The RCC recognizes that it was reasonable for the FAA to limit flight risk to 30E−6 E_C from debris based on the information available in 1999. Indeed, the National Academy of Sciences found, "a collective risk standard (i.e., a casualty expectation, or E_C) of 30E−6 per launch for members of the general public is consistent with risk standards of many other fields in which the public is involuntarily exposed to risk, both domestically and internationally."[104] Also, the Air Force document with range safety requirements provided information to justify 30E−6 E_C as a level defining acceptable launch risk without high management review.[105] When the FAA issued 14 CFR 415.35a, it believed that the federal launch ranges were implementing safety requirements to contain any hazards from toxic releases or DFO:

"For toxic releases and blast overpressure, the federal launch ranges implement specific safety requirements designed to keep toxic releases and the effects of blast from reaching the public. For example, if more than a given number of parts per million of a toxic release would reach people, a launch will be delayed until conditions improve. Likewise, if atmospheric effects threaten to carry overpressure impact to persons outside the federal launch site, a launch will be delayed. Because these measures achieve safety, the FAA will rely on them rather than implementing an E_C analysis requirement for toxic releases and blast overpressure" (64 Fed. Reg. 19439).

The FAA promulgated more comprehensive risk acceptability criteria that would limit the collective risk from launch to 30E−6 E_C for each hazard, such as debris, DFO, and toxics. Specifically in 2006, the FAA issued a rule to limit the collective launch risks such that "a launch operator may initiate the flight of a launch vehicle only if the risk associated with the total flight to all members of the public, excluding persons in waterborne vessels and aircraft, does not exceed an expected average number of 0.00003 casualties ($E_C \leq 30E{-}6$) from impacting inert and impacting explosive debris, $E_C \leq 30E{-}6$ for toxic release, and $E_C \leq 30E{-}6$ for far field blast overpressure."[106] This FAA collective risk criterion "for each hazard applies to each launch from liftoff through orbital insertion, including each planned impact, for an orbital launch, and through final impact for a suborbital launch."

A recent FAA regulation to establish launch risk criteria acknowledged "that a risk assessment that determines the total risk due to all hazards associated with a single launch would be an ideal approach." Indeed, the FAA's initial proposal (in October 2000) sought to "require that an aggregate of the hazards created by a particular launch not exceed an E_C of 30E−6" (67 Fed. Reg. 146). The FAA found that the ER and WR "were receptive to this approach because it supported a theoretical goal of launch risk management, which is to quantify all hazards in a single, normalized risk measure"; however, the launch industry objected to that proposal as overly restrictive. The FAA was motivated to establish a law consistent with the then current

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[103] 64 Fed. Reg. 19586 (21 April 1999), p. 19605, 19618.

[104] National Research Council. *Streamlining Space Launch Range Safety*. Washington, D.C.: National Academy Press, 2000. Finding 3-3 on page 19.

[105] Range Safety Office, Patrick Air Force Base. "Range Safety Requirements EWR 127-1." 31 October 1997. Superseded by AFSPCMAN 91-710.

[106] 81 Fed. Reg. 139 (20 July 2016), pp. 47017-47027.

practice at the ER and WR; thus the FAA's current regulation sets limits on ELV flight risks in a manner entirely consistent with the latest USAF requirements in AFSPCMAN 91-710.

The FAA's latest flight risk criteria for launch allows a theoretical maximum of 1E−4 E_C from toxic release, far-field overpressure (DFO), and impacting inert and explosive debris (81 Fed. Reg. 139). The E_C in the latest regulation are considered to one significant digit. Thus, computed values of casualty expectation ranging from 50E−4 to 149E−4 are all treated as 1E−4. Separate risk budgets are provided for launch and reentry. Therefore, limiting the collective risk for the GP to 100E−6 (1E−4) E_C per mission is reasonable and rational compared with federal laws governing commercial launch risks. Furthermore, the underlying rationale used to establish the FAA risk limits also supports the risk criteria presented in Chapter 3 of the standard. Specifically, a limit on the collective risk for the GP equal to 100E−6 (1E−4) E_C per mission:

a. can be derived "from launch risk guidance employed by the Air Force at its Eastern Range, Cape Canaveral Air Station (CCAS), and its Western Range, VAFB, to define acceptable risk," and
b. prevents exposing "the public to risk greater than normal background risk, which the FAA defined … as those risks voluntarily accepted in the course of normal day-to-day activities."[107]

This section shows how the 100E−6 E_C limit can be derived from the launch risk guidance employed by the Air Force. The following sections on risks accepted for comparable involuntary activities and comparable accident statistics demonstrate how the current 100E−6 E_C limit meets the second condition.

5.3.2.4 Comparable Accident Statistics and Background Risk Levels

Civil aviation meets the three conditions considered necessary to be a comparable involuntary activity, explained in Subsection 5.2.3. The RCC, the USAF, an American National Standard, and the Commonwealth of Australia identified the risk posed by conventional aircraft as a benchmark for the acceptable risk from launch vehicles as follows.

a. Public Law 81-60. In 1949, Congress enacted PL 81-60 (later published as 50 U.S.C. §501ff)[108], which authorized the Secretary of the Air Force to establish a joint proving ground, which became the present-day ER. This statute only authorized the *establishment* of a range, and does not apply to its current operations. In a report to the House of Representatives the statement was made that the location was chosen such that "*from a safety standpoint they* [guided missiles] *will be no more dangerous than conventional airplanes flying overhead.*"[109] This language was intended to allay public fears when missile testing was in its infancy and was not intended to set future standards. This language suggests that the launch and flight of launch vehicles should present no greater risk to the GP than the over-flight of conventional aircraft. Although this language is not binding in any way to current decisions made by any federal agency, it does indicate a

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[107] 64 Fed. Reg. 19586 (21 April 1999), p. 19605.
[108] Guided Missiles. 50 U.S.C. Chapter 19.
[109] H.R. Rep. No. 81-158, at 3 (1949).

logical and historical connection between appropriate risk levels for range activities and conventional aircraft.

b. EWR 127-1. In the past, the USAF requirements explicitly linked the involuntary risk imposed on the public from launches to the risk from conventional aircraft. "To provide for the public safety, the Ranges, using a Range Safety Program, shall ensure that the launch and flight of launch vehicles and payloads present no greater risk to the general public than that imposed by the over-flight of conventional aircraft." Note that "over-flight" in this context refers to the entire flight. The most recent study that quantified the annual risk to the population near Cape Canaveral from potential in-flight aviation accidents included accidents in the cruise and maneuvering phases of flights to and from remote airports, as well as the climb, approach, and descent phases of flight to and from local airports.[110]

c. RCC 323-18, Chapter 3 states that "Any UAV test operation must show a level of risk no greater than that for an operation or test of a piloted aircraft."

d. ANSI/AIAA S-061-1998, Section 4.5[111] ties public risk to general aviation over-flight. "During the launch and flight phase of commercial space vehicle operations, the safety risk for the general public *should be no more hazardous than that caused by other hazardous human activities (e.g. general aviation over-flight)*."

e. Prior to establishing regulations aimed at limiting the level of public risk associated with space launch activities, the Commonwealth of Australia funded a study to "develop a risk benchmark which can be used by the Space Licensing and Safety Office for evaluating the risk of casualties to the general public from space launch activities." That study concluded "*that it is reasonable to use the current collective risk of injuries to the public from aviation as a basis for setting a limit to the collective risk to the public from space launch activities*".[112]

The RCC is not alone in identifying aviation as a "comparable involuntary activity," and thus a legitimate benchmark for acceptable risks from range activities. Therefore, it is rational and reasonable to establish risk limits such that range activities "will be no more dangerous than conventional airplanes flying overhead." (H.R. Rep. No. 81-158)

There are several factors that complicate the comparison of risks posed to people on the ground from aviation and the risk criteria presented in Chapter 3 of the standard.

a. While aviation risks can be estimated using empirical data on the number of people seriously injured or killed on the ground, the risks posed by range activities are predictions based on computational models generally fraught with more uncertainty than the empirical data on aviation risks.

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[110] See footnote on page iii of Philipson 1994.

[111] ANSI/AIAA. *Commercial Launch Safety*. Reston: American Institute of Aeronautics and Astronautics, 1999.

[112] Fulton, N. and G. Robinson. *Benchmark Public Risk Levels for Australian Space Launch Activities*. CSIRO: Canberra, July 2000.

b. The available empirical data on aviation risks to ground dwellers does not clearly and consistently distinguish between consequences suffered by those exposed voluntarily and involuntarily.

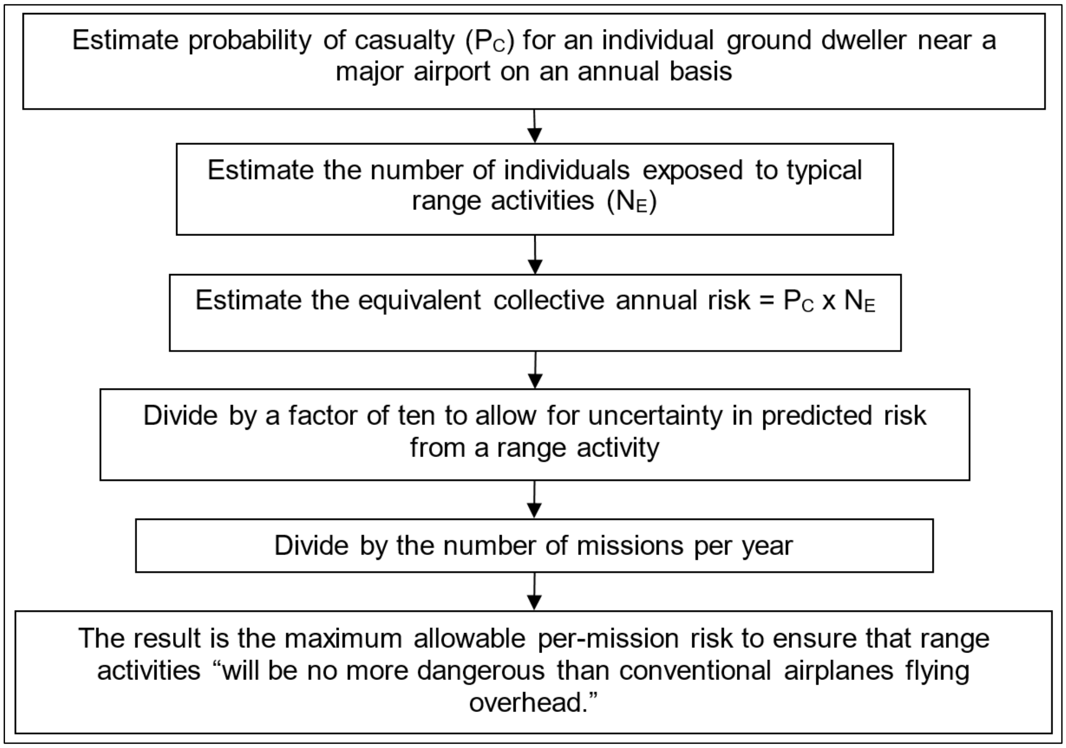
c. While the risks posed by aviation are due to millions of flights that occur all over the country, range activities are relatively infrequent and typically pose risks to a much more localized population.

d. The empirical data on aviation risks suggests that ground dweller risks are strongly dependent on proximity to an airport. There is, however, no study to resolve the dependence of ground dweller risk on proximity to an airport to the extent necessary to make definitive comparisons to the risks posed by range activities.

e. It is difficult to quantify the population exposed to risks from typical range activities or the risks posed by aviation to a comparable population.

NOTE	Section 5.10 describes how the risks posed to ground dwellers by conventional aviation can be used to help identify reasonable risk limits for range activities. The section also indicates that the data and analyses of the risk imposed by the over-flight of conventional aircraft indicate that a limit for the collective risk for the GP on the order of 100E−6 (1E−4) E_C for any single mission is reasonable and rational.

Despite these complications, the following data and analyses of the risk imposed by the over-flight of conventional aircraft strongly suggest that a limit for the collective risk for the general public on the order of 100E−6 (1E−4) E_C for any single mission is reasonable and rational. Figure 5-2 outlines the analysis steps taken to establish a rational connection between the standard collective risk limit and the empirically estimated risk to ground dwellers near a major airport in the U.S.



Estimate probability of casualty (P_C) for an individual ground dweller near a major airport on an annual basis

Estimate the number of individuals exposed to typical range activities (N_E)

Estimate the equivalent collective annual risk = $P_C \times N_E$

Divide by a factor of ten to allow for uncertainty in predicted risk from a range activity

Divide by the number of missions per year

The result is the maximum allowable per-mission risk to ensure that range activities “will be no more dangerous than conventional airplanes flying overhead.”

Figure 5-2. Outline of Logic used to Compare Aviation and Range Risks

Based on the data on all civil aviation accidents in the U.S. that killed people on the ground from 1964 to 1999[113], it was estimated that the average risk of fatality for individuals involuntarily exposed to civil aviation accidents within five miles of top 100 airports was about 3E−8 in the year 2000. Based on the decreasing trend noted in the number of involuntarily exposed people killed on the ground by civil aviation accidents between 1964 and 1999 and the projected increases in the number of airport operations and the U.S. population, it appears that the collective risk will remain fairly constant, increasing from 3.8 E_F in 2005 to 4.3 E_F in 2015. Thompson et al found that the uncertainty in these projections is a less important factor than the variability due to distance from an airport. Therefore, these estimates of the risk to ground dwellers posed by U.S. civil aviation are not expected to change much over the next 10 years.

As discussed in Subsection 5.1.2, the risk of fatality alone is not an optimal measure of public risk. An analysis of data acquired from the National Transportation Safety Board (NTSB) on injuries (both minor and serious as defined in 49 CFR 830.2) and fatalities for people on the ground from civil aviation accidents for the 20-year period from 1984 through 2003[114] shows that aviation accidents produce an average of about two to three times as many casualties as fatalities. As shown in Table 5-3, the average ratio of casualties to fatalities on the ground from civil aviation accidents is 2.5; this ratio is somewhat constant over the years (the 99.97% upper bound values are based on year-to-year variations) and applies to general aviation (relatively small airplanes) as well as commercial airline accidents. Table 5-2 shows that this ratio is close to typical predictions made for launch accidents involving debris hazards only. Using the ratio of

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[113] Thompson, K., R. F. Rabouw, and R. Cooke. “The Risk of Groundling Fatalities from Unintentional Airplane Crashes.” *Risk Analysis*. Vol. 21 n. 6 (December 2001). pp. 1025-1038.

[114] Paul Wilde. “Investigation of Risk Acceptability for Experimental Permit Regulation Development.” Technical Report 06-527/10.1-01. ACTA Inc., Torrance CA, December 2006.

about three casualties to one fatality on the ground from civil aviation accidents produces a rough estimate of 1E−7 for the average annual individual risk of casualty from civil aviation accidents for people that dwell within five miles of a top 100 airport.

Table 5-3. Ratio of Ground Casualties to Ground Fatalities based on NTSB Data from 1984 through 2003

Aviation Category	Average	99.87% Upper Bound
All U.S. Civil (Part 91, 121 and 135)	2.5	5.4
Airlines (Part 121)	2.0	5.9
General Aviation (Part 91)	2.7	5.4

Experience with large orbital ELVs at the federal launch ranges demonstrates that launch area risks are typically limited to approximately 300,000 people near the launch point.[115] In addition, experience with the flights of *SpaceShipOne*, the only suborbital RLV flights to date, indicates that the risks were borne by approximately 300,000 people. Of course, far fewer than 300,000 people bear the majority of the total public risk from typical launches; however, the aviation risks are also disproportionately borne by those under the dominant flight paths used for take-off and landing. (Evans 1997) Multiplying the average risk of casualty for individuals involuntarily exposed to civil aviation accidents within five miles of top 100 airports in the year 2000 (i.e., 1E−7) by 300,000 people equates to a collective risk of about 0.03 casualties per year. Therefore, a collective risk of no greater than 0.03 casualties per year for the GP would meet the intent to ensure range activities are no more dangerous than the over-flight of conventional aircraft. For the same reasons, a collective risk of no greater than 0.01 fatalities per year for involuntarily exposed people would meet the intent to ensure range activities are no more dangerous than the over-flight of conventional aircraft.

While aviation risks can be estimated using empirical data on the number of people seriously injured or killed on the ground, the risks posed by range activities are predictions based on computational models that are typically fraught with more uncertainty than the empirical data on aviation risks. To ensure that range activities pose a collective risk of no greater than 0.03 casualties per year (or 0.01 fatalities per year) for people involuntarily exposed, it is prudent to make a reasonable allowance for the uncertainty present in range safety risk predictions. The risk assessment process described in Chapter 2 takes steps to minimize this uncertainty; nevertheless, with all of the uncertainties in the modeling process and input data, any E_C estimate probably has, at the very least, plus or minus one order of magnitude of uncertainty. So, to make some allowance for the uncertainty inherent in range safety risk predictions, the RCC has established annual risk criteria that are approximately 10 times lower than the risks estimated for aviation over-flight based on empirical data. Furthermore, all criteria have been set to the nearest factor of three (approximately one-half order of magnitude on a logarithmic scale). Further refinement is not warranted due to the lack of precision in range safety risk predictions.

The preceding analysis demonstrates that limiting the collective risks to the GP from range activities to no greater than 0.003 casualties and 0.001 fatalities per year is reasonable and rational because a representative sample of about 300,000 people that dwell within five miles of a top 100 airport in the U.S. are exposed to comparable risks. The same logic used in previous

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[115] Philipson 1994 (Table 1 on page 6 and Table 7 on page 20).

versions of this standard can be used to link these annual collective risk criteria to per-mission criteria. Specifically, using an average of 30 missions per year these annual limits correspond to 100E−6 E_C and 30E−6 E_F. Using 30 missions per year is conservative in this context because the recent history from the ER and WR shows closer to 15 launches per year.

More specific factors considered relevant in this analysis are documented in Section 5.10

5.3.2.5 Internal Consistency

The annual and per-mission collective risk limits are consistent with the each other assuming on the order of 30 missions per year. This standard sets casualty risk limits that are consistently about a factor of three higher than the fatality limits for reasons discussed in Subsection 5.3.4.1.

As described in the previous section, all criteria have been set to the nearest factor of three (approximately one-half order of magnitude on a logarithmic scale) and further refinement is not warranted due to the lack of precision in range safety risk predictions.

5.3.2.6 Legal Considerations

The previous sections provide a rational explanation that establishes connections between the relevant facts and the collective risk limit of 100E−6 E_C (and 30E−6 E_F) per mission for the GP. These collective risk limits appear to be reasonable in light of the following.

a. Past RCC launch safety criteria.
b. Launch safety criteria used by other organizations.
c. Federal law governing launch and reentry risks.
d. Risks accepted for comparable involuntary activities.
e. Internal consistency (correlation with other criteria).

Comparisons of the criteria in this standard to *de manifestis* and *de minimis* levels are best done on an annual risk basis, as presented in Subsection 5.4.4.

5.3.3 General Public Individual Risk Per Mission (GP: 1E−6 P_C)

Limiting the individual risk for the GP to 1E−6 P_C per mission is rational and reasonable in light of the following topics that are discussed below. These topics include launch safety criteria used by other organizations, federal law governing launch and reentry risks, risks accepted for comparable involuntary activities, comparable accident statistics, and legal considerations.

5.3.3.1 Prior Safety Criteria

Limiting the individual risk for the GP to 1E−6 P_C per mission is consistent with current practice at the national ranges. Currently the majority of the ranges protect for a P_C of 1E−6 on a per-mission basis. Table 5-4 shows individual mission risk criteria for the GP currently used by various ranges.

Table 5-4. Individual Mission Risk for the General Public as of 2010

Range	Individual Probability of Casualty
Eastern Range	1E−6
Eglin AFB	1E−6
NASA – Wallops Flight Facility	1E−6
Naval Air Warfare Center Weapons Division Point Mugu (NAWCWD PM)	1E−6
Pacific Missile Range Facility	1E−6
Reagan Test Site	1E−6
Western Range	1E−6
White Sands Missile Range	1E−7*
RCC 321-17 Standard Criterion	1E−6
* Expressed as P[Hit]=1.E−07 and applies to both casualty and fatality	

5.3.3.2 Similar Regulatory Experience

The FAA promulgated a regulation in 2000 that limits the individual risk from an RLV mission to one in a million P_C for members of the public.[116] In 2006, the FAA issued a final rule with a similar individual risk limit for ELV launches.[117] The differences between the ELV and RLV regulations regarding individual risks are twofold. First, the RLV individual risk limit applies to all hazards, while the proposed ELV rule would limit the individual risk per hazard. Second, the RLV rule applies to risks from all phases of flight from liftoff through landing, while the ELV rule would apply from liftoff through orbital insertion. Thus, limiting the individual risk for the GP to 1E−6 P_C per mission is reasonably consistent with FAA regulations.

5.3.3.3 Comparable Accident Statistics and Background Risk Levels

5.3.3.3.1 Background risk

Subsection 5.3.2.4 presented data and analysis to demonstrate that the annual risks experienced by ground dwellers near major airports are comparable to the limits set in this standard. Such risks to airport-adjacent residents are produced by many thousands of operations while risks to range-adjacent residents are typically due to only a few dozen missions. Therefore, the individual risks to ground dwellers near an airport are undoubtedly extremely low on a per-flight basis compared to those near a range.

There are no directly comparable involuntary activities in terms of individual risks on a per-mission basis. For the purpose of comparing the per-mission individual risk limits set in this standard to other individual risk limits used to regulate comparable involuntary activities on an annual basis, there are reasons to believe that the same individual members of the public are typically not exposed to the maximum allowable risk from a large percentage of range activities that occur over a year. The reasons include the following.

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[116] 14 CFR 431.35b: “For public risk, the risk level to an individual does not exceed .000001 per-mission (or individual risk criterion of 1E−6).”

[117] 14 CFR 417.107b (71 Fed. Reg. 165): “a launch operator may initiate flight only if the risk to any individual member of the public does not exceed a casualty expectation (P_C) of 0.000001 per launch ($P_C \leq$ 1E−6) for each hazard.”

a. Wind conditions at most ranges are highly variable, so the highest public risk area typically depends on current wind conditions.

b. The time of day of range activities typically varies greatly from one activity to the next.

c. Individuals are typically highly mobile in the U.S. today.

With this in mind, a rough comparison can be made between the per-mission individual risk limits set in this standard (i.e., of 1E−6 P_C and 1E−7 P_F) and the annual individual risk limits used to govern comparable involuntary activities: land use in the vicinity of European airports and chemical installations, and the current practice of the DoD Explosives Safety Board (DDESB). European authorities have determined that, “although small compared with the risks from day-to-day activities, the risks to persons ‘on the ground’ from aircraft crashing on take-off and landing are comparable to those presented by large chemical installations.” Whether a public hazard is posed by the aviation or chemical industry, the Europeans generally recognize 1E−4 as the maximum annual individual risk of death that should be tolerated, and “1E−6 is universally considered to be broadly acceptable.”[118] The British specifically regard an individual annual risk of fatality below 1E−6 as “so low that they merge into the background risks of life, and they require no action” (Evans 1997). At least one U.S. Government agency has used the one in a million annual individual fatality risk limit: the DDESB established[119],[120] that the individual risk of fatality for any member of the public should be below 1E−6 on an annual basis due to the presence of an explosive storage site that needs a waiver from the DoD prescriptive standards, “until approval of risk based policy changes to DoD 6055.9-STD are incorporated.”

The United Kingdom (UK) and Netherlands (NL) have policies that anyone not gaining direct benefit from an activity must be removed from areas where the annual fatality risk exceeds 1E−4.[121] Within areas where the individual risk of fatality from aviation exceeds 1E−5 per year, both the NL and UK governments prevent any further building. The UK allows unrestricted development where the individual annual risk of fatality due to aircraft over-flight is less than 1E−5 (Davies et al). The NL has a more conservative approach than the UK: in areas where the individual annual risk of fatality is between 1E−5 and 1E−6 due to aircraft over-flight, the Dutch prevent future development of housing, hospitals, and/or schools, however; all existing development is permitted to remain. For land use planning around chemical installations, these governments have imposed less restrictive risk limits than those applied near airports in areas where the annual individual risks exceed 1E−5, but more restrictive requirements for risks between 1E−5 and 1E−6.

The purpose of these comparisons is to show the following.

a. Individual risks of fatality below 1E−6 per year have been considered “so low that they merge into the background risks of life, and they require no action.”

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[118] Davies, P. et al. “Public Safety Zones: Cork, Dublin and Shannon Airports.” Reference Report 7608. Department of Transport and Department of Department of the Environment and Local Government. February 2003.

[119] Memorandum, “320th DDESB Board Meeting,” 5 December 2001, Department of Defense Explosives Safety Board.

[120] Memorandum, “327th DDESB Board Meeting,” 14 December 2004, Department of Defense Explosives Safety Board.

[121] The results in Davies et al show that the 1E−4 annual individual risk of fatality contours is contained within the airport property for typical airports. Also see page B4.

b. An individual member of the public would have to be exposed to the maximum allowable individual risk from over a hundred range activities in a year to exceed the maximum annual risk tolerated by European governments in the vicinity of airport and chemical installations.

c. Although there are some differences between the limits imposed by European governments based on the annual individual risks to the public from the aviation and chemical industries, existing developments exposed to less than 1E−5 annual individual P_F generally are permitted to remain.

Keep in mind that the individual risk limits used to govern comparable involuntary activities are based on annual fatalities risks, while this standard sets limits the individual risk of casualty primarily (and fatality as a supplemental measure) on a per-mission basis. Considering the number of range activities per year, and the logic supporting the assumption that the same individual members of the public are unlikely to be exposed to the maximum allowable risk from a large percentage of range activities that occur over a year, the per-mission individual risk limits set in this standard (i.e., of 1E−6 P_C and 1E−7 P_F) appear generally consistent with individual risk limits governing comparable involuntary activities.

The NRC stated a safety goal that: “the overall mean frequency of a large release of radioactive materials to the environment from a reactor accident should be less than 1 in 1,000,000 per year of reactor operation.” Although this NRC risk criterion is on an annual basis with a different consequence, it is an example of a U.S. regulatory agency using 1E−6 as an important benchmark.

5.3.3.3.2 Comparable accident statistics

Comparable accident statistics were used to generate a Universal Risk Scales (URS) based on APT Research studies. The URS for injury presents risk statistics from historical accident data and regulatory standards in a common graphical format to help communicate risk levels and assist the decision maker in establishing acceptable risks. The URS for injury to an individual resulting from involuntary activities is shown in Figure 5-3. Note that the URS present annual risk since most accident data is given on an annualized basis. Making an assumption of 15 missions per year based on recent history from the ER and WR, per-event statistics can be approximated from annual accident data (some of which are summarized in Table 5-5). These data are presented to communicate historical risk levels, some of which are not necessarily viewed as acceptable. The data collected are for injuries that were medically attended to and caused one full day or more of restricted activity. This roughly correlates to AIS Level 2, which is a less severe injury than the AIS Level 3 adopted as the casualty measure. This more conservative measure serves as a reasonable upper bound for defining a maximum allowable risk.

Figure 5-3. Universal Risk Scale: Injuries for Annual Probability of Injury to an Individual Resulting from Involuntary Activities

Table 5-5. General Public Individual Probability of Casualty Risk[1]

Activity/Source	Per Event[2]	Annual[3]
Unintentional Strike by/against an object	1.03E−3	1.55E−2
Motor Vehicle Occupant	6.94E−4	1.04E−2
Battle of Britain (British Civilians)	6.67E−4	--
Lawn Mowers	1.67E−5	2.51E−4
Refrigerators	6.94E−6	1.04E−4
Severe Weather Events (Missouri – worst)	3.37E−6	5.06E−5
Severe Weather Events (U.S. average)	6.43E−7	9.64E−6
Commonality Criterion per mission	1E−6	--

1. Data is compiled from various sources: National Electronic Injury Surveillance System, Consumer Product Safety Commission, National Center for Injury Prevention and Control, U.S. Census Bureau, and House of Commons Library.
2. With the exception of the Battle of Britain, the per-event statistics are derived from annual statistics by dividing the annual values by 15 to model the assumption of 15 missions per year.
3. Risk is based on the exposed populations: Battle of Britain ~48 million, Missouri ~6 million, all others ~289 million.

5.3.3.4 Legal Considerations

The previous sections provide a rational explanation that establishes connections between the relevant facts and the individual risk limit of 1E−6 P_C (and 1E−7 P_F) per mission for the GP.

The standard individual risk limits are rationally connected to the available facts and are reasonable in light of the following conclusions from the previous sections.

a. Current practices of several of the national ranges include individual risk limits of 1E−6 P_C or 1E−7 P_F.

b. Federal law governing commercial RLV missions limits individual risk to 1E−6 P_C for members of the public.

c. European governments treat individual risks of fatality below 1E−6 per year as “so low that they merge into the background risks of life, and they require no action.”

d. Individual members of the public are typically unlikely to be subject to a maximum risk from a large percentage of range activities over a year.

e. An individual member of the public would have to be exposed to the maximum allowable individual risk from over a hundred range activities in a year to exceed the maximum risk tolerated by European governments on an annual basis in the vicinity of airport and chemical installations.

f. 1E−4 and 1E−6 fatalities per year have essentially been established in Europe as maximum tolerable and broadly acceptable levels, respectively. Because individual members of the public are typically unlikely to be subject to a maximum risk from a large percentage of range activities over a year, the standard individual risk limits of 1E−6 P_C and 1E−7 P_F per mission appear roughly between the maximum tolerable and broadly acceptable levels, but certainly closer to the broadly acceptable level.

5.3.4 General Public Annual Collective Risk (GPa: 0.003 E_C)

5.3.4.1 Prior Safety Criteria and Internal Consistency

Previous versions of this standard established an annual collective risk criterion of 0.001 E_F. That criterion was justified by:

a. prior use at the national ranges;

b. similar regulatory experience;

c. comparable accident statistics;

d. internal consistency with other criteria in the standard.

As shown in Table 5-3, NTSB data from the twenty-year period from 1984 through 2003 reveals an average ratio of about three casualties to one fatality on the ground from civil aviation accidents. This ratio of casualties to fatalities for ground dwellers exposed to aircraft accidents is fairly constant over the years and applies to general aviation (relatively small airplanes) as well as commercial airline accidents. Civil aircraft and range accidents that present inert debris hazards only are reasonably expected to involve generally similar materials, gross vehicle weights, and highly variable degrees of fragmentation. Since conventional aircraft accidents and typical range accidents that present inert debris hazards only are logically expected to produce a similar average ratio of casualties to fatalities for ground dwellers (i.e., close to three), an annual collective risk limit 0.003 casualties is consistent with the previously established RCC limit of

0.001 E_F for inert debris only. This is also consistent with the limits defined for the per-mission criteria as indicated in Figure 5-1.

The data in Table 5-2 show that a ratio of casualty expectation to fatality expectation less than three is typical for the dominant range hazards often addressed by risk management. Therefore, it is conservative to establish a limit on the annual collective risk of casualties from all range hazards that is three times higher than the previously established limit for fatalities due to inert debris only. Experience at the WR indicates "that one hazard usually predominates as the source of risk" because "the conditions that are conducive to driving up the risk of one hazard usually render another hazard less significant."[122] Furthermore, the ranges can often mitigate toxic and DFO risks by various means as described in Chapter 8. Therefore, an annual collective risk limit 0.003 casualties from all hazards is not unreasonably conservative relative to the previously established limit of 0.001 E_F for inert debris only.

5.3.4.2 Similar Regulatory Experience

Regulations typically use fatality risk metrics. Given the regulatory experience described below and the reasonability of using a factor of three between casualty expectation and fatality expectation (as presented in Subsection 5.3.3.1), limiting the annual collective risk for the GP to 0.003 is rational and reasonable.

5.3.4.3 Comparable Accident Statistics and Background Risk Levels

The data and analyses presented in Subsection 5.3.2.4 demonstrate that an annual limit of 0.003 GP casualties from range activities is reasonable and rational compared to the risk posed by aviation over-flight to a representative sample of about 300,000 people that dwell within five miles of a top 100 airport in the U.S. That conclusion was primarily supported by an analysis of empirical data that resolved ground dweller risks as a function of distance to an airport (irrespective of the distance from the dominant take-off and landing flight paths), which tends to produce an underestimate of the highest ground dweller risks near major airports. Other data and analysis of aviation-related risks presented in other sections also indicate that an annual limit of 0.003 GP casualties from a range's activities is reasonable and rational.

5.3.4.4 Legal Considerations

Limiting the annual collective risk for the GP to 0.003 is rational and reasonable in light of the following:

a. past RCC launch safety criteria;

b. similar regulatory experience;

c. comparable accident statistics.

5.3.5 Mission-essential and Neighboring Operations Personnel Casualty Risk Limits

The development of the criteria for tolerable risk for MEP and NOP (i.e., voluntarily accepted risks) started with the establishment of the tolerable risk levels for uninvolved personnel. The next step was to apply a factor to the risk acceptability for uninvolved personnel to obtain a risk tolerability level for MEP. Finally, an adjustment was made in the case of the collective risk of casualties as described below.

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[122] 65 Fed. Reg. 207 (25 October 2000), p. 63936.

As discussed in Subsection 5.2.3, people ordinarily accept a wide range of risks depending on their perception of the risks and benefits. Most importantly, people are far more tolerant of risks that are imposed on them voluntarily than risks imposed on them without any sense of benefit or consent. Applying a factor between voluntary and involuntary risks has historical precedent. Starr's landmark paper concluded that people who were exposed to risk voluntarily would accept 1000 times more risk for the same benefit as those who were involuntarily exposed to the risk. Subsequently, other researchers concluded that the factor of 1000 was too high and was highly variable and dependent on other factors. The risk acceptability criteria given in Chapter 3 of the standard for related workers (i.e., MEP and NOP) who are voluntarily exposed and receive direct compensation for their involvement in range activities, are generally 10 times higher than the risk acceptability for involuntarily exposed people. Using a factor of 10 is consistent with current practice at the national ranges[123], past RCC standards[124], NASA's range safety program requirements[125], and the policy of foreign governments (Great Britain Health and Safety Executive, p. 44). As shown in Figure 5-1, this factor of 10 is applied to all but one of the voluntary risk criteria.

5.3.5.1 Voluntary Risk Criterion

The only voluntary risk criterion in this standard that is not a factor of 10 higher than the corresponding criterion for the GP involves the collective risk of casualties. Specifically, the collective risk for MEP and NOP is limited to 300E−6 E_C, which is only three times the corresponding criterion for the GP. The RCC chose this more conservative criterion after determining that this is consistent with past risks experienced at the national ranges.

5.3.5.2 Comparable Accident Statistics and Background Risk Levels

Similar to the GP category, comparable accident statistics for this category are only available on an annualized basis. With a conservative assumption of 15 missions per year, per event, statistics can be approximated from annual accident data (Table 5-6).

Table 5-6. Mission-Essential Individual Casualty Risk[1]

Activity/Source	**Per Event [2]**	**Annual [3]**
Construction workers	2.81E−3	4.21E−2
Agricultural workers	2.2E−3	3.29E−2
Government workers	1.6E−3	2.40E−2
Service workers (police, firemen, etc.)	1.18E−3	1.77E−2
Gulf War	2.01E−4	--
Machinery	6.4E−5	9.59E−4
Commonality criterion per mission	**10E−6**	**--**

[1]Data is compiled from various sources: Bureau of Labor Statistics, National Center for Health Statistics, State Vital Statistics Departments, State Industrial Commissions, National Electronic Injury Surveillance System, Consumer Product Safety Commission, National Center for Injury Prevention and Control, U.S. Census Bureau, and U.S. Department of Veterans Affairs.
[2]With the exception of the Gulf War, the per-event statistics are derived from annual statistics by dividing the annual values by 15 to model the assumption of 15 missions per year.
[3]Risk is based on exposed population, which varies for each activity.

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[123] AFSPCMAN 91-710, paragraph 3.3.3
[124] RCC Standard 321, page 3-1.
[125] NASA-STD-8719.25, paragraph 4.3.3

5.4 Rationale for Fatality Guideline Limits

The fatality limits are essentially unchanged[126] from RCC 321-02; however, these criteria are now a supplemental metric for the reasons discussed in Subsection 5.1.2. The rationale documented in the RCC 321-02 Supplement Chapter 3 that is applicable to those limits is still valid and is presented below. Use of annual risk limits for individuals was determined by the RC as not being practical or feasible since it is impossible to track the whereabouts of an individual from mission to mission in order to accumulate their risk. Therefore, annual individual risk limits are no longer used. The rationale for the unused annual fatality limits is still retained here because it provided useful information and data to support the remaining related criteria.

Table 5-7 shows the supplemental fatality criteria for both the GP and MEP/NOP.

Table 5-7. Maximum Acceptable Fatality Risk to People

Per-mission Criteria	**General Public**	**Mission-essential**
Individual Probability of Fatality	0.1E−6	1E−6
Expected Fatalities	30E−6	300E−6
Annual Criteria		
Expected Fatalities	1,000E−6	10,000E−6

5.4.1 General Public Annual Individual Risk (GPa: N/A P_F). - **NO LONGER USED**

5.4.1.1 Prior Safety Criteria

The commonality criterion is comparable to historical data from the national ranges. The criterion reflects the same risk level that is used at the ER and WR (Table 5-8).

Table 5-8. Individual Annual Risk for the General Public

Range[1]	**Annual Probability of Casualty**
Eastern Range	1E−6
Western Range	1E−6
Commonality Criterion	**1E−6**[2]

1. Table lists only ranges that have criteria in this category
2. Probability of Fatality

5.4.1.2 Similar Regulatory Experience

5.4.1.2.1 Federal statutes

Federal statutes provide numerous precedents for acceptable risk levels. These are documented in numerous technical papers. One such paper[127] examined risk criteria employed as part of the regulatory procedures with 12 federal statutes promulgated by the Department of

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[126] The mission-essential individual probability of fatality limit was reduced from 3E−6 to 1E−6 to maintain the factor of 10 difference with the individual probability of fatality limit set for the public.

[127] Lorenz Rhomberg. "Federal Agency Risk Assessment and Risk Management Practices." In *Risk Assessment and Risk Management in Regulatory Decision Making: Final Report. Volume 2*. Washington, D.C.: Commission on Risk Assessment and Risk Management, 1997.

Labor, EPA, and the Food and Drug Administration (FDA) (listed in Appendix C). Eleven of the twelve consider individual risk in some manner.

Individual risk is used as a criterion in two distinct ways. In some cases, such as the Occupational Safety and Health Administration (OSHA), risk is used to trigger action by a regulatory agency. The second use targets allowable residual risk after implementation of a regulatory action. Table 5-9 presents information on a lifetime and annual basis, assuming a lifetime exposure of 70 years. The fourth column compares the debris risk standard to the risk criteria cited in the statutes.

Table 5-9. Summary of Individual Fatality Risk Criteria

Affected Group	Trigger Level		Target Residual Level		Debris Risk
	(Lifetime)	**(Annual)**	**(Lifetime)**	**(Annual)**	**(Annual)**
Public	1E−6 - 1E−4	1.4E−8 - 1.4E−6	1E−7 - 1E−4	1.4E−9 - 1.4E−6	1E−6
	(EPA, FDA)		(EPA, FDA)		

5.4.1.2.2 Regulating carcinogens

A review of 132 regulatory decisions involving cancer risks for which numerical risk estimates were available found a correlation in the levels of acceptable risk.[128] The review focused on the decisions to regulate in relation to acceptable individual risk, population (collective) risk, and total population at risk. The risk measures used varied significantly among the 132 cases and significant differences exist among the bases for the various risk estimates. Nevertheless, this review identified consistency in the apparent *de minimis* and *de manifestis* levels of concern underpinning the standards adopted. In the 132 cases studied, individual risks were always regulated when they rose above one in 12,500 (8E−5) per year and were regulated at lower risk levels when more than 10 cancers in the U.S. population per year were estimated. Individual risks were never regulated when they were below one in 500,000 (2E−6) annually and estimated cancers in the U.S. population remained fewer than about one in 20 years (5E−2 annual). The levels of protection provided by the debris standard are consistent with the foregoing *de manifestis* level. In some cases, because of the high visibility of a debris-producing event, the debris standard is more conservative than the *de minimis* level.

5.4.1.2.3 British Ministry of Defense

The British Ministry of Defense has adopted a *de manifestis* individual risk standard of 1E−6 per year for fatalities from operation of explosive storage facilities. For these same facilities the *de minimis* individual risk standard is 1E−8 per year. The UK Department of the Environment has stated that an individual risk of 1E−6 per year of serious health effects is acceptable.

5.4.1.2.4 Dutch acceptable risk standards

The acceptable risk standards used by Dutch industries for public individual fatality risk are 1E−6 per year for established nuclear power plants and chemical industries, and 1E−8 per year for future nuclear power plants.

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[128] Travis, C.C., S. Richter, E. Crouch, R. Wilson, and E. Klema. “Cancer Risk Management: A Review of 132 Federal Regulatory Decisions.” *Environmental Science and Technology*, Vol. 21, No. 5. May 1987: pp. 415-420.

5.4.1.2.5 Israeli Ministry of Defense

The Israeli Ministry of Defense uses 1E−5 as a directly comparable standard for maximum annual individual fatality risk from launch operations for the non-participating, uninformed GP. The Ministry tolerates higher risk levels for non-participating, uniformed workers in industrial facilities.

5.4.1.3 Comparable Accident Statistics and Background Risk Levels

An assumption was made that individuals who are not mission-essential should not incur a higher risk of fatality than risk experienced by the general population at home or in public. To facilitate evaluation of the criterion for risk to other personnel, comparisons are made to two categories from the accident database. Table 5-10 shows data on accidents occurring in public and Table 5-11 shows data on accidents in the home. These comparisons show that the commonality standard maximum risk to a non-essential individual is significantly less on an annual basis than the risks from accidents occurring in the home or in public.

Table 5-10. Fatalities Due to Accidents in Public

Public Event	**Individual Probability of Fatality**[a]
	Average Annually
Falls	1.61E−05
Drowning	8.44E−06
Firearms	2.30E−06
Fires and burns	7.67E−07
Air transport	3.45E−06
Water transport	2.68E−06
Railroad	2.30E−06
Other transport	1.15E−06
All other public[b]	3.84E−05
Total	7.56E−05

a. Based on total 1994 U.S. population of 260,711,000.
b. Includes: medical complications, excessive heat/cold, suffocation by ingestion, and poisoning, etc.
Note: Criterion for GP (Maximum) = 1.0E−6

Table 5-11. Fatalities Due to Accidents in the Home

Home Event [a]	**Individual Probability of Fatality**[b]
	Average Annually
Falls	3.26E−05
Poisoning by solids and liquids	2.45E−05
Poisoning by gases and vapors	1.92E−06
Fires and burns	1.50E−05
Suffocation-ingested object	5.37E−06
Suffocation-mechanical	2.68E−06
Firearms	3.45E−06
Drowning	3.45E−06
All other home[c]	1.34E−05
Total	1.02E−04

a. Includes: medical complications, excessive heat/cold, suffocation by ingestion, and poisoning.
b. Based on total 1994 U.S. population of 260,711,000.
c. Includes: electric current, explosive materials, hot substances, corrosive liquid, and steam.
Note: Data obtained from the 1995 National Safety Council, Accident Facts: 1995 Ed., Itasca, IL. Accident Facts were used to calculate the risk of several accidents on an annual basis.
Note: Criterion for GP (Maximum) = 1.0E−6

5.4.1.4 Legal Considerations

Risks are reasonable, and in the same range as the *de manifestis* level used by other agencies. Table 5-12 is a summary of the annual public fatality risk based on existing regulations used by the U.S. and foreign countries.

Table 5-12. Summary of U.S. and Foreign Annual Fatality Risk Criteria

	De Minimis	De Manifestis	Commonality Standard
Individual Risk (Public)	1.4E−9[a] - 2E−6[b] 1E−8[c]	1.4E−8[a] - 1E−6[a,d] 1E−6[c]	1E−6

a. Environmental Protection Agency
b. Regulatory carcinogen study
c. Clusters around this value
d. British and Dutch

5.4.2 General Public Individual Risk Per Mission (GP: 0.1E−6 P_F)

5.4.2.1 Prior Safety Criteria

The commonality criterion is consistent with historical data from the national ranges. Currently the majority of the ranges protect for a P_C of 1E−6. The commonality criterion protects against fatality; however, the risk level is an order of magnitude lower than that afforded to casualty. Therefore, consistency is maintained. Table 5-13 shows individual mission risk for the GP. Both casualty and fatality criteria are shown.

Table 5-13. Individual Mission Risk for the General Public

Range	Agency	Current as of 2010	
		P_C	P_F
Eastern Range	USAF	1E−06	No Criterion
Eglin AFB	USAF	1E−06	No Criterion
NAWCWD PM	Navy	1E−06	1E−07
Pacific Missile Range Facility	Navy	1E−06	No Criterion
Reagan Test Site - Kwajalein	Army	1E−06	1.E−07
Wallops Flight Facility	NASA	1E−06	No Criterion
Western Range	USAF	1E−06	No Criterion
White Sands Missile Range	Army	No Criterion	1E−07
RCC 321-23 Standard Criterion (summed over all hazards)		1E−06	1E−07

5.4.2.2 Similar Regulatory Experience

There are few types of regulatory experience other than range safety that address risks related to single events, such as launch, in contrast to ongoing operations of a facility. By extension, the annual regulatory experience cited in Subsection 5.4.1.2 justifies the maximum per-mission risk.

5.4.2.3 Comparable Accident Statistics and Background Risk Levels

Comparable accident statistics for this category are difficult to find because most accident statistics are given on an annualized basis.

5.4.2.4 Legal Considerations

Risks are reasonable. This criterion is below the *de minimis* level; however, the potential high visibility warrants the standard.

5.4.3 General Public Collective Risk Per Mission (GP: 30E−6 E_F)

5.4.3.1 Prior Safety Criteria

The numerical values for the maximum acceptable individual and collective fatality risks presented in Chapter 3 of the standard are identical to those established previously by the RCC (See RCC 321-02).

The updated fatality risk criteria in Chapter 3 of the standard limit the risks from all hazards throughout a mission, and not just the inert debris risks limited previously. The current standard clearly provides more comprehensive protection than the previous criteria because the same fatality risk limits now apply to the aggregated risks from all types of hazards associated with a range activity, not just the inert debris hazard. Therefore, the rationale used for the previous fatality risk criteria still applies to the updated criteria from a safety perspective. In addition, experience shows that the fatality risks posed by typical range hazards are small relative to those posed by inert debris. For example, Table 5-14 lists the typical ratio of fatality expectation to casualty expectation for the dominant range hazards often addressed by risk management. Therefore, it is reasonable and rational to set fatality risk limits for the total risks posed by a mission using the same numerical values as those previously established for inert debris only.

Table 5-14. Typical Ratio of Expected Fatalities to Casualties

Hazard Scenario	Range of E_F/E_C
Large inert debris impacts	0.6 to 0.8
Explosive and inert debris impacts	0.1 to 0.8, 0.25 typical
Distant focusing overpressure	0.001 to 0.03, 0.01 typical
Solid rocket propellant toxic release	0.001 typical

Notes: *These are based on AIS level 3 threshold for casualty.
*These results are based on various mixtures of sheltering levels.

The commonality criterion is comparable to historical data from the national ranges. Recognizing that the RCC criteria now apply to additional hazards besides inert debris, the criteria reflect the same or very similar risk levels used by the four ranges that use E_F criteria (Table 5-15). Note that the table also presents the E_C criteria.

Table 5-15. Collective Mission Risk for the General Public

Range	Agency	Current as of 2010	
		E_C	E_F
Eastern Range	USAF	1E−04	No Criterion
Eglin AFB	USAF	Not resolved	Not resolved
NAWCWD PM	Navy	1E−04	3E−05
Pacific Missile Range Facility	Navy	1E−04	No Criterion
Reagan Test Site - Kwajalein	Army	1E−04	3E−05
Wallops Flight Facility	NASA	1E−04	No Criterion
Western Range	USAF	1E−04	No Criterion
White Sands Missile Range	Army	No Criterion	3E−05
RCC 321-23 Standard Criterion (summed over all hazards)		1E−04	3E−05

5.4.3.2 Similar regulatory experience

Few types of regulatory experience (other than range safety) address risks related to single events, such as a launch, as opposed to ongoing facility operations. Existing precedents are provided on an annual basis.

5.4.3.3 Comparable accident statistics and background risk levels

Comparable accident statistics are difficult to find because ranges are event-oriented, whereas industries have continuous operations. If aircraft operating for a day are compared to a single operation at a range, then the following information can be used for comparison.

5.4.3.3.1 Risk to people on the ground from commercial aircraft

Accident data from the period 1980 to 1995 were analyzed to determine the average fatality rate (fatalities per departure) to people on the ground for air carriers and general aviation.[129] The average fatality rates for this group of people were 6E−7 per departure for air carriers and 3E−7 for general aviation. These average fatality rates were used in conjunction with published numbers of air carrier and general aviation operations (based on the assumption that each flight was counted as two operations – a landing and a departure) for FY93 to produce collective risk estimates to people on the ground in the areas adjacent to several sizes of airports. The results are shown in Table 5-16. This indicates that the launch day risk of living near a facility is similar to the everyday risk of living near a small airport and an order of magnitude less than the daily risk of living near a major airport. A more in-depth analysis of the risks to people on the ground from civil aviation is presented in Section 5.10.

Table 5-16. Risk to People on the Ground from Commercial Aircraft and General Aviation

	Number of Departures (1993)		
Airport	**Air Carrier**	**Gen. Aviation**	**Collective Fatality Risk**
Los Angeles, CA	3.1E+5	2.5E+4	~5E−4 per day

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[129] NTSB. *Annual Review of Aircraft Accidental Data. US Air Carrier Operations, Calendar Year 1990*. PB94-102787. 4 October 1993.

Orlando, FL	1.5E+5	1.2E+4	~3E−4 per day
Melbourne, FL	1.0E+4	9.6E+4	~9E−5 per day
Santa Maria, CA	9.4E+3	3.2E+4	~4E−5 per day

5.4.3.3.2 Internal consistency

This criterion correlates with and is supported by other criteria in this category as shown in Figure 5-1.

5.4.3.3.3 Legal considerations

Risks are very reasonable. This criterion is well below the *de minimis* level for collective protection; however, the potential high visibility warrants the standard.

5.4.4 General Public Annual Collective Risk (GPa: 1000E−6 E_F)

5.4.4.1 Prior Safety Criteria

The commonality guideline is comparable to historical data from the national ranges. Recognizing that the RCC guideline is now applicable to additional hazards besides just inert debris, the guideline reflects a risk level similar to that used at the ER and WR. Table 5-17 shows the collective annual risk for the GP.

Table 5-17. Collective Annual Risk for the General Public

Range[a]	**Annual Expected Casualties**
Eastern Range	1E−3
Western Range	1E−3
Commonality Criterion for E_F	**1E−3**[b]

a. Table lists only ranges that have criteria in this category.
b. Expected Fatalities.

5.4.4.2 Similar Regulatory Experience

At the federal level, only the NRC has considered numerical risk criteria for limiting annual collective risk. Their criterion protects large masses of people from effects of invisible radiation and are therefore very conservative. More applicable criteria have been identified at the foreign and local level as follows.

a. Hong Kong. Hong Kong has adopted acceptable public fatality risk profile standards for facilities storing hazardous materials. The *de minimis* annual collective risk standard is 7E−5; the *de manifestis* value is 7E−3.

b. Dutch Acceptable Risk Standards. The acceptable risk standards used by Dutch industries for collective public annual fatality risk are 1.1E−3 per year for established nuclear power plants and chemical industries, and 1.1E−5 per year for future nuclear power plants.

c. British Ministry of Defense. The British Ministry of Defense has adopted a *de manifestis* collective fatality risk standard of 6E−3; the *de minimis* collective fatality risk standard is 6E−5.

d. Santa Barbara County. The County of Santa Barbara in California uses risk-based guidelines for review of hazardous facilities. The maximum annual societal fatality risk to the GP surrounding a facility under these guidelines is 1.6E−3; additional constraints are imposed on the probability of any specific number of fatalities per year.

5.4.4.3 Comparable Accident Statistics and Background Risk Levels

5.4.4.3.1 Risk to people on the ground from commercial aircraft

Accident data from the period 1980 to 1995 were analyzed to determine the average fatality rate (fatalities per departure) to people on the ground for air carriers and general aviation (NTSB, 1994). The average fatality rates for this group of people were 6E−7 per departure for air carriers and 3E−7 for general aviation. These average fatality rates were used in conjunction with published numbers of air carrier and general aviation operations (based on the assumption that each flight was counted as two operations – a landing and a departure) for FY93 to produce collective risk estimates to people on the ground in the areas adjacent to several sizes of airports. The results are shown in Table 5-18.

Table 5-18. Risk to People on the Ground from Commercial Aircraft and General Aviation

	Number of Departures (1993)		
Airport	**Air Carriers**	**Gen. Aviation**	**Collective Fatality Risk**
Los Angeles, CA	3.1E+5	2.5E+4	~0.2 per year
Orlando, FL	1.5E+5	1.2E+4	~0.09 per year
Melbourne, FL	1.0E+4	9.6E+4	~0.03 per year
Santa Maria, CA	9.4E+3	3.2E+4	~0.02 per year

5.4.4.3.2 Comparative public risks due to military aircraft operations

Risks to the GP from military aircraft crashes were estimated for five representative Air Force bases selected on the basis of relatively large numbers of aircraft operations and their having relatively large nearby populations.[130] The assessment is based on accident data for the years 1977 through 1981 and on models addressing aircraft crash frequency by runway angular sector and representative aircraft crash area. Table 5-19 summarizes these results.

Table 5-19. Casualty Risk to General Public

Air Force Base	Annual Collective Risk
March AFB	0.004
Mather AFB	0.02
McClellan AFB	0.1
Nellis AFB	0.2
Sheppard AFB	0.01
Average	**0.07**

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[130] Philipson, L. and D. Hoefer. “Comparative Public Risks Due to Military Aircraft Operations.” J. H. Wiggins Company Technical Report 82-3093. Prepared for WSMC/SE under Contract FO4703-79-C-004. September 1982.

5.4.4.3.3 Aviation risk in the CCAS area

A study was performed to assess the PL 81-60 (discussed in Subsection 5.3.2.4) risks for the ER.[131] The risks from general aviation and military aviation flights over the region for both on and off-base were quantified. Air carrier operation risk was omitted because this risk was assessed to be negligible in comparison to general aviation and military aviation risks.

The risk estimates used the same population database as in launch risk analyses, with one exception: the transient population at the viewing stand or on the causeway during a launch was excluded. Moreover, methodologies for quantifying risk were, whenever possible, selected to parallel the methodologies used for quantifying launch risk. Because these risk estimates were being used to quantify a standard for acceptable launch risk levels, the analysis assumptions that could not be totally resolved were addressed one of two ways; either assumptions were treated so as to underestimate risks from aircraft over-flight or they were treated parametrically.

Thus, the study resulted in an estimate of annual collective casualty risk to the off-base populations ranging from 1.8E−2 to 8.8E−2. These results have been interpreted as providing a limit for risk to the GP but being of marginal relevance to worker risk. The text of the legislative history is not seen as addressing risk to essential workers.

5.4.4.3.4 Studies on acceptable collective risks in the United Kingdom

Multiple-fatality fire occurrence data from the UK, US, and worldwide were examined to formulate a basis for an acceptable fatality risk criterion in the chemical and process industry.[132,133] This study asserts that the acceptable level of societal risk is related to the size of the affected group. It bases this assertion on precedents in the requirements for design of different types of structures and on reasonableness of risk allocation. For a community of 100,000 people in the vicinity of the range, this criterion is equivalent to an annual (collective) fatality expectation of 6E−3, a collective risk level comparable to the standard. For the the approximate population of the United States in 1996 of 266E+6, this corresponds to a national collective risk criterion of 16, a value remarkably close to the acceptable national collective risk level of 10, above which allowable individual risk criteria are reduced for the purpose of regulating carcinogens.

5.4.4.4 Internal Consistency

This criterion correlates with other criteria in this category as shown in Figure 5-1.

5.4.4.5 Legal Considerations

This criterion is very reasonable. “One death in a millennium,” while not exactly precise, is a useful way to think of this standard.

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[131] Lloyd Philipson. “Refined Estimate of the Risk from Aviation Accidents to the Population in the CCAS Area of Concern.” Report #94-297/46-01. ACTA Inc., Torrance, CA, September 30, 1994.

[132] D.J. Rasbash. “Criteria for Acceptability for Use with Quantitative Approaches to Fire Safety.” Paper presented at the Fire Prevention for Industry and Trade, BFD, Symposium on Fire Protection Concepts: Zurich, 1984.

[133] D.J. Rasbash. “Criteria for Decisions on Acceptability of Major Fire and Explosion Hazards with Particular Reference to the Chemical and Fuel Industries” in *IchemE Symposium Series Number 58*. London: The Institution of Chemical Engineers, 1980.

Table 5-20 provides a summary of the collective annual risk for the public. The data was taken from a summary of the entire body of existing regulations used by the U.S. and foreign countries.

Table 5-20. Summary of U.S. and Foreign Annual Fatality Risk Criteria

	De Minimis	**De Manifestis**	**Commonality Criterion**
Collective Risk (Public)	$1.6E{-5}^{a}$ - $5E{-2}^{b}$ $1.1E{-5}^{c}$	$2E{-6}^{d}$ – 10^{b} $1.1E{-3}^{c}$	1E−3

a. Santa Barbara County.
b. Regulatory carcinogen study.
c. Clusters around this value.
d. Nuclear Regulatory Commission.

5.4.5 Mission-Essential Individual Risk Per Mission (ME: 1E−6 P_F)

5.4.5.1 Prior Safety Criteria

Four of the national ranges have used criteria in this category. The commonality criterion protects against fatality; however, the risk level is an order of magnitude lower than that afforded to casualty by the majority of the ranges. Therefore, consistency is maintained. Table 5-21 provides this data. The table also provides the criteria protecting against casualties.

Table 5-21. Individual Mission Risk for Mission-essential Personnel

Range	Agency	Current as of 2010	
		P_C	P_F
Eastern Range	USAF	1.E−05	No Criterion
Eglin AFB	USAF	1.E−05	No Criterion
NAWCWD PM	Navy	1.E−05	1.E−06
Pacific Missile Range Facility	Navy	1.E−05	No Criterion
Reagan Test Site - Kwajalein	Army	1.E−05	1.E−06
Wallops Flight Facility	NASA	1.E−05	No Criterion
Western Range	USAF	1.E−05	No Criterion
White Sands Missile Range	Army	No Criterion	1.E−06
RCC 321-23 Standard Criterion (summed over all hazards)		1.E−05	1.E−06

5.4.5.2 Similar Regulatory Experience

Few types of regulatory experience, other than range safety, address risks related to single events such as a launch, in contrast to the risks related to ongoing facility operations.

One directly comparable regulatory requirement lies within the Israeli criterion for defense community personnel participating in a test. The Israeli Ministry of Defense derives the allowable individual risk per test based on the planned number of tests per year and an annual criterion.

5.4.5.3 Comparable Accident Statistics and Background Risk Levels

The commonality criterion for voluntary risk is comparable to other voluntary risks taken every day in the U.S. For example, the number of automobile deaths per 200 miles is 3.6E−6 and the number of deaths per 200-mile trip in a private plane is 3.4E−5.

5.4.5.4 Internal Consistency

Mission-essential criteria, as a group, relates to GP at one order of magnitude higher risk. In addition, mission-essential criteria correlate to each other, as shown in Figure 5-1.

5.4.5.5 Legal Considerations

The criterion is reasonable. It is near the *de minimis* level.

5.4.6 Mission-essential Annual Individual Risk – **NO LONGER USED** (MEa: N/A P_F)

5.4.6.1 Prior Safety Criteria

Prior use at national ranges has been limited and inconsistent. To maintain reasonableness and consistency, an annual P_F of 3E−5 is the commonality criterion.

5.4.6.2 Similar Regulatory Experience

5.4.6.2.1 Occupational Safety and Health Administration

The U.S. Department of Labor, OSHA, must regulate chemical risks when it can show that they pose a significant risk. In the benzene Supreme Court decision,[134] Justice Stevens stated that "if the odds are one in a thousand..., a reasonable person might well consider the risk significant..." Based on a working lifetime of forty years, this translates into an annual individual risk of 2.5E−5.

5.4.6.2.2 Israeli Ministry of Defense

The Israeli Ministry of Defense uses an annual individual risk criterion of 1E−3 for MEP.

5.4.6.3 Comparable Accident Statistics and Background Risk Levels

The adopted maximum risk criterion compares favorably to actual average risk in other occupations.

The assumption is made that individuals who work as MEP on the range recognize and accept an inherent associated risk. This assumption allows direct comparison with the occupations in Table 5-22. This table illustrates that the maximum acceptable annual risk for any single individual is comparable to the average actual risk from a variety of industries.

Table 5-22. Occupational Fatalities

	Annual Probability of Fatality Per Person	
Industry (Averages)	**Dept. of Labor[a]**	**1994 Accident Facts[b]**
Agriculture	2.4E−04	2.6E−04
Mining, quarrying	2.7E−04	2.7E−04
Construction	1.5E−04	1.5E−04
Manufacturing	4.0E−05	4.0E−05

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[134] Industrial Union Department vs. American Petroleum Institute, 488 U.S. 607 (1980)

Transportation and public utilities	1.3E−04	1.2E−04
Trade	1.0E−04	2.0E−05
Services	3.0E−05	2.0E−05
Government	3.0E−05	3.0E−05
All Industries (Avg.)	5.0E−05	4.0E−05
Commonality Criterion for Mission-Essential Personnel (Maximum) = 1.0E−04		
a. U.S. Department of Labor, Bureau of Labor Statistics, Census of Fatal Occupational Injuries, 1994. b. Accident Facts, 1994 Edition, National Safety Council.		

5.4.6.4 Legal Considerations

Risks are reasonable based on comparison of other regulations, accident experience, and other criteria.

5.4.7 Mission-essential Collective Risk Per Mission (ME: 300E−6 E_F)

5.4.7.1 Prior Safety Criteria

Most ranges use this type of criterion. The commonality guideline is comparable to historical data from the national ranges. This is an important guideline to ranges because it is used by range safety organizations to help limit the total number of personnel exposed to any given mission. The guideline reflects the same or similar risk level to that used at four of the ranges as shown in Table 5-23. The table also provides, for completeness, the criteria for protecting against casualties.

Table 5-23. Collective Mission Risk for Mission-essential Personnel

Range	Agency	Current as of 2010	
		E_C	E_F
Eastern Range	USAF	3E−04	No Criterion
Eglin AFB	USAF	Not resolved	Not resolved
NAWCWD PM	Navy	3E−04	3E−04
Pacific Missile Range Facility	Navy	3E−04	3E−04
Reagan Test Site - Kwajalein	Army	3E−04	3E−04
Wallops Flight Facility	NASA	3E−04	No Criterion
Western Range	USAF	3E−04	No Criterion
White Sands Missile Range	Army	No Criterion	3E−04
RCC 321-23 Standard Criterion (summed over all hazards)		3E−04	3E−04

5.4.7.2 Similar Regulatory Experience

Few types of regulatory experience, other than range safety, address risks related to single events such as a launch, in contrast to ongoing facility operations. Existing precedents are provided on an annual basis.

5.4.7.3 Comparable Accident Statistics and Background Risk Levels

Comparable accident statistics are difficult to find because ranges are event-oriented, whereas industries have continuous operations.

5.4.7.4 Internal Consistency

A primary rationale for this criterion is its correlation to the single test criterion for individual MEP.

5.4.7.5 Legal Considerations

Risks are reasonable; they are significantly below *de minimis* level.

5.4.8 Mission-Essential Annual Collective Risk (MEa: 10000E−6 E_F)

5.4.8.1 Prior Safety Criteria

The commonality guideline is comparable to historical data from the national ranges. Recognizing that the RCC guideline is now applicable to additional hazards besides just inert debris, the guideline reflects a similar risk level as that used at the ER and WR. Table 5-24 shows collective annual risk for MEP.

Table 5-24. Collective Annual Risk for Mission-Essential Personnel

Range[a]	**Annual Expected Casualties**
Eastern Range	1E−2
Western Range	1E−2
Commonality Criteria for E_F	**1E−2**[b]

a. Table lists only ranges that have criteria in this category.
b. Expected fatalities.

5.4.8.2 Similar Regulatory Experience

Limited regulatory precedents have been found in this category, including the following.

5.4.8.2.1 British Ministry of Defense

The British Ministry of Defense applies a collective risk criterion of 6E−3 per year to all people (workers and surrounding populations) at explosive manufacturing facilities.

5.4.8.2.2 Israeli Ministry of Defense

The annual collective fatality risk for mission workers in Israel (assumed to involve 10 tests) may be as high as 2E−2.

5.4.8.3 Comparable Accident Statistics and Background Risk Levels

Collective risk is small relative to other industries.

5.4.8.4 Internal Consistency

An important rationale for this number is its correlation to the single test criterion. This guideline also reflects the multiplicative effect of other conservative criteria (e.g., few people x low risk per event x few discrete events = very low collective risks).

5.4.8.5 Legal Considerations

Risks are very small. They are well below the *de minimis* level. "One death in a hundred years" is a useful way to consider this criterion.

5.5 Rationale for Catastrophic Risk Criteria

The standard has several key issues that bear repeating. Subsection 2.2.1 of the standard includes a policy objective statement that "the risk of a catastrophic mishap should be mitigated." Section 3.8 states "catastrophic risk criteria are designed to protect against scenarios involving numerous casualties or fatalities" by facilitating the identification of scenarios that exceed these criteria and implementation of practical mitigations. The criteria were established primarily to mitigate the potential for catastrophes involving transportation systems, but they also have practical application for safety planning to protect people in the vicinity of the launch point. The catastrophic risk acceptability criteria presented in Chapter 3 of the standard address the fact that "surveys repeatedly confirm that accidents involving multiple fatalities on public transport are less socially acceptable than accidents involving private road transport,"[135] which rarely involve large numbers of casualties or fatalities. Governing land use in the vicinity of an airport based on individual risks alone has been criticized because "in any other industry tolerability is established on the basis of probabilities falling as the potential number of casualties/fatalities increases."[136] While that criticism may not be entirely valid,[137] the RCC endorses the catastrophe aversion incorporated into the criteria presented in Section 3.8 of the standard because criteria solely based on casualty expectation and individual P_C appear indifferent to the fact that accidents involving many casualties are perceived by the public as disproportionately more objectionable than those involving a few casualties. Furthermore, implementation of the catastrophic risk criteria in Chapter 3 of the standard should help a range refute potential criticism of using collective risk limits without complete quantification of uncertainty.

In this supplement, catastrophe[138] aversion limits are defined by the general formula

$$P[\geq N] \times N^{1.5} \leq \text{Criterion}$$

where

$P[\geq N]$	is the cumulative probability of all events capable of causing N or more casualties.
N	is the number of casualties associated with a scenario.
Criterion	is the maximum allowable collective risk for the event with various scenarios as feasible outcomes.

Section 3.8 of the standard recommends a risk criterion of 1E−4 for the GP (Subsection 3.8.3) and 3E−4 for MEP and NOP (Subsection 3.8.4). The above formula is used to define the recommended catastrophe aversion criteria, but is not used to indicate how to compute the

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[135] Grayling T, and Bishop S., Sustainable Aviation 2030, Institute for Public Policy Research, August 2001, p. 40

[136] Aviation Environment Federation. "Public Safety Zones - current policy and the case for change." Retrieved 16 October 2023. Available at https://www.aef.org.uk/uploads/NewsPullPSZ.doc.

[137] Neither the Dutch nor UK Governments intend to relate the planning zones at runway ends to levels of risk measures that overtly account for society's aversion to accidents with multiple fatalities and/or injuries because a) some argue that such risk criteria are not well developed in the land-use planning field, and b) "the proposed zones are intended to limit the exposure of large numbers of people, thereby controlling and minimizing" the risk of accidents with multiple fatalities and/or injuries. (Davies et al p. B3).

[138] In the academic community, the term risk aversion is used rather than catastrophe aversion. There is a convenience with the term risk aversion because if applies to all numbers of casualties starting with two, where the term catastrophe, depending upon the agency usually applies to five or more or ten or more.

potential for catastrophic outcomes. Section 4.3 provides guidelines designed to facilitate evaluation of catastrophe potential. Parallel logic applies to catastrophic fatality producing accidents using the maximum allowable collective fatality risk for the event with various scenarios as feasible outcomes.

The form of this catastrophe aversion criterion was chosen after a review of several catastrophe-averse models used by U.S. agencies and other agencies around the world.

Figure 5-4 summarizes the various methods reviewed during the development of this standard.[139] The line showing indifference to catastrophe in Figure 5-4 reflects no special concern for multiple casualties, i.e., no catastrophe (or risk) aversion. Criteria based on casualty expectation and individual risks contain no catastrophe aversion.

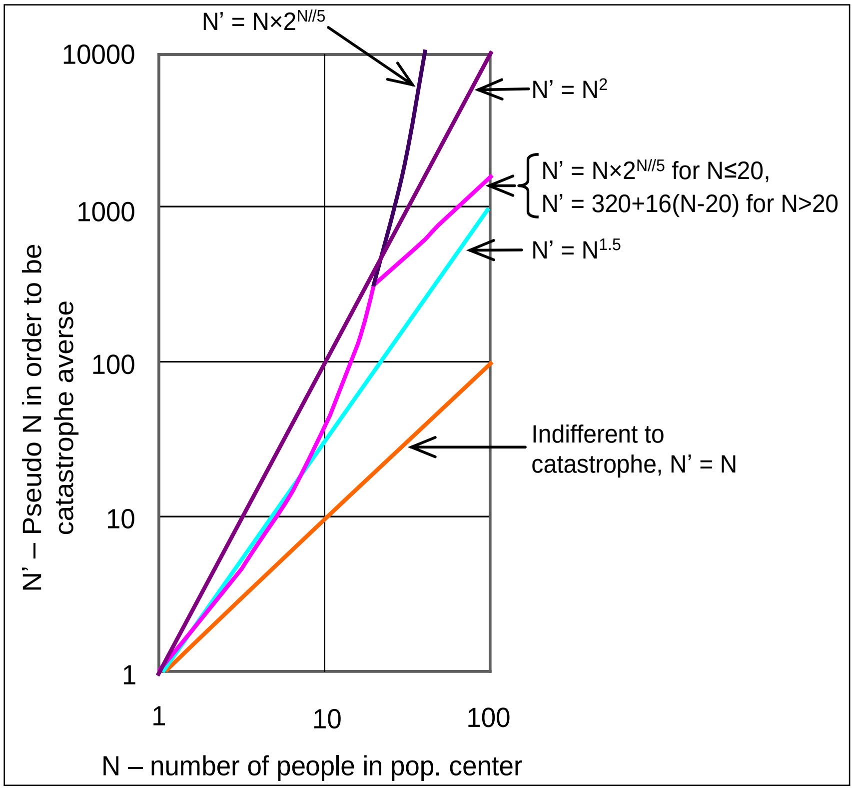

Figure 5-4. Comparison of Methods that are Used to Introduce Catastrophe Aversion into the Risk Analysis

The NL, both for industrial risk and explosive storage risk, has used the most catastrophe-averse formula: $P[\geq N] \times N^2 \leq$ criterion. This approach has also been used by the County of Santa Barbara in California (the location of VAFB, although never imposed upon VAFB) to protect against fatalities (with a less catastrophe-averse exponent of about 1.6 for serious injuries, defined by the County as “physical harm to a person that requires significant medical intervention”). This is represented by the line representing $N'=N^2$ in Figure 5-4.

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[139] Most of the methods shown are summarized in the risk analysis approaches by different countries in the NATO Allied Ammunition Storage and Transport Publication, NATO – AASTP-4, which was prepared by NATO AC/258, Risk Analysis Working Group (RAWG).

The curves in Figure 5-4 that use the factor $2^{N/5}$ are employed in Switzerland, Norway, and Sweden for handling risk due to potential explosions of stored, transported, or processed explosives. The Swiss modify the curve above N=20 so that it increases linearly with N and does not continue to rise so dramatically.

The RCC selected $N^{1.5}$ to incorporate a reasonable level of catastrophe aversion into the risk acceptability criteria. Figure 5-4 shows the RCC criteria in the center between no catastrophe aversion and the most conservative N^2. The RCC catastrophic risk criterion is similar to those that use of the factor $2^{N/5}$ method for N<10 and less restrictive for N>10. Specifically, the RCC catastrophic risk criterion does not impose unreasonable conservatism with respect to large concentrations of people, such as commercial aircraft or some ships, where a catastrophic accident could lead to numerous casualties. For instance, the value of $N^{1.5}$ for an aircraft carrying 400 people is $(400)^{1.5} = 8000$, which would inflate the pseudo-E_C or pseudo-E_F (described in Section 4.3) by a factor of 20.

5.6 Rationale for Aircraft Risk Management Requirements

5.6.1 Introduction

Previous versions of this standard provided different risk limits for people on aircraft than on land. The revised standard applies the same numerical limits on casualty risk to people on aircraft as those on land, and fatality risks as supplemental criteria to protect against all hazards to the GP and MEP.[140]

Aircraft hazard areas were based on the probability of impact (P_I) from “debris capable of causing a fatal accident.”[141] Such P_I limits are commonly used at the ranges as a generally convenient means to protect people on aircraft from unreasonable catastrophic risks; however, P_I limits are an indirect and imprecise means to set limit risks. The primary shortcoming is that P_I limits fail to limit the precise consequences that are onerous because of the extreme variability in the vulnerability of various aircraft to debris impacts. For example, some debris capable of causing a fatal accident to a highly vulnerable aircraft (such as certain types of helicopter) is unlikely to have much effect on a commercial transport aircraft. Thus, aircraft hazard areas based on P_I limits and minimum debris characteristics (mass, material, etc.) to ascertain what is capable of causing a fatal accident can produce overly conservative restrictions for air traffic or range activities. Therefore, P_I limits such as those specified in Sections 3.3 of the standard (whether combined with conservative or non-conservative debris thresholds) are not always the best way to ensure the safety of the traveling public. While the revised standard continues to endorse the use of P_I limits as convenient and efficient means to define hazard areas for aircraft, ranges now have an option to use explicit catastrophic risk criteria to ensure the safety of people on aircraft.

The revised standard provides greater flexibility by setting direct limits on aggregated risks instead of the previous approach of defining aircraft hazard areas based on P_I limits. Subsection 5.1.1 provides the rationale for aggregated risk limits, and the same logic applies to extending those limits to account for exposed populations in aircraft. Such aggregated risk limits provide the maximum flexibility for the management of risks to various exposed populations, including those in various transportation modes. The probability of impact limits intended to

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[140] The term “essential personnel” is used here to refer to mission essential and critical operations personnel, which are formally defined in the glossary,

[141] See paragraphs 3.3.1 and 3.3.2 of RCC 321.

constrain the catastrophic risks posed to people on-board aircraft, in combination with the hazard thresholds and vulnerability models in Chapter 6, are often a convenient and efficient means to define hazard areas as discussed below. Setting limits on the aggregated risk to all exposed populations allows more sophisticated methods to ensure reasonable risks with potentially fewer restrictions on air traffic.

5.6.2 Rationale for Limits on Probability of Impact

The established practice at most national ranges is to ensure risk to all aircraft from launch operations is minimal by using containment areas. Normally, containment is achieved by constraining operations or by closing air lanes through agreements with the FAA.

A significant consideration in establishing this standard is the size of the fragment that could hazard aircraft. This consideration results in two limits: one for probability of impact with debris capable of causing a casualty; and a more stringent limit for debris capable of causing a catastrophic accident. The thresholds given in Chapter 6 should be used to define these two debris sizes as described in Chapter 4. This approach results in a standard that is conservative since many impacts by debris near the thresholds defined in Chapter 6 are unlikely to cause casualties.

5.6.2.1 Limit of 1E−7 Probability of Impact for Non-mission Aircraft

Limiting non-mission aircraft to regions where the probability of impact with debris capable of producing a casualty does not exceed 1E−6 and where the probability of impact with debris capable of producing a fatality does not exceed 1E−7 will demonstrate compliance with the qualitative standard described in Subsection 5.6.2. Data from the NTSB aviation accident database indicates that there was an average of eight fatal accidents on U.S. air carriers (operated under 14 CFR Part 121) or scheduled flights (under Part 135) for every ten million departures during the 20-year period from 1984 to 2003. This suggests that the probability of a fatal accident has been about 8E−7 per departure of a U.S. commercial air carrier aircraft over the last 20 years. The data behind these estimates generally exclude incidents involving sabotage or suicide, since these are not considered accidental.[142] Not surprisingly, this data also shows that the background risk accepted by a passenger on a commercial transport flight appears to fall between the long- and short-term acceptable risk levels identified in the FAA's Advisory Circular (AC) 39-8, which are described below. The background risk accepted by occupants of U.S. general aviation aircraft may be significantly higher than commercial passengers. Data from the NTSB aviation accident database indicates that the probability of a fatal accident per departure of aircraft operated under Part 91 was about 8E−6, or about ten times higher than that for commercial aircraft passengers during the same 20-year period. This estimate is more uncertain due to the relatively unreliable data on the number of general aviation departures compared to commercial flights.

The FAA uses AC 39-8 "to identify unsafe conditions and determine when an 'unsafe condition is likely to exist or develop in other products of the same type design' before prescribing corrective action" for transport aircraft.[143] Specifically, AC 39-8 is aimed at assessing the risk of unsafe conditions on products associated with the power plant or auxiliary power unit

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[142] NTSB. *Survivability of Accidents Involving Part 121 U.S. Air Carrier Operations, 1983 Through 2000*. Safety Report NTSB/SR-01/01. March 2001. Retrieved 17 October 2023. Available at https://www.ntsb.gov/safety/safety-studies/Documents/SR0101.pdf.

[143] FAA, "Continued Airworthiness Assessments of Powerplant and Auxiliary Power Unit Installations…"

installations on transport category airplanes. The general concepts, safety goals, and definitions (especially for the consequences of concern) presented there are relevant to the development of standards for public protection, particularly for the protection of the flying public from spacecraft hazards. For example, AC 39-8 recognizes "that acceptable risk levels should be regarded as upper limits, to be allowed only when reducing the risk further would result in undue burden." This FAA guideline is functionally equivalent to the RCC preference to ensure safety by complete containment of range hazards.

The FAA circular provides short-term acceptable risk levels that equate to where "the malfunction is beginning to contribute more risk than the aggregate risk from all other causes, including contributions from the crew." Specifically, AC 39-8 identifies the probability of no greater than 4E−6 for a level 4 event as a short-term acceptable risk for each flight. Level 4 events include serious injuries or worse (i.e., casualties), hull loss when occupants were on-board, and forced landings. The guidance in AC 39-8 uses the NTSB definition of serious injuries; however, "the level 4 risk guidelines are intended to cover exposures to the most severe of 'serious injuries' (i.e., life-threatening injuries)." Therefore, the level 4 event guideline may be relaxed if only non-life-threatening injuries are involved (such as simple fractures).

The circular identifies the probability of no greater than 1E−9 for a level 4 event as a long-term acceptable risk for each flight.

The long- and short-term acceptable risk guidance published in AC 39-8 set important bounds that can be used to define acceptable aircraft risks. Any space activity that meets the long-term acceptable risk guidelines in AC 39-8 avoids unreasonable risks from a range activity. Conversely, any range activity that generates aircraft risks in excess of the short-term acceptable risk guidelines does not protect against unreasonable risks. Since only a fraction of the range activity-generated debris impacts capable of producing a casualty on an aircraft are likely to actually produce a level 4 event, compliance with the 1E−6 probability of impact criterion given in paragraph 3.3.1.a of the standard will ensure that no aircraft are exposed to unacceptable short-term risks as defined in AC 39-8. Therefore, limiting non-mission aircraft to regions where the probability of impact with casualty-capable debris on an aircraft does not exceed 1E−6 and the probability of impact by fatality-capable debris does not exceed 1E−7 will ensure reasonable aircraft risks based on the guidelines given in AC 39-8.

When this standard was first established, statistics were gathered on comparable risks of aircraft being struck by objects in midair. Two non-military sources of midair strikes have resulted in downed aircraft, as shown in Table 5-25. These statistics indicate that the risks resulting from a preexisting hazard of either bird strikes or midair collisions exceed the risks allowed by this standard because only a fraction of the impacts with debris capable of producing a casualty on an aircraft are reasonably expected to produce a serious injury or worse.

Table 5-25. Annual Risk for Flights in the U.S. Based on a 5-Year Average (1993-1997)[a]

	Number of Fatalities (E_F/year)	Number of Injuries	Probability of Fatality/Flight[2, b]	Probability of Injury/ Flight[4, b]
Bird Strikes	1 (0.2/yr)[1, c]	10 (2/yr)[3, d]	3.2E−9	3.2E−8
Midair Collisions	96 (19.2/yr)[3, a]	31 (6.2/yr)[3, d]	3.1E−7	1.0E−7

a. Impact statistics are based on a 5-year average (1993-1997). All of the midair collisions involved fixed-wing aircraft. In this time period collisions between helicopters, ultralights, and gliders occurred, but they were not considered in this study. During the 5-year period, 29 aircraft were struck by birds, resulting in 1 fatality and 10 injuries; 124 aircraft were involved in midair collisions, resulting in 96 deaths and 31 injuries.
b. Assuming an average of 62,281,350 flights per year for all fixed-wing, powered aircraft in the U.S. (based on air traffic activity at the FAA and contract airport control towers and facilities).
c. Indian Shores, Florida (7/15/94). A pelican impacted the windshield of a Cessna 172 causing the incapacitated pilot to lose control, pitch up, invert the aircraft, and impact the water.
d. Nashville International Airport, Nashville, Tennessee (7/8/96). A Southwest Airlines Boeing 737 ingested a bird in the left engine on takeoff, causing a compressor stall. Excessive braking due to a rejected takeoff caused a fire to erupt from the right brake. During the evacuation of the plane, 5 passengers were injured, 1 seriously; 117 passengers and 5 crew members were not injured. There were five other injuries from birds in this 5-year period. Three of the injuries were caused by birds penetrating the windshields of aircraft, striking the pilots. The other two injuries were caused by the pilots striking the ground while maneuvering to avoid contact with flocks of birds.
1. NTSB. "Aviation Accident Database & Synopses." https://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx.
2. FAA. *Statistical Handbook of Aviation*. Washington, D.C.: Federal Aviation Administration, 1995.
3. Philipson 1994.
4. Philipson and Hoefer 1982

Subsection 4.4.4 demonstrates that proper implementation of the P_I limits for aircraft hazard areas and use of the AVMs and hazard thresholds in Section 6.4 will ensure compliance with the individual and catastrophic risk criteria established in Chapter 3 of the standard. Thus, limiting the P_I with debris capable of producing a casualty on an aircraft is a reasonable and rational means to ensure that range activities do not pose risks that exceed: a) the background risks for people in aircraft; b) risk guidelines used by the FAA to "determine unsafe conditions…for transport aircraft"; c) the individual risk limits established in this standard; d) the catastrophic risk criteria; and e) current practice at the national ranges.

5.6.2.2 Rationale for 1E−6 Probability of Impact for Mission Aircraft

The criterion for protection of mission aircraft has been derived from the criterion for non-mission aircraft and the principle that MEP may be subjected to a factor of 10 times the risk tolerable by the GP. The previous section shows that this criterion is consistent with risk guidelines used by the FAA. Thus, the standard criteria are reasonable in light of currently used criteria that have provided an excellent safety record and current FAA guidelines. The criterion was designed to provide catastrophe aversion and to be consistent with the collective risk criterion as described in Subsection 4.4.4.

5.6.3 Rationale for Mishap Response Requirements

This section provides the rationale for the requirement given in Subsection 3.3.4 of the standard:

> The range must coordinate with the FAA to ensure timely notification of any expected air traffic hazard associated with range activities. In the event of a mishap, the range must promptly inform the FAA of the volume and duration of airspace where an aircraft hazard is predicted.

Range coordination with the FAA is reasonable and prudent because the FAA is the executive agency with primary responsibility for aircraft safety. The RCC has chosen to avoid setting a specific quantitative standard for risk acceptability in the event of a mishap because:

a. appropriate measures for aircraft protection in the event of a range mishap depend on many factors, such as the type of aircraft in the vicinity and the nature of the aircraft hazard;

b. conditional risk is fundamentally different than pre-flight risk;

c. the definition of aircraft hazard areas in the event of a range mishap is a topic where range safety practices and technology advances are evolving[144]; and

d. specific RCC limits could stifle innovation in this important area.

5.7 Rationale for Ship Risk Management Requirements

5.7.1 Introduction

Previous versions of this standard provided different risk limits for people on ships than on land. The revised standard applies the same numerical limits on casualty risk to people on ships as those on land. As a secondary concern, the standard also describes criteria for fatality risks to protect against all hazards to the GP and MEP.

Ship hazard areas were based on the P_I by debris capable of causing a casualty and debris capable of causing a catastrophic accident. Such P_I limits are commonly used at the ranges as a generally convenient means to protect people in these transportation systems from risk. These were intended as a simplified approach to ensure the contribution to collective risk from ships was small; however, the simplified P_I limits are an indirect and imprecise means to limit risks. In particular, they do not account for the variability in ships and in the consequences of a debris impact. In some cases the limits were unnecessarily onerous, such as when an event produced almost exclusively small debris. In other cases, the limits do not ensure the contribution to collective risk is small; for example, the risk from a single large fragment upon a passenger vessel (such as a ferry) could be large. They also did not explicitly account for explosive or toxic effects. Therefore, P_I limits, whether combined with conservative or non-conservative debris thresholds, are not always the best way to ensure the safety of the traveling public. The revised standard therefore no longer directly endorses P_I limits, but still allows for use of simple threshold models of vulnerability.

The revised standard provides greater flexibility by setting direct limits on aggregated risks instead of the previous approach of defining ship hazard areas only based on P_I limits. Subsection 5.1.1 provides the rationale for aggregated risk limits, and the same logic applies to extending those limits to account for exposed populations in ships. Such aggregated risk limits provide the maximum flexibility for the management of risks to various exposed populations, including those in various transportation modes. The individual ship risk limits, in combination with the hazard thresholds and vulnerability models in Chapter 6, are often convenient and efficient means to define hazard areas. Setting limits on the aggregated risk to all exposed populations allows more sophisticated methods to ensure reasonable risks with potentially fewer restrictions on ship traffic.

5.7.2 Rationale Application of Common Risk Criteria to Ships

The International Maritime Organization (IMO) is the United Nations organization for safety and environmental protection regulations for maritime activities. The IMO has been developing a risk-based approach to safety and environmental protection regulations (Skjong). The IMO prefers to refer to the risk evaluation criteria instead of the standard risk acceptance

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[144] VanSuetendael, R. et. al. "Accommodating Commercial Space Operations in the National Airspace System" in *The Journal of Air Traffic Control*. Vol. 47, No. 3. Air Traffic Control Association: Alexandria, July-Sept 2005.

criteria to emphasize that the criteria will not be the only factor in a decision. The IMO has not yet agreed to any explicit risk evaluation criteria, but a formally proposed one is under consideration. The IMO-proposed explicit risk evaluation criteria would essentially follow the approach taken by the UK Health and Safety Executive (HSE). The IMO proposal and current HSE regulations use annual individual risks to define the following three risk regions.

a. An intolerable region (above the maximum tolerable risk level), where risks must be reduced regardless of costs.
b. A broadly acceptable region (below the broadly acceptable risk level) where risks are too small to require reductions that incur cost.
c. A middle region where risks should be "As Low as Reasonably Practicable." In this region, risks should be reduced as long as the risk reduction is not disproportionate to the costs.

The IMO's proposed risk evaluation criteria are based on the premise that involuntary risks should be "substantially below the total accident risks accepted in daily life," but "similar to risks that are accepted from other involuntary sources". The IMO proposal endorses the risk thresholds put forward by the HSE. Individual annual fatality risks are as follows.

a. Below 1E−6 are broadly acceptable for everyone: crew and public.
b. Above 1E−3 are intolerable for crew.
c. Above 1E−4 are intolerable for the public (passengers and public ashore).

The IMO proposal notes that it may be appropriate to have a more demanding target for new ship designs and that individual annual fatality risks should be:

a. below 1E−4 for crew; and
b. below 1E−5 for passengers and public ashore.

Note that the IMO criteria are for individual annual fatality risks, whereas the standard defines limits for P_C per mission. Since only a fraction of the impacts capable of causing a ship accident are expected to produce a fatality, the 1E−6 probability of impacts causing a casualty to each person on-board appears to be conservative relative to the IMO criteria.

Therefore, a 1E−6 probability of a casualty for each person on-board appears reasonable in light of:

a. IMO's proposed risk evaluation criteria;
b. the improbability of the same individuals on ships being threatened by multiple launches in a year unless they are spectators voluntarily participating in the event;
c. the conservative definition of a ship accident (such that a low percentage of these boat accidents caused by a debris impact would typically produce a casualty or fatality);
d. the uncertainty in the overall calculation of risk for ships exposed to debris from range activities.

Furthermore, the best estimates of the annual individual risks historically accepted by people on ships show that limiting non-mission ships to regions where the P_C does not exceed 1E−6 will demonstrate that the risks are less than the background risk associated with being aboard a ship.

a. Annual individual risks are on the order of 1E−4, based on 20 years of data from 1978-1998 for crews of various ship types (Figure 1 in Skjong).

b. The risk of 3 to 1000 or more fatalities per year from collision, grounding, and fire are between 1E−4 and 1E−3 for passenger ships with 3000 people on-board (see Figure 6 in Vanem and Skjong[145]).

5.8 Rationale for Spacecraft Protection Requirements

5.8.1 Introduction

Spacecraft protection consists of two primary activities: a) prescreening to assess which existing objects on orbit are potentially at risk from a pending launch; and b) for those objects identified as potentially at-risk evaluation of the required separation in time and space from the launch vehicle. This section provides the rationale for the determination of which on-orbit objects are potentially at risk and the criteria for protecting such objects.

5.8.2 Pre-screening Criteria

The two altitude screens stated in Subsection 2.2.5 of the standard were predicated on the current operating regions of manned spacecraft and the known performance capabilities of launched vehicles and components. Criteria for screening launched objects against a minimum orbital altitude and planned proximity to manned spacecraft were established based on the current operating regions. The rationale for those screens is as follows.

- The minimum altitudes of the Space Shuttle, ISS, and Shenzhou spacecraft were considered when establishing the initial screen for launch vehicles, jettisoned components, or planned debris needing to exceed 150 km altitude before CAs are necessary. Space Shuttle history indicated that their lowest orbit was 122 nm, or 226 km and the ISS minimum altitude is in the range of 310 to 320 km before maneuvers to boost the orbit are considered. The Chinese Shenzhou 5 and 6 spacecraft were launched to a minimum altitude of 211 km before raising the orbit to a final perigee of approximately 332 km. The RC also considered that other manned objects could be inserted into lower orbits than current manned objects, however, there are operational and protective concerns regarding the population of satellites and debris in those lower orbit bands and whether manned spacecraft can be sustained in those orbits for long periods of time. For these reasons, and discussions with NASA offices responsible for protecting and determining when to maneuver the ISS, the minimum altitude of 150 km was determined to be appropriate. In addition, this is consistent with current findings and regulations of the FAA/AST office responsible for licensing commercial U.S. launches.

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[145] Vanem, E. and Skjong, R. “Collision and Grounding of Passenger Ships – Risk Assessment and Emergency Evacuations.” Paper presented during the 3rd International Conference on Collision and Grounding of Ships, Izu, Japan, 25-27 October 2004.

- The second screen is intended to eliminate unwarranted CA. This screen requires the maximum (3-sigma) altitude capability of the launch vehicle, components, or planned debris to be within 50 km of, or above, the operating altitude of the manned spacecraft before a CA screening is required. Even though it has been in practice for several decades, the RC recognized that 200 km, when used with a spherical miss distance, is very conservative when considering the likelihood that a conjunction will occur. In addition, CAs are typically calculated using nominal or expected performance of the vehicle, and the inclusion of malfunction scenarios is considered impractical. It was considered extremely remote for the planed trajectory of a launch vehicle or its components to threaten a manned spacecraft by exhibiting performance beyond their 3-sigma altitude capability and, in addition, to traverse an extra 50-km separation distance. The 50-km separation distance is also equivalent to the recommended radial dimension when using ellipsoidal miss distance volumes; hence the altitude screening allows the analyst to perform a simple assessment beforehand as to the likelihood of a conjunction.

5.8.3 Collision Probability

If it is assumed that up to one collision in 1000 years is acceptable and that the average annual world-wide launch rate to a sufficient altitude to pose a risk to manned spacecraft is of 100 flights, then a hit probability of 1E−5 per spacecraft per launch would be tolerable. This is the same level of protection afforded to ships; however, most ship crews and passengers have life-saving devices available to them and also the chance of being rescued. Not all spacecraft have lifeboats readily available and the capability to perform rescues in space is almost non-existent today; therefore, an additional order of magnitude level of protection level (1E−6) would be warranted. The additional order of magnitude is justified to account for uncertainty in risk prediction (See also Figure 5-2).

A separate justification or rationale for adopting the 1E−6 criterion for collision probability is that the RC considered the crew aboard manned spacecraft should have the same level of protection as public aircraft.

5.8.4 Ellipsoidal Miss Distance Volume

Typically, the greatest dispersions associated with an orbiting object or a launch vehicle are in their respective in-track directions. Since a 200-km miss distance has been used by the ranges for several decades, it can provide an acceptable upper bound on in-track dimension of the miss distance volume and continue the excellent record for COLA that has been successfully used against occupied spacecraft.

A 50-km miss distance perpendicular to the in-track axis for both the radial and cross-track dimensions was selected after reviewing the following:

- the observed cross-track variability of launch vehicles;
- the position and arrival time variability of spacecraft;
- mission assurance CAs against other classes of space objects that have been performed over the years with 35 km or less miss distances.

Therefore, miss distance volumes of 200 km in-track by 50 km cross-track and radial were defined as the acceptable ellipsoidal volume and 200 km retained as the spherical volume, either of which is to be applied about the manned spacecraft during the CA.

5.8.5 Duration of Conjunction Assessment

In evaluating the language in the previous versions of the standard and to what duration the individual ranges were performing or providing data for the CAs, the RC found that the language was conflicting and the practices varied from range to range. For suborbital missions, the duration should cover at least the period of flight. Limiting duration to orbit insertion or orbit insertion plus one revolution does not ensure adequate protection to manned spacecraft. Events observed in the recent past, for launch objects inserted into LEO or park orbit, has determined conjunctions occurring with the ISS three or four revolutions *after* orbit insertion. In addition, CAs must also consider jettisoned components that typically occur after orbit insertion and may remain in different orbits than the launch vehicle's upper stage or payload. The committee found that the proper duration for the analysis was dependent on several factors that determine adequate time for a meaningful CA:

a. the type and shape of orbit (park, transfer, interplanetary, circular, highly elliptical) of the launch vehicle or jettisoned components in relation to the manned spacecraft;
b. the orbital period of the manned spacecraft relative to orbital period of launch vehicle or jettisoned component;
c. the altitude of the launched object relative to the manned spacecraft;
d. the time required by either the CSpOC to catalogue the object(s) or the period of coverage another agency or range user may be performing in their CA for mission assurance or other purposes and including the manned spacecraft;
e. the time to perform a COLA for the newly cataloged object;
f. the time needed to coordinate with the conjuncting on-orbit satellite's operator to plan a COLA maneuver;
g. the time needed to perform the on-orbit COLA maneuver.

These actions can represent a significant gap in the time from when a range has stopped pre-mission COLAs and the actual mission day on-orbit COLA operations performed by the CSpOC for the newly cataloged, newly launched object. Therefore, the RC has determined that the COLA trajectory duration should be no less than three hours after liftoff. This was determined by CSpOC to be adequate for a LEO launch of the Antares vehicle to the ISS. It should be noted that this duration may not be long enough in all situations.

For near circular LEO or park orbits insertion typically occurs for altitudes of 125 to 175 km while manned spacecraft are at higher altitudes (300 – 350 km). Often, conjunctions for objects in park orbits result from the object being within 200 km miss distance of the manned spacecraft but whose maximum altitude capability is greater than 100 km from the spacecraft. Conjunctions in this case are more likely due to inclination crossings at large, separated distances rather than altitude crossings that are more likely to produce a collision. Therefore, extending CAs past one revolution may identify multiple encounters in subsequent revolutions of the manned spacecraft and launch objects, especially when their periods are nearly synchronous.

Many of these conjunctions may be mitigated by the additional CA and COLA screening criteria described in subsections 2.2.5 of the standard and 5.8.2. The CSpOC will likely have catalogued and be tracking objects remaining in LEO after 6 to 9 hours. Since objects in LEO have periods of from 90 to 95 minutes per revolution, the analyst should consider extending the duration of the CA for approximately four to six revolutions past orbit insertion to cover the period until the launched object is catalogued.

Launch vehicles or components in moderately to highly elliptical or transfer orbits and interplanetary trajectories are likely to produce conjunctions that potentially would result in collisions. For these type missions, the previous practice of ending the CA at orbit insertion did not address the more likely conjunction due to an altitude crossing and resulted in inadequate protection of the manned spacecraft. Similarly, if the assessment duration was extended to orbit insertion plus one revolution, the threat to manned spacecraft would only be addressed if the launch vehicle or component was directly injected into this type orbit on ascent. For geosynchronous or moderate earth orbit missions, orbital insertion first occurs with park orbit, and then subsequent powered flight segments produce the elliptical transfer orbit involving an altitude crossing. Thus, assessment duration needs to be extended to cover these additional powered and coast flight segments and, in particular, until the vehicle or components clear the altitude of the manned spacecraft by at least the miss distance criteria selected or until the collision probability is expected to be within acceptable limits. Often a jettisoned stage is left in park orbit for these missions and must also be screened against the manned object as described in the previous paragraph. The analyst should consider that orbital periods of moderate elliptical orbits typically range from 600 to 120 minutes per revolution and the CSpOC will likely have catalogued the launched objects after one to five revolutions, respectively.

5.8.6 Arrival Time and Separation Uncertainty of the Launch Vehicle and Spacecraft

Unless collision probability is calculated, the current practice is to base CAs on miss distance separation of point estimates of the launched object and the spacecraft. A simple application of known or estimated arrival time dispersions of the vehicle and spacecraft could provide an analysis product consistent with similar practices in containment or risk assessment. In some cases, ranges will account for arrival time dispersions simply by adding buffers to launch wait periods based on maximum arrival time dispersion per revolution of an assumed maneuvered spacecraft. This approach is overly conservative.

It would be more appropriate to increase miss distance volumes directly by the appropriate amount to account for spatial dispersions and to increase launch wait periods but only by the arrival time dispersion of the launch vehicle and the uncertainty of known maneuvers of the spacecraft. Historically, the large miss distance of 200 km spherical could be assumed to account for dispersions in the launch vehicle and spacecraft; however, the RC considered it more mathematically rigorous to treat the miss distance and dispersion criteria as separate and combine them in the manner recommended in Subsection 4.6.3. For practical consideration, the dispersions associated with the launch vehicle may be significantly larger than the dispersions associated with the spacecraft such that only the launch vehicle dispersions need to be addressed.

5.8.7 Manned Spacecraft Protection Criteria Rationale

The large separations required between orbiting manned spacecraft makes it improbable that more than one such spacecraft is at risk at a time. Moreover, not all anticipated impacts to a manned spacecraft will precipitate a casualty of an individual inside that spacecraft due to one or more of the following safeguards: shielding, redundant systems, hull containment capability, and module isolation capabilities (closing affected module hatches, maneuvering capability, and escape modules). It is estimated that no more than one casualty would be produced per one hundred collisions because one or more of these safeguards are expected to exist for any manned space vehicle. Protecting to a collision probability of 1E−6 for manned spacecraft is expected to ensure that the collective risk to all passengers on-board the spacecraft is less than 1E−4 and, hence, adequately safe.

The rationale for using 1E−6 as the PoC when E_C is set at 1E−4 is due to the expense, time to recover, national priority, and visibility that manned spacecraft involve. Furthermore, this high degree of protection is reasonable given that implementation of the protection criteria has not resulted in inordinate impact to national range launch programs. The rationale for this approach is similar to using a containment approach where significant impacts to launch program objectives are not created.

5.8.8 Manned Spacecraft vs. Mannable

An earlier version of the standard, as well as many NASA, DoD, and FAA regulations, have differentiated between spacecraft capable of being manned (mannable or inhabitable) and those that are actually manned. The standard identifies requirements for manned spacecraft and mannable spacecraft en route to manned spacecraft.

The RC reasoned that human life could be compromised under two conditions. The first condition begins when an object intended to be manned is compromised while en route to a manned orbiting facility and concludes when the object is docked to the facility and access is established. The second condition is the result of loss of cargo vital to sustain life on the orbiting facility. If the mannable vehicle is not intended to be occupied again after separating from the manned spacecraft, then it would no longer be considered a manned object and therefore afforded the same level of protection as an active satellite.

An example of this is the Cygnus vehicle that should be considered manned while en route to or docked with the ISS, but considered only as an active satellite after final separation since it is designed to burn upon reentry. Similarly, if a spacecraft is capable of sustaining life but has been placed into orbit for demonstration or testing purposes without means to dock and be boarded, then it should be categorized as an active satellite and protected to that level. In the same manner, if a spacecraft is mannable but is not being maintained by boost events to avoid space debris for a significant period of time (over a year) then it would be considered unmanned.

It was decided that other habitable spacecraft would be protected to the level of active satellites and removed from the manned spacecraft criteria. The rationale for that decision included the following considerations.

a. Risk threshold requirements to protect human life are always more strict than thresholds to protect assets.

b. There exists in the standard a criterion for active and mannable spacecraft that did not exist in the standard when mannable spacecraft were afforded protection.

c. Some owners of mannable spacecraft have no plans to place humans onboard. For example, the Chinese Tiangong-1, which was launched in 2011 as a mannable two-year testbed, is still orbiting but lost telemetry communication/control in 2016. There are no plans to man the spacecraft and it should not be afforded a higher protection than the more expensive Hubble satellite telescope.

d. Failed hull integrity checks, a standard pre-boarding procedure, would negate boarding. Although that event may be costly it would not jeopardize human safety.

5.8.9 Unmanned/Active Spacecraft Protection Criteria Rationale

Using a collision probability of 1E−4 for unmanned or active spacecraft is conservative considering the rationale in Subsection 5.8.1. This collision probability has been implemented out of consideration for the expense, time to replace, national priority, and complexity of space vehicles. This high standard is also not expected to severely limit the launch range projects as evidenced by the adoption of this criterion for many ambitious space missions to include intercepts in space.

5.9 Rationale for Infrastructure Tier 1 Maximum Severity Classes and Protection Acceptance Criteria

The risk metrics for protecting infrastructure are based on assessing maximum damage at DSL 2 and DSL 5. The damage severity risk metric and these two damage levels incorporate the essential diagnostic elements of functional impairment as well as implicitly time to repair, both of which are generically important considerations for the protection of all types of infrastructure in terms of minimizing impairment to high-level system functionality. The current recommendation to exclude explicit dollar-loss damage assessment is deliberate in view of the practical difficulties in assigning meaningful numbers to complex event scenarios and because the acceptance criteria itself is designed to address this in a discrete albeit qualitative way. Dollar-loss damage assessment protection can be incorporated at Tier 1 as necessary.

The recommendations for protection to infrastructure segregate damage classes into the four categories: nuisance to infrastructure, elective repair, mandatory repair, and severe system consequences to infrastructure.

- Nuisance to infrastructure, people, and range operations. All consequences acceptable to government and developer/operators.
- Elective Repair to infrastructure required with minimal social/political/economic consequences (no accident/environmental assessments). All consequences confined.
- Mandatory Repair to infrastructure required with minimal social/political/economic consequences and only local authority involvement. All consequences confined.
- Severe System Consequences: mandatory repair with significant $ cost and/or accompanied by potential derivative exposure, and involvement of extra-local authorities. Potential for cascading consequences.

Tolerable acceptance criteria within each of these classes are set for damage severity at the unit component level or cumulative probability for a critical number of unit components.

The recommendation for four maximum damage severity classes was driven by both logical deduction and by comparison with existing practices. One rationale driven by deduction is that four classes are the minimum number that will span the range of damage, for the unit component DSL 1 through 5 (with only 2 and 5 actually being used) and so as to permit incorporation of the network-centric aspects associated with infrastructure consequence assessment. Admittedly this is a pragmatic deduction, but nonetheless aligned with the principle of simplicity. This reasoning will be elaborated further shortly.

Industry precedent for the use of four damage classes can also be found in Table 5-26 (published by Munich Re, one of the world's largest reinsurance companies)[146], which does not specifically address tolerable acceptance criteria. It is, however, tailored to per-event assessment (consistent with per-mission assessment). There is a long tradition for such an approach, in consideration of natural hazards. As Friedman points out, *"insurance is one means of protection against the natural hazards for fixed property."*[147]

Table 5-26. Catastrophe Categories Used by Munich Re

Catastrophe category		Overall losses					and/or fatalities
		Loss profile	1980s*	1990s*	2000s*	2010*	
0	Natural event	No property damage	-	-	-	-	none
1	Small-scale loss event	Small-scale property damage	-	-	-	-	1-9
2	Moderate loss event	Moderate property and structural damage	-	-	-	-	>10
3	Severe catastrophe	Severe property infrastructure and structural damage	US$ >25m	US$ >40m	US$ >50m	US$ >60m	>20
4	Major catastrophe	Major property, infrastructure and structural damage	US$ >90m	US$ >160m	US$ >200m	US$ >250m	>100
5	Devastating catastrophe	Devastating losses within the affected region	US$ >275m	US$ >400m	US$ >500m	US$ >650m	>500
6	Great natural catastrophe "GREAT disaster"	Region's ability to help itself clearly overtaxed, interregional/international assistance necessary, thousands of fatalities and/or hundreds of thousands homeless, substantial economic losses (United Nations definition). Insured losses reach exceptional orders of magnitude.					

Clearly differences of terminology exist, and moreover the focus in Table 5-26 is on threats from natural occurrences (nominally weather/seismic related). Extrapolating to range-related threats and excluding the catastrophe categories 0, 5, and 6 for the reason that they have no analogy with range activities, then that leaves four remaining categories: 1, 2, 3, and 4.

A pragmatic rationale for four damage classes is that it enforces a logarithmic ranking of tolerable acceptance across at least four decades. This seemed on intuitive grounds the minimum severability for criteria for "some very localized damage that can be ignored" to "damage with high dollar loss, cascading consequences and derivative exposure to people".

Developing generic acceptance criteria for these maximum damage severity risk metrics is particularly challenging as a result of the vast range of infrastructure and its fragility and the interconnectedness of components that may not be documented or easily quantified. One obvious source of potential guidance would be of course existing standards.

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[146] Department of Energy. "Insurance as a Risk Management Instrument for Energy Infrastructure Security and Resilience." March 2013. Retrieved 16 October 2023. Available at https://www.energy.gov/sites/prod/files/2013/03/f0/03282013_Final_Insurance_EnergyInfrastructure.pdf.

[147] Don Friedman. "Natural Hazard Risk Assessment for an Insurance Program." *The Geneva Papers on Risk and Insurance – Issues and Practice*, Volume 9 Issue 1. Palgrave Macmillan UK: 1984. p. 59.

Table 5-27 shows the risk acceptance matrix presented in MIL-STD-882E. Item 3 in the foreword of this standard states:

> DoD is committed to protecting personnel from accidental death, injury, or occupational illness and safeguarding defense systems, infrastructure, and property from accidental destruction, or damage while executing its mission requirements of national defense. Within mission requirements, the DoD will also ensure that the quality of the environment is protected to the maximum extent practical. Integral to these efforts is the use of a system safety approach to identify hazards and manage the associated risks.

Table 5-27. MIL-STD 882E - Risk Assessment Matrix

SEVERITY PROBABILITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated (F)	Eliminated			

The standard thus does include infrastructure within the envelope of its system safety approach.

A few comments are useful here. First, the standard is primarily focused on protection to people and secondarily to the environment. Protection to infrastructure is explicitly addressed primarily through dollar-loss assessments. That this is so can be inferred from the severity categories, reproduced in Table 5-28.

Table 5-28. MIL-STD 882E Severity Categories

Description	Severity Category	Mishap Result Criteria
Catastrophic	**1**	Could result in one or more of the following: death, permanent total disability, irreversible significant environmental impact, or monetary loss equal to or exceeding $10M.
Critical	**2**	Could result in one or more of the following: permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, reversible significant environmental impact, or monetary loss equal to or exceeding $1M but less than $10M.
Marginal	**3**	Could result in one or more of the following: injury or occupational illness resulting in one or more lost work day(s),

		reversible moderate environmental impact, or monetary loss equal to or exceeding $100K but less than $1M.
Negligible	**4**	Could result in one or more of the following: injury or occupational illness not resulting in a lost work day, minimal environmental impact, or monetary loss less than $100K.

A second comment relates to a distinction on how 882E affords protection to items within the system it is intended to cover. As can be seen from Table 5-27 the risk assessment matrix is intended to rank risk into discrete categories. In this respect, Table 5-27 is similar to the proposed risk categories in the standard in Table 3–1 (and Table 3–2), which also serve to rank risk to infrastructure. From one viewpoint therefore 882E does not provide intrinsic tolerability acceptance criteria.

Tolerability for nuisance to infrastructure should be anchored to levels below background accident or incident rates. Many infrastructure components undergo regular maintenance regimes and a certain fraction of components are insured assuming some type of damage will instigate the need for replacement. Moreover, insurers and independent data brokers to whom risk is often transferred have compiled aggregate claims statistics, and by inference these rates set a baseline of insurability. For situations where damage leads to DSL 2 or DSL 5 at the unit component level, such data can be useful for guiding the selection of reasonable level of risk acceptance. Difficulties arise because of the variability of infrastructure, the discrepancy between natural background damaging events and threats from range operations, and its network-centric functionality, which is a consideration not addressed in current rationale for acceptance criteria for people. The occurrence statistics for natural hazards are often cited as a dilemma by insurers, as these events tend to be distributed in an “extreme value” fashion. Occurrence statistics for non-catastrophic mission-based hazards over a sufficient period (annually, say) likely differ in distribution.

It could be argued that insurance for infrastructure is rarely obtained *only* for natural hazards. As Bratt[148] pointed out, insurance plays a vital part in wind farm projects due to the very nature of the development. Many other hazards threaten infrastructure, and insurance is tailored to cover hazards that include: all risks; breakdown; loss of revenue; supply agreements; complements to manufacturers’ warranties; public liability insurance; environmental impairment liability; employers liability; legal expenses arising from operational mishaps (e.g., fires, collapse); and directors and officers. The actuarial calculations behind insurers’ commitments to infrastructure seem to involve occurrence statistics that are indeed more similar to an ensemble of mission-specific events. (As a side remark, a useful distinction between critical assets and infrastructure may also perhaps be examined from this standpoint.)

It is insightful to examine specific cases within this framework to develop rational acceptance criteria for tolerable risk to unoccupied infrastructure by examining the similarities with the same protection issues faced by insurers.

For example, the current total domestic wind turbine capacity is about 100 GW or 1E8 kW, as taken from Figure 5-5. An average unit wind turbine capacity is less well-documented, but Figure 5-6 implies that a current value of 1000 kW is not unreasonable. These values lead to

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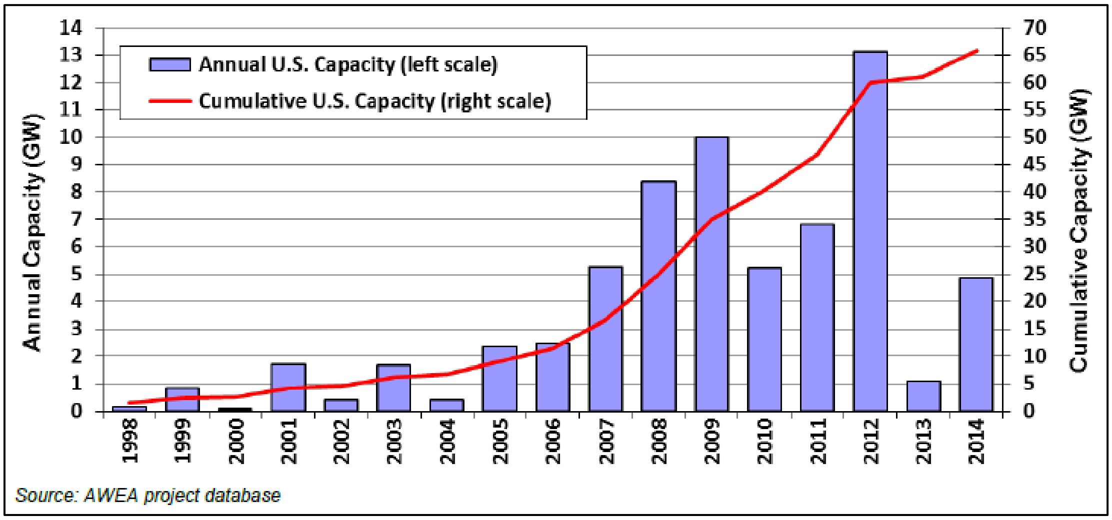
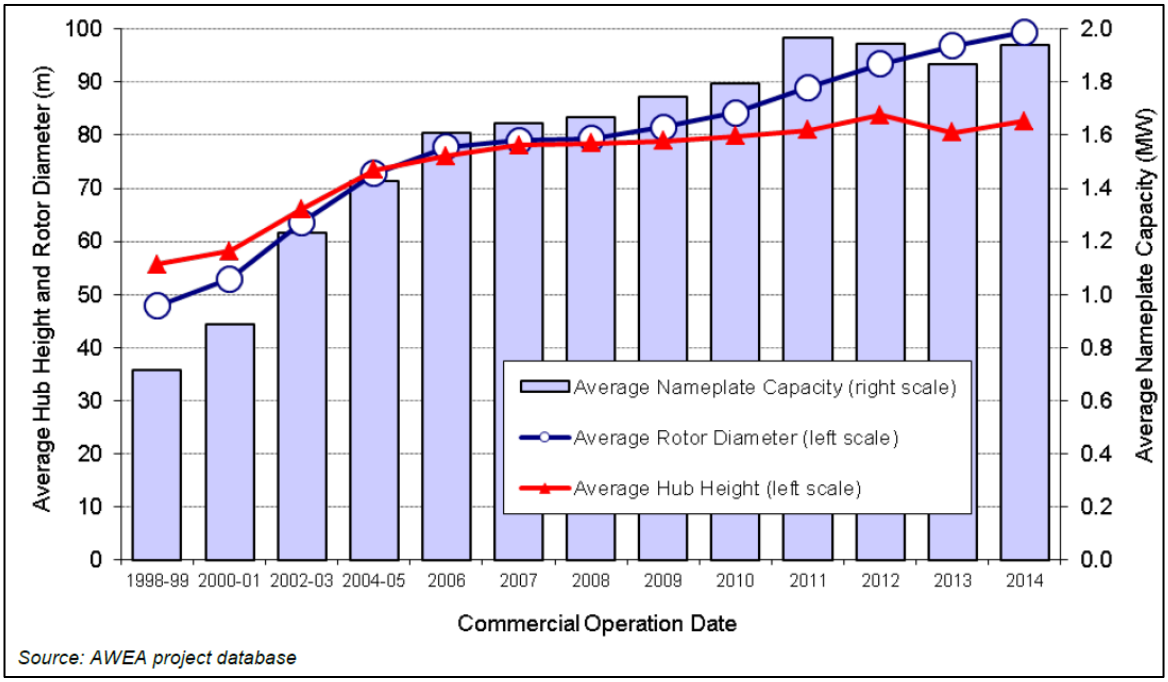
[148] Bratt, Gary. “Study of Renewable Energy Project Risk Factors Influencing the Insurance Industry.” Master’s thesis, University of Strathclyde, 2010.

an inference of about 100,000 total installed wind turbines. This value appears excessive and is reduced by a factor of two to 50,000.[149]



Source: AWEA project database

Figure 5-5. Annual and Cumulative Growth in U.S. Wind Power Capacity



Source: AWEA project database

Figure 5-6. Average Turbine Nameplate Capacity, Rotor Diameter, and Hub Height Installed during Period (Only Turbines Larger than 100 Kw)

Blade failures and fires are common accidents, with industry-reported values from one source being 3800 per year and 50 per year, respectively. Another source of pooled insurance data documents roughly 1200 total claims over the last 25 years, or about 50 claims per year

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[149] Department of Energy. "2014 Wind Technologies Market Report." August 2015. Retrieved 16 October 2023. Available at https://www.energy.gov/sites/prod/files/2015/08/f25/2014-Wind-Technologies-Market-Report-8.7.pdf.

across the industry. This value seems low given the number of annual accident and failure occurrences. A value of 100 is used here. While an insurance claims rate is not the same thing as a strict damage rate measure, it seems reasonable to explore the use of these data as a type of surrogate for same.

These rough calculations indicate that a background claims rate on a unit wind turbine basis is no greater than a rate of (100/50,000) or 0.002 claims per turbine per year, or 1E−3 claims per year, to an order of magnitude. For corresponding damage elevated beyond nuisance the rate is expected to be lower by one or more orders of magnitude.

If it is assumed that infrastructure insurance is primarily obtained and structured to address the maximum severity category of mandatory repair, the previous estimate is tentatively taken as support for the current recommendation where in Tier 1 the acceptability threshold at the least stringent level of maximum severity (namely nuisance to infrastructure) is set at 1E−3 on a per-mission basis.

As Table 3–2 in the standard shows, the current protection afforded to mandatory repair to infrastructure is recommended to be 1E−5 on a per-mission basis. Using the usual assumption of 33 missions per year this corresponds to an annual level of 1E−5 × 33 = 3E−4 per year, which is more stringent than the background inferred above.

While 882E does not provide explicit acceptance criteria (described earlier), it does provide frequency of occurrence bins as shown in Table 5-27 and Table 5-29. The document also describes the DoD’s version of damage severity categories, broadened to incorporate risk to people as well.

Table 5-29. MIL-STD-882E Example Probability Levels

Description	Level[1]	Individual Item	Fleet/Inventory*	Quantitative
Frequent	A	Likely to occur often in the life of an item	Continuously experienced.	Probability of occurrence greater than or equal to 10^{-1}.
Probable	B	Will occur several times in the life of an item	Will occur frequently.	Probability of occurrence less than 10^{-1} but greater than or equal to 10^{-2}.
Occasional	C	Likely to occur sometime in the life of an item	Will occur several times.	Probability of occurrence less than 10^{-2} but greater than or equal to 10^{-3}.
Remote	D	Unlikely, but possible to occur in the life of an item	Unlikely but can reasonably be expected to occur.	Probability of occurrence less than 10^{-3} but greater than or equal to 10^{-6}.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced in the life of an item	Unlikely to occur, but possible.	Probability of occurrence less than 10^{-6}.
Eliminated	F	Incapable of occurrence within the life of an item. This category is used when potential hazards are identified and later eliminated.		

[1] Occurrence rates for A through E are interpreted on an annual basis.

Table 5-30 compares the limits set in 882E against the limits set in the standard. The shaded boxes in Table 5-29 indicate the frequencies selected for comparison. The exclusion of bounding categories seemed reasonable as the most frequent would always be mitigated against and the least frequent may be considered superfluous for range-related threats. If these frequencies are interpreted on an annual basis, as is the case here, the per-mission frequencies shown in the shaded yellow cells results assuming a launch rate of 33 missions per year.

Table 5-30. Guidance Provided by 882E Ranking on a Per-Mission Basis

Consequence bins defined by 882E	882E Appendix		**Recommended maximum severity bins for infrastructure**	882E ACTA		**RCC 321 Table 3-2**	**Assessment with respect to 882E**
	Lower	Upper		Lower	Upper		
Catastrophic	3E−8	3E−8	Severe System Consequences	3E−8	3E−8	1E−6	Too high(a) (1.5 orders of magnitude)
Critical	3E−8	3E−5	Mandatory Repair	6E−6	5E−5	1E−5	OK
Marginal	3E−5	3E−4	Elective Repair	6E−5	5E−4	1E−4	OK
Negligible	3E−4	3E−3	Nuisance	2E−3	5E−3	1E−3	OK

The occurrence frequencies can be examined from the perspective of design lifetime. The definitions that result are shown in Table 5-31. If these frequencies are translated into per-mission terms, the right-hand columns of Table 5-30 (shaded purple) result.

Table 5-31. Frequency Table Definition

Category	**Qualitative Definition**	**Quantitative Definition**		
		20 yr DL	*50 yr DL*	*Interpretation*
Frequent	Over the design life of the project, the event is expected to occur on an intermittent basis	a) 0.5 yr^{-1} b) 1 yr^{-1}	a) 0.2 yr^{-1} b) 1 yr^{-1}	a.) over life of project will occur many (> 10) times; b.) annually
Probable	Over the design life of the project, the event is expected to occur randomly	0.15 yr^{-1}	0.06 yr^{-1}	Expected to occur several times (3) over the design life
Occasional	Over the design life of the project, the event is expected to occur infrequently	0.05 yr^{-1}	0.02 yr^{-1}	Expected to occur once over the design life
Remote	Over the design life of the project, the event is expected to occur rarely	5E−4 yr^{-1}	2E−4 yr^{-1}	One chance in 100 will occur during the design life
Improbable	Over the design life of the project the event is not expected to occur	3E−6 yr^{-1}	3E−6 yr^{-1}	Shift to FAA maximum probable loss criterion

The simple calculations summarized in Table 5-31 imply tolerability within Tier 1 for nuisance to infrastructure based on this broad interpretation as lying within the interval 2E−2 and 5E−3. The current recommended value of 1E−3 is conservative by a factor of five.

Perhaps the most apparent difference between Table 5-30 and the recommended criteria lay in the most maximum severity category, namely Severe System Consequences, where differences of an order of two in magnitude are evident. Such results may be indicative of over-conservatism if potential derivative risks to people are excluded.

5.10 Using Aviation as a Benchmark for Launch Risk

As discussed in Subsection 5.3.2.4, there is broad recognition that aviation is a legitimate benchmark for acceptable risks from launch activities. This section describes how the risks posed to ground dwellers by conventional aviation can be used to help identify reasonable risk limits for range activities. The following data and analyses of the risk imposed by the over-flight of conventional aircraft indicate that a limit for the collective risk for the GP on the order of 100E−6 (i.e., 1E−4) E_C for any single mission is reasonable and rational.

Thompson et al examined data on all civil aviation accidents in the U.S. that killed people on the ground from 1964 to 1999, focusing their analysis on the involuntary risks of fatality resulting from an airplane accident and excluded fatalities related to voluntary exposure, such as being on the airstrip. For example, Thompson et al considered a ground crew member or someone killed while taking pictures on the runway voluntarily exposed. They classified people who live on private property near airports as involuntarily exposed because there are no policies to warn them about the risk, "even though some might reasonably suspect that living near an airport leads to heightened exposure."

Thompson et al found that the involuntary risk of fatality to individuals on the ground from civil aviation accidents increases by about a factor of 100 within two miles of an airport, from about one in a hundred million (1E−8) to one in a million (1E−6) per year for a hypothetical person that remains in the same location for an entire year. They found that the increase in individual risk due to proximity from an airport appears somewhat greater near the busiest 100 airports, and somewhat less near the busiest 2550 airports; however, those differences appear to be negligible given the limited spatial resolution of the data, where the distance from the airport was considered instead of the distance from the runway under the dominant take-off and landing flight paths. The current lack of resolution in the aviation ground dweller data permits identification of only very approximate risk levels, and prevents a more detailed analysis from credibly separating the background risk related to commercial flights (flown under 14 CFR Part 121 or Part 135) from general aviation (flown under 14 CFR Part 91) near airports on a nationwide basis.[150] The recent development of ground dweller risk models for European airports suggests that further study could produce more precise estimates than those presented here (Evans 1997).

The data and analysis presented by Thompson et al is insufficient to identify a precise background risk to involuntarily exposed groups of people in the vicinity of airports; however, ACTA, Inc. estimated that the average risk of fatality for individuals involuntarily exposed to civil aviation accidents within five miles of top 100 airports was about 3E−8 in the year 2000 as follows.

Thompson et al projected one fatality related to operations at a top 100 airport in the year 2000 from all types of civil aviation accidents.[151] An accident was considered related to an airport if <u>all</u> the following conditions were met:

a. the airport was registered with the FAA;

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[150] The ANSI/AIAA Commercial Launch Safety standard suggested that such an estimate of the background risk presented by non-commercial aviation might provide a better basis for comparison to risks accepted from launches.
[151] See page 1033, Thompson et. al.

b. the airport was the origin or final destination of the flight;
c. the accident occurred within ten miles of the airport.

Thompson et al projected an E_F equal to 0.94 in the year 2000 for all airport-unrelated accidents across the entire U.S.[152] ACTA assumed that the risks from airport-unrelated accidents are independent of proximity to an airport. ACTA estimated that 36% of the U.S. population lived within ten miles of a top 100 airport in the year 2000 based on the results shown in Figure 6 of Thompson et al and an assumption that those lines continue with the same slope beyond the five mile mark where the graph ends at 13%. Based on Figure 7 from Thompson et al, ACTA estimated that the average individual risk of fatality in the year 2000 was approximately 6E−9 for people that dwell between five and ten miles of a top 100 airport.

By using the following five values estimated for the year 2000 based on Thompson el al:

a. 13% of the population live within five miles of a top 100 airport.
b. 36% of the population live within ten miles of a top 100 airport.
c. An E_F equal to 1.0 for all types of civil aviation accidents related to the Top 100 airports.
d. An E_F equal to 0.94 for all accidents across the entire U.S. unrelated to airports.
e. A total population of the U.S. given in Table IV as 275,306,000.

and the following equations:

Risk within 10 miles of a top 100 airport = risk related to airport + risk unrelated to airport

$$EF_{TOTAL}^{10MILES} = EF_{RELATED}^{10MILES} + EF_{UNRELATED}^{10MILES}$$

$$EF_{TOTAL}^{10MILES} = \left(3.4x10^{-9}\right)(0.36)(275{,}306{,}000) + 1 = 1.34 \qquad (5\text{-}1)$$

Risk within 10 miles of top 100 airport = risk within 5 miles + risk between 5 and 10 miles:

$$1.34 = \left(P_{TOTAL}^{5MILES}\right)(0.13)(275{,}306{,}000) + \left(6x10^{-9}\right)(0.36 - 0.13)(275{,}306{,}000)$$

It is estimated that:

$$P_{TOTAL}^{5MILES} = 2.7x10^{-8} \qquad (5\text{-}2)$$

Thus, it was estimated that the average risk of fatality for individuals involuntarily exposed to civil aviation accidents within five miles of top 100 airports was about 3E−8 in the year 2000.

The principle shortcomings of the above estimate are:

a. the Thompson el al data reported ground dweller risk as a function of distance from the airport only, not in terms of the distance from a runway under the dominant take-off and landing flight paths; and

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[152] See equation 20 also on page 1033, Thompson et. al.

b. there is currently no high-fidelity data on the distribution of population density near the top 100 airports in the U.S.

While these shortcomings are real, this estimate is still valid for the intended purpose as a benchmark for acceptable launch risks because there are reasons to be confident that the actual risks from aviation are even higher. The first reason is related to the spatial distribution of ground dweller risk from aviation near an airport. Figure 7 in Thompson et al assumes that people dwelling at an equal distance from a major airport are subject to an equal risk; however, some European nations now govern land use near airports based on triangular public safety zones that extend from the runways (Davies et al) based on data from various empirical analyses (Evans 1997). Thus, it is clear that the annual risk from aviation over-flight for ground dwellers located at a particular distance from the airport *and* under the dominant flight paths is much higher than the average annual risk for any location at the same distance from the airport. More simply stated, a person located directly under the dominant flight paths say 1 mile from an airport is exposed to much higher risk than a person located a mile from an airport but away from the dominant flight paths.

Specifically, a comparison of the annual individual P_F contours computed for the Cork and Dublin airports and Figure 7 of Thompson et al shows about two orders of magnitude difference: directly under the dominant take-off and landing flight paths Davies et al estimated 1E−6 P_F contours extend well beyond five miles from the runway, where the Thompson data indicates P_F levels flatten out below 1E−8. Therefore, the average ground dweller risks posed by aviation based on Thompson et al underestimate the actual risks posed to ground dwellers directly under the dominant take-off and landing flight paths.

Thompson et al made projections of the annual involuntary risk to people on the ground from U.S. civil aviation accidents in the years 2000, 2005, 2010, and 2015. Based on the decreasing trend noted in the number of involuntarily exposed people killed on the ground by civil aviation accidents between 1964 and 1999, the projected increases in the number of airport operations, and the U.S. population, the results suggest that the collective risk will remain fairly constant in that period, increasing from 3.8 E_F in 2005 to 4.3 E_F in 2015. Thompson et al found that the uncertainty in these projections is a less important factor than the variability due to distance from an airport. Therefore, these estimates of the risk to ground dwellers posed by U.S. civil aviation are not expected to change much over the next 10 years.

The risk of fatality alone is not an optimal measure of public risk. Therefore, ACTA analyzed data acquired from the NTSB on injuries (both minor and serious as defined in 49 CFR 830.2) and fatalities for people on the ground from civil aviation accidents for the 20-year period between 1984 and 2003. The NTSB data shows that aviation accidents produce an average of about two to three times as many casualties as fatalities. As shown in Table 5-32, the average ratio of 2.5 casualties to fatalities on the ground from civil aviation accidents is somewhat constant over the years (the 99.87 upper bound values are based on year to year variations) and applies to general aviation (relatively small airplanes) as well as commercial airline accidents. In this case, the number of casualties was computed by adding the number of serious injuries, as defined in 49 CFR 830.2, to the number of fatalities reported by the NTSB. This ratio is close to the average of predictions made for failures of ELVs as shown in Table 5-29. The ratio is a little lower for Space Shuttle launches (shown in Table 5-30) probably because the predicted casualties from Space Shuttle failure are more the result of exploding propellant than inert debris. All of these E_C predictions were based on AIS 3 or greater, including fatality.

Table 5-32. Ratio of Ground Casualties to Ground Fatalities based on NTSB Data from 1984 through 2003

Aviation Category	Average	99.87% Upper Bound
All U.S. Civil (Part 91, 121 and 135)	2.5	5.4
Airlines (Part 121)	2.0	5.9
General Aviation (Part 91)	2.7	5.4

The results in Thompson et al indicate that the risk to people involuntarily exposed to civil aviation accidents is substantially higher for people who dwell near airports. The average annual individual risk of casualty from civil aviation accidents for people that dwell within five miles of a top 100 airport was (roughly) estimated at 1E−7. This estimate was formed by extrapolating the results presented by Thompson et al that showed about a third of the total collective risk of fatalities was borne by people dwelling within about five miles of a top 100 airport in the year 2000, and the ratio of about three casualties to fatalities on the ground from civil aviation accidents observed in the data acquired from the NTSB.

The data acquired from the NTSB provides evidence to bolster confidence in the estimate of about 3.5 fatalities a year between 2005 and 2015 for people involuntarily exposed to risk from civil aviation accidents across the entire U.S. The data acquired from the NTSB shows about 17 casualties as an annual average for all types of civil aviation during the four years from 2000 to 2003, including those that Thompson et al would consider voluntarily exposed but excluding all casualties due to intentional acts (such as the terrorist attacks in 2001). A comparison of the data from Thompson et al (fatalities from involuntary exposure) to the NTSB's data (total ground fatalities from civil aviation) results in a ratio of about two between total fatalities aind involuntary exposure fatalities. Dividing the 17 casualties recorded on average for the four years from 2000 to 2003 by two produces an estimate of 8.5 casualties for people involuntarily exposed. Dividing 8.5 by 2.5, the ratio of casualties to fatalities on the ground from civil aviation accidents results in an estimated 3.4 fatalities for people involuntarily exposed, which is remarkably close to the projection of 3.5 E_F listed for the year 2000 in Table IV of Thompson et al.

Experience with orbital ELVs at the federal launch ranges demonstrates that launch area risks are typically limited to approximately 300,000 people near the launch point.[153] In addition, experience with the flights of *SpaceShipOne*, the only suborbital RLV flights to date, indicates that the risks were borne by approximately 300,000 people.[154] Of course, far fewer than 300,000 people bear the majority of the total public risk from typical launches. Aviation risks to ground dwellers are also disproportionately borne by those under the dominant flight paths used for take-off and landing. Multiplying the average risk of fatality for individuals involuntarily exposed to civil aviation accidents within five miles of top 100 airports in the year 2000 (i.e., 3E−8) by 300,000 people equates to collective risks of about 0.01 fatalities and 0.03 casualties per year. Therefore, a collective risk of no greater than 0.03 casualties per year for the GP is a reasonable

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[153] Philipson 1994 (Table 1 on page 6 and Table 7 on page 20).

[154] Erik Larson. "Quantitative Public Risk Analysis for SpaceShipOne." Report #04-527/1. ACTA Inc., Torrance, CA, December 30, 2004.

safety goal for spaceflight because a representative sample of about 300,000 people that dwell within five miles of a top 100 airport appear to be exposed to a comparable risk due to civil aviation over-flight. For the same reasons, a collective risk of no greater than 0.01 fatalities per year for involuntarily exposed people is a reasonable safety goal for spaceflight activities.

While aviation risks can be estimated using empirical data on the number of people seriously injured or killed on the ground, the risks posed by range activities are predictions based on computational models, typically fraught with more uncertainty than the empirical data on aviation risks. It is prudent to make a reasonable allowance for the uncertainty present in range safety risk predictions to ensure that range activities pose a collective risk of no greater than 0.03 casualties per year (or 0.01 fatalities per year) for people involuntarily exposed. The risk assessment process described in Chapter 2 takes steps to minimize this uncertainty. Nevertheless, with all of the uncertainties in the process, a one-order-of-magnitude (factor of 10) degree of uncertainty probably remains in any calculation. Although there is little data available to substantiate that estimate, recent efforts also indicate that any E_C estimate for launch probably has at the very least plus or minus one order of magnitude of uncertainty.[155] Therefore, a reasonable allowance for the uncertainty inherent in range safety risk predictions suggests that the annual risk criteria for range activities should be at least 10 times lower than the risks estimated for aviation over-flight based on empirical data. Furthermore, the standard risk criteria have been set to the nearest factor of three (approximately one-half order of magnitude on a logarithmic scale). Further refinement is not warranted due to the lack of precision in range safety risk predictions.

NOTE	The foregoing analysis demonstrates that limiting the collective risks to the GP from range activities to no greater than 0.003 casualties and 0.001 fatalities per year is reasonable and rational because a representative sample of about 300,000 people that dwell within five miles of a top 100 airport in the U.S. are exposed to comparable risks. The same logic used in previous versions of the standard can be used to link these annual collective risk criteria to per-mission criteria. Specifically, using an average of 30 missions per year these annual limits correspond to $100E{-6}$ E_C and $30E{-5}$ E_F.

A previous ACTA analysis of the risk from general aviation accidents to people in the vicinity of the CCAS provides additional evidence on the estimated background risk to people on the ground from civil aviation in the U.S. (Philipson 1994). Specifically, Philipson estimated a minimum of 0.018 E_C on the ground annually from general aviation accidents in an area with a total population of about 267,000 people. This result appears roughly consistent with the foregoing estimate that all civil aviation over-flight poses a collective risk of about 0.03 E_C per year for a group of 300,000 involuntarily exposed people that dwell within five miles of a top 100 airport.

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[155] Collins, J., S. Carbon, and E. Larson. “Development of Risk Profiles and Risk Uncertainty Models for Application to Launch Risk Analysis – FY05 Activity.” Report No. 05-551/5.4-02. ACTA, Inc., Torrance, CA, September 2005.

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CHAPTER 6

Hazard Thresholds

Characterization of human and structural vulnerability to the hazards associated with launch and flight is a critical element in risk analysis and management. It requires addressing the vulnerability of unsheltered people to the various hazards as well as characterizing the effects of these hazards on buildings and other structures. The vulnerability of humans, buildings, and other structures is an evolving field of study, and publishing a single set of vulnerability curves could stifle innovation in this important element of FSA. Therefore, while previous editions of the standard have published vulnerability curves for hazardous debris, the RC has determined that it better serves the interest of the national ranges to replace the vulnerability curves with a set of consensus threshold values. The threshold values included in this chapter are intended to allow analysts to perform conservative risk estimates. Analysts should verify the suitability of these thresholds for other applications such as containment before using them for those applications. When a flight safety analyst has access to valid vulnerability relationships, allowing a more refined analysis, these relationships should be used in place of the thresholds published in this chapter.[156]

The material in this chapter is organized as follows. The first section clarifies the meaning and intended use of hazard thresholds. The second section presents hazard thresholds for unsheltered persons. The third section provides hazard thresholds for people inside of buildings, ships, and aircraft. The fourth section provides information for establishing hazard thresholds for damage to critical assets. As applicable, separate subsections are devoted to fragment hazards and explosive overpressure hazards. In each subsection, terms are defined and hazard thresholds are cited. Each subsection also includes an explanation of how thresholds were determined with appropriate references for methodology, supporting data, and/or supporting practices.

The scope of this chapter is limited to hazard thresholds. Chapter 2 provides guidelines for the overall risk management process. Chapter 7 discusses approaches and considerations for debris risk assessment models.

6.1 Defining Criteria for Hazard Thresholds

6.1.1 Threshold Philosophy

Thresholds have been determined that represent a low probability that the adverse outcomes will occur. In a perfect world, the term "low probability" would be quantified with a value such as 1%. Unfortunately, this is at best an approximation in the real world. Purely empirical models are frequently limited by the size of the data samples. Very large sample sizes are required to confidently report a 1% value. Analytic methods draw on a combination of engineering models and reasonable statistical assumptions. Exact values for low percentile points

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[156] Flight safety analysts choosing to use the fatality curves published in earlier versions of RCC 321 must assure that their intended application is consistent with the assumptions used in developing those curves. Notable assumptions for the fatality curves were that all debris weighs less than two pounds and that populations at risk are reasonably represented by median adult males. Analysts employing other numerical criteria published in earlier versions of RCC 321 should verify these numbers are still credible in the light of improved understanding of vulnerability.

are critically dependent on the statistical assumptions. Alternative, equally credible assumptions about probability distributions can change a value from a 1% to a 5% or to a 0.1% value.

The threshold values provided in this chapter can be used to define consequences in a simplistic (Tier 1) manner to provide conservative risk estimates. Risk analysis can be conducted using a two-tiered approach. The Tier 1 approach allows an analyst to initially employ relatively simple metrics to establish a casualty (or other consequence) from a hazard threshold. For example, the Tier 1 approach would count any person as a casualty if they are predicted to be impacted above the threshold values. If the range determines that the result of the Tier 1 analysis demonstrates adequate safety, no further analysis is required within conservative assumptions. If the Tier 1 analysis indicates excessive risks, then a potential alternative to risk mitigation is implementing a Tier 2 approach. The Tier 2 approach replaces the hazard thresholds with valid vulnerability models. In general, the thresholds presented herein that should be used are:

a. to determine if a more sophisticated analysis is warranted;

b. as an alternative when higher-fidelity models are unavailable;

c. as an alternative when the quality of the data available to support the analysis is so low that an additional margin of safety is prudent.

6.1.2 Hazard Generation and Uncertainty

Hazards may be generated by planned events or by malfunctioning systems. Examples of planned events that produce hazards include jettisons of hardware, weapon system engagements, and boosters/rockets that produce toxic exhaust. Most hazards associated with malfunctions begin with an event that produces hazardous fragments ranging in size from intact vehicles down to small fragments. Following the initial hazard-producing event, there is frequently a series of events that modify the nature of the original hazard or generate secondary hazards. These events may produce additional fragmentation through explosions; may release toxic vapor, particulates, or aerosols; or may produce other unforeseen hazards.

Hazard-generating events occur in a dynamic environment. The initial conditions for each subsequent event are dependent on the previous event(s) and the propagation of the hazard through the atmosphere. Moreover, the ground impact of fragments with attached solid propellant, contained liquid propellant, or ordnance may result in an explosion generating a blast wave and/or a release of toxic materials.

Uncertainties are associated with each step of this process, beginning with the initial generation of a hazardous event and continuing the propagation of each related hazard through the subsequent hazardous events, and ultimately to people or property at risk. The hazard thresholds characterized in this section relate to the threats generated by inert debris and blast waves. It is useful to group the uncertainties into a group associated with the hazard level and uncertainties associated with the people or structures at risk. This introductory material addresses hazard level uncertainty; discussions of some of the uncertainties associated with the people or structures at risk are presented in each applicable subsection.

The hazard level uncertainty at each receptor depends on the uncertainties in each step of hazard generation and propagation as well as the uncertainty associated with the hazard propagations. Fragment catalogs for all classes of debris-generating events are known to contain significant levels of uncertainty. Although there are important differences among the different types of fragment-generating events, most fragment catalogs share several common characteristics.

a. Time dependency of fragmentation is either neglected or highly simplified. For example, there may be an initial fragmentation followed by secondary fragmentation when explosive fragments hit the ground.
b. Catalog development typically begins with defining those factors that are known with confidence. Subsequent steps involve choices the analyst makes among various credible assumptions. Discrete values and probability distributions consistent with the limited known information and the assumptions are then used to build the fragment catalogs. There is rarely a single credible choice for an assumption.
c. Formulation of the catalog development analysis is strongly biased by the catalog developer's prior experience with predicting fragmentation and the prior data requirements of the fragment list users with whom the catalog developer worked. This affects a number of important choices, such as whether to model a particular variable by providing selected statistics, discrete values, or probability distributions and which specific fragment characteristics to model.

How the flight safety analyst sees these uncertainties and the options to evaluate their implications depends both on the methodology employed by the fragment catalog developer and the risk analysis tools available to the flight safety analyst. Some risk analysis tools are designed to employ discrete lists of well-specified fragments. Other tools employ combinations of discrete values together with probability distributions for other values. This uncertainty is frequently expressed by flight safety analysts in two distinct ways. First, uncertainty may be expressed in the values characterizing a fragment or group of fragments based on the assumption that the particular fragment catalog, as a whole, is correct. Second, uncertainty can be accounted for with the definition of alternative fragment catalogs that recognize frequently there are alternative credible breakup patterns for the missile or rocket. When alternative credible fragment catalogs can be identified, they can each be evaluated against the hazard criteria. The flight safety analyst may then choose to compute a weighted average of the resulting risks or use a bounding analysis as deemed appropriate. This approach can also be used to explore known biases or data limitations in the methodologies on which the catalog was based.

The use of threshold criteria is sensitive to both the individual fragment characteristics and the characteristics of the fragment catalog. A critical parameter is the number of pieces of debris above the threshold mass (especially for aircraft). A related parameter is the mass distribution of pieces. This parameter, in conjunction with fragment drag characteristics, determines fragment impact kinetic energy. Fragment projected area and fragment materials are also important parameters. Most of the structural vulnerability thresholds are keyed to conservative assumptions about fragment shape and density.

In addition to the uncertainty in characteristics of impacting fragments, human vulnerability can be affected by fragment protrusions and lacerating edges. Fragment catalogs typically do not report this type of information and it is not practical to predict either fragment impact orientations or the state of rotational motion at time of body impact.

Blast wave hazards are typically characterized by the pressure and positive impulse (the area under the initial positive portion of a pressure versus time curve) at a receptor. The uncertainties at the receptor arise three types of uncertainty: in the effective yield of the explosion; in the propagation resulting from atmospheric and terrain effects; and in local amplification at the receptor by terrain and structures.

6.2 Unsheltered People

This section presents hazard thresholds for two hazards: fragment and blast. Within the boundaries of a range, people at risk are typically able-bodied adults. Outside the range, people potentially exposed often include people of all ages and physical conditions. Consequently, it is vital that threshold criteria be designed to protect a diverse population in terms of ages and physical conditions.

Hazard thresholds presented are values above which people are treated as experiencing particular levels of injury. Thus, a blunt trauma casualty threshold should be interpreted as meaning that a person struck by a fragment with kinetic energy above the threshold becomes a casualty. As discussed in Chapter 7, the determination of the area within which a person is vulnerable depends on the dimensions of a person and the dimensions of the fragment.

As an initial approximation outside of the immediate launch area, most debris impacts are nearly vertical. Under these circumstances, exposed persons are typically represented as having a circular vulnerable region with a one-foot radius.

Table 6-1 summarizes the injury thresholds for people presented in this section.

Table 6-1. Injury Thresholds

Hazard Mechanism	Injury Level	Threshold Value
Blunt trauma	Casualty	11 ft-lb
Blunt trauma	Fatality	25 ft-lb
Chunky penetration	Casualty	34 ft-lb/in^2
Overpressure	Casualty	2 psi

6.2.1 Fragment Hazards

When a fragment impacts the human body, body segments are accelerated, and portions of the body segments may be deflected. Excessive acceleration of body organs or excessive body deformations cause injuries known as blunt trauma. Fragments impacting directly over a fragile organ, such as the liver, can cause localized blunt trauma.

Heavy fragments can crush body segments between the fragments and a rigid object such as the ground or a wall. Threshold impact kinetic energies to protect against blunt trauma and crushing injuries are governed by levels required to protect against blunt trauma.

Penetrating injuries can result from relatively small, compact high-speed blunt fragments such as a bullet (chunky penetration) striking the body. These impacts injure by penetrating the body wall and depositing energy in the tissue. Glass shards and ragged metal may cause lacerating penetration injuries. Most commonly, these laceration injury levels are dependent on the orientation of the impacting fragment with respect to the body surface.

6.2.1.1 Blunt Trauma and Crushing Injuries

The threshold criterion for protection against blunt trauma and crushing injuries is 11 ft-lb impact kinetic energy. This criterion is designed to afford protection against injury levels of an AIS of level 3 or worse. The threshold criterion for protection against blunt trauma and crushing fatalities is 25 ft-lb impact kinetic energy.

6.2.1.1.1 Development of the hazard thresholds

The 11 ft-lb criterion is based on precedent and upon models of human vulnerability demonstrating the effectiveness of the chosen level as a screening criterion.

The national ranges have used a variety of criteria to determine that an impacting fragment is hazardous. Some of these have been based on impact kinetic energy; some of them have been based on the ballistic coefficient of an impacting fragment; some of them have been based on higher-fidelity injury modeling. The 11 ft-lb impact kinetic energy criterion is the lower bound of all previously used criteria. Moreover, in a number of cases this value was used to protect against all levels of injuries. The FAA/AST published an NPRM (67 Fed. Reg. 146 pp. 49455-49521) that adopted 11 ft-lb as a threshold criterion for all commercial launches.

The 25 ft-lb lethality threshold was derived from the lethality curves by body part presented in Feinstein[157], which presents 10%, 50%, and 90% fatality curves by body part. These curves were previously interpreted as representing points on a lognormal probability distribution and used to derive the RCC 321-97[158] lethality curves. The 1% point on the RCC lethality curves for standing adult male persons is 18.5 ft-lb; the 1% point average of sitting, standing and prone positions is 21.7 ft-lb.

Careful review of RCC 321-97 shows a significant modeling error. Standing persons are treated as having more than a 40% probability of being impacted in the thorax by vertically falling fragments. This error arose by treating impacts to the shoulders as impacts to the thorax. Horizontal impacts to the thorax pose a serious threat of fatality. By contrast, vertical impacts to the shoulders are one of the least threatening impacts to produce fatalities.

Using the conservative assumption that the vertical impacts are dominated by the vulnerability of the head would result in a 1% threshold for adult males of 28 ft-lb. The treatment of the head as the most vulnerable body part is also appropriate for seated persons. Prone persons would have significant exposure to the thorax. For certain fragment weights, Feinstein shows the thorax to be more vulnerable at the 1% threshold. Nevertheless, only a small portion of the exposed population is in a full prone position. When prone persons represent a significant portion of the population, a more stringent criterion of 16 ft-lb should be used as the 1% threshold for adult males.

Data provided in Haber et al[159] suggests that overall 1% population thresholds can be estimated as seven-eighths of the adult male threshold. The 25 ft-lb fatality threshold was

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[157] Feinstein, D., W. F. Heugel, M. L. Kardatzke, and A. Weinstock. *Personnel Casualty Study*. IITRI J6067. July 1968. Retrieved 17 October 2023. Available at https://apps.dtic.mil/sti/citations/AD0842573.

[158] Range Commanders Council. *Common Risk Criteria for National Test Ranges: Inert Debris, Supplement to Standard 321-97*. February 1997. Superseded. Available on request to RCC Secretariat.

[159] Haber, J. M., A. M. Linn, and H. Der Avanesian. "Human Vulnerability to Inert Debris." Report 05 550/3.101. ACTA Inc.: Torrance, CA, September 2005.

computed on this basis. (The same logic would provide a 14 ft-lb fatality threshold when prone persons dominate the exposure.)

An additional important source of conservatism for standing persons is that the casualty area/fatality area computation in Chapter 7 treats the entire exposed area of the person as being as vulnerable as the head.

6.2.1.1.2 Confidence in models

While kinetic energy by itself is not necessarily a good predictor of injury, blunt trauma injury is strongly dependent on the mass (m) and velocity (v) of the fragment. No single simple function of mass and velocity correlates well with injury for all fragment weights. This has been recognized for some time. Feinstein et al shows several weight regimes for injury modeling. The proposed measures for predicting injury are of the form mv^x. The exponent of the velocity depends on the fragment mass. A major reason why no single function of mass and velocity applies universally is that body response to an impact, not impacting fragment characteristics, causes injury. Excessive displacement of organs and strains within tissues cause damage. Nevertheless, for the purpose of establishing an injury threshold, impact kinetic energy is a valid and available quantity. The 11 ft-lb threshold provides a significant but reasonable amount of conservatism in protecting against blunt trauma and crushing injuries.[160]

Figure 6-1 compares the proposed threshold value of 11 ft-lb to the predicted P_C from blunt trauma injuries for the GP (a mixed population of adults and children) (Haber et al). Impacts on the head (vertically), thorax, and abdomen (horizontally) are shown for various fragment weights. In all cases, the 11 ft-lb criterion is at or below the threshold of injury predicted by the models. Although only one set of model results is illustrated here, this conclusion is supported by the human vulnerability modeling community.[161,162,163]

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[160] Haber, Jerry and Hrire Der Avanesian. “Human Vulnerability to Inert Debris.” Paper presented during the 29th Explosives Safety Seminar: New Orleans, 2000.

[161] Stuhmiller, J., K. Kan, K. Ho. *Interim Total Body Model: A Model of Impact Injury*. Technical Report J2997.43-00-107. San Diego: Jaycor Inc., April 2000.

[162] Feinstein et. al., 1968.

[163] Cooper, G. J., R. L. Maynard, M. C. Stainer, and B. P. Price. “The Biomechanical Response of the Thorax to Nonpenetrating Impact with Particular Reference to Cardiac Injuries.” *Journal of Trauma*, Vol. 22, No. 12. Dec. 1982, pp. 994-1008.

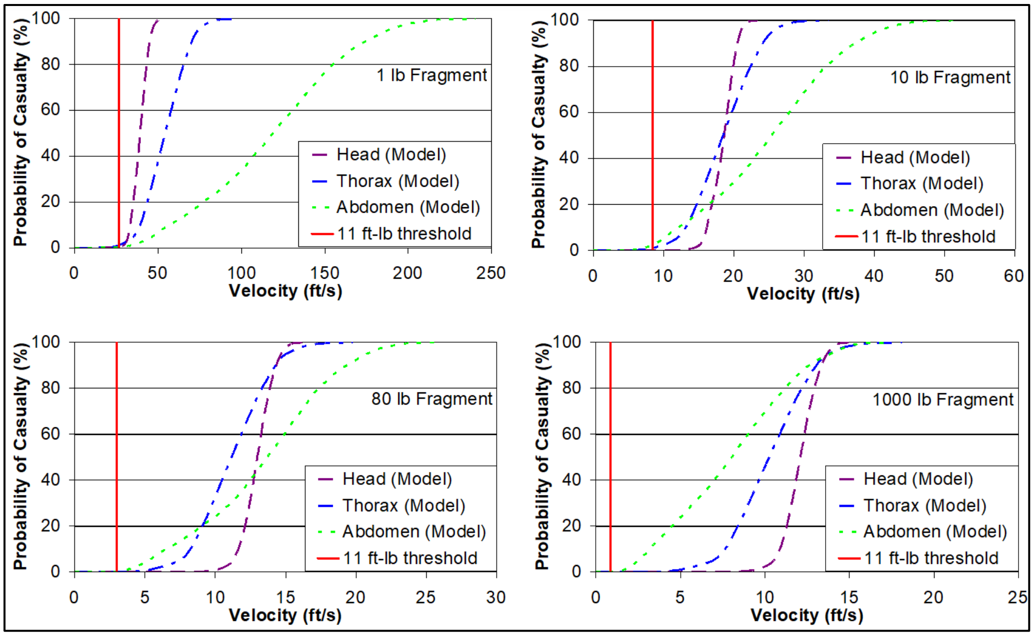

Figure 6-1. Eleven ft-lb Criterion and Probability of Casualty Curves for the General Public

Figure 6-2 shows that in addition to providing threshold level protection for all of the GP, the 11 ft-lb criterion provides significant protection for children. The figure compares the 11 ft-lb threshold with selected injury models and sample data points including impacting golf balls, baseballs, and a small fragment from the skin of a destroyed vehicle. The modeled injury curves have a probability of approximately 75% of resulting in an injury severity level of the labeled AIS level and approximately 25% of the next higher AIS level. The chart shows AIS level 3 for a median adult male and AIS levels 1, 2 and 3 for a one-year-old child. The curves for a child are shown to provide an indication of the conservatism of the criterion. The curves for a one-year-old child are based on modeling only the mass of a one-year-old. No adjustment has been made for the difference in injury level that a child receives as a result of a given body part response (e.g., head acceleration) in comparison to an adult. Therefore, these curves should be interpreted as indicative of the conservatism of the criterion rather than to be taken as literally predicting the injury level. Nevertheless, the curves in Figure 6-2 for one-year-olds indicate that the 11 ft-lb criterion protects the child against the AIS level 3 injuries for most of the range of weights and for lesser injuries for the larger weights.

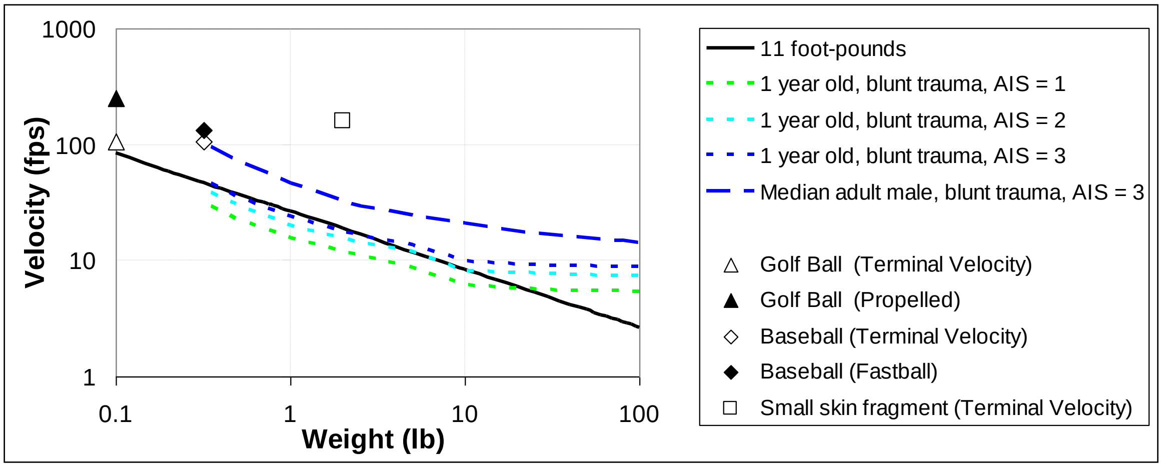

Figure 6-2. Comparison of 11 ft-lb Criterion with Injury Models and Sample Data Points

6.2.1.1.3 Effect of input data uncertainty

Input data includes fragment characterization and characterization of persons at risk. Uncertainty associated with the impacting fragment was discussed in Subsection 6.1.2. It is not generally possible to know the type of person who might be hit, other than on a statistical basis. While the 11 ft-lb criterion is believed to offer reasonably adequate protection even for small children, it is much less conservative for small children than it is for adults. Moreover, blunt trauma is one of several possible injury mechanisms as noted in this section. Each fragment should be evaluated for all of the relevant injury mechanisms.

6.2.1.2 Chunky Penetrating Injuries

Penetration injuries require two conditions. First, the fragment must penetrate the protective combination of clothing and skin. Second, having penetrated the clothing and skin protecting the tissue, the fragment must possess sufficient residual energy to cause significant damage to internal tissue or organs. Fragments with a small contact area have a greater chance of penetrating the protective layer about the body; however, once the skin has been fully penetrated, fragments with small effective cross-sections can pass through the body without transferring significant energy levels to the surrounding tissue. Nevertheless, impact kinetic energy per contact area of the fragment is the best single parameter predictor of the onset of significant injury.

The threshold criterion for protection against non-lacerating penetration injuries is a kinetic energy to area ratio of 34 ft-lb/in^2.

6.2.1.2.1 Development of the hazard thresholds

Essentially all simplified models of penetrating injuries are based on the ratio of the impact kinetic energy, *E*, of the fragment to the area, *A*, presented by the fragment. Where models differ significantly, however, is in the definition of the area *A*. In some cases *A* is the average cross-sectional area of the fragment, while in others, it is a smaller initial contact area. This leads to a large variation in the reported value of energy-to-area (*E/A)* statistics.

Table 6-2 displays the reported median and threshold values for *E/A* for various levels of penetration (skin penetration or casualty) with various amounts of protection (light clothing, bare skin) from a variety of sources.[164],[165],[166]

Table 6-2. Reported Energy/Area Values for Penetrating Injuries

Type of Value	Consequence	Protection	*E/A* (ft-lb/in^2)
Median	Skin penetration	Bare skin	40-109
Median	Skin penetration	Light clothing	80
Median	Casualty	Light clothing	85
Threshold	Skin penetration	Bare skin	10-64
Threshold	Casualty	Light clothing	34

The threshold value for casualty is of primary interest. A threshold *E/A* of 34 ft-lb/in^2 is reported for casualty-level injuries (AIS $\geq$ 3) for persons with light clothing protection. Only Lewis, et. al. and Sturdivan reports values for casualties. This value is, broadly speaking, consistent with the conservative end of the range of reported values for skin penetration.

6.2.1.2.2 Confidence in models

This *E/A* value for P_C with light clothing is conservative, as it is below some of the reported thresholds for bare skin penetration. Reasons for the conservatism might include a somewhat different experimental setup leading to differences in the data, actual differences in the model or analysis, or differences in the definition of *A*.

The definition of *A* used in Sturdivan is the average cross-sectional area, which is a larger value than if *A* were defined as an initial contact area. A larger value of *A* obviously leads to a smaller value of *E/A*. This is advantageous for two reasons. First, the average cross-sectional area is far easier to estimate than the initial contact area for a generic fragment and is likely to be the area actually used in computing *E/A* for breakup lists, whether or not it was used in the underlying vulnerability model. Second, in setting threshold values, a conservative approach is desirable to ensure that the at-risk population is adequately protected, and this value meets that standard as well. Thus, the value 34 ft-lb/in^2 appears reasonable.

6.2.1.2.3 Effect of input data uncertainty

There are a few caveats, however, as some of the input parameters could affect the threshold. No consideration has been given to the possibility of greater sensitivities of children, the aged, and the infirm populations. For skin penetration only there is not expected to be significant differences due to youth, though the elderly might be slightly more susceptible. For the injury after skin penetration, children might be more susceptible to intrusion by a fragment of a given size than an adult. For example, their internal organs are closer together, so a fragment of

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[164] Lewis, J. H., P. A. Coon, V. R. Clare, and L. M. Sturdivan. "An Empirical/Mathematical Model to Estimate the Probability of Skin Penetration by Various Projectiles." Technical Report ARCSL-TR-78004. April 1978. Aberdeen Proving Grounds, Maryland.

[165] Larry M. Sturdivan. "A Mathematical Model of Penetration of Chunky Projectiles in a Gelatin Tissue Simulant." Technical Report ARCSL-TR-79055. December 1978. Retrieved 17 October 2023. Available at https://apps.dtic.mil/dtic/tr/fulltext/u2/a063525.pdf.

[166] Vincent J. DiMaio. "Penetration and Perforation of Skin by Bullets and Missiles." *The American Journal of Forensic Medicine and Pathology*, Vol 2, No. 2. June 1981.

a fixed size that might impact a single organ in an adult is conceivably more likely to impact multiple organs in a very small child. The direct impact of organs, however, is not explicitly accounted for in this model, just the energy deposited in the tissue. Thus, this threshold criterion is likely to be less conservative for populations of children.

Additionally, for populations with significantly different levels of clothing protection (such as extreme tropical or equatorial populations), this threshold criterion is less conservative.

As mentioned above, the differences in fragment presented area and how it is measured have an effect on the threshold. Using an area measurement of only the contact area would yield larger values of *E/A*. Moreover, fragments of different characteristics (e.g., compliance, shape, etc.) are expected to vary significantly in the threat posed as will the location on the body of the impact.

6.2.2 Blast Hazards

Blast hazards represent a second mechanical injury hazard. The explosive safety community refers to the air-blast injuries produced by the direct effect of the shock wave on the body as primary injuries. The acceleration of the body wall by the shock wave transmits shock waves into closed body cavities. The imparted energy is dissipated at interfaces between tissue and air or different tissue types having different densities. This energy dissipation produces damage to tissue. Typical primary injuries include damage to the ear, the larynx, the gastro-intestinal tract, and the lungs. Injuries produced by fragments of the explosive device or debris from the environment are called secondary injuries. Injuries produced by the gross displacement of the body by the blast overpressures and subsequent impact on hard or sharp parts of the environment are called tertiary injuries.[167] This section addresses primary injuries. Secondary injuries are addressed by the section on fragment injury.

The threshold criterion for protection against air-blast overpressure injuries is 2 pounds per square inch (psi) incident overpressure. This threshold is designed to protect against primary injuries. The threshold does not address secondary and tertiary injuries.

It is broadly accepted in the national range community that protection against eardrum rupture should define the air-blast overpressure threshold. Nevertheless, published values range from 2 psi[168] to 5 psi.[169] The 2 psi value was adopted as the most recent published value and the most conservative. All of these values are asserted to be 1% probability of effect thresholds. Moreover, essentially all overpressure vulnerability models are based on common sets of test data. Variations in threshold are ascribed to how the data has been analyzed and modeled. In order to place this threshold in context, Table 6-3 lists sensitivities to overpressure for various body parts.

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[167] Keith Galbraith. *Review of Blast Injury Data and Models*. Great Britain: Health and Safety Executive, 1998.

[168] Richmond, D. R. et al. “Damage-Risk Criteria for Personnel Exposed to Repeated Blasts.” Paper presented during the 20th Department of Defense Explosives Safety Seminar: Norfolk, 1982.

[169] Bowen, G., E. R. Fletcher, and D. R. Richmond. *Estimate of Man’s Tolerance to the Direct Effects of Air Blast*. Albuquerque: Lovelace Foundation for Medical Education and Research, 1968.

Table 6-3. Body Part Sensitivity to Overpressure

Organ	Threshold (1%) Overpressure (psi)	Median Overpressure (psi)
Middle/inner ear*	0.2	1
Eardrum	2	15
Larynx	6	10
Gastro-Intestinal Tract	8	12
Lungs	11	16

* Middle/inner ear injury thresholds are included for completeness although they are regarded as less severe injuries

As noted above, the conservative approach of using a lower bound estimate of 1% thresholds was used in developing the overpressure criterion. Nevertheless, no consideration has been made for possible greater sensitivities of children, the aged, and the infirm. Body mass differences are expected to be an important factor in the susceptibility of children's organs in the abdomen and the thorax. It is not expected that body mass differences will be important in determining eardrum susceptibility. The pliability of the tissue constituting the eardrum may, by contrast, be quite variable in these other population groups. It is speculated that the eardrum would be more pliable among young people and more rigid and thinner among older or infirm populations. Additionally, some have suggested that the size of the ear cavity should affect the eardrum response to overpressure waves.

Thus, while the threshold is conservative, extra precautions might be considered when populations at risk are expected to include significant numbers of elderly or infirm persons. Very low overpressures are highly sensitive to variations in propagation conditions, uncertainty in characterizing source terms, and terrain conditions. While the 2 psi overpressure is at the low end of air-blast overpressures, it is high enough so these factors are not expected to dominate.

6.3 People in Buildings

6.3.1 Fragment Hazards

Kinetic energy thresholds for buildings and transportation system structures are thresholds for penetrating the protective structure. Thus, a fragment may deplete all of its kinetic energy in the act of penetrating the structure or it may have residual kinetic energy after penetrating the structure. Conservatively, an analyst may consider all fragments that penetrate the structure as hazardous. Alternatively, the analyst may add to the residual kinetic energy after structural penetration the kinetic energy the fragment acquires falling to a level/height at which it can reach a person. The hazard from any secondary fragments formed during the penetration process must also be considered. The kinetic energy of primary and secondary fragments may be compared with the thresholds for injuring people.

Hazard thresholds for building structures are based on the conservatively estimated minimum hazard that can penetrate the roof of the building. Even at the threshold level there is more than an order of magnitude variation between the least vulnerable and the most vulnerable structures. Thus, it was necessary to categorize structures to limit the excess conservatism contained in the threshold values. Consistency with fundamental models would require a classification based on roof characteristics; however, this approach would result in building classes that would be difficult to use by a flight safety analyst. Instead, four different building classes have been defined that more directly relate to the type of information that may be available to an analyst from community planning maps, census data and similar sources.

Class A
- Mobile homes and trailers
- Temporary office trailers

Class B
- Single-family dwellings
- Duplex and fourplex residential dwellings
- Small condominiums and townhouses
- Small apartment buildings

Class C
- Small retail commercial buildings (gas stations, stores, restaurants, strip malls)
- Small office and medical office buildings

Class D
- Manufacturing plants
- Warehouses
- Public buildings (large shopping malls, large office buildings, large apartment buildings, hotels, etc.)

These building classes were then translated into the structural roof types. Typically, this resulted in more than one structural type for a given class of buildings as indicated below. Finally, the weakest structural type (designated by asterisks “*”) within each class was chosen, conservatively, to represent that class of buildings.

Class A
- 22 gage corrugated steel roof
- 24 gage corrugated aluminum roof*
- ½ inch plywood roof

Class B
- Wood roof*

Class C
- Composite roof (rigid insulation on steel)*
- Corrugated steel roof (pre-engineered metal building type roof)
- Light-weight concrete on corrugated steel decking roof

Class D
- Light-weight concrete on corrugated steel decking roof*
- Reinforced concrete slab roof

Table 6-4 shows penetration threshold values for the four classes of buildings described above. This table shows the building category by class and weakest construction, and penetration thresholds in terms of the minimum kinetic impact energy of a compact, irregularly shaped tumbling steel fragment (C_D = 0.75) impacting the roof at terminal velocity at 5,000 feet mean sea level (MSL).[170] Fragment weights corresponding to the minimum kinetic energy for penetration are also listed to assist the analyst in interpreting the criteria. Steel was selected as the basis for these calculations because it is the densest of the most common fragment materials. "Compact fragments" are defined as fragments having relatively small surface area-to-volume ratios.

Table 6-4. Threshold Values for Roof Penetration

Building category		**Penetration Criteria**	
Generic Class	**Roof Construction**	**Minimum Weight Fragment (lb)**	**Minimum Kinetic Energy (ft-lb)**
A	24 gage corrugated aluminum	0.037	17
B	5/8 inch plywood	0.075	30
C	Composite roof (2 inch rigid gypsum insulation on steel purlins)	0.075	30
D	3½ inch light-weight concrete on 22 gage corrugated steel decking	0.500	414

6.3.1.1 Development of the Hazard Thresholds

The values presented in Table 6-4 are based on structural vulnerability models[171],[172],[173] demonstrating the effectiveness of these levels as screening criteria. These computations include several levels of conservatism.

- Threshold values for roof penetration were conservatively selected in lieu of threshold values for injury given roof penetration. The impact kinetic energy to penetrate a roof depends on the shape and density of the fragment, the construction of the roof, and the impact geometry. Fragments impacting a roof in the region between supporting beams require less kinetic energy to penetrate the roof than fragments impacting over supporting structure.
- The weakest structural type within a building class was chosen to represent that class of building.
- Steel, the densest common fragment material, was used for the calculations.

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[170] An impact altitude of 5,000 feet MSL was selected to be representative of impact altitudes over inland ranges. When applied to a coastal range it represents an additional source of conservatism.

[171] Hasselman, T. and M. Legg. "Update of Casualty and Fatality Risk Models for Roof Penetration by Inert Debris." Technical Report 00-430/16.4-02. ACTA Inc., Torrance CA, September 2000.

[172] Bogosian, D. and B. Dunn. "An Analytical Model of Debris Penetration into Conventional Buildings: Hazard Area Computational Kernel (HACK), Version 1.2." TR-96-28.1, Karagozian and Case, Glendale, CA, 1996.

[173] J. D. Stevenson. "Design Against Impact Loads" in *Structural Analysis and Design of Nuclear Power Plant Facilities*. New York: American Society of Civil Engineers, 1980.

6.3.1.2 Confidence in Models

Confidence in the models used to obtain the threshold values given in Table 6-4 was established in a 2005 V&V effort[174].[175] Following completion of the verification effort, validation of the models was conducted by comparing analytically predicted results with available experimental data[176,177]. Independent validation of the analytical model was performed by Bogosian and Dunn.

Tests with both steel and concrete impactors (fragments) were conducted against concrete and wood targets. Impacting objects consisted of spheres of various sizes fired against the targets at various speeds. These tests support the effectiveness of the Table 6-4 values as screening criteria. For many of the test cases the model and the test results agree. Whenever the model disagrees with the test results, the model is conservative. In other words, it predicts penetration for a case for which no penetration was observed.

Finally, the use of threshold penetration values as risk criteria ignores any tolerance by the human body to insult. The net effect of compounding conservatisms in the fragment characteristics, roof penetration models, and human injury models is what may be considered very conservative results. This level of conservatism is necessary to ensure safety in situations where more specific data is unavailable.

6.3.1.3 Effect of Input Data Uncertainty on Application of Model

Input data uncertainty is associated with the impacting fragment and with the roof model, the former being the larger (See Subsection 6.1.2).

The uncertainty associated with the input parameters of roof structures has been investigated (American Bureau of Shipping 2000), but so far only for steel frame buildings. In this case, variations in design configuration as well as material properties were considered. For present purposes, where penetration energy thresholds are of interest, it is primarily the uncertainty in the material properties of the roof plates that affect the penetration energy threshold. For corrugated steel decking, the coefficient of variation was found to be approximately 22%.

These relatively small uncertainties are considered to be more than offset by the conservative assumptions on the fragment characteristics (compact steel fragments) and roof penetration models used to estimate threshold penetration values.

6.3.2 Blast Hazards

When the front of an air blast wave strikes the face of a structure, reflection occurs as shown in Figure 6-3. As a result, the building surface facing the explosion experiences overpressure levels at least twice that of the free-field (commonly called side-on) wave front.

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[174] Verification is defined as ensuring that the mathematical algorithms comprising the models are solved correctly in a numerical sense, while validation is defined as ensuring that the mathematical models themselves correctly represent the physics of the intended applications.

[175] Hasselman, T. et al. "Structure and Vehicle Vulnerability Models for Inert Debris." Technical Report 05-550/3.2-02. ACTA, Inc., Torrance, CA, September 2005.

[176] Tancreto, J., J. Tatom, and M. Swisdak, Jr. "SPIDER – A Test Program to Determine the Response of Typical Wall and Roof Panels to Debris Impact." 2004-10001DT. Paper presented during the 31st Department of Defense Explosives Safety Seminar, San Antonio, TX, August 2004.

[177] Naval Facilities Engineering Center. "SPIDER 1B Testing Quick-Look Report." RBESCT Meeting, Huntsville AL, November 2004.

The reflected shock front propagates back into the air in all directions with the high-pressure region expanding outward towards regions of lower pressure.

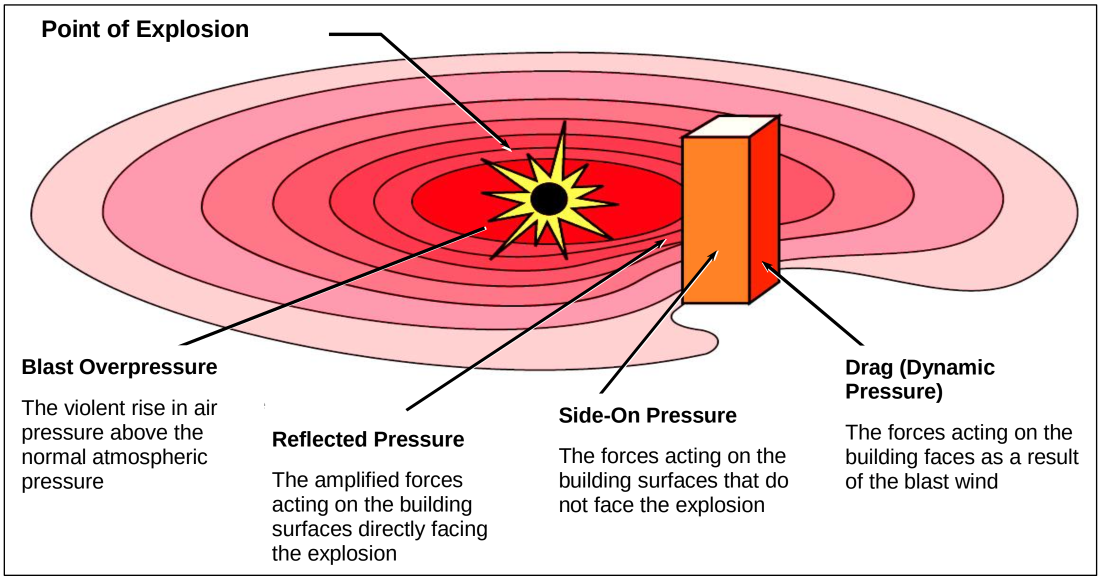

Figure 6-3. Air Blast Impacting a Structure

As the blast wave front continues to move forward, the reflected overpressure on the face of the structure quickly drops back to the level without reflection plus an added drag force associated with the wind (dynamic) pressure caused by acceleration of the air mass. The wave front then bends, or diffracts, around the structure as shown in Figure 6-4 (b through e in the figure).

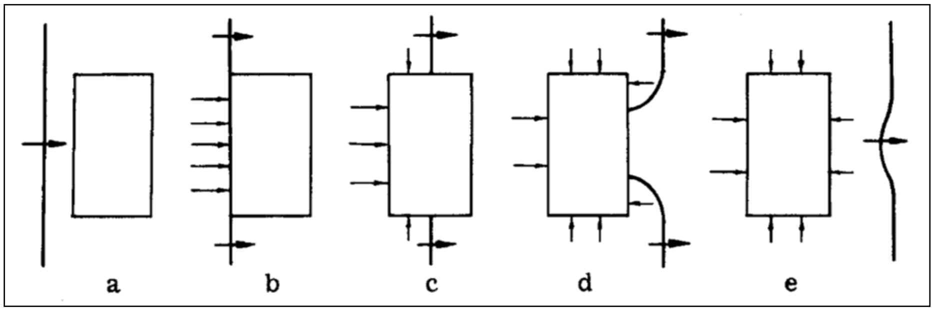

Figure 6-4. Diffraction of Blast Front Across Structure (Looking Down)

At (b), the wave front has just reached the front face and will be reflected back. At (c), the blast wave has proceeded half way down the structure; (d) depicts the loading as the blast wave has just passed the rear of the structure. At this time, the pressure on the front face has dropped to some extent while the pressure begins to build up on the back face. Finally, in (e), when the blast front has passed the structure, approximately equal pressures are exerted on the sides and top and a pressure differential exists between the front and back faces due to wind forces.

The pressure differential between the front and back faces has its maximum value when the blast wave has not completely surrounded the structure producing a lateral (or translational) force that tends to deflect the structure in the same direction as the blast wave. This force is known as diffraction loading because it operates while the blast wave is being diffracted around the structure. The extent of diffraction loading is strongly dependent on the size/geometry of the structure.

When the blast wave has engulfed the structure, the pressure differential is small and the loading is then almost entirely due to the drag pressure exerted on the building by the blast wind. The actual pressures on all faces of the structure are in excess of ambient but decrease steadily until the positive phase of the blast wave has ended (see Figure 6-5). Hence, the diffraction loading on a structure (without openings) is eventually replaced by an inward compression (squeezing action) combined with the dynamic pressure of the blast wave.

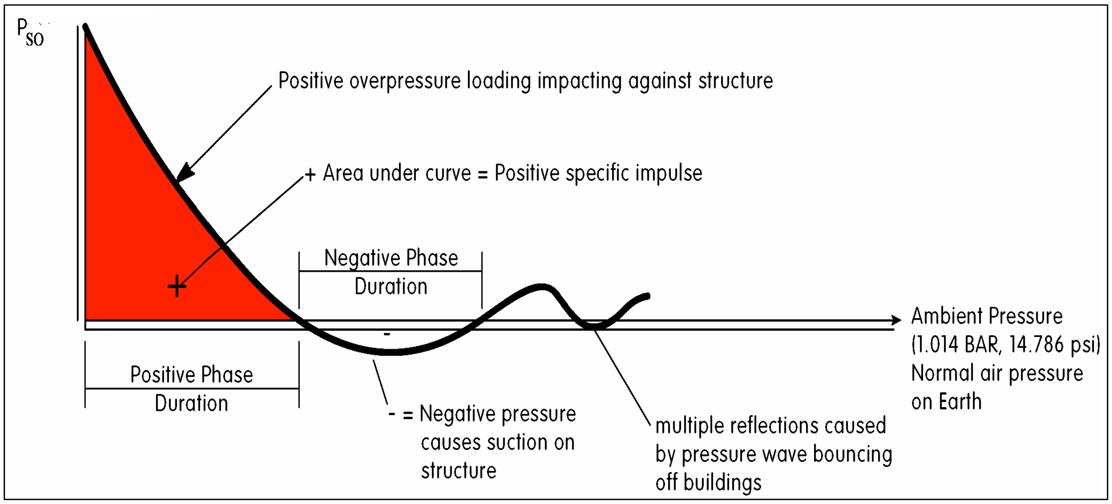

Figure 6-5. Free-field Blast Overpressure Time History

Diffraction and drag loads acting on a structure can result in significant damage (and even collapse) resulting in injuries to occupants from thrown debris, flying glass shards, and structural collapse. The levels of structural/window damage and injuries are functions of both the peak overpressure (amplitude) and impulse (area under the pressure versus time curve over the positive phase duration) of the blast wave shown in Figure 6-5.

Large-footprint buildings with small windows and door areas and strong exterior walls respond mainly to diffraction loading. For small structures or structures with many openings, however, the pressures on different faces (or individual structural elements) from diffraction forces act for only a short time and are quickly equalized. These drag-sensitive structures respond primarily to the drag forces whose magnitudes correlate with the duration (or impulse) of the blast wave. Drag-sensitive structures include television and electric transmission towers, utility poles, smokestacks, and steel buildings with light walls of asbestos, aluminum, or corrugated steel. (Some steel buildings can become drag-sensitive because of the failure of the walls at low overpressure that result in many openings.)

Window breakage is primarily the result of overpressure loading from the diffraction of the blast wave around the structure. Once a window fails, the differential pressure acting on the shards (the diffracted plus dynamic pressure acting on one side and atmospheric pressure on the interior of the structure) accelerates them inward until the pressure equalizes on the shards or the blast wave dies out. The velocity imparted to glass fragments and their potential to injure occupants is therefore strongly dependent on the impulse, or duration, of the blast wave.

Based on the above discussion, the threshold criteria for protection against building damage and injury[178] to its occupants due to blast waves is broken into two parts.

a. No windows: When buildings have no windows, the threshold criterion is 1 psi incident (or free-field) overpressure at a distance measured from the center of the explosive source to the nearest point on the structure.

b. Windows: When buildings have a significant amount of glazed area[179], the threshold criterion depends on the impulse of the blast wave, or equivalently, the yield of the explosion as follows:

    (1) For yields ≤ 50,000 pounds equivalent Trinitrotoluene (TNT) yield: Threshold criterion = 0.50 psi incident overpressure.

    (2) For yields > 50,000 pounds equivalent TNT yield: Threshold criterion = 0.25 psi overpressure.

The 1-psi threshold criterion defined for structural damage is consistent with the DDESB's guideline for the distance buildings (without windows), which must be sited from an explosive source for air blast effects.[180] The lower overpressure criteria for structures with windows, 0.5 psi and 0.25 psi, were set to ensure a low probability of serious injuries due to glass breakage for TNT equivalent yields of up to 50,000 pounds and above 50,000 pounds, respectively.

The air blast threshold criteria defined above are conservative estimates of the overpressure levels at which the onset of serious injuries occurs based on available accident and controlled test data. For example, the 1-psi free-field (incident) overpressure threshold level for structural damage is shown overlaid in Figure 6-6 on an overpressure-impulse (OP-I) diagram model developed for a small wood frame structure (~2500 square feet). Also superimposed on the damage OP-I diagram are accident and test data gathered from several different sources relating to the blast damage of lightly constructed structures. The numbers in the small circles indicate the percent damage estimated for lightly constructed structures (structures vulnerable to air blast) exposed to the air blast from conventional bombs and nuclear explosions. Also shown along the axes of the OP-I diagram are regions of expected damage from other researchers. The red lines running diagonally across the OP-I diagram represent the overpressure and impulse for various size TNT explosions (although not shown, the lower OP-I values are explosions farther from the receptor while the higher OP-I values are for closer explosions). Recognizing the significant variability that is reflected in the data due to construction, geometry, and blast loading, the damage OP-I diagram is in general agreement with these data. At the 1-psi threshold, there is little chance of structural damage and therefore virtually no chance of serious injuries from structural damage as shown by the serious injury OP-I diagram in Figure 6-7.

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[178] Protection against injury is intended to be a protection against severe injury or casualties (AIS≥3).

[179] The threshold presented for buildings with windows is intended to be applied only for buildings with low exposed population densities. It is to be used only for direct overpressure loading; it is not to be applied to DFO analyses.

[180] Department of Defense. "Defense Explosives Safety Regulation 6055.09 Edition 1." DESR 6055.09, Edition 1. 13 January 2019. May be superseded by update. Retrieved 16 October 2023. Available at https://www.denix.osd.mil/ddes/denix-files/sites/32/2021/08/DESR-6055.09-Edition1.pdf.

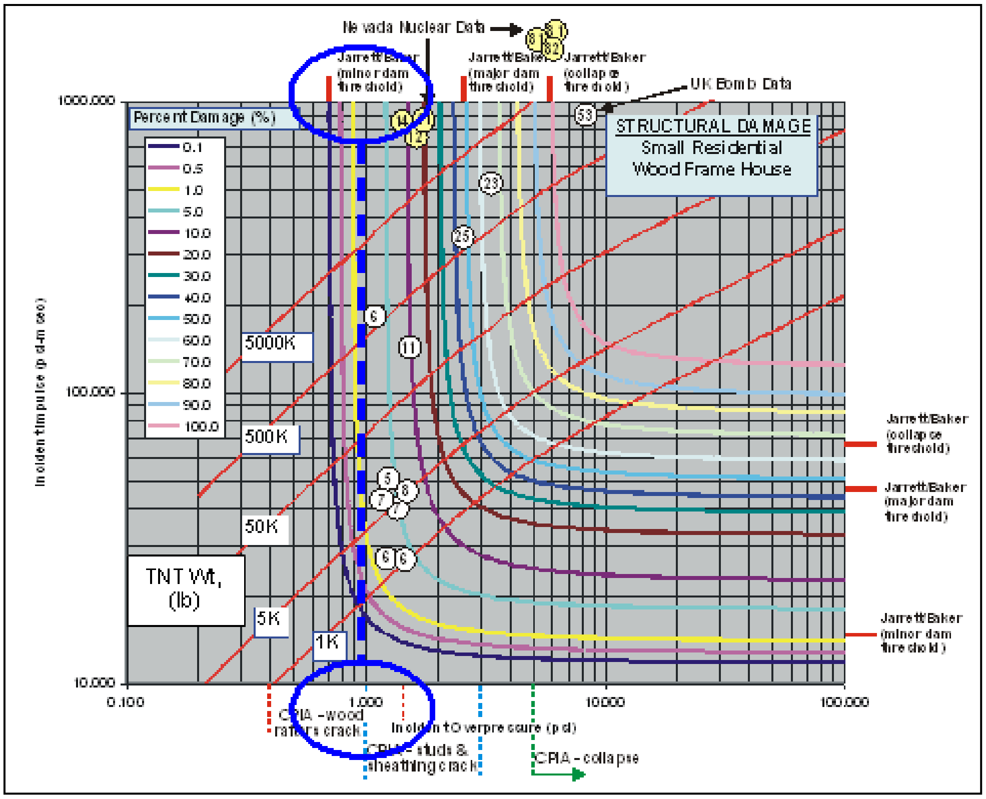

Figure 6-6. Structural Damage due to Air Blast Impacting Lightly Constructed Structures

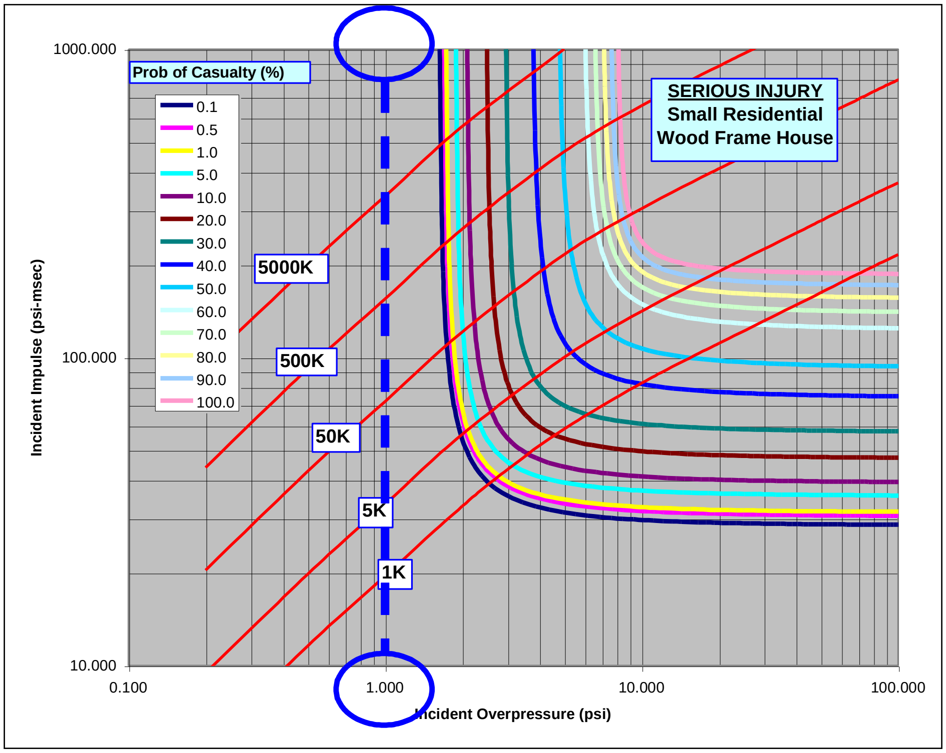

Figure 6-7. Serious Injury Due to Air Blast Impacting Lightly Constructed Structures

Figure 6-8 and Figure 6-9 show OP-I diagrams for the probability of breakage and serious injury for large, annealed (weaker) glass windows. Overlaid on these diagrams are the 0.25 psi and 0.5 psi threshold levels for explosions with equivalent TNT weights of >50,000 lbs and <50,000 lbs, respectively. Figure 6-8 and Figure 6-9 indicate that although a significant percentage of these large and relatively weak windows could break, shards that enter the room are unlikely to present a hazard to occupants. Although incident overpressure is used as a convenient metric for these diagrams, the results account for the effects of reflected overpressures predicted for building walls. These physics-based OP-I breakage and injury models are consistent with observed data. For example, Figure 6-9 shows the overpressure levels below which there were no recorded glass-related serious injuries from the Khobar and Oklahoma City bombings. More detailed comparisons show good agreement between these computational predictions and the evidence from historical events (such as Khobar Towers and Oklahoma City explosions) and DoD test data.[181] The 0.5 psi threshold for explosions <50,000 lbs of TNT conservatively falls below these two data points. Also note that the 0.5 psi threshold becomes more conservative for smaller TNT weights.

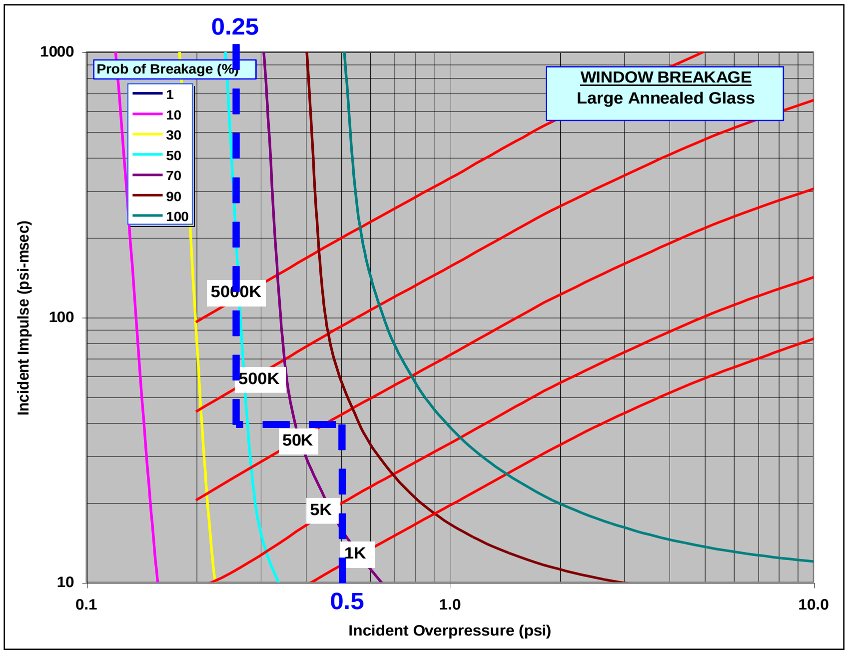

Figure 6-8. Breakage Due to Air Blast Impacting Large, Annealed Windows

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[181] Wilde, P. and J. Chrostowski. “Comparing Explosive and Inert Debris Vulnerability Model Results to Historical Event Data.” Report 06-527/9.2. ACTA, Inc., Torrance, CA, June 2006.

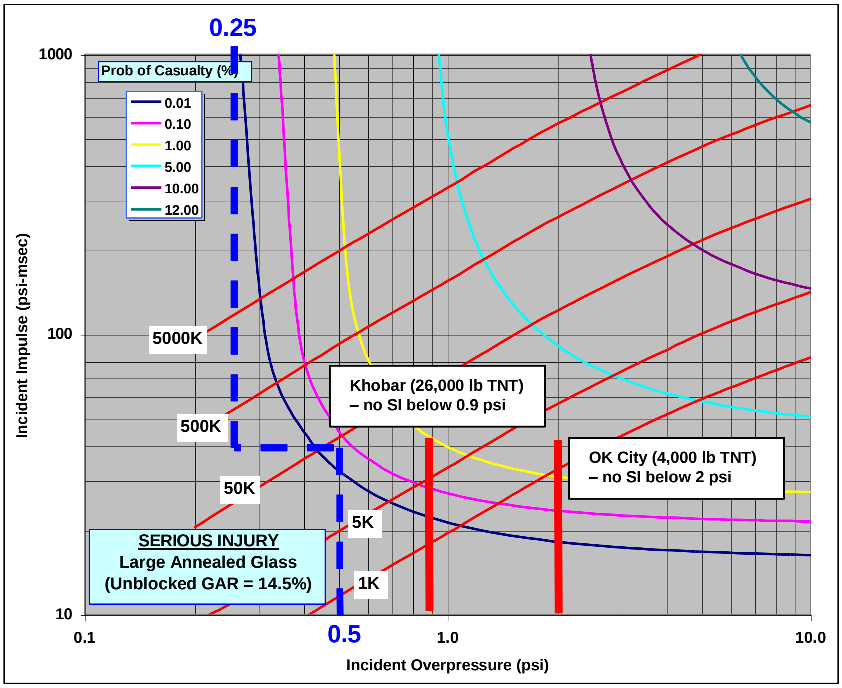

Figure 6-9. Serious Injury Due to Air Blast Impacting Large, Annealed Windows

As stated above, the threshold side-on overpressure levels (also called incident or free-field levels - those measured at the location of interest but neglecting the presence of the structure) were conservatively set to essentially eliminate the probability of serious injuries for the most vulnerable building and window types. In practical situations an explosion can affect people in a large area, occupants will be distributed across many building types, and each building type could have various numbers, types, and sizes of windows. Air blast models are available (such as the OP-I diagrams shown in Figure 6-6 through Figure 6-9) to more accurately estimate the probability of serious injury. These models estimate the full range of occupant injury for different generic structure and window types.[182]

Application of these thresholds uses two types of input data: characterization of the blast loading, and characterization of the buildings at risk. The thresholds have been formulated so that the only critical building characteristic is the presence of windows. When there is uncertainty as to whether buildings have windows, the analyst should conservatively assume windows are present. Larger uncertainties are associated with the explosive yield and overpressure. The analyst is advised to consider the effects of terrain, buildings, and meteorological conditions on overpressure levels.

6.4 People in Aircraft

The consequences of fragments impacting aircraft range from cosmetic to catastrophic. Factors determining the consequences include: fragment mass, shape, material, and impact velocity vector; aircraft type and velocity vector; location; and geometry of impact. In contrast to ships and ground-based receptors, aircraft velocities contribute significantly to the relative velocity of a fragment with respect to the aircraft and, hence, to the impact kinetic energy.

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[182] Lambert, R., J. Chrostowski, P. Wilde, and W. Gan. “Structure and Vehicle Vulnerability Models for Explosion Overpressure.” Technical Report No. 05-550/3.2-01. ACTA, Inc., Torrance, CA, September 2005.

Moreover, aircraft are complex systems with some parts that may be relatively easily damaged by small dense rigid debris (such as metal parts of a fragmented missile).

Aircraft vary significantly in their vulnerability. Some parts of an aircraft are critical to flight while other parts are not, and some portions are more easily damaged by debris than others. In addition, there is significant variation among aircraft including:

- types of aircraft (helicopters, airplanes);
- size (two orders of magnitude); and
- the purpose for which they were designed (military, passenger transport, private use).

The differences are manifested in many ways, such as different systems (engines, control, pressurization, etc.), locations of systems (fuel tank, control lines, etc.), materials used in construction (skin type, windshield type, support structures, etc.), and reliability (military planes are designed to survive attack and passenger planes have significant redundancy, whereas general aviation has much lower levels of protection).

6.4.1 Tier 1 Aircraft Vulnerability Thresholds

As a result of the complexity of the problem, the original version of the standard published criteria based on the most vulnerable systems of the most vulnerable aircraft. This offered the advantage of simplicity at the cost of being much more conservative than necessary for impacts on other portions of the most vulnerable aircraft or other aircraft classes. This level of protection may unnecessarily limit missions and/or increase costs significantly.

These early versions of the standard were based on a screening standard designed to protect the windshields of general aviation airplanes and to protect small turboshaft piston engines with axial flow compressors. Such engines were cited as being used to power small aircraft and helicopters such as the Bell Jet Ranger. Criteria were defined based on FATEPEN2 (an empirical code) analyses of windshields and expert opinion evaluations of the vulnerability of the piston engines and the windshield of general aviation planes.[183] Based on these criteria, conservative threshold fragment mass criteria applicable to any aircraft were developed[184], as follows:

- Tungsten debris: 0.5 g
- Steel debris: 1 g
- Aluminum debris: >1 g

These thresholds were based on defining the minimum mass piece that could cause failure of a piston engine (which therefore could lead to loss of the aircraft) and the minimum mass piece that could penetrate a windshield (which could potentially incapacitate the pilot, leading to loss of the aircraft).

Since very little rocket and missile debris is composed of material of higher density than steel, such as tungsten, a one-gram compact fragment has traditionally been used as the threshold

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[183] Yatteau, J.D., R.H. Zernow, and R.F. Recht. *Compact Fragment Multiple Plate Penetration Model (FATEPEN 2), Volume I: Model Description; Volume II: User's Manual*. Dahlgren: Naval Surface Warfare Center, 1991.

[184] Cole, J. K, L. W. Young, and T. Jordan-Culler. "Hazards of Falling Debris to People, Aircraft, and Watercraft". SAND97-0805. April 1997. Retrieved 16 October 2023. Available at https://www.osti.gov/biblio/468556.

for hazard to aircraft. Some analysts have treated low-density fragments separately. These thresholds remain appropriate for all aircraft with the exception of commercial transport and transoceanic business jet aircraft, as defined below, unless less conservative thresholds can be justified.[185]

Table 6-5 lists threshold masses for the vulnerability by aircraft class to launch vehicle debris impacts considering the Commercial Transport class (CT), the Jumbo Commercial Transport class (JCT), the Business Jet (BJ) class, and all other aircraft classes. The thresholds listed are conservative estimates of the minimum compact steel fragment mass that will produce a casualty with a 1-3% conditional probability given an impact. These thresholds were derived from the modified FAA penetration equation as described in detail elsewhere[186,187] and summarized below. These thresholds correspond to fragments impacting the aircraft at an angle close to normal to the surface (low obliquity impacts). These Tier 1 values have been updated since the last version of the supplement to reflect several factors: the target of defining thresholds in this supplement at the 1% probability of occurrence is imprecise; the 1% casualty conditional probability level has been increased; and there is inconsistent model fidelity in each model to characterize the vulnerability at 1% conditional P_C. The previous version of the supplement indicates a 2.1 g threshold; however, this value demonstrated false precision as vulnerability was only calculated at 2 g and 3 g. Therefore, the approximate 1% threshold is placed at 2.0 g. The BJ has a similar area vulnerable to casualty at a comparable fragment mass level; however, the smaller size yields a higher conditional P_C than for the CT and JCT.

Table 6-5. Tier 1 Thresholds for Aircraft

Aircraft Class	Threshold mass (g)
Commercial passenger transport jets (CT and JCT)	2.0
Business jets (BJ)	1.0
All other aircraft	1.0

The calculations for the BJ class showed 2.2% probability of penetration at 0.6 grams and 2.3% probability of penetration at 1 gram. These values were derived from a higher-level modeling fidelity than were performed for the other aircraft, which still use the 1-gram vulnerability thresholds dictated by ingestion of a fragment by small turbine jet engines. This threshold was selected with less precision and fidelity than that conducted for the BJ model. It was therefore chosen to increase the conditional P_C to within 3% for the Tier 1 thresholds to reflect the imprecision and maintain consistency in level of prediction fidelity between the BJ and other aircraft.

Hazard volumes may be based on the maximum projected area of the aircraft potentially exposed to all debris fragments above the Tier 1 threshold masses given in Table 6-5. This provides protection of aircraft in compliance with the probability of impact requirements in

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[185] For example, some military aircraft are hardened to protect against debris and projectiles. Therefore, higher thresholds would apply; however, such research has not been applied to this particular problem. Thus, the conservative 1-gram value should still be used.
[186] Wilde P., C. Draper, I. Lottati, E. Larson, and T. Hasselman. "Vulnerability of Commercial Transport Aircraft to Debris from Space Accidents." Report No. 06-527/11.3. ACTA Inc, Torrance, CA, April 2007.
[187] Wilde, P. and C. Draper. "Aircraft Protection Standards and Implementation Guidelines for Range Safety." Paper presented during the 48th AIAA Aerospace Sciences Meeting; Orlando, 2010.

Subsection 3.1.1 of the standard. For example, a valid Tier 1 approach to demonstrate compliance with the standard is using the maximum projected area to restrict non-mission CT aircraft from volumes of airspace where the cumulative probability of impact of debris above the threshold masses exceeds 1E−7. The maximum projected area is the two-dimensional projection of the aircraft in the plane that is perpendicular to the fragment velocity vector (relative to the aircraft) of the largest aircraft potentially exposed. [188]

It is important to emphasize that there exists a potential for adverse consequences to occur from impacts to CT aircraft with masses below the Tier 1 threshold. For example, the more-detailed AVMs currently underlying the CT class vulnerability model presented below indicate that there is a very small chance of a casualty if a fragment between 0.4 and 2.1 grams impacts the cockpit. Specifically, according to the present model for a cockpit (which is the least well-developed element of the model) a compact steel fragment below the 2.1 gram threshold could penetrate the aircraft skin and potentially produce a penetration injury of a crew member. Therefore, the only intended use of the threshold masses presented in Table 6-6 is as a Tier 1 model: accounting for all impacts above the threshold anywhere on the aircraft as producing an adverse consequence. In addition, it is important to emphasize that the 2.1 gram Tier 1 threshold for CT applies only to fragments composed of materials that are no more dense than 8100 kg/m^3 (506 lb/ft^3).

Table 6-6. Tier 2 AVMs for Business Jet Aircraft

BJ Casualty		**BJ Catastrophe**	
Fragment Mass (g)	**Vulnerable Projected Area (ft^2)**	**Fragment Mass (g)**	**Vulnerable Projected Area (ft^2)**
0.599	0.0	10	0.0
0.6	10.2	20	40.4
3.99	10.2	30	203.1
4	80.3	40	210.2
5	107.9	50	215.9
6	122.6	60	220.7
7	135.8	70	224.8
8	143.1	80	228.4
9	149.6	90	231.7
10	152.2	100	239.3
20	220.0	150	257.7
30	396.2	200	285.1
40	413.7	250	318.6
50	426.1	299	341.1
60	438.0		
70	446.9		
80	454.8		
90	461.9		

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[188] In terms of plan and front areas and assuming an aircraft flying horizontally and debris falling vertically, $A^{proj} = A^{front}\sin(\theta) + A^{top}\cos(\theta)$, where θ is the angle of the impact vector from the vertical, i.e. $\theta = \tan^{-1}\left(v_{aircraft} \;/\; v_{debris}\right)$, where these velocities are relative to the ground.

100	473.0	
150	505.9	
200	543.5	
250	585.0	
299	614.1	

6.4.2 Tier 2 Vulnerability Model for BJ, CT, and JCT Aircraft.[189]

The following Tier 2 models are intended to facilitate evaluation of the risk from an event that can produce an on-board casualty and the risk of a catastrophic event, involving multiple casualties and the potential loss of the aircraft. Passenger jets[190] have a high priority for protection. Their size results in a bigger target, making the probability of impacting them generally higher than for many other planes. There is evidence that business jets present a larger area susceptible to a casualty producing event for fragments between about 2 to 30 grams (Wilde et al, April 2007) as reflected in the vulnerability models below. Moreover, these classes of aircraft carry many passengers so that the consequence of an impact may be very high. They are therefore designed to meet strict standards for structural integrity, redundancy of critical system, etc. Therefore, detailed studies have been performed to study their vulnerability.

a. CT Aircraft Class. The CT aircraft class is limited to aircraft with all the following characteristics:

- aluminum skin (composite skin aircraft have not been studied);
- multiple turbofan engines; and
- governed by the FAA certification requirements of 14 CFR Part 23/25.

Generally, CT aircraft have:

- highly redundant separated critical systems (fuel line, control systems, etc.);
- a pilot and co-pilot, such that casualty of one does not cause a catastrophic accident;
- redundant turbofan engines that are very resistant to debris impacts and are designed to prevent fan blades from exiting nacelle, causing more hazards;
- aluminum skin attached to aluminum ribs and spars;
- single-walled fuel tanks in wings;
- swept back wing design and aerodynamic shape;
- reinforced windshields that are quite resistant to debris.

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[189] Note: The results listed in this document have been cross-validated with empirical data. Peer review has been performed by the Aircraft Survival specialists at China Lake.

[190] Larson, E. and I. Lottati. “Status Report on Investigation of the Vulnerability of Aircraft to Debris from Space Accidents.” Report 05-527/9.4. ACTA, Inc., Torrance, CA, December 2006.

These characteristics are typical of CT aircraft, though they are not present in all CT aircraft, especially those not regulated by the FAA.[191],[192]

As noted, no models have yet been developed to address the vulnerability of composite aircraft. A new model has been developed to address aircraft with larger top areas (greater than 1967 ft^2 or front areas greater than 305 ft^2). These larger aircraft should be modeled using the JCT model.

b. BJ Class. The BJ class includes all multi-engine, jet-propelled aircraft that have the capability to carry no more than 20 passengers for hire. All aircraft within the BJ class primarily exhibit:

- aluminum skin and structural members;
- two pilots during operation; and
- design and maintenance requirements defined by the FAA certification requirements of 14 CFR Part 23/25.

The BJ class excludes:

- single-pilot versions of otherwise BJ class aircraft;
- emerging “very light jets” with composite skins or structures; or
- aircraft that rely on propeller-based propulsion.

Therefore, the same consequence analysis assumptions used for the CT class were also applied to the BJ class (Wilde and Draper).

The vulnerability analysis produced the relationships presented in Table 6-6, Table 6-7, and Table 6-8 between the mass of the impacting fragment and the projected vulnerable area of the aircraft. The data are provided for two levels of consequences based on the projected vulnerable area resulting in a single casualty and that resulting in a catastrophe for a BJ, a CT, and a JCT. Each fragment mass listed in the tables is to be interpreted as the smallest mass at which the projected area is vulnerable to the consequence.

Table 6-7. Tier 2 AVMs for Commercial Jet Transport Aircraft

CT Casualty		CT Catastrophe	
Fragment Mass (g)	**Vulnerable Projected Area (ft^2)**	**Fragment Mass (g)**	**Vulnerable Projected Area (ft^2)**
0.3	0.0	8	0.0
0.4	15.3	9	1.0
2	15.3	10	5.1
3	199.2	20	58.2
4	207.6	30	114.4

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[191] Wilde, P., C. Draper, I. Lottati, E. Larson, and T. Hasselman. “Vulnerability of Commercial Transport Aircraft to Debris from Launch Vehicles.” Report No. 07-610, ACTA Inc., Torrance, CA, September 2007.

[192] Schnalzer, R, J. Haber, E. Larson, L. Cao, and S. Carbon. “Aircraft Vulnerability Modeling Updates and Other Improvements to RRAT and CRTF Regarding Aircraft Risks.” Report 15-926. ACTA Inc., Torrance, CA, June 2015.

5	214.3	40	183.4
6	220.0	50	244.8
7	224.9	60	309.7
8	229.2	70	365.7
9	234.1	80	429.5
10	241.7	90	480.6
20	362.0	100	534.2
30	442.7	150	801.4
40	525.3	200	1042.0
50	597.5	250	1083.4
60	671.5	299	1137.5
70	735.3		
80	806.1		
90	863.3		
100	922.5		
150	1211.8		
200	1468.6		
250	1522.9		
299	1587.5		

Table 6-8. Tier 2 AVMs for Jumbo Commercial Jet Transport Aircraft

JCT Casualty		**JCT Catastrophe**	
Fragment Mass (g)	**Vulnerable Projected Area (ft^2)**	**Fragment Mass (g)**	**Vulnerable Projected Area (ft^2)**
0.3	0.0	8	0.0
0.4	15.3	9	5.9
2	15.3	10	14.1
3	199.2	20	97.4
4	207.6	30	190.5
5	214.3	40	293.8
6	220.0	50	390.8
7	224.9	60	482.7
8	229.2	70	583.0
9	239.0	80	667.8
10	250.7	90	751.1
20	401.2	100	831.7
30	518.8	150	1240.0
40	635.7	200	1516.5
50	743.5	250	1573.7
60	844.5	299	1645.6
70	952.6		
80	1044.3		
90	1133.8		
100	1220.0		

150	1650.3	
200	1943.1	
250	2013.2	
299	2095.6	

Each of these tables shows the functional relationships between the mass of an impacting fragment, m (in grams), and the projected vulnerable area, A_{PROJ}, (in ft^2) of each class of aircraft vulnerable to a casualty-producing event (i.e., a single casualty regardless of the occupancy of the aircraft), A_{CAS}^{PROJ} , and a catastrophic event, A_{CAT}^{PROJ} , respectively.

Table 6-6, Table 6-7, and Table 6-8 apply to all fragments composed of materials that are no denser than 8100 kg/m^3 (506 lb/ft^3). The casualty area or catastrophe area (A_{PROJ} in the previous tables) must be modified as described below for use as a reference area on a horizontal surface (A_I) in standard probability of impact computations (much like the plan area of a building is often used to compute the probability of impact on a building).

The AVMs account for the velocity of the fragment, the velocity of the aircraft, and the various areas of the aircraft. The casualty area or catastrophe area (A_{PROJ} in the following equation) given by the AVMs must be modified as follows for use as a reference area (A_I) in standard probability of impact computations (much like the plan area of building is often used to compute the probability of impact on a building).

$$A_I = A_{PROJ} \frac{\sqrt{v_A^2 + v_d^2}}{v_d} \qquad (6\text{-}1)$$

Figure 6-10 shows the casualty AVM comparisons for the three classes of aircraft considered in Tier 2. The BJ class shows less vulnerability area leading to a single casualty for all fragments below 300 grams. The CT class and JCT class have very similar vulnerability profiles for fragments with masses up to about 10 grams; for larger fragments the JCT’s larger area is important.

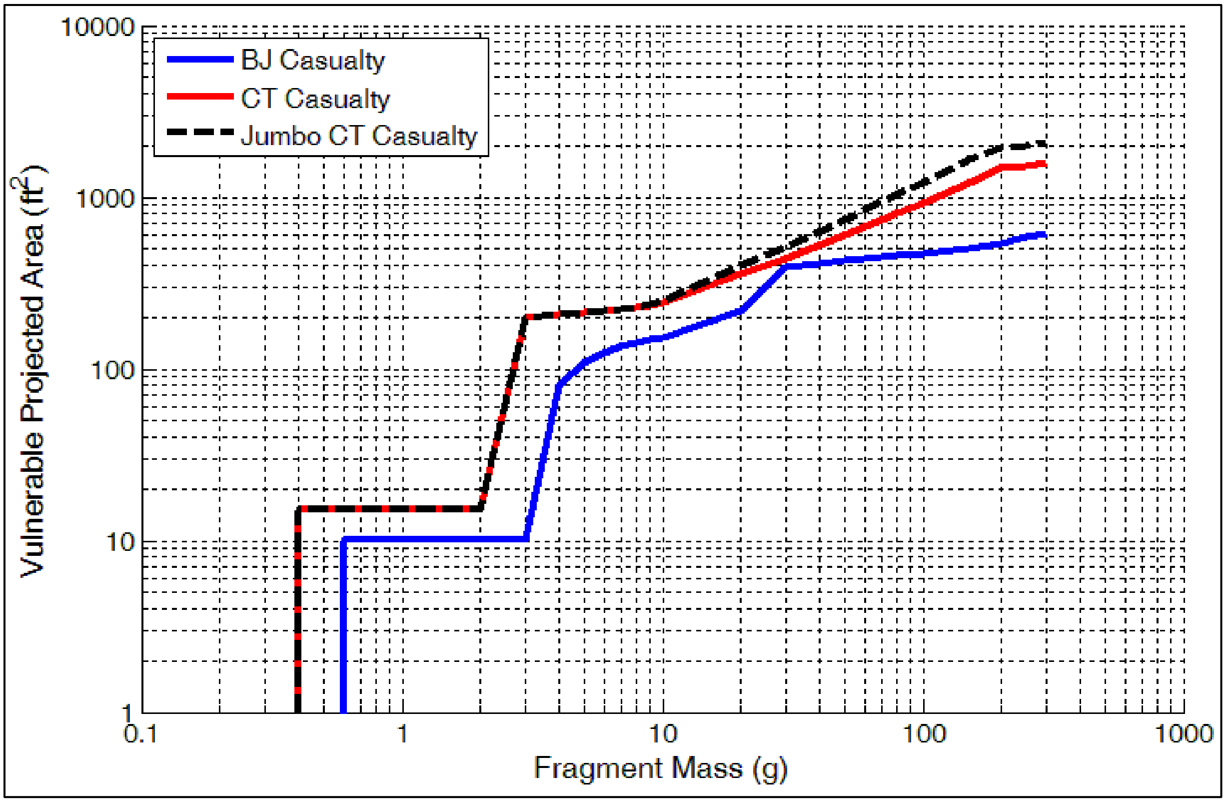

Figure 6-10. Illustration of BJ, CT and JCT Aircraft Casualty Vulnerability Models

The AVMs for catastrophe are presented in Figure 6-11 for Tier 2. The BJ class has less vulnerability area for casualty than for a CT nearly throughout the entire fragment mass range except between 25 – 40 grams. The difference is due to the variable thickness on the upper wing surface of a CT. The BJ has an intermediate thickness that is constant from root to tip. Penetrations do not occur for a BJ within this range of masses, but occur all at once rather than incrementally for a CT and a JCT. Again, the JCT yields the highest vulnerability due to a higher overall surface area.

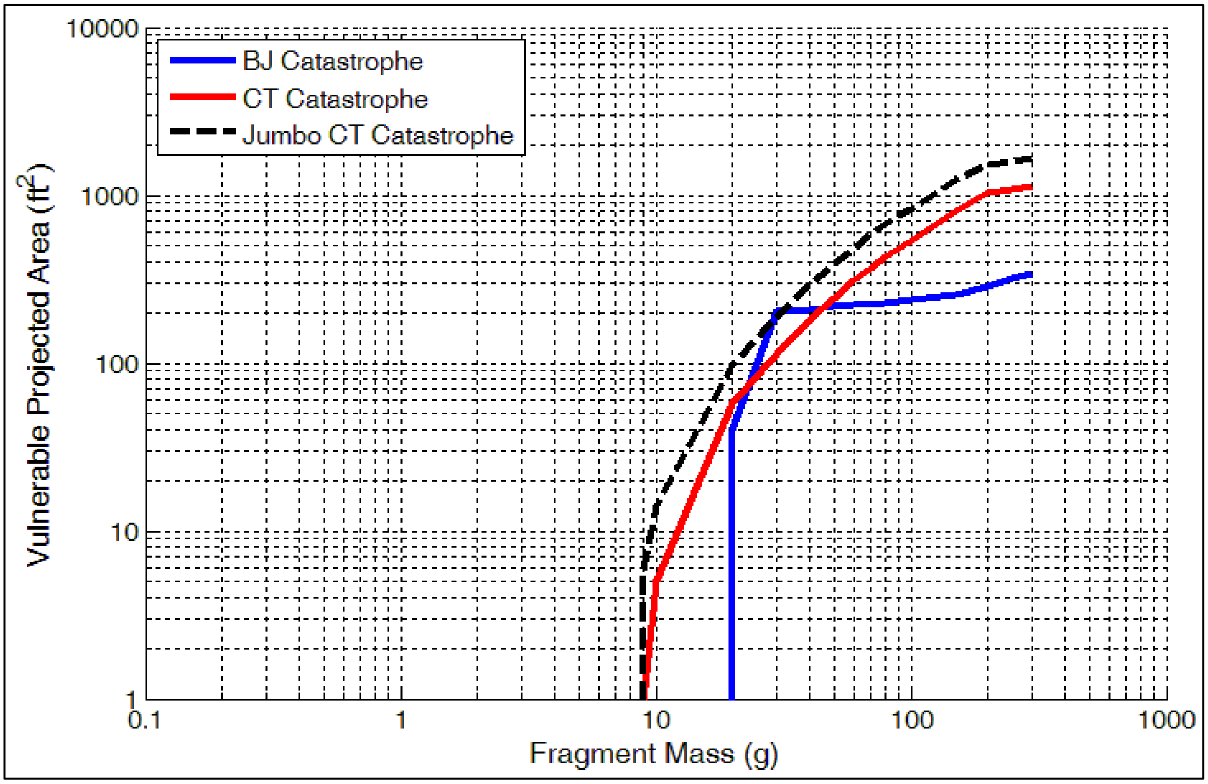

Figure 6-11. Illustration of BJ, CT, and JCT Aircraft Catastrophe Vulnerability Models

These simplified generic BJ, CT, and JCT AVMs are based on the best available information, methods, and reasonably conservative assumptions made in each area where there was no conventional approach or there was un-quantified uncertainty. The impacting object is assumed to be a compact steel fragment with penetration characteristics reasonably represented by a solid cube impacting face-on. These model results assume that fragments are falling at terminal velocity at aircraft cruising altitudes (which may be twice the terminal velocity at ground level).[193] These AVMs were subject to independent review by recognized experts. Thus, these AVMs are considered valid for use in the development of aircraft hazard areas designed to comply with the standard. There remains considerable uncertainty about the results because of the limited test data available on impacts at highly oblique angles, which are clearly important to the vulnerability of CT aircraft.

These AVMs are based on a modified form[194,195,196] of the FAA-Joint Technical Coordinating Group penetration equation that conservatively uses a shear constant equal to 210 MPa. This constant was empirically derived for impacts to thin plate made of aircraft aluminum

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[193] Small fragments will normally have low ballistic coefficients, producing a sufficiently high drag to weight ratio such that they will slow to speeds near terminal velocity before they could impact aircraft. The only place that **small** fragments will have a significantly higher speed than terminal velocity is likely to be in the **immediate** vicinity of a launch accident or intercept event, from which it is assumed that aircraft would normally be excluded anyway.

[194] Wilde et al, April 2007.

[195] Seng, S., J. Manion, and C. Frankenberger. "Uncontained Engine Debris Analysis Using the Uncontained Engine Debris Damage Assessment Model." DOT/FAA/AR-04/16. September 2004. Retrieved 17 October 2023. Available at http://www.tc.faa.gov/its/worldpac/techrpt/AR04-16.pdf.

[196] Wilde and Draper, 2010.

only.[197] Thicker plate impact tests conducted later led to a revised value of 276 MPa for this parameter.[198] These new tests were to establish:

a. the minimum perimeter of the projectile presented area, regardless of obliquity, instead of the perimeter of the subtended presented area of the projectile, and

b. an important modification to the obliquity term as described in Wilde et al (April 2007) and Wilde and Draper.

Regardless of the vulnerability model or hazard threshold levels used, aircraft hazard areas should be based on the **largest aircraft** in use in the region of concern for two reasons. First, the largest aircraft present the largest vulnerable area of any commercial transport. Therefore, they will define hazard areas that are reasonably expected to provide adequate protection for all other types of commercial transport aircraft. Second, the best available probabilistic AVM results indicate that while other common types of aircraft can exhibit a higher conditional probability of adverse consequences at threshold levels (given an impact) than those associated with other commercial transport aircraft examined (Wilde et al, April 2007) the larger total area susceptible to adverse consequences drives the risks. **No attempt should be made to scale the vulnerability models presented here for application to other commercial transport aircraft**. Instead, it is recommended that the equations be applied as stated to all planes in the commercial transport class as defined at the beginning of this section.

6.4.2.1 Development of AVMs

The AVMs presented here are based on an event tree analysis of commercial transport aircraft, an empirical equation developed by the FAA described in Wilde et al (April 2007), and physics-based models of launch vehicle debris impacts on a simplified aircraft geometry described in Wilde et al (April 2007) and Wilde and Draper.

The event tree analysis examined design practices and FAA regulations to determine smallest debris that could lead to failure modes. This analysis, combined with past experience with impacts on this class of aircraft, produced the following fundamental conclusions (Wilde and Draper, and Wilde et al, April 2007).

a. A fuel tank penetration through the top surface of the wing is benign. Previously, penetrations with an area of at least two square inches were considered potentially catastrophic due to fuel loss and potential explosions caused by hydrodynamic ram. Critical review of a Naval Air Warfare Center Weapons Division China Lake study of a generic twin jet[199] resulted in a reevaluation of the consequences of the penetration of the top surface of the fuel tanks. These conclusions were based on an FAA analysis showing the explosions and fires occurring as a consequence of fragment impacts on the aircraft

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[197] Steven Lundin. "Engine Debris Fuselage Penetration Testing, Phase I." DOT/FAA/AR-01/27. August 2001. Retrieved 17 October 2023. Available at http://www.tc.faa.gov/its/worldpac/techrpt/AR01-27.pdf.

[198] Lundin, S. and R. Mueller. "Advanced Aircraft Materials, Engine Debris Penetration Testing." DOT/FAA/AR-03/37. December 2005. Retrieved 17 October 2023. Available at http://www.tc.faa.gov/its/worldpac/techrpt/AR03-37.pdf.

[199] Manion, J., R. Phillips, and W. Pease. "Commercial Aircraft Vulnerability Probability Modeling." Contract No. ASTAFRL2-B. Available on request to the RCC Secretariat office.

were extremely unlikely.[200] Moreover, the study provided a basis for establishing that the potential fuel loss from penetration of the top of the wing would not inhibit safe landing of the aircraft.

The FAA AC 39-8 concludes that holes in the fuel tank smaller than an area of 2 square inches do not warrant a "severe" designation. Leakage from the bottom of the fuel tank poses a higher threat to the continued safety of the aircraft because of the greater rate of fuel loss (pressure and gravity) and the greater likelihood of leakage into nacelles or dray bays that may cause fires (FAA, 1997). Moreover, while multi-compartment wing fuel tank aircraft may be able to survive such penetrations, more detailed analyses are required to ensure that this is possible particularly for transoceanic flights. Marginal ability to complete flight with residual fuel could compromise an aircraft's ability to divert, if required, for weather. Thus, while penetrations of the top of the wing are treated as benign (for fragments with masses less than 300 g), penetrations of the lower surface of the wing are regarded as catastrophic.

b. Critical structural components are those that provide essential structural functionality; the failure of these components leads to unsafe continued flight. The vulnerability models in previous versions of the standard treated fuselage ribs and wing stringers as critical components potentially threatened by fragments with masses less than 300 g. Penetration of these components was assessed as catastrophic. Re-evaluation of critical structural components found spars to be the only pertinent critical structural component that are vulnerable to penetration of fragments below 300 g. The updated evaluation found that penetration of fuselage ribs does not occur in the identified fragment range. Additionally, structural redundancy in the stringers prevents a catastrophic outcome from the impact of a fragment less massive than 300 g. Not all spar penetrations are regarded as failure inducing. The penetrating fragment must span the smaller of two distances: a) the distance between the spar stiffeners and b) the height of the spar. Although cubic steel fragments less than 300 g do not have this span, rod-like fragments of the same mass may pose a realistic threat to some spars they penetrate. Fragments were modeled as steel fragments with a diameter of 0.64 inches (like a bolt) and the resulting length compared with the minimum spar dimension to assess if a penetration was catastrophic.

c. The potential for a catastrophic outcome from a single launch vehicle debris impact on an engine of a commercially certified aircraft is negligible (Wilde et al, April 2007). This finding is based on the facts that: (1) certified commercial aircraft must be able to continue safe flight following the loss of thrust from any single engine; and (2) debris impacts are unlikely to generate a potentially catastrophic condition due to engine fragment throw.

d. Historical experience indicates that fragment impacts from uncontained gas turbine failures often produce significant damage without casualty or other serious consequences, even prior to the implementation of FAA design guidelines intended to reduce this threat.

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[200] FAA. *The Potential for Fuel Tank Fire and Hydrodynamic Ram from Uncontained Aircraft Engine Debris*. DOT/FAA/AR-96/95. January 1997. Retrieved 16 October 2023. Available at http://www.tc.faa.gov/its/worldpac/techrpt/ar96-95.pdf.

Specifically, even prior to implementation of AC 20-128A,[201] fragment impacts from uncontained gas turbine engine failures were about six times more likely to produce significant damage without casualty than an outcome involving casualties, hull loss, or a crash landing (Seng et al, 2004).

e. The only other failure mode for debris smaller than 300 g that resulted in non-trivial probability of a casualty was a penetration of the fuselage, which could directly injure a crew member or passenger or lead to a non-catastrophic depressurization event (Wilde et al, April 2007).

The AVMs presented here are consistent with the input parameter uncertainties and sensitivities found using the best available techniques (Wilde et al, April 2007, and Larson and Lottati). Simulations of penetration also included other sensitivity studies, such as impact location on the aircraft, skin thickness, aircraft velocity, and fragment parameters. Although the true extent of the modeling uncertainty contained in the present results is unknown, these results are based on the best available information and reasonably conservative assumptions made in each area where there is no conventional approach or there is un-quantified uncertainty. Since these results are based on the best available information, and are based on analysis that has been independently reviewed, they are deemed appropriate for immediate use; however, ranges should continue to use the more conservative thresholds already established (i.e., the 1-gram steel cube and others defined in the standard) for all other types of aircraft because no attempt has been made to update the vulnerability models for other aircraft types. It is important to ensure the present AVMs are applied only to aircraft in the correct class. The estimated risk could be significantly under-stated if the thresholds or vulnerability models are used for aircraft that do not meet the requirements of the class. Applicable aircraft classes are defined at the beginning of Subsection 6.4.2.

6.4.2.2 Confidence in Models

To assess the confidence in the thresholds, the shape of the fragment and orientation upon impact were varied. A reasonably conservative (more penetrating) shape was used to develop the present AVMs. It is theoretically possible for a fragment to penetrate with lower mass if the shape and orientation were ideal (such as a thin rod impacting end on); however, this scenario is considered remote because fragments are generally assumed to be tumbling as they fall or immediately following first contact with the aircraft.

In addition, the aircraft vulnerability analysis is considered conservative for the following reasons.

a. The FAA penetration equation was modified and implemented in a manner (as described in Wilde and Draper) that produced conservative results compared to the available test data (i.e., data from Wilde et al, April 2007).

b. No credit is taken for possible survival of multi-compartment fuel tank aircraft after penetration of the bottom of the compartment.

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[201] FAA. "Subject: Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure." AC 20-128A. 25 March 1997. May be superseded by update. Retrieved 16 October 2023. Available at https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-128A.pdf.

c. China Lake required failure of ***two adjacent*** spars to produce a catastrophe; the current model treats failure of any spar as a catastrophe.

d. Although the new model requires a penetrating fragment striking a spar to span the distance between stiffeners or the height of the spar itself and fragments are treated as a 0.64 inch diameter bolt for this assessment:

   (1) penetration is based on the smaller contact area of a cube rather than the long rod impact area;

   (2) orientation of an impacting rod in the direction to span the critical dimension of the spar is an unlikely event; and

   (3) failure of spars near the wing tip (where spar dimensions are smaller) are less likely to cause catastrophic events.

e. The ballistic resistance of interior wall panels and insulation for the fuselage and cockpit was neglected due to insufficient data.

f. Experience shows that this class of aircraft can land safely after sustaining substantial damage from uncontained engine fragment impacts or even a missile strike (Wilde et al, April 2007).

6.5 People on Ships

As discussed in Section 4.5, the consequences of the debris hazard to ships are more complicated than those to buildings because of two effects: a fragment impact can sink the ship; and for explosive impacts near a ship, the water affects the propagation of energy. An inert fragment impacting upon a ship can affect a person on-board either directly or because it sinks the ship. An explosive impact either on the ship or in the water nearby can hazard a person through several mechanisms. These various mechanisms must be considered in the evaluation of risks. To assess consequences, including the P_C to a person on-board a ship, this section provides Tier 1 models for inert impacts upon ships and for explosive impacts. There are two sets of Tier 1 models for ships: one defines thresholds for penetration of the deckhouse roof and another for penetration of the hull (i.e., a potential catastrophe).

The threshold level of hazards to produce a particular consequence can vary by more than an order of magnitude between the least vulnerable and the most vulnerable types of ships. Thus, to reduce the conservatism, different thresholds were developed for various categories of ships. Consistency with the underlying models would require a classification based on structural characteristics. This approach would produce ship structural classes that would be difficult to use by a flight safety analyst. Instead, six different ship classes are defined that more directly relate to the type of information that may be available to an analyst: the length of ships. The following length categories include the types of ships indicated below each category.

<u>Ships less than 25 feet in length</u>

- Small fishing vessels
- Small pleasure craft

<u>Ships 25 to 50 feet in length</u>

- Small to medium size fishing vessels

- Small to medium size pleasure craft

Ships 50 to 100 feet in length
- Medium sized fishing vessels
- Medium sized pleasure craft
- Tug boats

Ships 100 to 200 feet in length
- Large fishing vessels
- Large pleasure craft
- Coast Guard patrol ships

Ships 200 to 295 feet in length
- Large fishing vessels
- Large pleasure craft
- Coast Guard patrol ships

Ships greater than 295 feet in length
- Container ships
- Tankers[202]
- Other cargo ships
- Pleasure cruise ships[203]
- Military ships

While the foregoing classification of ship categories is based on the length of the vessel, vulnerability is more directly related to the construction approaches. Design guides drawn from the American Bureau of Shipping (ABS) rules and other trade publications (listed in Appendix C) show that the choice of construction is related to size (in particular the 200 ft and 295 ft distinctions are directly drawn from ABS standards). For this reason, the fragment impact hazard thresholds were evaluated for both the length of the vessel and roof construction material. Typically, this resulted in more than one structural material type for a given length category as illustrated in Figure 6-12 and the list that follows.

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[202] LNG tankers are designed and built to the requirements specific for such vessels, in addition to those in the Rules for Building and Classing Steel Vessels. If there are any differences in the deckhouse roof thickness (and none are expected according to the Guide for Building and Classing Membrane Tank LNG Vessels) the requirements for the deckhouse on an LNG tanker are expected to be more stringent than those for a general steel vessel.

[203] The penetration thresholds for steel vessels apply to passenger cruise ships. American Bureau of Shipping (February 2001) refers to the Rules for Building and Classing Steel Vessels for scantling requirements of the deckhouse.

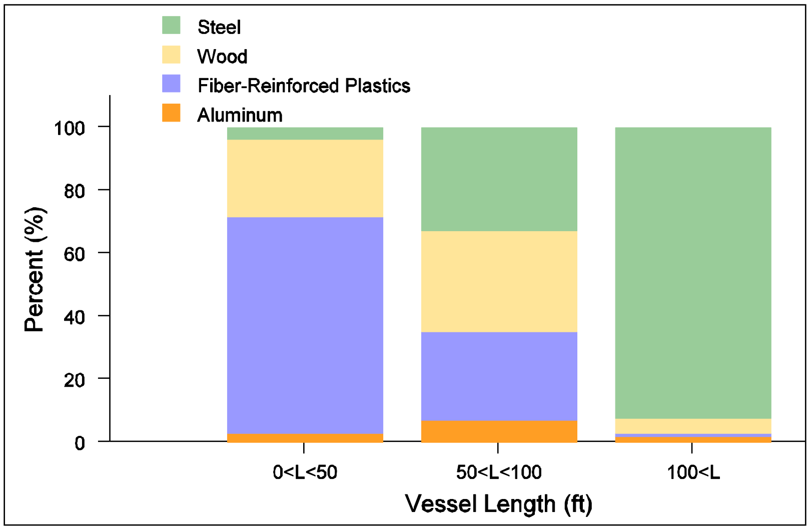

Figure 6-12. Hull Materials for Vessels of Different Lengths

Ships less than 25 feet in length

- No roof is assumed; use risk for unsheltered people for direct impact
- Wood hull

Ships 25 to 50 feet in length

- Wood*
- Fiber-reinforced polymer (FRP)

Ships 50 to 100 feet in length

- Wood*
- FRP
- Steel high-speed craft
- Steel displacement craft

Ships 100 to 200 and 200 to 295 feet in length

- Steel high-speed craft
- Steel displacement craft*

Ships greater than 295 feet in length

- Steel*

Finally, the weakest structural material type within a category was chosen, conservatively, to represent that category of ships. These structural material types are indicated by the asterisks in the itemized list above.

The combined effective casualty or catastrophe area for a fragment is a function of the consequences of inert impacts on the ship, an explosion on the deck of the ship, and a nearby explosion (each described below).

The total effective casualty area for a person under cover of the deck (such as inside the deckhouse) is given by Equation (6-2).

$$\begin{aligned} A_{CasShelt}(\text{Frag}, Y) &= Min\{A_{ship}, Max[A^{shelt}_{Cas,inert}(\text{Frag}), A^{shelt}_{Cas,DeckExpl}(Y)] \\ &\quad + A_{ship}[(1 - F_{fuel})P_{LossHull}(\text{Frag}) + F_{fuel}P_{deckpen}(\text{Frag})]\} \\ &\quad + 2(L_{ship} + W_{ship})r_{Cas,near}(Y) + \pi\left(r_{Cas,near}(Y)\right)^2 \end{aligned} \tag{6-2}$$

Where

A_{ship}, L_{ship}, W_{ship} are the area, length, and width of the ship;
Frag refers to properties of inert fragment on impact (mass, velocity, area, kinetic energy, etc.);
Y is yield of explosion of fragment, which may be computed with different factors for deck (hard surface) and water impact;
$A^{shelt}_{Cas,inert}$ is the direct casualty area for sheltered persons due to direct impact (see Subsection 6.5.1);
$A^{shelt}_{Cas,DeckExpl}$ is the casualty area for sheltered persons due to explosions on the deck (see Subsection 6.5.3.2; this already accounts for deck explosions that cause loss of vessel);
F_{fuel} is the fraction of the deck area that has fuel underneath;
$P_{LossHull}$ is the probability of hull loss due to inert damage (Subsection 6.5.2);
$P_{deckpen}$ is the probability of deck penetration by the fragment (Subsection 6.5.1);
$r_{Cas,near}$ is the effective radius for a casualty due to a nearby explosion (Subsection 6.5.3.1; this already accounts for nearby explosions leading to loss of vessel).

The Max function compares the two mechanisms for local effects of a fragment (inert and explosive) that are likely to be from impacts in the same area. The second line of the right side of the equation accounts for casualties due to loss of the ship, which can occur at a distance from the person, and thus the impact area does not overlap with the direct effects (so is added). The Min function ensures that the combination of casualty areas from direct impacts does not exceed the total area of the ship. The final line accounts for nearby explosions, where the first term is the rectangular water areas at the sides, front, and back of the ship, and the second term is from each of the four corners of the ship whose water area is a quarter disc shape that sum to a full disc. This is added to the effective casualty area due to direct impacts on the ship.

The unsheltered casualty area (for people standing on the deck) is the same, except the direct impacts now consider the unsheltered casualty (which is not specific to ships—see Subsection 7.6.4). The nearby explosion term is the same as for sheltered people, as the blast transmission through the water is more likely to cause casualties than air blast effects. So, this casualty area is given by Equation (6-3).

$$\begin{aligned} A_{CasUnshelt}(\text{Frag}, Y) &= Min\{A_{ship}, Max[A^{Unshelt}_{Cas,inert}(\text{Frag}), A^{Unshelt}_{Cas,deck\_expl}(Y)] \\ &\quad + A_{ship}[(1 - F_{fuel})P_{LossHull}(\text{Frag}) + F_{fuel}P_{deckpen}(\text{Frag})]\} \\ &\quad + 2(L_{ship} + W_{ship})r_{Cas,near}(Y) + \pi\left(r_{Cas,near}(Y)\right)^2 \end{aligned} \tag{6-3}$$

For catastrophes the equation is similar, except it does not include the direct effects because these typically only injure a few people. Subsection 6.5.3 provides the probability of loss of ship due to a deck explosion $P_{Loss,DeckExpl}(Y)$ and the effective radius for loss of vessel due to nearby explosion, $r_{Loss,near}(Y)$, which gives:

$$\begin{aligned} A_{Catastophe}(\text{Frag}, Y) &= A_{ship}\left[\left(1 - F_{fuel}\right)P_{LossHull}(\text{Frag}) + F_{fuel}P_{DeckPen}(\text{Frag}) \right. \\ &\left. + P_{Loss,DeckExpl}(Y)\right] + 2\left(L_{ship} + W_{ship}\right)r_{Loss,near}(Y) + \pi\left(r_{Loss,near}(Y)\right)^2 \end{aligned} \tag{6-4}$$

For simplicity, fatality areas may be considered to be the same as casualty areas, although this includes significant conservatism, as the overpressure levels required to cause a fatality are in fact larger than for a casualty.

In prior versions of this document a simplified, ultra-conservative approach was suggested: set $P_{PenetrateHull}$ equal to $P_{PenetrateDeck}$, This reduces complexity significantly, resulting in:

$$\begin{aligned} A_{Cas} &= Max\left(A_{CasUnshelt}, A_{ship}P_{PenetrateDeck}\right) + A_{EffCasExpl} \\ A_{Catastrophe} &= A_{ship}P_{PenetrateDeck} + A_{EffCatExpl} \end{aligned} \tag{6-5}$$

This does provide a conservative result, often overly conservative, resulting in high probabilities over a large region (as many more fragments have enough energy to penetrate the deck than the hull); however, there was previously no guidance provided for modeling of explosive debris (no method to determine $A_{EffCasExpl}$ or $A_{EffCatExpl}$). Ignoring this mechanism does not account completely for risk and could underestimate risk despite the conservatism of the inert component of the calculation. It is therefore recommended that the non-simplified equations above be used when possible, and if the simplified equations are used, they are used only (a) with the appropriate modeling of explosive casualty and catastrophe areas (see Subsection 6.5.3); and (b) where the resulting over-conservatism of the results is practical (it can be impractical if warning areas are so large that they will be ignored or if observation requirements are too costly).

6.5.1 Fragment hazards for occupied areas

A fragment that penetrates the roof of the deckhouse can result in injuring people inside the deckhouse. For this discussion, any *occupied* area of the ship can be considered part of the deckhouse. In computing consequences to people, the vulnerable area is the casualty area of the fragment, not the area of the deckhouse (or ship). Penetration threshold values for the deckhouse for six ship length categories are shown in Table 6-9. This table shows the ship category defined in terms of length and weakest construction, and penetration thresholds in terms of the minimum kinetic impact energy of a compact, irregularly shaped, tumbling steel fragment (CD = 0.75) impacting the roof at terminal velocity at MSL. Fragment weights corresponding to the minimum kinetic energy for penetration are also listed to assist analysts in interpreting the criteria. The penetration criterion was developed for steel fragments because it is the densest of the most common fragment materials. The appropriate conservative use of these thresholds is to assume 100% probability of deck penetration ($P_{deckpen}$) if the fragment impact properties exceed both criteria and 0% if they are less than either one.

Table 6-9. Threshold Values for Ship Cabin and Deckhouse Roof Penetration

Ship Category		Penetration Criteria	
Generic Class of Ship	**Roof Material**	**Minimum Mass Fragment (lb)**	**Minimum Kinetic Energy (ft-lb)**
< 25 ft	No roof is assumed	Use criteria for unsheltered persons	
25-50 ft	1/2 inch plywood	0.055	23
50-100 ft	3/4 inch plywood	0.137	75
100-200 ft	0.10 inch steel	1.2	1,300
200-295 ft	0.20 inch steel	4.4	7,800
> 295 ft	0.3125 inch steel	10.0	16,000

The thicknesses for FRP and wood roofs were calculated using the scantling rules provided in Gerr[204]; the thicknesses for the steel roofs for vessels of 100 ft to 295 ft in length are based on the minimum required thickness in the *Guide for Building and Classing Motor Pleasure Yachts*[205]; the minimum roof thickness for steel vessels with a length of 295 ft or more was taken from *Rules for Building and Classing Steel Vessels Under 90 Meters in Length*[206] to be conservative.

For deckhouse impacts, the effective casualty area ($A_{Cas,inert}^{shelt}$) is limited to approximately three times the fragment area; fragments that can cause more significant damage will lead to penetration of the hull and potential casualty to all on-board. The effective casualty area can be used in the computation of P_C -producing impact, P_C to a person on-board, and E_C to people on-board.

6.5.1.1 Development of the Hazard Thresholds

Fragment impact kinetic energy thresholds for roof penetration are based on compact steel fragments impacting the roof vertically at terminal velocity for the particular fragment at MSL. A nominal drag coefficient of 0.75 was assumed for irregular-shaped tumbling fragments. Compact fragments are defined as fragments having relatively small surface area-to-volume ratios. These computations include several levels of conservatism.

a. Threshold values for roof penetration were conservatively selected in lieu of threshold values for injury given roof penetration. The impact kinetic energy to penetrate a roof depends on the shape and density of the fragment, the construction of the roof, and the impact geometry. Fragments impacting between support beams require less kinetic energy to penetrate the roof than fragments impacting over supporting structure. Moreover, vertically impacting fragments typically require less kinetic energy to penetrate than do fragments impacting at some lesser angle.

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[204] Dave Gerr. *The Elements of Boat Strength: for Builders, Designers and Owners*. Camden: International Marine, 2000.

[205] American Bureau of Shipping. *Guide for Building and Classing Motor Pleasure Yachts*. Houston: American Bureau of Shipping, 2000.

[206] American Bureau of Shipping. “Part 3. Hull Construction and Equipment” in *Rules for Building and Classing Steel Vessels under 90 Meters (295 Feet) in Length, 2006*. Houston: American Bureau of Shipping, 2005.

b. The weakest structural type within a ship class was chosen to represent that class of ships.

c. Steel, the densest common fragment material, was used for the calculations.

6.5.1.2 Confidence in Models

Confidence in the steel plate penetration model used to obtain the critical penetration kinetic energies shown in Table 6-9 is based on comparative studies documented in Baeker et al (1984)[207], Hasselman et al (1999)[208], and Gan (2006).[209] These studies compared various empirical models with published test data and with nonlinear finite element calculations.

Confidence in the wood model (drawn from Bogosian and Dunn) was established via comparison with test data.

For the penetration of steel plate targets, the Stanford Research Institute (SRI) and the Ballistics Research Laboratory (BRL) equations have been widely used. Comparisons with several sets of experimental data show that the BRL equation gives reasonable agreement with all of them, while the performance of the SRI equation is less satisfactory.[210] The BRL equation has been used to establish the penetration thresholds for steel roofs in Table 6-9.

6.5.1.3 Level of Conservatism in Threshold Values

There are two types of input data uncertainty to consider: input data uncertainty associated with the impacting fragment; and the uncertainty associated with the roof model, with the former being the larger (See Subsection 6.1.2).

Consistent with the level of simplification, significant uncertainties and inaccuracy are to be expected when aggregating dozens of vessel length/construction combinations into the five generic classes and in the characterization of the impacting fragments. The uncertainties and inaccuracy are dealt with through conservative assumptions in the development of the thresholds, including assumptions made in the determination of the vessel scantlings, the characterization of the fragments, and the derivation of the penetration models. Considering all these factors together, the final thresholds are believed to contain a level of conservatism commensurate with the intended purpose.

6.5.2 Fragment Hazards for Unoccupied Areas

Impact of a fragment can cause casualties even if a person is not impacted by the fragment or secondary debris. This can occur in two ways: first if the fragment penetrates the deck (and other materials) above the region where fuel is present; and second, if the fragment penetrates all levels and causes significant damage to the hull. The penetration to fuel can lead to an explosion; for most ships, a fragment that has enough energy to ignite fuel also has sufficient energy to penetrate the hull, and thus this consideration is redundant. For ships carrying volatile fuel, such as liquid natural gas (LNG), a penetration of the deck above the fuel storage area is a potential catastrophe. Thus, for these ships, the penetration thresholds for the deckhouse (Table 6-9) should be used for the entire vessel.

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[207] Baeker, J.L., L. Philipson, and D. Tran. *Offshore Oil Hazards*. Redondo Beach: J. H. Wiggins Company, 1984.

[208] Hasselman, T., X. Li, and W. Gan. "Casualty and Fatality Risk Models for Roof Penetration by Inert Debris." Report #400/11.4-03. ACTA Inc., Torrance, CA, September 1999.

[209] W. Gan. "A review of Empirical Steel Plate Perforation Formulas." Interoffice Correspondence, June 2006.

[210] Norman Jones. "Low Velocity Perforation of Metal Plates", in *Shock and Impact on Structures*. C. A. Brebbia and V. Sanchez-Galvan, eds. Boston: Computational Mechanics, 1994.

Table 6-10 shows significant hull damage thresholds for the six ship length categories described above.

Table 6-10. Threshold Values For Significant Hull Damage

Ship Category		Penetration Criteria	
Generic Class of Ship	**Deck/hull Material**	**Minimum Mass Fragment (lb)**	**Minimum Kinetic Energy (ft lbf)**
< 25 ft	One plywood layer: 0.75 inch	0.6	25
25-50 ft	Two plywood layers: 0.5 inch and 0.75 inch	0.7	115
50-100 ft	Two plywood layers: 0.75 inch each	1.0	205
100-200 ft	Two steel layers: 0.1 inch and 0.2 inch	35	40,000
200-295 ft	Two steel layers: 0.2 inch and 0.3 inch	115	71,000
> 295 ft	Two steel layers: 0.2 inch and 0.4 inch	6300	1,250,000

The appropriate conservative use of these thresholds is to assume 100% probability of loss of the hull ($P_{LossHull}$) and thus loss of vessel if the fragment impact properties exceed both criteria and 0% if they are less than either one.

6.5.2.1 Development of the Hazard Thresholds

The values presented in Table 6-10 are based on ship structural vulnerability models[211,212], which are extended from the building structure vulnerability models (Hasselman and Legg; Bogosian and Dunn). The modeling of steel ships has been extended to account for the fact that the steel plates of the deck and hull are welded to the supporting structure. The development of the thresholds considered impact of a wide variety of fragments ranging in mass, area, and impact velocity (within 50% of terminal velocity at sea level). To assess significant damage, a minimum hazard area (effectively the area of hull damaged) was selected for each ship class. For small ships, this was a damage that was bigger than just a simple punch-through because a small hole in the hull is not likely a casualty-producing event, even for a small boat. Also, large vessels are compartmentalized, and major structural elements need to be defeated to cause significant damage that would likely result in casualties.

The computations include two significant levels of conservatism.

- Threshold values for significant damage to the hull were conservatively selected. The impact kinetic energy to penetrate through the deck and the hull depend on the shape and density of the fragment, the construction of the ship, and the impact geometry. One

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[211] Hasselman, T. and I. Lottati. “HACK/CF - Hazard, Casualty and Fatality Risk Models for Structure Penetration by Vertically Falling Inert Debris.” Report #09-696/3.2R1. ACTA SC, Vandenberg AFB, CA, September 2009.
[212] Erik Larson. “Proposed Updates to RCC 321 Regarding Ship Protection.” Report 14-861/01. ACTA INC., Torrance, CA, September 2014.

significant conservatism in the model was that all intermediate decks and structure were ignored; only the top deck and the hull were considered.

- The weakest structural type within a ship class was chosen to represent that class of ship. Usually ships are significantly stronger than specified; for example, cargo ships often have 1” thick hulls.

6.5.2.2 Confidence in Models

Confidence in the threshold values given in Table 6-10 was established through a two-step process. Confidence in the modeling approach was established by a V&V effort (Hasselman et al, 2005). For modeling of the penetration of wood decks, the wood penetration equation (for ships 50-100 ft) is the same as for smaller ships. For modeling of the penetration of steel plates, the SRI and the BRL equations have been widely used. Comparisons with several sets of experimental data show that the BRL equation gives reasonable agreement with all of them, while the performance of the SRI equation is less satisfactory (Jones, 1994). The BRL equation has been used to establish the penetration thresholds for steel roofs in Table 6-10.

These models however, were not designed for ships, and in particular, this approach for modeling damage to the hull includes significant uncertainty. All values for hull thickness have been chosen to represent minimum acceptable values, attempting to ensure the threshold values are not under-predicting risk. For example, large cargo ships often have double hulls where the outer hull is one inch thick or more.

6.5.2.3 Effect of Input Data Uncertainty on Application of Model

For fragments near the thresholds, a small change in the impact parameters can result in significant change in risk results, as the effective area of consequence increases from little more than the area of the fragment to the entire area of the ship. This may be an increase by several orders of magnitude. The models are designed to ensure risk is not underestimated, so if a fragment is above and close to a threshold and it is constraining to a mission, a higher-fidelity study of the potential damage to a ship from the fragment could lead to significantly lower estimates of risk to a ship.

6.5.3 Explosion Hazards

There is a number of mechanisms that can cause people on ships to be hazarded by a fragment or motor that explodes on impact. Obviously, a fragment that impacts the ship deck and explodes is a serious concern, even for relatively small yields. An explosion of a fragment upon water impact near the ship is a complicated phenomenon, as the explosion may lead to an air blast wave, a surface wave, and an underwater pressure wave. The partitioning of energy among these consequences depends on the depth beneath the surface of the water when the explosion initiates.

- An *air blast* hazards people on the ship in three different ways: those on the deck of a ship are hazarded directly (see the thresholds for unsheltered people in Section 6.2); those anywhere on-board are hazarded if the blast wave leads to significant structural damage or capsize; and those inside may also be hazarded by broken windows and other debris.
- A *surface wave* can lead to capsize of ships, especially small boats.

- An *underwater pressure wave* more effectively transmits energy to the ship than the air blast wave. Although such a direct pressure wave is small near the surface, in shallow water the pressure wave reflected from the seafloor can be a significant hazard.

6.5.3.1 Nearby Explosions

Assessing the consequence of explosions in the water near a vessel must address a complex set of phenomena. There are many effects that can lead to hazards to vessels; the relative importance of these effects varies with the size of the vessel. This makes the modeling much more complicated than on land. The models presented in this section are a simplified approach for estimating the probability of two consequences: casualty to a person on-board (useful for individual P_C and casualty expectation calculations) and the loss of vessel (useful for catastrophe modeling).

The governing casualty mechanism from an explosion with the smallest yield is often loss of hull integrity in shallow water; however, this changes as a function of yield. For example, for small boats with a large yield explosion, the largest damage radius is due to capsize from a surface wave in deep water. For explosions in the vicinity of small ships, the loss of ship hazard radius is larger than any hazard radius that leads directly to a casualty.

Each model is characterized by two parameters. This first is the minimum yield, below which the consequence is extremely unlikely to occur regardless of how close to the ship the explosion occurs. The second parameter is a consequence distance. This is intended to be used to compute the consequence area. It is an approximation to the more complicated integral of the probability of consequence as a function of distance, shown in Equation 6-6, and thus is only appropriate where the probability density of the explosion (or the probability density of the ship class) is nearly uniform over a distance several times larger than the hazard radius. Table 6-11 tabulates these parameter values by ship category.

$$r_d = \frac{1}{\pi} \int_{ship\ edge}^{\infty} \Pr(\text{consq})\, r\, \mathrm{d}r\, \mathrm{d}\theta - A_{ship} \qquad (6\text{-}6)$$

Table 6-11. Threshold Loss of Ship Distances for Explosions in Water

Ship Category	Hazard Criteria	
Generic Class of Ship	**Minimum Yield (lb-TNT)**	**Loss-of-Ship Distance (ft), $r_{Loss,near}$**
< 25 ft	0.01	$37.5\ Y^{0.333}$ (≈ 1.3 psi)
25-50 ft		
50-100 ft		
100-200 ft	10.0	$7\ Y^{0.36}$
200-295 ft		
> 295 ft	50.0	$12\ Y^{0.27}$

Table 6-12 provides effective threshold distances for an explosion in the water near a ship that can cause a casualty to a person on-board for different ship categories as a function of yield.

Note that many people may become casualties at once from a nearby explosion, even if the ship is not significantly damaged.

Table 6-12. Threshold Casualty Distances for Explosions in Water

Ship Category	Hazard Criteria	
Generic Class of Ship	**Minimum Yield (lb-TNT)**	**Casualty distance (ft), $r_{Cas,near}$**
< 25 ft	Same as loss-of-vessel	
25-50 ft		
50-100 ft		
100-200 ft	3.0	$20\ Y^{0.375}$
200-295 ft		
> 295 ft	10.0	$7\ Y^{0.44}$

These models are illustrated in Figure 6-13 in comparison with a 3-psi overpressure distance.

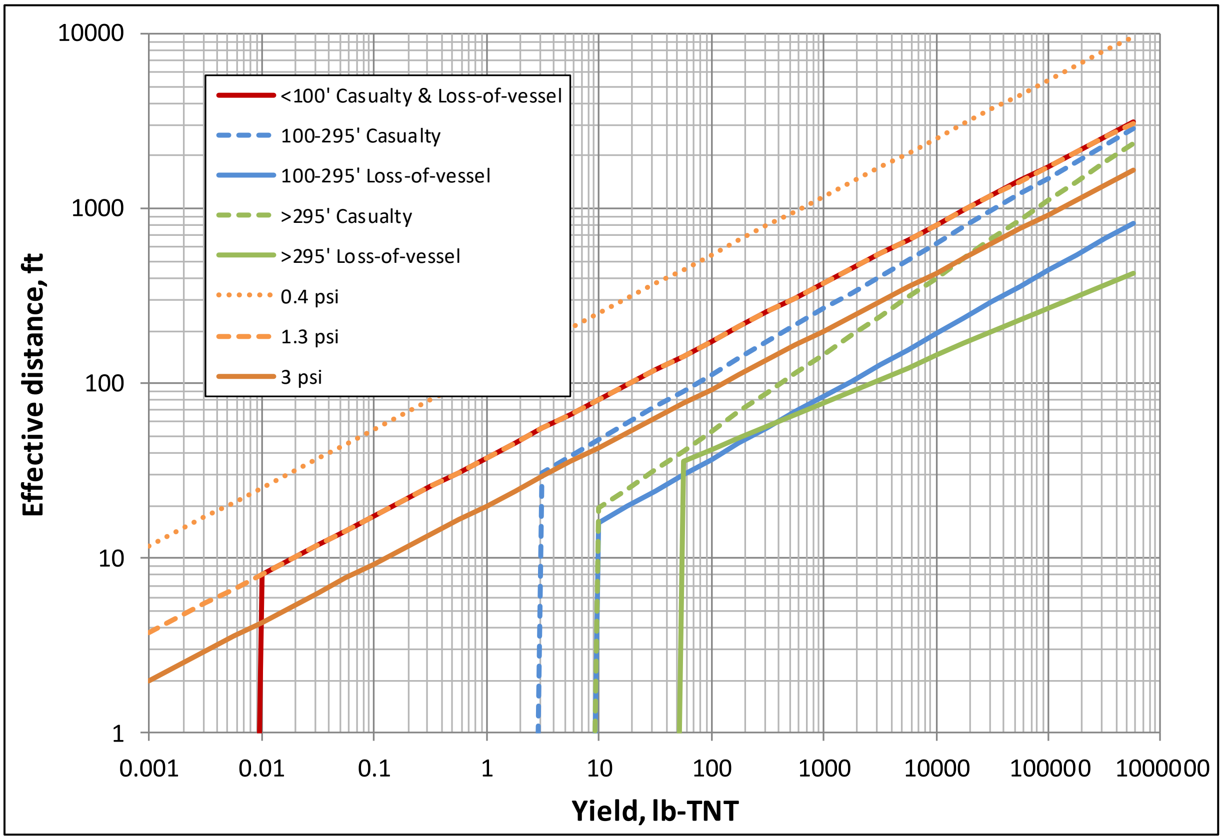

Figure 6-13. Thresholds of Hazard Distance for Explosive Impacts Near a Ship

As evident from the figure, for a simple analysis, a threshold of 1.3 psi ($\approx 37.5\ Y^{1/3}$) may be used for casualty and catastrophe, but this includes significant conservatism for larger ships.

6.5.3.1.1 Development of models

These models were developed using a physics-based model in a software program designed for this purpose. The tool computes the P_C to an individual on-board a ship due to nearby explosions, considering the various hazard mechanisms that may occur (Lambert et al, 2005 and Larson, 2014). This was performed for various ship sizes in various water depths. This includes three possibilities: capsizing due to either a wave or blast wave; window breakage from the blast wave; and casualties due to falls and hull failure as a result of an underwater pressure wave. The effective casualty and catastrophe area were computed as a function of yield, and then the resulting data was fit with a simplified function. In the fitting process, conservatism was applied - the resulting hazard distance at each yield is greater than the maximum hazard distance for any vessel within the class at any ocean depth.

6.5.3.1.2 Confidence of models

Modeling of the effects of explosions on nearby ships is a complicated process and has significant uncertainty. Based on comparison with other modeling approaches, these results are believed reasonable - it is thought that these models over-predict risk, but are not excessively conservative. There are many modeling choices that are poorly constrained by data, such as the likelihood of capsize due to a large wave; the partitioning of blast energy into air, surface wave, and underwater pressure wave; reflection of the wave from the ocean bottom; the response of a ship to an impacting pressure wave; and the likelihood of a hull failure due to a pressure wave. In addition, under certain conditions (such as deep water) some hazards are no longer relevant and the hazard distance for some yields may be much less in these situations. In particular, the hazard to small vessels from very small yields is likely quite over-conservative.

If impacts of explosive debris near ships significantly constrains a mission (especially if it is from yields near the minimum cutoff), a higher-fidelity model may result in significant reduction in risk.

6.5.3.1.3 Effect of input data uncertainty on application of model

The models are smooth with respect to yield above the minimum threshold, thus avoiding excessive threshold effects in this model due to small changes in estimating yield; however, there is often significant uncertainty as to whether a fragment will explode upon impact. This is, of course, a critical factor in the modeling of consequences.

6.5.3.2 Explosions on ship deck

It is possible that a fragment could impact the ship structure and then explode. Obviously, this is a very undesirable situation, but if the yield is sufficiently small, the consequences are negligible. For direct impacts of explosive debris on structures, the explosive yield is the useful independent variable. Table 6-13 and Table 6-14 provide simplified consequence models for explosions on the deck of the ship. The casualty area is given for a person who is under protection of a deck or deckhouse roof. The fatality area is not significantly different from the casualty area for an explosion on the deck.

Table 6-13. Deck Explosion Consequences for Ships < 100 ft

Yield (lbs-TNT)	Sheltered casualty area (ft^2), $A^{shelt}_{Cas,DeckExpl}$	Probability of loss of ship, $P_{Loss,DeckExpl}(Y)$
<0.03	0	0

0.03 to 0.1	$10\ A_{\text{ship}}\ Y$	$10\ Y$
>0.1	A_{ship}	1.0

Table 6-14. Deck Explosion Consequences for Ships > 100 ft

Yield (lbs-TNT)	**Sheltered casualty area (ft^2),** $A^{shelt}_{Cas,DeckExpl}$	**Probability of loss of ship,** $P_{Loss,DeckExpl}(Y)$
<0.05	0	0
0.05 to 0.5	$80\ Y$	0
0.5 to 1.0	$\max[80\ Y, 2A_{\text{ship}}(Y-0.5)]$	$2(Y-0.5)$
>1.0	A_{ship}	1.0

The explosive casualty area for unsheltered people who are not in a cabin or a deckhouse, $A^{Unshelt}_{Cas,deck\_expl}(Y)$, can be found as the maximum of the sheltered casualty area in the tables above and the unsheltered explosive casualty area. The unsheltered explosive casualty area is the area inside the radius to the threshold overpressure for serious injuries (see Section 6.2).

6.5.3.2.1 Development of models

Modeling of explosions of propellant fragments has been performed for buildings and for cargo ships[213], but not for smaller vessels. These models provide the hazard, casualty, and fatality area as a function of yield, but do not provide a minimum yield for hazard. Direct impacts of explosive debris are likely to be a low probability, and thus low-fidelity modeling is likely sufficient. These models for ships have been directed from the wood and pre-engineered metal building models as described in Larson.

6.5.3.2.2 Confidence of models

These models are based on models of explosions on buildings, not on ships, which is a significant caveat to the models. The model translation for ships has been designed to be conservative (over-predicting the casualty area and the probability of loss-of-ship). Therefore, these simple models are useful to ensure risk is below acceptability criteria, but are considered placeholder models in the absence of a specific modeling effort. In particular, the models are likely significantly over-conservative for small-yield explosions, but this is not usually a significant contributor to total risk. If risk due to direct impacts of explosive debris is constraining to a mission, this is obviously an area where higher-fidelity study could be performed.

Limited verification of these models has been performed for building impacts based on actual data of explosive impacts on roofs. The models were shown to be reasonably conservative (over-predicting the hazard area by a reasonable amount for risk analysis). No verification has been performed for ships.

6.5.3.2.3 Effect of input data uncertainty on application of model

The model is smooth with respect to yield (except for a small jump at the minimum yield), thus avoiding excessive threshold effects in this model due to small changes in estimates

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[213] Jon Chrostowski. “Development of Consequence Models for Explosive Roof Impacts.” Report #11-766/1.3-01. ACTA, Inc., Torrance, CA, September 2011.

yield. There is often significant uncertainty as to whether a fragment will explode upon impact, and this is, of course, a critical factor in the modeling of consequences.

6.6 Spacecraft

The hazard threshold discussion for spacecraft differs in several important ways from other sections of this chapter, as follows.

- The hazard assessments from launch vehicles to manned spacecraft do not consider off-nominal trajectories because:
    - the 3-sigma nominal covariance around the nominal trajectory is very large yet the risk of a collision from a nominal trajectory is still relatively low;
    - the expectation is that expanding covariance from the large 3 sigma nominal trajectories will dominate on-orbit trajectory failures risks;
    - the lack of aerodynamic failures, the low probability of on-orbit failures, and the fact that launch ranges are generally hands-off following the orbital gate suggest that malfunction scenarios that generate on-orbit debris are expected to be very low probability events;
    - the CSpOC is not set up to address malfunction scenarios.
- All manned and active satellites would be expected to sustain failure to any module colliding with a launched object such that determining the threshold of sheltering to diminish the consequences of impact adds little value for typical space launches.

As such, this supplement cannot include the usual narratives describing the basis of thresholds, the confidence in the models, or the uncertainty in these models. This section surveys approaches used to determine risks to manned/active spacecraft from small debris.

6.6.1 Routine CSpOC Spacecraft Collision Avoidance Screening Thresholds

For calculating sheltering/hardening and vulnerability for manned spacecraft, the smallest orbital debris that CSpOC tracks is somewhat larger than 5 cm. The ebb and flow of small debris resulting from atmospheric drag at lower orbits and limitations of the capability of space tracking assets restrict the ability to improve space debris catalog of smaller less predictable orbital debris.

The size of debris to which any given spacecraft is vulnerable to is expected to be smaller than anything in the orbital debris catalog that CSpOC maintains. Therefore, everything in the orbital catalog whether debris or microsatellites is significant when considering spacecraft collision that may disable the spacecraft. Furthermore, the debris in the catalog is considered significant for considerations of debris generation from a collision.

6.6.2 Spacecraft Collision Avoidance Screening Thresholds

In some cases, an analysis is performed to identify the risk to a spacecraft from the existing background debris based on debris size verses density estimates across all anticipated orbital planes. These types of analysis either consider the smallest size fragment to which a particular spacecraft is vulnerable or calculate several classes of vulnerability areas vs. debris densities in a particular orbital plane. A detailed treatment of this approach can be found in NASA publications.[214]

6.6.3 Planned Debris and Considerations for Hazard Thresholds

When debris is planned to be injected into an orbit that affects manned spacecraft altitudes, the vulnerability levels and associated critical areas utilized in accompanying risk assessments is found by looking at design criteria for the manned spacecraft. NASA developed a compendium of vulnerability levels and critical cross-sectionalal areas for the ISS in 2004, then subsequently developed additional vulnerability data for other spacecraft. These data were provided in two parts: the first for the Russian modules (Zarya, Zvezda, etc.) that are vulnerable to smaller debris and comprise a smaller area; and the more robust U.S. modules with larger vulnerable areas. For hazardous debris from 3 mm to 1 cm, the ISS vulnerable area was 125 m^2 with a critical cross-sectional area of 30 m^2. For hazardous debris greater than or equal to 1 cm the ISS vulnerable area specified was 725 m^2 and the critical cross-sectional area is 180 m^2. See Table 6-15, which is a 2008 update to the 2004 ISS assessment (NASA 2008).

Table 6-15. Probability of No Penetration Limits for Various Spacecraft

Vehicle	Threat	Failure Mode	Minimum Probability of No LV/LC or LM	Risk/(Area X Time) (%/[m^2–yr])	Critical *Al* OD (cm) at 7 km/s & 0 deg ^
Apollo Command & Service Module	MM	LV/LC	0.996 per 8.3 day lunar mission	0.25	0.16
Skylab Module	MM	LV/LC	0.995 for 8 month mission	0.003	0.2
Shuttle Orbiter	MMOD	LV/LC	0.995 per mission	0.013	0.08 – 0.5
	MMOD	LM	0.984 per mission	0.5	0.08
Gamma-ray Large Area Space Telescope Anti-Coincidence Detector	MMOD	LM	0.99 for 5 years	0.02	0.2
Hubble Space Telescope	MMOD	LM	0.95 for 2 years	0.03	0.16
ISS	MMOD	Potential LM, LC/LV	0.98 to 0.998 per critical element over 10 years	0.001	0.6 – 1.3
		Potential LM, LC/LV	0.76 PNP cumulative over 10 years for all critical elements	0.001	0.6 – 1.3
		LC	0.95 probability of no crew loss due to MMOD over 10 years	0.0003	0.6 – 1.3
Crew Exploration Vehicle	MMOD	LV	0.993 probability of no vehicle loss due to MMOD over 5 years at ISS	0.0015	0.4 - 0.6
		LV	0.9998 probability of no vehicle loss due to MMOD per lunar mission	0.0004	0.4 – 0.6

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[214] NASA. "Handbook for Limiting Orbital Debris." NASA-Handbook 8719.14. 30 July 2008. May be superseded by update. Retrieved 17 October 2023. Available at https://standards.nasa.gov/standard/nasa/nasa-hdbk-871914.

Notes:
^ This column provides the size of the largest fragment that is NOT expected to penetrate the space vehicles listed. Fragments are assumed to be aluminum debris pieces be traveling at 7 km/s & 0 degrees inclination. Fragment size is characterized by the fragment outside diameter measured in centimeters.
Abbreviations:
MMOD = Micro-Meteoroid Orbital Debris
MM = Micro-Meteoroids
LC = Loss of crew
LM = Loss of mission
LV = Loss of vehicle

6.6.4 Vulnerability of Spacecraft to Debris

On the ISS there is a variety of sheltering design criteria depending on the country responsible for the design of the module. The resultant probability of no penetration on that design criteria is provided in Table 6-15.

6.6.5 NASA Manned hardening/sheltering design criteria

NASA uses 1-cm size debris for the manned hardening/sheltering design criteria without a specification on the kinetic energy. The remainder of this subsection is taken from NASA Handbook 8719.14 Subsections 4.6.3.1 and 4.6.3.2.

> General vehicle design standards for MMOD protection for human spaceflight projects managed by JSC are given in the NASA JSC Design and Procedural Standards Manual [anon. 2004]. The following summarizes requirements for the MMOD protection system:
>
> - Protection levels against impacts from micrometeoroids and orbital debris (MMOD) for spacecraft structures shall be determined by Hypervelocity Impact tests and analysis.
> - MMOD risks for loss of crew (LOC), loss of vehicle (LOV), and loss of mission (LOM) shall be no greater than MMOD risks for previous spacecraft (ISS and Space Shuttle) (see Table 6-15).
> - The MMOD risk assessments shall be updated as the MMOD environment definitions change.
> - Actual damage from MMOD impacts shall be identified and compared to predictions to track and trend MMOD effects on the spacecraft.
>
> Crewed vehicles from the early years of space exploration have used the probabilistic approach to design meteoroid shielding. Table 6-15 provides a listing of historical MMOD protection design levels for human spaceflight programs along with examples of robotic spacecraft. Generally, critical penetrations are defined (for human exploration vehicles) as those that would endanger the survivability of the vehicle and crew. Mission success and functionality criteria have been applied to human exploration as well as non-crewed spacecraft. Criteria are met when the MMOD protection system and operational techniques for the spacecraft meet or exceed the minimum acceptable probability of no penetration causing LOV/LOC or LOM.
>
> Other options have been accepted by various programs to monitor the effects of MMOD impacts by on-board sensors, to inspect particularly sensitive or high-risk areas of the

vehicles for MMOD damage, and to carry repair kits that provide a means to patch critical MMOD damage to thermal protection system materials (for Space Shuttle) and pressure shell (for ISS). In addition, operational flight rules have been implemented to operate in attitudes that reduce MMOD risk to the maximum extent possible.

The ISS has meteoroid and debris protection limits consistent with past programs. As such, it carries by far the most capable meteoroid/debris shields ever flown. This is because ISS is larger and exposed longer than other space vehicles. The ISS is the largest spacecraft ever built. More than 11,000 m^2 of surface area are exposed to the space environment. These factors increase the expected number of meteoroid and debris impacts. To meet comparable protection limits, ISS shielding must be more effective. For instance, most ISS critical hardware exposed to the MMOD flux in the velocity vector (front) or port/starboard (sides) directions is protected by shields effective at stopping 1-cm to 1.3-cm-diameter aluminum debris particle at typical impact velocity and angle (9 km/s, 45°). In comparison, the Mir space station was only able to stop 0.3 cm particles, the Space Shuttle Orbiter was capable of stopping 0.2 cm to 0.5 cm particles, and Apollo and Skylab were able to stop 0.15 cm to 0.2 cm particles under similar impact conditions. ISS also has the ability to maneuver to avoid ground-trackable debris particles (typically >10 cm diameter). As a result of its large internal volume, the crews of ISS have time to locate and isolate leaks, if they occur, by closing hatches. Hole repair kits are manifested, and crews are trained to repair a leak in a module if it occurs. Crew escape vehicles are docked to ISS in the event of a major event requiring evacuation.

6.6.6 Size verses Kinetic Energy

The space community has used debris area rather than kinetic energy to define the vulnerability or sheltering criteria because the fragments hit with a predictable velocity in LEO.

6.7 Critical Assets

Critical assets are primarily susceptible to the impact of inert and explosive debris. These hazards can not only damage the structural elements of critical buildings, but also puncture and damage the contents of buildings. Since this chapter is intended to provide information for establishing hazard thresholds, the damage levels for critical assets located in buildings are conservatively assumed to be the same as those that would make the buildings unusable. Although the damage to contents is not specifically addressed, a description of the structural damage of the building may be adequate for a person with knowledge of the contents and operational mission to determine the approximate damage.

Vulnerability models are used to assess the damage to critical assets and evaluate whether they would still be useable following a mishap. The level of damage to assets is expressed in terms of the percent structural damage. Since the policy objective for protection of critical assets is to maintain the ability to function following a launch mishap, the structural damage must be relatively minor so that it can be easily and readily repaired following a mishap in order to minimize the interruption to operations.

6.7.1 Structure Types

National ranges, both DoD and commercial, contain a wide variety of buildings with different types of construction. The type of building construction is a primary factor that affects how sensitive assets are to damage produced by inert and explosive debris. Light structures (such as metal and wood structures) or weaker structures (such as those with load-bearing, un-reinforced masonry walls) will tend to be more susceptible to the penetration of inert debris and the effects of blast loading than stronger structures (such as reinforced concrete block and reinforced concrete); however, if a stronger structure fails, it can be more hazardous to the building contents because of the weight of the structural materials. Other factors that may affect the susceptibility of an asset to debris hazards include the size and number of floors of the building.

The material included in this section is based on the building construction shown in Table 6-16 through Table 6-18. It is a subset of the structure types used at the ER and WR to describe on-base buildings. These structure types were chosen to cover the range of construction likely to be used for critical assets.

Table 6-16. Structural Design for a 120’ x 180’ Three-Story Steel Frame Building

Structure	Plate/Diaphragm[1]	Joist[2]	Girders[3]
Roof	Verco 1.5” deep 22 Gauge with 3.5” Concrete	16 K 3 6’ Spacing 24’ Spacing	W 21 x 44 24’ Spacing 30’ Span
Floors	Verco 1.5’ deep 20 Gauge with 4” Concrete	18 K 5 6’ Spacing 24’ Span	W 21 x 62 24’ Spacing 30’ Span

[1] Roof/Floor deck description in Verco Manufacturing Co. catalog
[2] Joist designation consistent with VULCRAFT – K series open-web steel joist
[3] I-beam girder designation consistent with steel construction

Table 6-17. Structural Design for a 240’ x 150’ Three-Story Reinforced Concrete Building

Structure	Plate/Diaphragm	Steel Joist	Steel Girders
Roof	4.5” Slab 3/8” Rebar @12”	12” x 20” Xsection w/2 – 1” Rebar (#9) 7.5’ Spacing 30’ Span	24” x 27” Xsection w/6 -1.27” Rebar (#10) 30’ Spacing 30’ Span
Floors	4.5” Slab 3/8” Rebar @ 12”	12” x 22” Xsection w/3 – 1” Rebar (#9) 7.5’ Spacing 30’ Span	24” x 30” Xsection w/8 – 1.27” Rebar (#10) 30’ Spacing 30’ Span

Table 6-18. Structural Types for Air-Blast Loads

No.	General Description	Size	# Story	Walls	Roof	Frame
1	Small Reinforced Concrete Office/Commercial	Small	1-3	8” Reinforced Concrete	4” Reinforced Concrete	Concrete Shear Wall
8	Medium Reinforced Masonry	Medium	1-3	8” Reinforced Block	Lt Weight Metal on Joist	Steel Moment Resisting
10	Medium Metal Office/Commercial	Medium	1	Light Metal	Lt Weight Metal on Joist	Steel Moment Resisting
17	Ground-Based Radar Flight Safety Equipment	Small	NA	Metal Structure	NA	NA

18	High Bay Metal Vertical Assembly Bldg	Large	1	Metal	Metal/Joist	Steel Moment Resisting
19	Blast Resistant Reinforced Concrete	Small	1	12”-16” Reinforced Concrete	12” Reinforced Concrete	Concrete Moment Resisting
20	Medium Reinforced Masonry	Medium	1-3	8” Reinforced Block	4” Reinforced Concrete	Reinforced Block Bearing Wall
N0TES: 1) SMALL =< 5,000 FT^2, MEDIUM = 5,000 – 20,000 FT^2, LARGE => 20,000 FT^2						

For buildings with different construction, the rules for selecting a damage model to estimate their susceptibility to the impact of inert and explosive debris are described in Chrostowski and See.[215] In general, for a blast analysis, the selection should first be based on the roof and the walls of the lowest floor. Then, if the roof and wall combination do not match any of the generic structure types, the selection should be based on the wall type and building footprint area.

6.7.2 Damage Assessment Criteria

6.7.2.1 Inert Debris

The level of building damage from inert debris can be evaluated based on the fraction (percentage) of the roof area damaged by the impact of debris capable of penetrating the structure. Penetration occurs when the kinetic energy of a fragment exceeds the energy required to fail a structural member. The damaged area is commonly referred to as the “hazard area”. It represents the portion of the roof area between major supports that fails due to a fragment impact. As a general rule, the hazard area should be doubled for steel and concrete roofs to account for tearing back the roof so that the repaired portion of the roof can be properly joined to the undamaged portion of the roof.[216] If debris breaches the building envelope, then additional damage can be caused to the building interior and contents.

The acceptable level of damage from inert debris is the level below which there is no appreciable degradation in mission operations. It will be influenced by the time and cost of repairing the asset (which includes the resulting impact on range activities) and the potential consequences of a catastrophic event. For example, if the time and cost to repair a critical asset is very large, then the range commander/asset owner should strongly consider limiting the potential damages. For this reason, the choice for an acceptable level of percent damage is somewhat subjective and there is no single level appropriate for all cases. The ranges should select an acceptable level of damage that will minimize the impact to operations without being overly conservative.

6.7.2.2 Explosive Debris

The U.S. Army Corps of Engineers has established the damage categories shown in Table 6-19 for buildings subjected to a bomb blast.[217] For each category, it includes the expected percentage of total damage to the building, a description of the level of damage, and whether the building is repairable and reusable. Ranges can use these same categories for establishing the

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[215] Chrostowski, J. and A. See. “Structure and Window Database Maintenance.” Technical Report No. 05-551/3.1. ACTA, Inc., Torrance, CA, September 2005.
[216] Collins, J., S. Carbon, and J. Chrostowski. “Development of Quantitative Methods to Compute Maximum Probable Loss.” Technical Report No. 06-527/11.6-01. ACTA Inc.: Torrance, CA, December 2006.
[217] U.S. Army Corps of Engineers. *Estimating Damage to Structures from Terrorist Bombs Field Operations Guide*. Washington, D.C.: The Corps, July 14, 1999.

percent damage limit from blast loads caused by the impact of explosive debris. Note that the threshold level for possible repair of buildings damaged by explosive debris begins at 20% total building damage. This threshold is suggested to meet the policy objective for protection of critical assets.

Table 6-19. Building Damage Categories for Air-Blast Loads

Damage Category	Percent Total Building Damage	Damage Description	Repairable and Reusable
Severe	60 to 100	Frame collapse and massive destruction. Little left standing. Majority of personnel will suffer fatalities.	No
Heavy	40 to 60	Large deformation of structural members and major nonstructural component damage. Majority of personnel will suffer serious injuries with 10 to 40% suffering fatalities.	Very unlikely
Moderate	20 to 40	Some deformation of structural members and extensive nonstructural damage. Majority of personnel will suffer lacerations and blunt trauma from window glazing fragments or other nonstructural member debris. Zero to 10% of personnel suffer fatalities.	Possible
Minor	10 to 20	Little or no damage to major structural members and some damage to nonstructural. Personnel will suffer mostly minor and some serious lacerations and blunt trauma from window glazing fragments or nonstructural member debris.	Most probable
Minimal	0 to 10	Window damage extensive and light or local damage to nonstructural members. Personnel will suffer minor lacerations from window glazing fragments or other nonstructural member debris.	Yes

6.7.2.3 Cost of Repair

The consequences of inert and explosive debris impacts can be further quantified in terms of the expected cost of repairing critical assets. One approach for doing this is to determine the percentage of damage to the building components (roof, floors, and exterior walls), and then determine the cost of repairing them by using standard engineering cost estimating practices with rates based on the region of the country where the repair is being done. The cost estimate should account for both demolition and reconstruction costs.

6.7.3 Prediction of Debris Impact Effects

6.7.3.1 Inert Debris

Roof/floor penetration models have been developed for various categories of structures found at the ER and WR. For most roof types, there are three levels of protection: one for people on the top floor, one for people one floor lower, and one for everyone farther from the roof. An initial estimate of the damage caused by an inert fragment impacting a steel or concrete roof can be obtained by using curves similar to those shown in Figure 6-14 and Figure 6-15. The figures show the average hazard area of a cubic medium-density fragment (35 lb/ft^3) impacting a three-story steel frame or concrete building as a function of fragment weight. Higher and lower density fragments will have different effects.

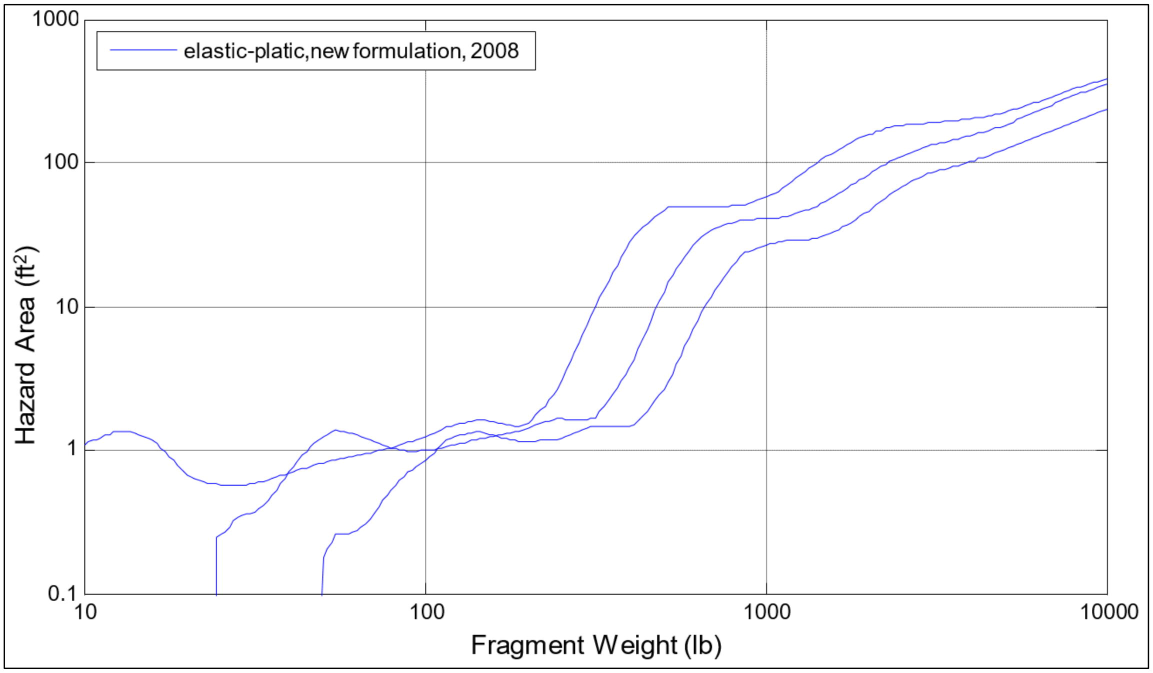

Figure 6-14. Three-Story Steel Frame Building, Hazard Area[218]

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[218] Figure 6-14 and Figure 6-15 include three curves. The top curve is for the roof of the structure, the middle curve is for the first floor below the roof, and the bottom curve is for the next floor below that.

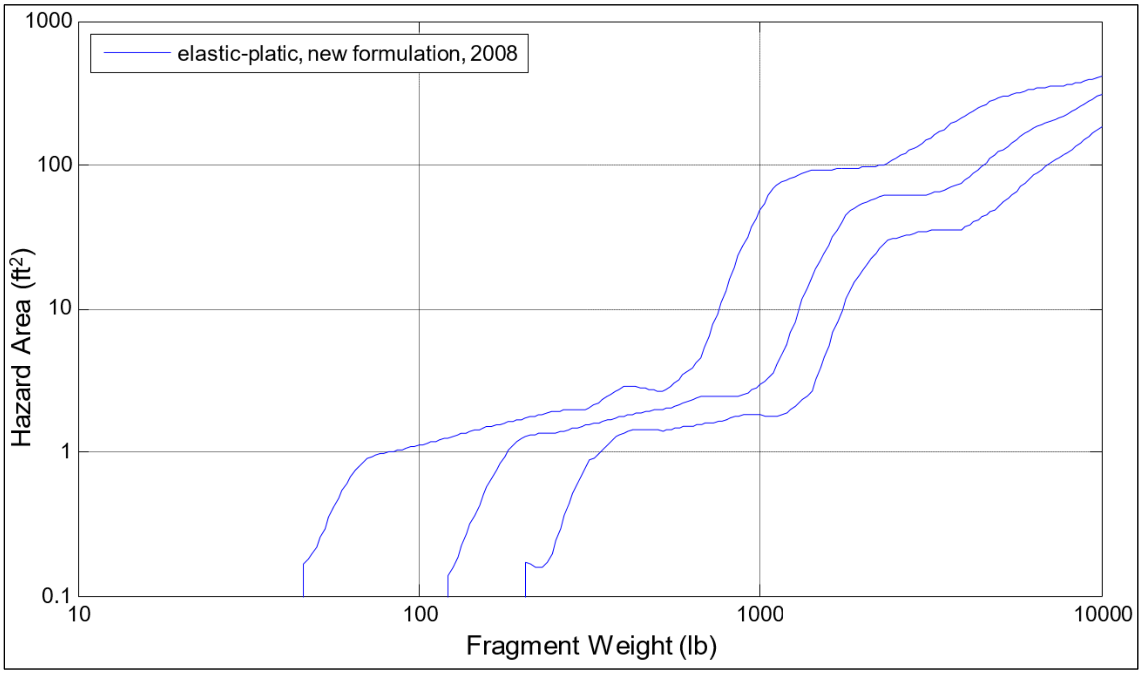

Figure 6-15. Three-Story Concrete Building, Hazard Area

6.7.3.2 Explosive Debris

Subsection 6.3.2 describes the characteristics of blast waves and their effects on a building. The damage caused by blast waves is primarily a function of the peak overpressure and applied impulse. Blast loads can cause the failure of building walls, windows, vertical support members, and roof.

A methodology has been developed to estimate the damage to buildings using OP-I curves. The curves are calculated by constructing a simple model of the building components that compares the dynamic response characteristics of the components (considering their mass, stiffness, and strength) to calculated blast load characteristics (both reflected peak shock pressure and impulse).[219] Component damage levels are determined based on this comparison, and then the overall building damage is computed as an average of the component damage levels.

Figure 6-16 through Figure 6-22 include OP-I curves from work that the ER and WR did using the FASTBLAST program[220], which is used to automate the development of the OP-I diagrams. Knowing the expected charge weight, it is possible to use these figures to predict the level of building damage based on the behavior of typical construction. Each figure is for a particular type and size of building. The damage should be interpreted as the percentage of the building square footage destroyed or unusable.

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[219] The Eastern and Western Ranges used the Facility Damage Assessment Program (FACEDAP) developed by the U.S. Army Corps of Engineers to calculate the blast damage to structural components.

[220] Chrostowski, J. et al. “Development of Structure and Vehicle Vulnerability Models FY 2004 Activities.” Technical Report No. #04-530/3.2. ACTA Inc., Torrance, CA, September 2004.

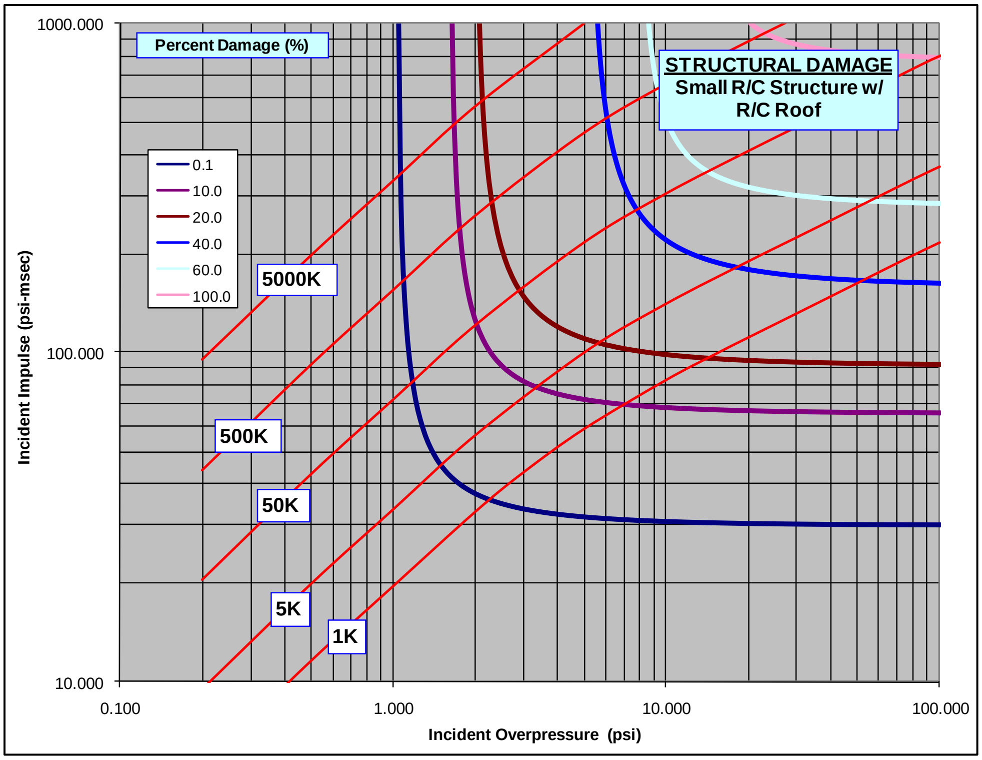

Figure 6-16. Small Reinforced Concrete – Structure #1

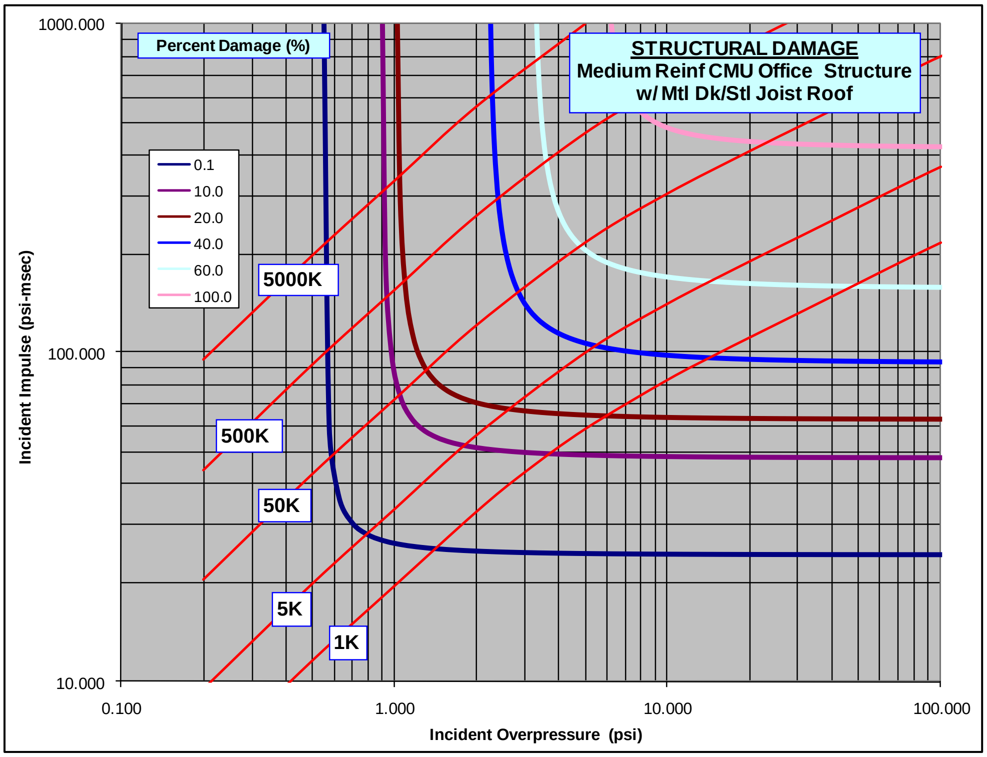

Figure 6-17. Medium Reinforced Masonry – Structure #8

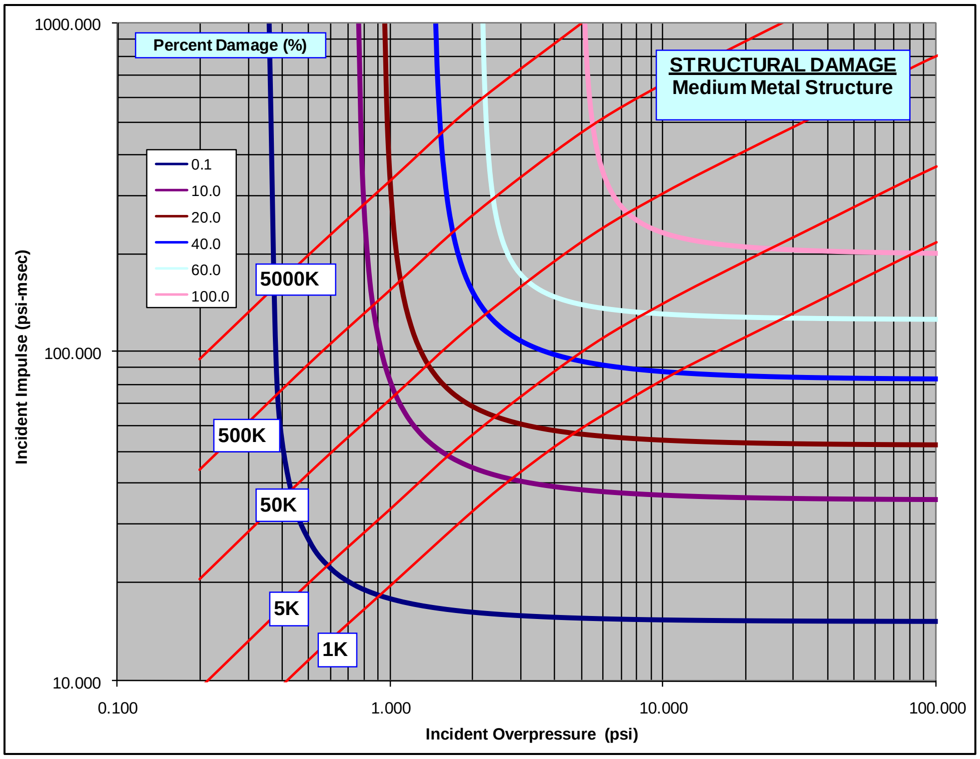

Figure 6-18. Medium Metal – Structure #10

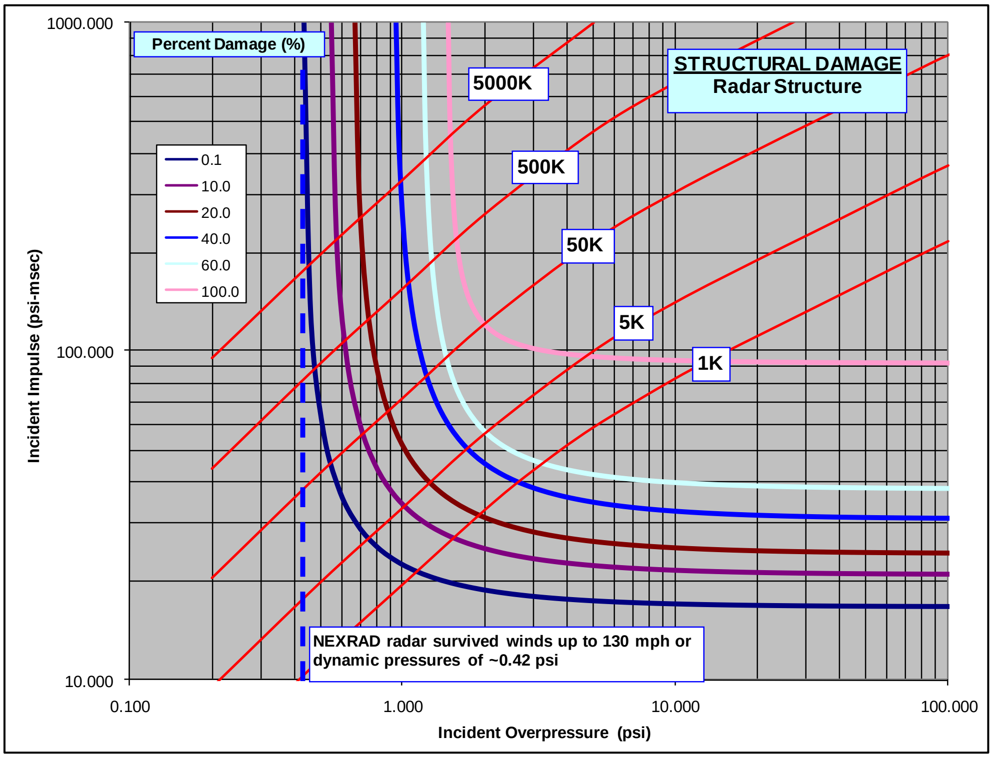

Figure 6-19. Ground-based Radar – Structure #17

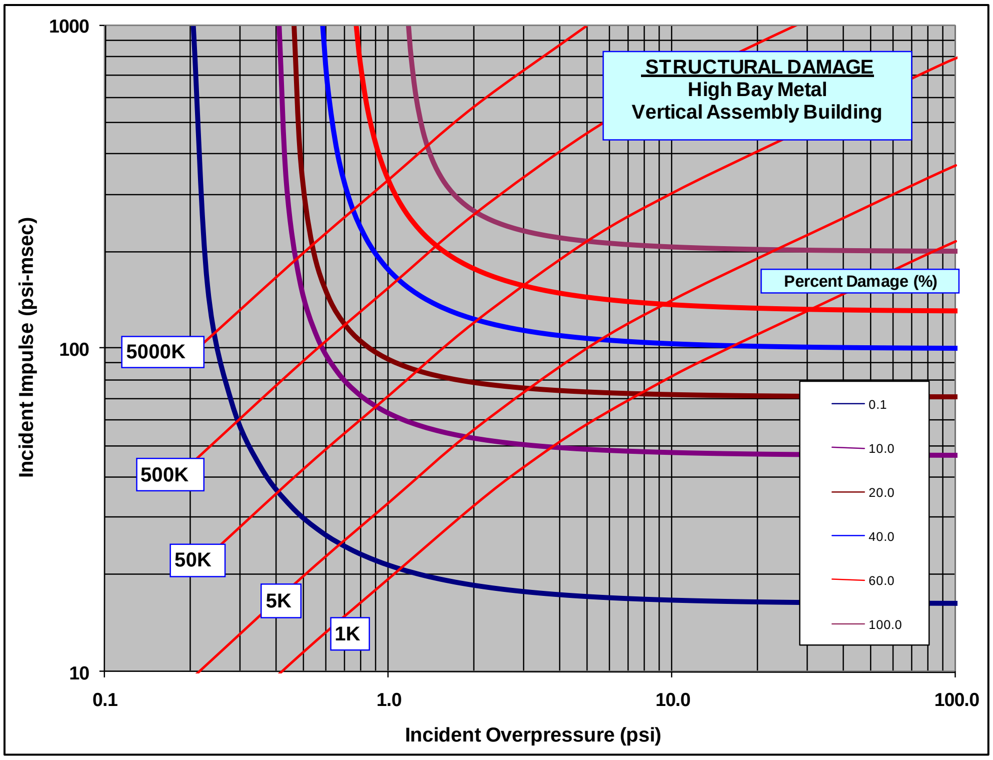

Figure 6-20. High Bay Metal Vertical Assembly Building – Structure #18

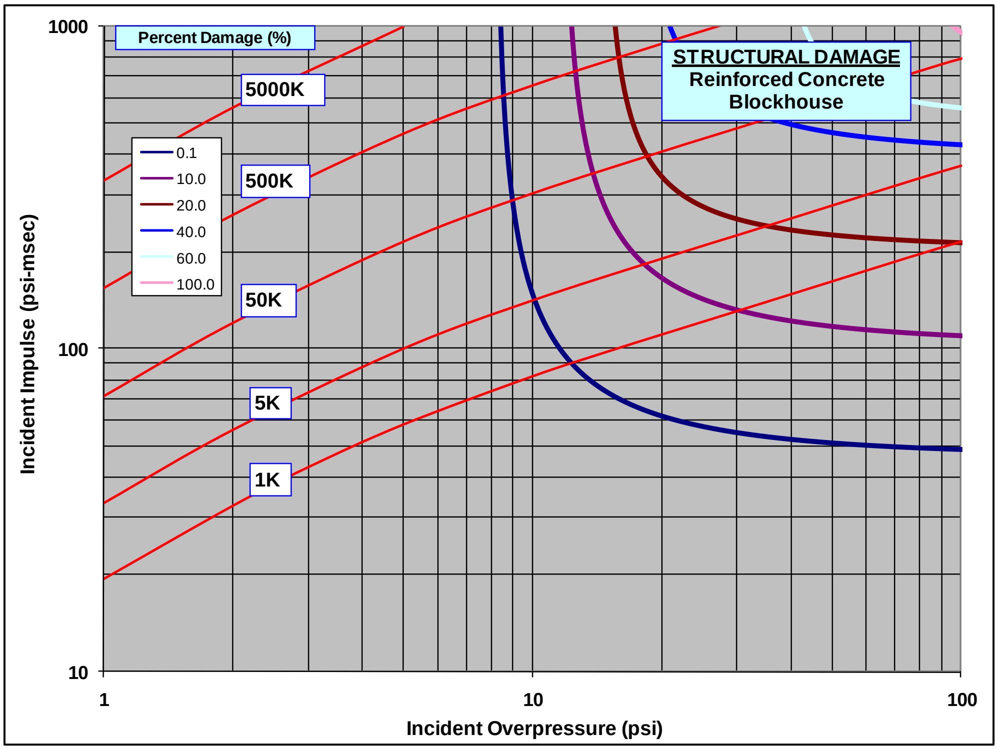

Figure 6-21. Blast-resistant Reinforced Concrete – Structure #19

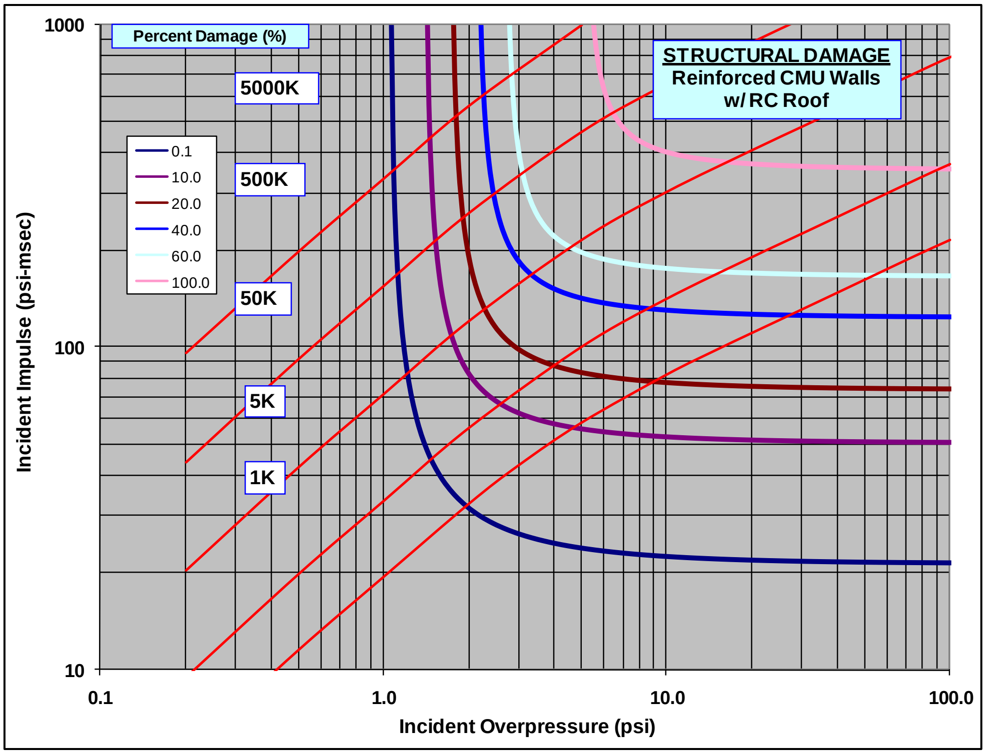

Figure 6-22. Medium Reinforced Masonry – Structure #20

6.7.3.3 Confidence In Models

Confidence in the models used to determine the hazard area for inert debris impacts is covered in Subsection 6.3.1.2.

Confidence in the models used to determine the damage from explosive loads acting on buildings was established in a validation effort documented in Lambert et al. It consisted of comparing analytically predicted results with test data and higher-fidelity blast models. Conclusions from this effort, along with observations from other reviews of the underlying models used to develop the OP-I diagrams, included the following.

a. The FACEDAP component OP-I diagrams are known to be conservative, primarily because the damage criteria (center span deflection to component length, or joint rotation) are conservative.

b. The OP-I diagrams with hyperbolic contours provide conservative results for smaller charge weights, especially at higher damage levels.

c. The FASTBLAST program overestimates damage at lower blast levels and provides more reasonable damage estimates at higher blast levels.

6.8 Infrastructure

Table 4-19 displays examples of the enormous universe of infrastructure exposures. Infrastructure requiring protection can range from single electrical insulator elements and segments of transmission lines (each having hazard areas of a few square inches, or square inches per unit length) to wind turbines exceeding the dimensions of current aircraft. Moreover, each unit component of infrastructure contributes to the functionality of the larger system of which it is a subsystem. The aggregate of unit components generally has a sizeable total area, mandating the examination of unit component criticality for missions with even low-impact probabilities of planned debris or probabilities of vehicle failure and break up.

It follows that attempting to define hazard thresholds formulated to cover most infrastructure is likely to result in over- and under-conservatism. This statement can be seen to apply to equipment components belonging to a similar type that nonetheless span vastly different ratings capacities (e.g., a 1-kW wind turbine versus a 5-MW wind turbine), as well as the large variability in component manufacturing, installation, and so forth. To some extent, regulatory codes exist that dictate commonalities that constrain variability among products from disparate manufacturers. But the situation is much less well-defined than as, for example, codification of the construction of building structures.

This being acknowledged, there are several factors that have been identified that can serve to simplify the development of useful hazard thresholds. First, the classification of infrastructure into three general categories provides a general classification between inherently robust infrastructure and more fragile types of equipment. Electrical transformers, for example, that are a (heavy) Type I unit component are unlikely to be affected by displacement from over-pressure, and debris impacts are likely to induce only secondary consequences, such as loss of coolant. Action and effort can be placed on Tier 1 functional consequence assessment, and Tier 2 vulnerability assessment can proceed with the knowledge that some uncertainty in hazard thresholds can be tolerated, since the severity of damage at the unit component level is less important than the system-level functional assessment.

Generally speaking, immediate damage from debris to functionality can be assessed by focusing on debris perforation. This focus allows hazard thresholds to focus on external damage. It is to be expected that greater commonality in the choice and selection of equipment enclosures, nacelles, cases, and coverings exists in this realm than for elements of internal construction.

Physical scaling relationships are another simplifying factor to address the great range of scale variation that exists with infrastructure. This is done for electrical transmission lines and for composite-based enclosures for wind turbines.

6.8.1 Infrastructure Types

An attempt to enumerate all type of infrastructure that require protection is outside the scope of the current supplement. Table 4-19 provides in lieu of such an enumeration a classification into three generic types. At the most basic level for damage assessment and risk modeling, one can think of these three categories as a classification of infrastructure into unit components that can be thought of as point receptors, line receptors, and area receptors. Damage is thus assessed at the unit component level using vulnerability models appropriate for each type of receptor.

6.8.2 Damage Assessment Criteria

The principal assessment criterion for inert debris at this stage is damage severity based on external failures - namely perforation of the enclosure or (in the case of Type III infrastructure) perforation into or through a cross-section of a unit-length of an item.

6.8.3 Prediction of Debris Impact Effects

Infrastructure as a protection class is generally considered to be unoccupied in this standard. Therefore, prediction of damage to people inside infrastructure is not considered, as is done with protection of buildings, ships, and aircraft. As mentioned earlier, assessment based on damage to internal subsystems at the unit component level for infrastructure is not considered at this time. Debris impact effects therefore do not take into account such damage metrics as residual velocity.

Damage severity for infrastructure is currently defined beginning at the *unit component* level for all types of infrastructure according to the definitions in Table 4-21.[221] Typical functions of the unit components and contribution to system level functionality by class are listed in Table 4-19.

There are two operational damage severity categories of interest in Table 4-21: DSL 2 and DSL 5. Protection to infrastructure is achieved by limiting the probability of DSL 2 to unit components and the cumulative probability to a critical number of unit components being damaged at this level or greater.[222] In addition, higher-fidelity analyses will consider a systematic assessment of the severity of the maximum system-level consequences that could plausibly result due to unit component damage along with cascading damage to secondary infrastructure or possibly derivative exposure to people.

In a sense, buildings, ships, and aircraft are simply specific example of infrastructure; risk assessment processes for these components can be found in earlier sections of this chapter. Hence, the existing hazard thresholds based on kinetic energy for debris impacts on metallic skins (aircraft) and for construction materials used for buildings may be used for the infrastructure in Table 4-19, if found to be applicable.

Recommendations for prediction of damage impacts to renewable infrastructure do not currently exist for a wide class of infrastructure, namely for those manufactured with:

a. FRP composite elements (such enclosures, aerodynamic surfaces, structural elements, and electrical insulators);
b. electrical transmission lines; and
c. non-composite electrical insulators (porcelain or glass).

The FRP composites represent a very broad class of material construction. Figure 6-23 provides recommendations for perforation of inert debris through FRP surfaces less than two inches in thickness. The uncertainty associated with validation data that seems to be evident in Figure 6-23 is more a reflection of the underlying spread in impact toughness that arises from the many different types of construction. The recommended equation in the figure represents a lower bound to the data currently available.

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[221] A unit component is the minimal set or collection of equipment that is necessary to fulfill the basic functions required of the infrastructure to be protected. As an example, for a wind turbine farm, the unit component would be a single wind turbine. A unit component can be considered analogous to a single person (individual).
[222] These two categories may be qualitatively interpreted as analogous to human causality and fatality.

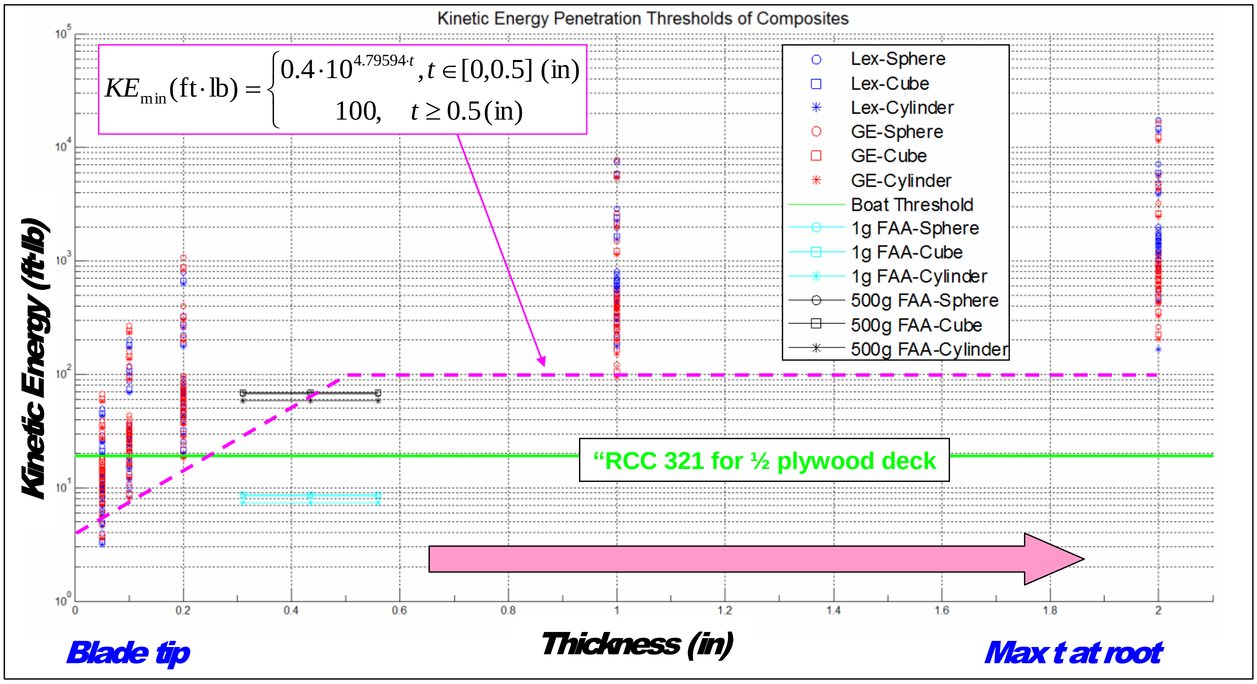

Figure 6-23. Penetration Thresholds for Materials Used in Wind Turbine Blade Construction

Notes:
Materials illustrated are common thermoplastic and FRP
Kinetic energy penetration threshold = dashed magenta line
Current penetration threshold for 0.5 inch plywood (19 ft-lb) = green line

Transmission lines, by virtue of their length and their "series" nature, represent a significant infrastructure hazard area and also a critical functional link. While in many cases the system-level functionality may be mitigated by redundancies, it should be stressed that situations can and do occur when mitigation may not be operative.

The current vulnerability thresholds for transmission lines assume aluminum conductor steel reinforced (ACSR) conductors, which are the most common. These are stranded steel-core aluminum-sheathed in construction.

For a conductor, DSL 2 is defined as damage that could have the outcome of reducing the effective cross-section and mechanical strength through damage to the aluminum strands. No damage to the steel core is assumed to occur. Because the core is designed to provide most of the mechanical support for the conductor, the consequence is to reduce the power capacity of the line. It likely will otherwise remain functional, although suitable de-rating will be required to avoid heating. For very high voltage lines corona effects are noted as consequences in some of the literature. Damage to the conductors that produces sharp edges leads to large local electrical fields and significant dielectric losses to the environment, which leads to local heating and possible runaway thermal phenomena that could melt the line.

The definition for DSL 5 is "through" damage, wherein the impactor critically impairs or severs the steel core. Damage at this level will lead to complete loss of functionality of the line. The possibility for power outages to consumers is clearly present, even in an "n−1" situation. Were the grid to be temporarily operating in an "n" condition, the certainty of outages would be unity. Downed lines also have the potential to cause fires if not detected by sensors that would otherwise trip electrical breakers. Derivative exposure is therefore a distinctly possible outcome for DSL 5.

Many dozens of ACSR conductor types exist, spanning several ranges of power/voltage capacity and mechanical strengths; however, there is industry standardization. Once the type of conductor is known, industry tables can be used to determine the conductor diameter for vulnerability assessment.

Figure 6-24 is used to assess the type of consequence for debris having a certain impacting kinetic energy.

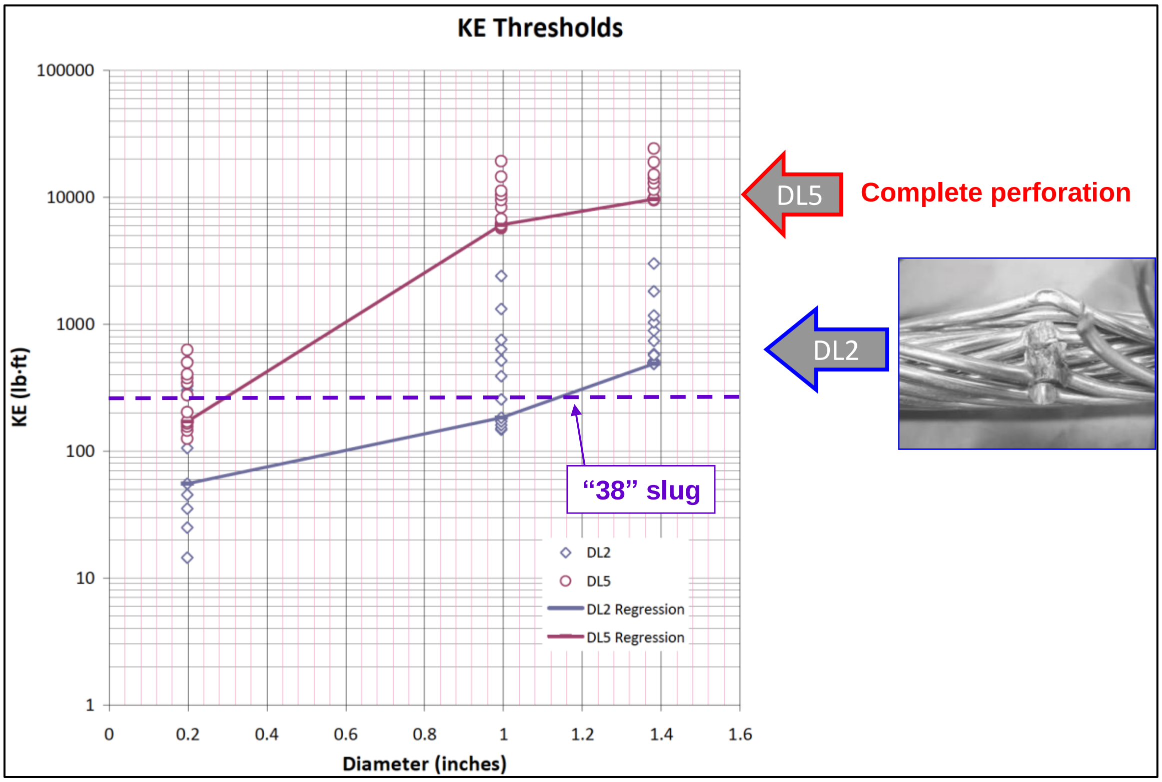

Figure 6-24. ACSR Penetration Thresholds for DSL 2 and 5

Notes:
The figure illustrates thresholds for ACSR transmission conductors from 0.2 in to 1.4 in diameter

Insulators perform critical mechanical and electric functions. This is true for both transmission lines and in other usages, such in electrical substations, where they are used in great numbers. The primary threat from range-related threats is assumed to be debris. Functional unit component failures for insulator are categorized by fail/no-fail criteria. That is, no distinction between DSL 2 and DSL 5 is made at this time.

National standards, such as CSA C411-1 and ANSI C29-2, have been found that specify impact strengths, with typical values shown in the respective columns of Table 6-20. Manufacturer recommendations often incorporate safety factors. A conservative impact damage threshold of 50 ft-lb is currently recommended for ceramic insulators.

Table 6-20. Kinetic Energy Impact Thresholds for Ceramic Insulators

Units	CSA C411-1 Requirements	ANSI C29-2 Requirements	Sediver Recommendation
Joules (N-m)	5-10	5-10	45
ft-lb	3.7-7.4	3.7-7.4	33.2

Composite insulators are not currently addressed.

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CHAPTER 7

Approaches and Considerations for Debris Risk Assessment Models

This chapter documents the important considerations and factors that should be addressed in developing good debris risk assessment models. To do this the overall process of computing debris risks has been broken down into its primary modeling areas. For each of these modeling areas there is a section that describes the function and purpose of the model followed by a discussion of the modeling in terms of the general approach and the considerations and factors to be addressed. For many of the sections, there is also a discussion of the data that may be available for input to the model. Where appropriate, alternative modeling approaches and considerations are presented based on the type of data used.

The intent of this chapter is to provide guidelines for developing good models rather than prescribing specific models or methods. General approaches are discussed to provide guidance to the modeler and to record lessons learned over many years of developing debris risk models at the major test ranges.

The models discussed here are those needed to compute the debris impact risks for a given debris-generating event such as a vehicle failure scenario or a weapons system debris-generating event, such as a target intercept. A vehicle failure scenario is defined to be a specific mode of failure occurring at a specific time of flight and resulting in a specific type of vehicle breakup; this includes the case where the vehicle remains intact to impact. Failure scenarios may include very unlikely events that need to be addressed because of their potential catastrophic outcome.

Many of the modeling considerations and factors presented in this chapter may not need to be addressed. This will depend on the application of the model, the level of fidelity required, the availability of data, and the time constraints for performing an analysis. For many of the models, alternative modeling approaches are presented, ranging from relatively simplistic to relatively complex, with the complex models generally requiring increased development time, more detailed input data, and increased computation time. The analyst will need to determine the complexity of the models required for the application. In some cases, simpler models can, using the appropriate assumptions and input data, lead to conservative (high) estimates of the debris risks and may be sufficient if the resulting levels of risk are acceptable. Also, a range that can achieve a low level of risk by containing debris within predefined boundaries may be able to employ simple worst-case models to demonstrate that containment is achieved. Worst-case models must address maximum deviations from nominal conditions, malfunctions leading to worst-case lateral turns, wind conditions that can push hazardous debris out of the planned containment area, etc. A range that has missions for which debris containment cannot be achieved, and for which the levels of risk can exceed acceptable limits, may need to use more complex models to assure that adequate safety is achieved.

As an aid to locate material relevant to the area of debris risk assessment modeling of concern, Table 7-1 presents a guide to the content of each of the chapter sections. The table also serves as an outline of the steps in the modeling process.

Table 7-1. Guide to Contents of Chapter 7

Para.	Modeling Area	Notes
7.1	Vehicle Breakup Debris Models	Characterization (weights, sizes, ballistic coefficients, etc.) of the fragments expected to result from vehicle breakup or from a weapons test, such as an intercept. Debris includes an intact vehicle or component of the vehicle if no breakup is expected. Breakup can result from abnormal aerodynamic and inertial loads, activation of an FTS, weapon system action (intercept, etc.), or reentry heating.
7.2	Debris Dispersion Models	The term “debris dispersions” is used to refer to the variation in the position of a fragment as it falls and at impact (or at a specified altitude). The sources of debris dispersion include variations in the initial breakup state vector due to deviations of the vehicle from the nominal (intended) trajectory prior to breakup, and the dynamic effects on the fragments during free fall. Includes a discussion of important considerations for an impact predictor.
7.2.1	Vehicle Normal Trajectory Uncertainty due to Guidance and Performance Factors	Dispersions due to breakup state vector variations resulting from normal variations in the vehicle guidance system and motor performance. These variations are within expected limits and are influenced by various factors such as launch day atmospheric conditions and variations in the thrust achieved by operating motors.
7.2.2	Vehicle Malfunction Turns	Dispersions due to breakup state vector variations resulting from deviations of a vehicle from its intended trajectory following a hardware or software failure (malfunction), including a failure of the vehicle guidance system.
7.2.3	Debris Imparted Velocities	Dispersions due to velocities imparted to vehicle fragments. These imparted velocities can be produced by the explosive charges used in FTSs, pressure forces created by an explosion, rupture of a pressurized vessel, rotational motion of the vehicle, and/or weapon system events such as a hit-to-kill intercept.
7.2.4	Fragment Aerodynamic Drag Uncertainty	Dispersions due to uncertainty in the aerodynamic drag force acting on a fragment.
7.2.5	Fragment Aerodynamic Lift Effects	Dispersions due to uncertainty in the aerodynamic lift force acting on a fragment.
7.2.6	Wind Drift and Wind Uncertainty	Dispersions due to wind acting on a fragment. Includes both the shift in the position of a fragment during free fall due to the expected wind, and uncertainty due to the uncertainty in the wind.
7.2.7	Free Flight of Inadvertently Separated Thrusting Motors	Dispersions due to free flight of inadvertently separated thrusting motors. This affects the dispersions of the debris resulting from the subsequent breakup of a motor (or of the intact motor if no breakup occurs).

7.3	Debris Distribution Models	Characterization of the overall uncertainty distribution for fragment position during free fall and at surface impact, accounting for all sources of position uncertainty. Uses the output of the debris dispersion models discussed in Section 7.2. The debris distribution models are used to compute probabilities of fragment impact.
7.3.3	Impact Distribution Functions for Multiple Dispersion Sources	Generation of two-dimensional impact uncertainty distribution functions to represent multiple sources of debris dispersion.
7.3.4	Scatter Plots for Multiple Dispersion Sources	Generation of two-dimensional scatter plots to represent impact uncertainty due to multiple sources of debris dispersion.
7.3.5	Considerations for Three-Dimensional Models	Generation of three-dimensional debris position uncertainty distributions. May be required for computation of impact probabilities for an aircraft or a spacecraft following a prescribed flight path.
7.4	Impact Probability Models	Using the distribution models developed in Section 7.3 to compute probabilities of fragment impact onto populated locations and other assets of concern. The focus is on the computation of impact probabilities using two-dimensional characterizations of debris impact distributions. (Computation of impact probabilities using three-dimensional distributions is addressed in Subsection 7.3.5).
7.5	Modeling for Explosive Fragments	Addresses modeling issues specific to the computation of risks for explosive fragments, where hazards result not only from the fragment directly impacting an asset but also from the products of the explosion (explosive loads, ejected secondary debris).
7.5.1	Explosive Yield Models	Prediction of the explosive yield of the impact explosion of a fragment carrying volatile material (liquid propellants, solid propellant, etc.). The yield is expressed in terms of the weight of TNT that would produce an essentially equivalent explosion.
7.5.2	Risk Computation for Explosive Fragments	Computation of the risks resulting from blast loads (defined by peak overpressure and impulse) and secondary debris generated by an explosion. Includes computation of casualties for people directly exposed to blast loads and indirectly hazarded due to structural damage or collapse and window breakage.
7.6	Vulnerability and Casualty Models	Models to predict the level of injury or damage to humans, structures, or vehicles due to impact by a fragment or due to blast loads. These models are used to relate probability of impact to E_C or E_F.
7.6.1	Human Vulnerability Models	Prediction of the probability of human casualty or fatality.

7.6.1.1	Human Vulnerability to Inert Debris Impact	Probability of casualty/fatality due to direct impact by a fragment or by secondary debris.
7.6.1.2	Human Vulnerability to Blast Loads	Probability of casualty/fatality due to exposure to blast loads (overpressure and impulse).
7.6.2	Model for the Casualty Area for Inert Debris Impact in the Open	Area within which an unsheltered person becomes a casualty/fatality due to fragment impact and secondary effects.
7.6.3	Structural Vulnerability Models	Assessment of damage to structures and prediction of casualties/fatalities for occupants.
7.6.3.1	Vulnerability Modeling for Inert Debris Impact on a Structure	Prediction of casualties/fatalities within a structure due to inert debris penetration of the structure.
7.6.3.2	Vulnerability Modeling for Explosive Debris Blast Loads on Structures	Prediction of casualties/fatalities within a structure due to blast loads acting on the structure.
7.6.4	Ship/Boat Vulnerability Models	Vulnerability of ships/boats to inert debris and to explosive debris, and prediction of resulting casualties/fatalities.
7.6.5	Aircraft Vulnerability Models	Vulnerability of aircraft to inert debris impact.
7.7	Models for Casualty Area and Fragment Probability of Casualty	Computation of casualty area, or fragment probability of casualty, based on the vulnerability models presented in Section 7.6. These quantities are used in the prediction of casualty/fatality expectation.
7.8	Risk (Casualty/ Fatality) Expectation Models	Combining the output of the preceding models to generate risk estimates (casualty/fatality expectations, individual probability of casualty/fatality). Includes discussion on development of a population library.
Note: Although the resulting debris data is an input to the debris risk models, it is of such fundamental importance, involving challenging modeling considerations, that it has been given its own section. Other input data items will be discussed in more general terms in the specific sections where the data are used in the model(s).		

7.1 Vehicle Breakup Debris Models

7.1.1 Model Description

If a missile or space vehicle malfunctions, it may break up spontaneously or it may be destroyed by the RSO, resulting in hundreds or thousands of primary components and pieces. In some cases, malfunction or failure may simply mean that the vehicle has strayed outside normal limits. It is also possible that a malfunctioning vehicle will remain intact to impact. For warheads and kinetic-kill vehicles, fragmentation results from a planned event. Precisely how (or even whether) breakup occurs is subject to considerable uncertainty. Although many pieces are inert, breakup may also produce intact (or nearly so) components, propellant tanks with or without propellant, solid-propellant chunks, and high-pressure vessels that may explode or rupture violently upon impact. The character of vehicle breakup is likely to change throughout flight as propellants are consumed and aerodynamic loads change. Breakup characteristics may also be failure-mode dependent. A debris model appropriate for risk computations defines the characterizations of the fragments expected to result from vehicle breakup, including the case where no breakup occurs.

Regardless of whether or how breakup occurs, there are two fragment models of interest:

- Model 1. The breakup model as it exists immediately after failure.
- Model 2. The debris model as it exists upon impact with objects on the ground (open areas, people, structures) and with objects above the ground (aircraft, satellites).

It may require considerable effort to map fragment Model 1 into Model 2. Things to be considered during this mapping include progressive breakup (not all fragmentation occurs at the time of failure); propellant utilization or consumption; dynamics associated with burning propellant; whether or not the burning continues within a partially intact motor; aero-thermal effects on inert materials including ablation; ignition and combustion of energetic materials that survive breakup; and fragment demise (disappearance from the catalog).

The goal of the debris-modeling process is to define the numbers of pieces, weights, sizes, aerodynamic characteristics, and breakup-imparted velocities for the debris produced under all breakup conditions that may pose a risk. Included are characteristics of the debris that influence the behavior of the debris between failure and impact (or other encounter). Results obtained after accounting for all secondary effects include the revised debris catalog at encounter and the corresponding fragment weights, sizes, and residual explosive potential.

In some cases it may be possible to format the detailed debris information for direct input to risk-analysis software; however, the debris lists for some vehicles are extensive, and most risk-analysis software has limitations in the number of debris categories allowed. Additionally, much of the debris may differ in only minor details, thus leading to inefficiency in computations with little gain in accuracy of results. Consequently, for the sake of efficiency in computations and to accommodate limitations in most risk-analysis software, the debris lists are condensed into a smaller number of classes, with all fragments in any one class having similar characteristics. The goal is to develop a set of debris classes so that the hazards associated with the “mean” piece in a class adequately represent the hazards of each piece in the class. When done properly, the resulting risks are not affected significantly.

7.1.2 Data Sources

When developing debris models for risk estimations, the analyst usually begins with information supplied by the vehicle manufacturer (as listed below). This data may not always be available, so in some cases the analyst will need to develop a debris model using assumptions and data from similar vehicles/components.

a. Description of vehicle and payload: Overview of vehicle with scaled diagram; general arrangement and dimensions of components including alternate and optional components; description of materials used in construction; inert weights and propellant types and weights for every stage and component; nature and purpose of a typical flight or mission of interest.

b. <u>Engine and/or motor data</u>: Including case material (outer case, lining, insulation, thickness, density); descriptions of nozzles and steering mechanisms; descriptions of propellant types and ingredients; propellant density; propellant weights versus time.

   (1) Solid Motor: Motor core radius (to outer edge of propellant); grain design; internal pressure; and web thickness versus time.

   (2) Liquid Engine: Pumping and pressurization systems and associated stored energy, materials, and pressurization.

c. <u>Description of FTS (command, automatic, separation)</u>: Type of system (terminates thrust, destroys vehicle, induces tumble, etc.); descriptions of all components and activation mechanisms; exact locations of all charges (beginning point, length, gap, ending point); descriptions of circumstances for any delays in activation of charges; discussion of whether and under what circumstances destruct might ignite a non-thrusting motor.

d. <u>Trajectory data for a typical mission</u>: Nominal and dispersed trajectories; comprehensive malfunction trajectories or malfunction turn data; event times (ignitions, steering programs, burnouts, jettisons). Trajectory data are used to obtain vehicle velocity and altitude from which to calculate aerodynamic and inertial loads for use in estimating vehicle breakup. Event times are used to indicate vehicle configuration at each breakup time.

e. <u>Descriptions of planned debris</u>: Jettisoned components; aerodynamic and inertial breakup of jettisoned components; nozzle closure covers, etc.

f. <u>Breakup debris lists</u>: The manufacturer's expected debris resulting from destruct action and subsequent aerodynamic loads at various event times including numbers of fragments, weights and dimensions of pieces, construction materials, drag characteristics (reference area, ballistic coefficient, or drag coefficient versus Mach number), and breakup-imparted velocities. In some cases, manufacturers also provide expected debris from breakup resulting from aerodynamic and inertial loads on a malfunctioning vehicle. When such lists are not provided and these types of breakups are feasible, then it is left to the risk analyst to develop them.

g. <u>Kinetic intercept debris lists</u>: Estimate of intercept debris resulting from a hit-to-kill interaction between an interceptor and target vehicle, or more generally from any introduction of controlled external energy leading to vehicle failure and breakup (e.g., high-intensity laser). Debris estimates should consider variations in the intercept event such as a glancing blow that may result in relatively few, mostly large fragments versus a direct head-on impact that generates very large numbers of relatively small fragments. Kinetic intercept debris lists are typically generated by the risk analyst using standardized programs and input data files based on the materials and configuration of the vehicle.

7.1.3 <u>Modeling Considerations</u>

Considerations for developing a debris model are discussed below.

a. In developing a debris model, the analyst may consider the various failure response modes, breakup circumstances, outcomes, and debris classes to be accounted for in the risk computations.

b. For many launch vehicles, the debris characteristics will depend on whether breakup occurs as a result of a destruct action or as a result of failure (explosion, abnormal aerodynamic and inertial loads, etc.).

c. Supplied debris lists should be checked for accuracy and reasonableness before they are used. Some debris lists only model fragmentation based on a uniform distribution of size and quantity of fragments. One easy check is to compare the total weight of all fragments with the known dry weight of the vehicle. Another check is to compare the new information with corresponding information for the same vehicle or similar vehicles. Investigations into early launch accidents (where debris was recoverable) have provided some insight into how vehicles break up. If a manufacturer's list differs substantially from expectations, the risk analyst may either modify the list or justify the supplied list based on destruct system design and component construction and materials. An example of poor modeling that may be modified is the breakup of solid rocket motor propellant into chunks of equal weight. In particular, many manufacturers' debris lists have been prepared only for use in estimating risks to people and structures on the ground. They under-predict the numbers of low-mass debris that may need to be considered when estimating risks to aircraft and spacecraft.

d. Supplied values of breakup-imparted velocities can be checked for reasonableness using empirical equations for pressure ruptures and explosions. More-sophisticated models can be used to estimate maximum imparted speeds of propellant and case fragments from a destructed thrusting solid rocket motor. Breakup-imparted speeds are highly uncertain. Often, an estimate of the maximum imparted speed is assumed to represent a three-sigma value of a one-sided normal probability distribution or of a Maxwellian distribution. Imparted velocity direction is also highly uncertain and is often modeled as equally probable in all directions, though other distributions may be required for special circumstances.

e. The possibility of failure of the destruct system should be considered. System failure may be due to loss of command communications, loss of battery power, failures or ruptures of vehicle systems resulting in loss of control or power connectivity, or inaction or delayed action of the RSO. The latter may occur because of mission rules established before launch. If the destruct system fails, there is a possibility of an intact impact accompanied by an explosive yield or the possibility of breakup from aerodynamic or inertial loads. Associated debris models for these scenarios might be required.

f. Some supplied debris lists provide drag reference areas instead of actual areas for some fragments. Actual fragment areas are needed for roof penetration and effective casualty area computations.

g. Every accident investigation provides new insight into how launch vehicles break up, and leads to changes in debris modeling. Future investigations are likely to continue these changes. The nature and extent of breakup seems to strongly depend on the nature of the failure and the interaction of the failure with the destruct system. Even if experiments could be conducted to repeatedly break up the same vehicle design with command destruct, the resulting fragments would likely vary significantly among the trials. Even the manufacturers are unsure how their vehicles will break up by command destruct. For example, one manufacturer with years of experience recently lowered the second-stage fragment count by an order of magnitude. As another example, two manufacturers of similarly sized and constructed solid rocket motors provided lists of miscellaneous hardware debris (i.e., debris that is not case or propellant). One list contained 1106 fragments, while the other contained 2 fragments. Part of the problem may be due to application. In earlier years, supplied debris lists were used primarily to determine hazard areas for containment. In more recent years, the debris lists have also been used for risk estimation. A realistic debris model is more important for risk estimation than it is for containment prediction.

h. Varying lengths of time may elapse between breakup and encounter, depending upon when in-flight failure occurs. Debris characteristics may change during these time intervals, especially for propellant-bearing components and solid propellant chunks.

i. For solid propellant systems, the risk assessment must include consideration of a large number of propellant dynamic, thermodynamic, and chemical factors. These factors include, but may not be limited to the following.

    (1) If the motor is burning at the time of fragmentation, the mechanisms that might quench the motor or the propellant chunks must be considered. Conversely, if the motor is not burning at the time of fragmentation, the mechanisms for potential ignition of the propellant or the propellant chunks must be considered.

    (2) Ignition mechanisms may include heating associated with the breakup event, internal pressure of the motor at breakup, external dynamic pressure at time of breakup, and both symmetric and asymmetric heating of the fragments by aero-thermal forces during propagation after breakup.

    (3) The dynamics are different for propellant adhering to case fragments than for free-falling propellant chunks. Fragment tumble can also affect ignition and combustion mechanisms.

    (4) The kinetics of propellant burning are known to be dramatically different at the low ambient pressures associated with free-falling propellant chunks as compared to those for the operational pressures of the motor. Thus, propellant fragments and propellant in damaged motors will burn at different rates than in an intact operational motor, and the burning of fragments may be asymmetric due to fragment dynamics. While vehicle vendors can provide the burn rates for motor operational pressures, burn rates for low pressures are usually not available and will need to be estimated based on limited experimental data for the solid propellant or similar propellants and may require extrapolation to the pressures of concern. The influence of the shock wave around a supersonic propellant fragment and the buildup of product gases behind the fragment on the burn rate are other considerations.

    (5) The dynamics of thrust associated with asymmetric fragment combustion may need to be considered.

    (6) Solid propellant chunks can completely burn up (demise) during free fall, particularly if they are burning immediately following motor breakup.

j. For liquid-propellant components, it may be necessary for the analyst to decide whether the nature of breakup allows the propellants to remain on-board.

   (1) If so, and the component was thrusting, the possibility of continued propellant consumption (and thrusting) may need to be considered. Additionally, it may be necessary for the analyst to decide whether the heat of reentry causes remaining propellants to boil off or leak from damaged tanks.

   (2) If not, the breakup will typically disperse the liquid as an aerosol that has dynamics including interaction with atmospheric oxygen (or other chemicals) and possible ignition of fuel components, heating and absorption of pressurized liquids or cryogenic fuels in the atmosphere, and the possible settling of both inert and toxic fuel components over a broad area following dispersion. Aerosolized and vaporized fuel components, particularly toxic components, must be considered separately from treatment of inert, non-explosive solid debris.

k. The demise of inert fragments can occur during free fall due to ablation or melting, especially for inert debris reentering from space.

l. For missions involving planned intercepts of vehicles, the development of intercept debris models (debris from the interceptor and from the target) as well as the dispersions of the debris require a special modeling approach. Dynamic loading during an intercept is typically modeled by a statistical tool that has been validated through comparison with data from laboratory tests. Because of the high energy associated with these events, consideration needs to be given to the material content and configuration of the impacting bodies, the closing velocity, the size and mass distributions of the fragments (having extensive low mass/small area tails), and the post-intercept velocities including the perturbation of the average velocity of the fragments resulting from each body due to the net momentum transfer between the bodies. Energy loss can result in melting, frictional ablation, vaporization, and ionization of impacted metals, as well as production of an optical flash that represents a significant portion of the relative energy. Typically, three classes of intercept debris generation models can be applied:

   (1) purely statistical models (of which impact is the best known) that apply constrained power-law or exponential distribution models to fragment size and mass;

   (2) empirical models (of which kinetic impact debris distribution is the best known) that use constraining test data to determine limiting fragments and constrain the parameters used in statistical models to generate the smaller fragments;

   (3) high-fidelity physics-based models, typically hydrocodes, that are high-fidelity finite element models for shock propagation and penetration, but are constrained from accurate depiction of the smaller fragments due to the limiting size and time resolution of the element models, and that are often prohibitively expensive to run.

7.1.4 Model Uncertainty

7.1.4.1 FTS, Aerodynamic, and Inertial Breakup

Every accident investigation provides new insight into how launch vehicles break up, which leads to improvements in debris modeling. Future investigations are likely to continue these changes. The nature and extent of breakup seems to depend strongly on failure mode and the interaction of the failure mode with the destruct system operation. If the risk analyst could foresee all plausible breakup scenarios and assign an accurate probability to each, and if accurate debris lists could be determined for each scenario, the resulting probabilistic debris model would lead to improved accuracy of the estimations of risk; however, none of these are possible. The analyst cannot be sure that breakup scenarios have been included that should not have been, or that important scenarios are missing. The ability to prepare a complete debris list is also compromised by the inability to track all but the largest of the debris fragments, to recover more than a fraction of the largest fragments, and to reconstruct fragment dynamics from the positions of recovered fragments. Even if an accurate model for all scenarios existed, the associated probabilities of occurrence would be based on engineering judgment. Sensitivity studies may be conducted to estimate the variations in risks from variations in breakup scenario probabilities and from variations in the extent of breakup associated with each scenario; however, the uncertainty in risk due to incompleteness in the list of credible breakup scenarios remains unknown.

7.1.4.2 Intercept Impact Breakup

In many ways, the uncertainty in breakup models for debris from intercepts is even greater than the uncertainty in FTS and aerodynamic breakup models. It is simply impossible to recover the debris from intercepts, and controlled tests are generally restricted to scaled models of the interceptor at velocities below – sometimes significantly below – the velocity of the intercept being modeled. The debris resulting from an intercept is dependent on the relative orientation of the interceptor and the target at contact, the point of contact; and a variety of other conditions that significantly affect the post-impact breakup and dynamics. Localized energy transfer under impact conditions can exceed the melting temperatures – or even the vaporization temperatures – of components, resulting in mass loss by mechanisms that cannot be tracked by either ground or air/space testing. Fracture lines may result from system joints, component weak spots, force concentrators, and other phenomena only apparent under hypervelocity impact conditions. Both localized thermo-mechanical effects (including the effects of stored energy in the system) and systematic effects can change the final chemical state of a fragment, its condition of velocity and spin, its shape and mass, and overall dynamic performance.

7.2 Debris Dispersion Models

Debris dispersion models are models to predict the dispersions of debris occurring from vehicle breakup, during free fall, or at surface impact. Vehicle breakup may include an intact vehicle that has lost thrust or is tumbling rapidly. The term “debris dispersions” is used to refer to the variation in the position of a fragment as it falls and at impact (or at a specified altitude). The sources of debris dispersions include the deviation of the vehicle from the nominal (intended) trajectory prior to breakup and the dynamic effects on the fragments during free fall.

Debris dispersions are computed during free fall or at a specified altitude to assess aircraft or spacecraft risks, and at surface impact to assess risks to people and property on the surface (ground or water). The debris dispersions result in both an expected (mean) shift in the position of a fragment during free fall or at impact, and in an uncertainty in this position. Dispersion models are discussed for each of the significant sources of debris dispersion.

Fundamentally, debris dispersions need to be modeled for each hazard-producing fragment resulting from vehicle breakup; however, fragments may be (and often are) combined into fragment groups (classes) and the dispersions are modeled for each group (Section 7.1 addresses fragment grouping).

The focus of the discussion is on the development of debris dispersions at surface impact (or at a specified altitude); however, additional considerations that should be addressed for defining 3-dimensional dispersions are also discussed. The primary purpose of modeling 3-dimensional fragment distributions is to compute impact probabilities for an aircraft or spacecraft that is following a specified flight path at a given speed. Modeling of the 3-dimensional cloud requires that the dispersions of the debris be defined as a function of time.

There are three approaches that have been used to define debris dispersions. The first is to statistically represent the dispersions using models that relate the dispersions at surface impact (or at a specified altitude) to the initial breakup state vector using closed form solutions. The second is to perform Monte Carlo simulations of fragment trajectories from the breakup point to develop random impact points (scatter plot) to define the dispersions. The third is to compute the maximum (or near maximum) debris dispersions to define the limits of the impact displacements.

The significant sources of debris dispersion that are addressed, due to both trajectory deviations of the vehicle and dynamic effects on the fragments during free fall, are:

a. vehicle normal trajectory uncertainty due to guidance and performance factors;
b. vehicle malfunctions resulting in significant trajectory deviations (referred to as malfunction turns);
c. velocities imparted to fragments at vehicle breakup;
d. uncertainty in the drag characteristics of a fragment;
e. aerodynamic lift effects acting on a fragment;
f. dispersion due to wind drift, including the uncertainty in the wind profile;
g. free flight of inadvertently separated thrusting motors.

Other sources of dispersion may need to be considered, but they are usually minor contributors to the overall debris dispersions. These sources include uncertainty in the atmospheric density, variations in the impact altitude due to terrain, and uncertainties introduced by the Earth model employed.

An important tool used in the generation of debris dispersions is an impact predictor (often referred to as a propagator). The impact predictor is used to compute the trajectory of a fragment from vehicle breakup to a specified time, altitude, or surface impact. Although the impact predictor is not discussed as a separate model in this chapter, it is important to note that it can compute fragment state vectors with sufficient accuracy and computational speed. Important considerations for a good impact predictor are:

a. rapid computation speed to meet the requirements for having to compute large numbers of trajectories (various flight times, failure modes, and fragments/fragment groups);
b. capability to handle high initial decelerations;
c. use of an appropriate atmospheric density model for the region of concern;
d. ability to handle wind forces;

e. ability to model aerodynamic forces in a rarified (high altitude) atmosphere.

7.2.1 Vehicle Normal Trajectory Uncertainty due to Guidance and Performance Factors

7.2.1.1 Model Description

Even when a vehicle is flying normally, the state vector of the vehicle at the onset of failure, and subsequently at the time of breakup, is uncertain due to the normal variations in the vehicle guidance (including preplanned and responsive maneuvers, inertial sensor tolerance, guidance algorithm performance accuracy, etc.) and in the motor performance (thrust variation, steering tolerance, etc.). Atmospheric conditions (particularly atmospheric density and wind) affect both guidance and motor performance. The resulting vehicle state vector uncertainty leads to uncertainty (dispersions) in the locations of the vehicle breakup debris during free fall and at impact. The purpose of the vehicle guidance and performance dispersion model is to quantify the debris dispersions.

7.2.1.2 Data Sources

Data to define a vehicle's guidance and performance state vector uncertainty are typically generated by the vehicle vendor and are in one of three forms.

a. Historically, the most common form was what are referred to as 3-sigma trajectories to reflect the fact that they are intended to represent dispersions from the nominal trajectory that are near maximum (i.e., will be rarely exceeded). 3-sigma trajectories are generated for various conditions to cover the range of state vector variation. A common set of trajectories includes those for a 3-sigma low-performing (low thrust) vehicle (often referred to as a cold trajectory), a 3-sigma high-performing vehicle (often referred to as a hot trajectory), a 3-sigma deviation to the left of the nominal trajectory plane (left trajectory), and a 3-sigma deviation to the right of the nominal trajectory plane (right trajectory). In some cases other trajectories may be provided, such as a 3-sigma high altitude (lofted) and a 3-sigma low altitude (depressed) trajectory.
b. Increasingly, the vehicle vendor will provide a family of dispersed trajectories to characterize the potential dispersions of the vehicle trajectory due to variations in the various environmental, guidance, and performance parameters that govern the trajectory.
c. In less-frequent cases, the vehicle vendor will provide statistics for the state vector (versus flight time) giving the standard deviations in the state vector position and velocity components and, sometimes, the correlations between the components. These provide the terms for a covariance matrix defining the state vector uncertainty statistics.

There are special data issues and modeling considerations that need to be addressed when a mission involves an intercept of a vehicle or its payload (designated the target) by another vehicle/payload (designated the interceptor), where the uncertainties in both the target and interceptor state vectors at intercept need to be addressed. Some of these considerations and the type of data used are discussed below.

7.2.1.3 Modeling Considerations

The modeling of debris dispersions due to guidance and performance factors generally varies with the type of data available from the vehicle vendor. The models compute fragment dispersions at surface impact (or at a specified altitude or a specified time) due to guidance and performance factors for a vehicle that breaks up or loses thrust while following a normal trajectory, or due to uncertainty in an intercept state vector.

a. The modeling of debris dispersions due to guidance and performance is the least straight-forward when the vehicle state vector uncertainty is defined in the form of 3-sigma trajectories. In this case, consideration needs to be given to how to apply the data to define dispersions.

    - One approach is to use the state vectors at a given flight time from each of the 3-sigma trajectories to compute the corresponding impact points for a given fragment/fragment group. These points can then be used to define the 3-sigma limits for the impact dispersions. Exactly how the impact points are used to compute the impact dispersions is up to the interpretation of the analyst. For example, the most extreme impact points in the up-range, downrange, cross-range left, and cross-range right directions could be used to define a contour fit of the points and to interpret this contour as a 3-sigma dispersion contour.

    - Another approach is to use the 3-sigma trajectory state vectors to estimate state vector component uncertainties to generate covariance matrices for the state vector for selected flight times. Corresponding fragment impact dispersions can then be estimated using one of the approaches discussed below. The state vector standard deviations for a given flight time can be estimated from the differences between the nominal state vector and the 3-sigma trajectory state vectors for each state vector component. While this process provides estimates of the component standard deviations it does not provide estimates of the correlations between state vector components, and thus does not generate a complete state vector uncertainty covariance matrix. As discussed above, this can result in overstated debris impact dispersions.

b. The modeling of debris dispersions due to guidance and performance factors is the most straightforward in the less common case where the vehicle vendor provides a covariance matrix defining the vehicle state vector uncertainties as a function of flight time. There are two approaches that can be used to propagate the covariance to define debris dispersions.

    - The first approach is to propagate the state vector uncertainties for given failure times using analytical models (such as partial derivatives) to relate impact (or altitude) displacements to perturbations in the initial state vector components. The analytical model parameters will vary as a function of the initial state vector and of the fragment drag characteristics (ballistic coefficient or drag coefficient versus Mach number).

    - The second approach is to use the nominal vehicle state vector and the covariance matrix to generate perturbed state vectors for a given failure time and to propagate these for a given fragment (or fragment group) to impact using an impact predictor. The resulting impact point scatter plot can then be used to define the statistics of the impact dispersions. A sample scatter plot is shown in Figure 7-1 where impact points resulting from many random selections of the initial state vector are shown for two fragment ballistic coefficient values. The coordinates of the impact points (latitude-longitude, x-y, or other coordinate system) are used to calculate the mean impact point and the moments of the impact dispersions.

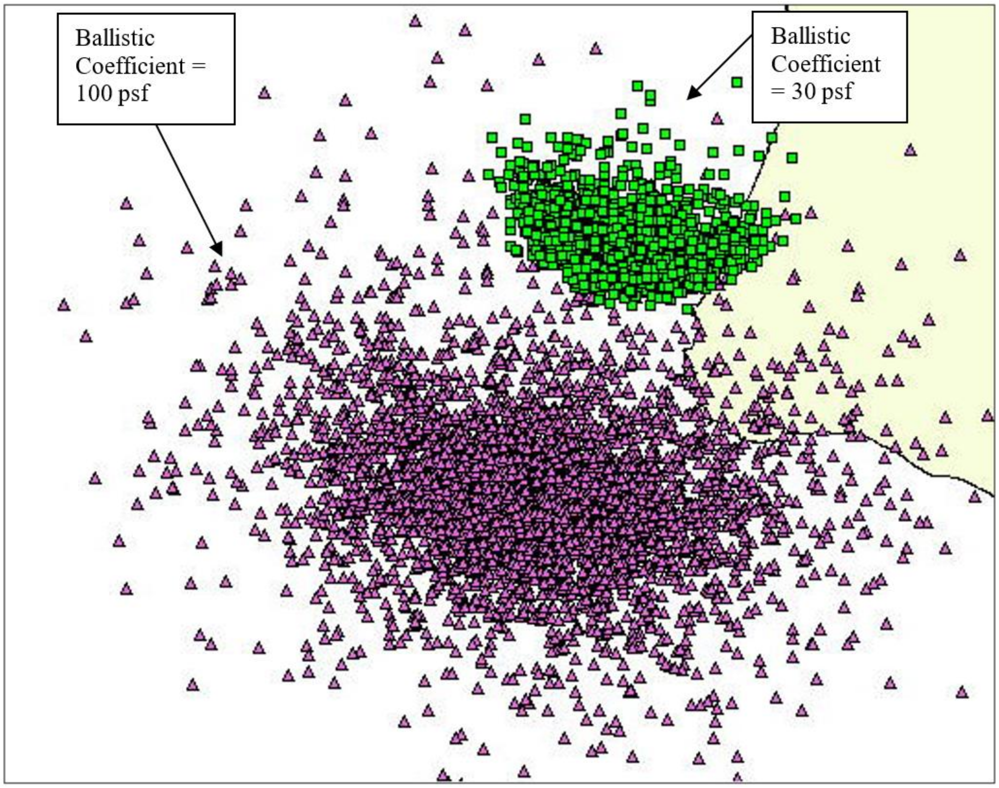

Figure 7-1. Sample Impact Point Scatter Plot

c. If the vehicle vendor provides a family of dispersed trajectories to characterize potential vehicle dispersions, the modeling is similar to the case where the vehicle vendor provides a covariance matrix.

- The initial set of vendor-provided state vectors for given failure can be used to compute impact points and the resulting scatter plot to define the statistics of the impact dispersions.
- As an alternative, the dispersed trajectories can be used to generate a covariance matrix that is then propagated using analytical models, as discussed above.

d. When the mission involves an intercept of a vehicle or its payload by another vehicle/payload launched usually from different sites on a coordinated schedule, additional factors must be considered.

- Some launch vehice maneuvers may be initiated based on energy management requirements involving on-board and off-board sensor information regarding the target vehicle. This information is used to guide the vehicle toward the target and generate the necessary maneuver commands.
- After either the target or the interceptor vehicle reaches a ballistic trajectory, additional maneuvering may be planned. For example, the target vehicle may maneuver to simulate evasive actions by a threat vehicle, and the interceptor will conduct both normal steering maneuvers as sensor data is improved and responsive maneuvers based on command guidance or on-board course correction planning.

The ICVs are used to define the maximum allowable volume of space in which an intercept can occur. The ICV encompasses the net effect of the interceptor trajectory, including normal targeting, normal dispersions, and responsive planning and control; and the target trajectory, including dispersions from its nominal trajectory. The allowable size and shape of the ICV are often restricted based on safety criteria used to contain debris within allowable boundaries or to achieve acceptable levels of risk. The ICV can be used to define variations in intercept debris impact points by generating impact points for various intercept state vectors selected from the ICV.

While the guidance and performance dispersions represent the state vector uncertainty for a vehicle following a normal trajectory, these data do not properly represent the state vector uncertainty for a vehicle that breaks up (or is destructed) while in a malfunction turn. These guidance and performance dispersions should, however, be accounted for as an additional source of state vector uncertainty over and above the consequences of the malfunction turn. Data to define guidance and performance state vector uncertainties during a turn are normally not generated by vehicle vendors. The risk analyst is thus faced with the challenge of how to define the guidance and performance debris impact dispersions for a vehicle in a turn. Lacking better data, the data for the normal trajectory may have to be used as an estimate of the state vector uncertainties during a malfunction turn due to guidance and performance factors.

7.2.2 Vehicle Malfunction Turns

7.2.2.1 Model Description

A vehicle malfunction turn is defined to be any notable deviation of a vehicle from its intended trajectory that results from a failure (malfunction) of the vehicle hardware or software, including a failure of the vehicle guidance system. It includes everything from gradual turns off course to gravity turns to tumbling turns. It is often detected by abnormal deviations of the vehicle’s projected IIP from the nominal IIP trace. The state vector at the time of breakup for a vehicle that is in a malfunction turn is highly uncertain due to the number of possible failure modes resulting in the turn; due to the uncertain response of the vehicle to the failure condition; and due to the response of an RSO to the deviation from the intended trajectory. The resulting state vector uncertainty leads to uncertainty (dispersions) in the locations of the vehicle breakup debris during free fall and at impact. The purpose of the malfunction turn model is to define the debris dispersions resulting from the trajectory deviations from the time of the failure to the time of vehicle breakup, flight termination, or impact.

There are many failure modes that can cause a malfunction turn, each of which needs to be considered. Possible malfunction turn failure modes include, but are not limited to the following.

a. A motor nozzle assembly failure causing loss of full control of the thrust direction resulting in an unplanned offset of the thrust vector. This could result, for example, from a failure of one or more nozzle actuators leading to a nozzle stuck in place, drifting to null, going hard-over, or randomly moving; or from a failure in a thrust injection system used to control the thrust vector direction.

b. A failure in the vehicle control system (hardware or software) leading to an erroneous command to the thrust vector control system.

c. A failure of a nozzle, such as a nozzle burn-through, leading to a loss of a portion of a nozzle and a thrust offset.

d. The complete loss of a nozzle assembly in a solid rocket motor resulting in a complete loss of thrust control, and, usually, a significant drop in the thrust.

e. The loss of or a significant reduction in the thrust for one of the motors on a vehicle with multiple operating motors (core vehicle or strap-on motor).

f. An inadvertent separation of one or more strap-on motors.

g. A case burn-through for a solid rocket motor or a leak at a case joint, resulting in a side thrust at the location of the burn-through and a reduction in the main thrust.

7.2.2.2 Data Sources

The primary sources of data to define malfunction turn behavior are vehicle vendors. If malfunction turn data are not available from the vendor, data can in some cases be developed using an appropriate trajectory simulation program.

This requires a significant amount of data for the launch vehicle such as thrust, mass properties, and aerodynamic coefficients (including coefficients for a vehicle at large angles of attack). Unless the failure is a simple one to model)such as a vehicle with a single thrusting motor with the nozzle locked in an offset position) the malfunction behavior may require that the vehicle control system be modeled. This may not be possible without significant information and models from the vendor.

Malfunction turn trajectories are best obtained from vehicle vendor data. Alternatively, an analyst may generate malfunction trajectories from more basic data provided by the vendor. Malfunction turn data generated by vehicle vendors has primarily been of two types, detailed in the first two bullets below. Either type may include additional information to support development of debris impact dispersions. The remaining bullets describe additional malfunction turn data that is occasionally available.

- One form of malfunction turn data is what is referred to as velocity turn curves. These curves give the turning capability of a vehicle expressed in terms of the time history of the vehicle velocity vector magnitude and velocity vector turn angle for turns initiating at various flight times. The turn angle is the angle between the vehicle velocity vector at the start of a turn and that at a given time into the turn. The velocity magnitude and turn angle may be generated for various failure scenarios. Often the curves are generated both for pitch plane turns (the failure causes the vehicle turn in its pitch plane) and for yaw plane turns (the failure causes the vehicle turn in its yaw plane). The turn curves may be generated either ignoring the force of gravity during the turn or including gravity (or both). The purpose of generating turn curves ignoring gravity is to allow the velocity turn data to be used to estimate turns where the velocity vector is turning in a plane (plane containing the vehicle velocity vector at the start of the turn) other than that for which the turn data are generated. In this case the effect of gravity acting during a turn needs to be accounted for in the model used by the analyst (by adjusting the vehicle turn state vector time history).

  The major shortcoming with the velocity turn curve data is that the attitude of the vehicle and its velocity vector during a turn are not defined. Therefore, an assumption must be made regarding the direction that the velocity vector turns. A common assumption used is that the velocity remains in a specified plane, where the plane can have any orientation about the initial velocity vector.

- A higher-fidelity form of malfunction turn data is full 6 degree-of-freedom malfunction trajectories giving the full state vector, including the vehicle attitude, as a function of time into a turn. Trajectory data in this form are becoming more common. Typically, a family of trajectories is generated for selected flight failure times for each of the many failure modes representing the range of vehicle malfunction response. In addition to providing a full state vector during a turn (thus eliminating the need to assume the direction for the velocity) the attitude data can be used to define the orientation of the vehicle at the time of vehicle breakup or destruct. The orientation canthen in turn be used to initiate free-flight simulations for an inadvertently separated thrusting motor or to account for the directionality of velocities imparted to fragments at breakup.
- In addition to the malfunction turn curves or trajectories, the vehicle vendor often will either: provide data to determine when during a turn a vehicle is expected to break up due to aerodynamic and inertial loads (including the centrifugal forces experienced by a tumbling vehicle); or specify that breakup will not occur. This may be provided as the time into each turn that breakup is expected to occur or, for malfunction trajectories, as a loading condition, such as the q-alpha (dynamic pressure times angle of attack) value at which breakup would be expected. In some cases the time or loading condition will be expressed as a range of values to account for uncertainty.
- Other data that may be provided are the relative probabilities of the malfunction turn curves or malfunction trajectories for each flight time. The vendor may provide these relative probabilities, or it may be necessary for the range safety analyst to estimate them after discussions with the vendor. These probabilities are important for the computation of impact dispersion statistics from random impact points generated using the turn data.

7.2.2.3 Modeling Considerations

Two important factors need to be addressed when modeling malfunction turn dispersions.

a. The first factor relates to the fact that a launch vehicle may break up during a turn due to the abnormal aerodynamic and inertial loads or due to the propagation of the initial failure condition (such as the propagation of a nozzle burn-through leading to an explosion). Breakup initiated by aerodynamic/inertial loads may also activate an automatic destruct system/inadvertent separation destruct system (ISDS) that further affects the vehicle breakup. To account for such breakup, the turns should be terminated at the point where breakup is predicted. The breakup time could be that provided by the vendor, the latest breakup time if a time range is provided, or (if a Monte Carlo approach to modeling the impact dispersions is used) a randomly selected breakup time from a provided or estimated probability distribution.

NOTE	In some cases it might be appropriate to assume that breakup will not occur during a malfunction turn so as to maximize the vehicle dispersions, and thus the dispersions of the vehicle fragments. This may (but not necessarily) lead to conservative risk predictions that could be adequate if these risks are within

	acceptable limits. If the risks are not acceptable it may be necessary to re-compute the dispersions accounting for breakup during the turns.

b. The second factor relates to the effect of an FTS and the associated flight termination criteria on the dispersions. To account for this, malfunction turn simulations should model vehicle breakup as occurring whenever violation of a flight termination condition occurs. This requires tracking the flight termination condition during simulations of the turns and initiating termination (due to activation of the FTS by the RSO) when it is violated. Flight termination conditions are defined by established criteria such as the crossing of a destruct line by the vehicle's projected vacuum impact point, the crossing of an ILL by a projected debris footprint, or the violation of lines on a vertical plane position chart.

(1) The determination of the time into a turn when vehicle breakup due to flight termination action will occur should include the delay time from when a flight termination criterion is violated to when actual vehicle destruct occurs. This delay time accounts for the time for the range safety software and hardware to display the position and movement of the vehicle; the human reaction time to detect the malfunction and activate the FTS; the system delays in sending, receiving and processing the flight termination signal; and the time for the flight termination hardware to perform its function. Often this delay time is defined as a time range or a probability distribution to account for uncertainty.

(2) In addition to termination of a turn due to violation of the basic flight termination criteria, a vehicle that is in a malfunction turn may be terminated: 1) to prevent impact of an intact vehicle; 2) because the vehicle is erratic and the potential exists to lose positive control; or 3) because the performance of the vehicle is unknown and the possibility exists to violate established flight safety criteria. The analyst should also take this into consideration for determining if and when a turn is terminated.

If both vehicle breakup and flight termination can occur during a turn, the earliest of the breakup/termination times for these two phenomena is normally used. The analyst should keep in mind that the vehicle fragmentation that results from aerodynamic or inertial forces will, in most cases, be significantly different than that resulting from flight termination activation.

With either form of the malfunction turn data (turn curves or turn trajectories) the analyst can choose to use the malfunction state vectors to: 1) determine only the limits of debris dispersions at surface impact (or at altitude); or 2) generate random impact points (scatter plot). Scatter plot points can be used to compute the statistics of the debris impact dispersions or to generate a histogram of the random impact points, or risk computations can be made for each random impact point[223].

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[223] Risk computations can be performed for each of the random impact points, with the dispersions due to other sources of impact uncertainty accounted for as part of the Monte Carlo simulations used to generate the random impact points, or as part of an uncertainty distribution about the random impact point. The risk contribution for each

The limits of the debris dispersions (such as the maximum up-range, downrange, cross-range left, and cross-range right dispersions) can be used to approximate the region within which impact will occur, but this does not give any information as to the character or statistics of the impact distribution. With this approach the limits are often assumed to represent the 3-sigma dispersion contour, and an assumption may have to be made by the analyst as to the corresponding impact probability distribution. If risks are to be controlled by containment of debris, such as keeping it within specified range boundaries, the limits of debris impact may be all that is required. The containment approach could also be used to define clearance areas for ships and aircraft.

Computation of the fragment impact dispersion limits is different depending on whether malfunction turn curves or turn trajectories are employed.

c. With turn curves the maximum dispersions can be estimated by selecting the maximum velocity turn angles and, applying the corresponding velocity magnitudes, computing the projected impact points for a given fragment or fragment group. This may need to be done for each of the turn curves for each flight failure time and for various orientations of the turn plane in order to determine the maximum dispersion.

d. With turn trajectories there will be many trajectories, and the challenge is to select the proper malfunction trajectories that will sufficiently define the limits of the fragment impact dispersions for a given failure time. It may be necessary to compute the projected impact points for each of the trajectories, and possibly for various times during each trajectory, and then select the impact points that define the impact dispersion limits.

Random state vectors at vehicle breakup or flight termination are used to compute corresponding impact points resulting in a scatter plot. A scatter plot is generated for each fragment/fragment group of concern. The state vectors are generated by a Monte Carlo analysis of the malfunction trajectory and the breakup event (time and mode of vehicle breakup or flight termination).

- If turn curves are used, the turn trajectories for a given failure time can be generated by randomly selecting a turn curve, assuming that the turn occurs in a plane, and randomly selecting the turn plane orientation. The relative probabilities of the turn curves and the probability distribution for the turn plane orientation angle are needed to make the random selections. These relative probabilities and/or the turn plane orientation probability distribution will need to be estimated if they are not available from the vehicle vendor. Once a turn curve and turn plane are selected the state vector during the turn can be computed using the velocity turn angle and magnitude history to define the velocity vector and, by integrating the velocity, the position vector during the turn. If the turn curves are generated ignoring gravity effects, the effect of gravity will need to be accounted for.
- If turn trajectories are used, they can be randomly selected from the set of trajectories provided. Relative probabilities of occurrence of the trajectories are needed to make

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random impact point would, of course, need to be multiplied (weighted) by its relative probability of occurrence before combining with the distribution for other random impact points to get the total risk for the debris-generating event.

the random trajectory selections. These relative probabilities will need to be estimated if not available from the vehicle vendor.

Statistics of the impact dispersions can be computed from the coordinates of the impact points in a scatter plot. These statistics provide information for selecting an appropriate impact distribution function.

Alternatively, the scatter plot random impact points can be used to generate a histogram of the impact point distribution. This histogram provides the most accurate representation of the impact distribution; however, computation of impact probabilities using a histogram is generally more complex and computationally intensive versus using a closed form impact distribution function.

7.2.3 Debris-Imparted Velocities

7.2.3.1 Model Description

Vehicle breakup generally results in velocities imparted to the resulting fragments. These imparted velocities are produced by the explosive charges used in FTSs, by pressure forces created by an explosion, by the rupture of a pressurized vessel or motor, and/or by the rotational motion of the vehicle at the time of breakup or flight termination. For weapon systems, velocities are created by hit-to-kill intercepts or warhead detonations. The direction and magnitude of the imparted velocities are often difficult to predict and are thus highly uncertain. The magnitude of the imparted velocities will vary with the way a vehicle breaks up; the variation in the explosive pressures created; the uncertainty in the pressure level in a rupturing vessel; the fracture pattern of motor cases, pressure vessels and other hardware; etc. The imparted velocity of each fragment will tend to have a preferred direction relative to a vehicle’s orientation. Many of the same uncertainty factors for the imparted velocity magnitude apply to the imparted velocity direction. In addition, the uncertainty in the orientation of the vehicle at breakup (particularly if it is turning off course or tumbling) adds to the uncertainty in the net imparted velocity direction.

The imparted velocity influences the post-breakup state vectors of the fragments and thus affects the trajectories and dispersions of the fragments during free fall and at impact. The purpose of the imparted velocity debris dispersion model is to define these dispersions.

7.2.3.2 Data Sources

A primary source of imparted velocity data is the velocity magnitudes provided by vehicle vendors for FTS-activated breakup of the launch vehicle. In some cases velocity magnitudes may be given for other modes of vehicle breakup such as an explosion.

a. Typically, only a single velocity magnitude is given for each fragment or fragment group, and no information is given as to the direction of the velocity. Possibly an uncertainty range for each magnitude will be specified or a statistical uncertainty, such as 1-sigma standard deviation, will be provided.

b. If imparted velocities are not provided by the vendor, or velocities for a different mode of failure are needed, the velocities can be estimated using existing models based on physical principles or on velocity measurements obtained from launch vehicle accidents (usually by analyzing video recordings of an accident).

   Various models have been developed by launch vehicle vendors and the flight test ranges to predict velocities for fragments created by vehicle explosions and pressure vessel rupture. These models can be used to predict imparted velocities or to check the reasonableness of velocities provided by vendors. There are also models available to predict velocities, as well as the debris, resulting from hit-to-kill intercepts (such as the generally accepted kinetic impact debris distribution model).

7.2.3.3 Modeling Considerations

The analyst will first need to determine whether to characterize the dispersions by defining only the maximum (worst-case) dispersions in various directions, whether to develop a scatter plot to compute the statistics of the dispersions or a histogram defining the impact distribution, or to compute the risks directly for each random impact point.

a. If only the maximum dispersions are to be generated, then a best estimate of the maximum imparted velocity magnitude will need to be made. This maximum imparted velocity magnitude can then be used to compute maximum dispersions at impact (or at altitude) by iterating on the imparted velocity direction and computing the corresponding impact trajectories. Impact points for a range of credible imparted velocity directions are necessary to determine the maximum dispersion in all directions.

b. If a scatter plot is to be generated, the statistical characteristics of the imparted velocity must be determined. When only a single imparted velocity magnitude is provided, its statistical significance must be interpreted (i.e., is it a maximum value, a mean, or a given percentile on a probability distribution) to estimate a probability distribution for the velocity magnitude. If a range of values or an uncertainty in the specified value are provided, this can be used to better define the probability distribution. A distribution for the velocity direction is also needed. In the absence of any specific information, the velocity is often assumed to have an equal likelihood of being in any direction (uniform spherical distribution). This is predicated on the fact that the direction of the velocity relative to the vehicle is highly uncertain, and the attitude of the vehicle at the time of breakup may also be highly uncertain. In cases such as a vehicle explosion during a normal trajectory or a planned detonation, a best estimate of the imparted velocity direction can be made, and the uncertainty in the direction can be defined by a probability distribution about the preferred direction (such as a conical distribution with the centerline of the cone aligned along the preferred direction).

   The probability distributions for the imparted velocity vector (magnitude and direction) are used in a Monte Carlo analysis to compute the scatter plot (set of drag corrected impact points). The scatter plot points can be used to compute the impact dispersion statistics (mean, standard deviations, etc.) or a histogram, or the random impact points can be used directly in risk calculations.

c. Three additional factors should to be considered when developing debris impact dispersions due to imparted velocity.

   (1) The impact dispersions often become significantly non-linear as the velocity magnitudes become large, especially for low ballistic coefficient fragments. Also, at higher initial altitudes the direction of the imparted velocity can produce significant non-linearity. Thus, linear methods (such as influence coefficients) to compute impact dispersions should only be used for relatively small imparted velocity magnitudes and lower altitudes. An impact predictor capable of handling high

decelerations can be used to compute impact points for high-magnitude imparted velocities.

(2) Imparted velocities can result in fragments that enter into stable or temporary orbits, and it may be necessary to eliminate the fragments for the computation of surface impact risks while accounting for them when assessing the short-term or long-term risks to orbiting assets.

(3) The distribution of imparted velocity impact points can be irregular or highly skewed such that a simple closed-form function, such as a bivariate normal distribution, will not adequately represent the actual distribution. These cases require a more complex method to characterize the distribution (such as an impact point histogram) or the use of a Monte Carlo method to compute risks for each individual impact point.

7.2.4 Fragment Aerodynamic Drag Uncertainty

7.2.4.1 Model Description

The location of a fragment during free fall or at impact is significantly affected by the aerodynamic drag force acting on the fragment. The drag characteristics of the fragments resulting from the breakup of a vehicle can usually only be roughly estimated. This uncertainty leads to uncertainty in the trajectory of the fragments during free fall and thus to dispersion during free fall and at impact. The uncertainty in fragment drag characteristics results from the fact that the manner in which a vehicle will break up can only be estimated and, even for a well-defined fragment, the drag characteristics will vary or be uncertain due to the uncertainty in how the fragment will fall (stabilized at a given orientation, tumbling, etc.). In addition, the character of fragments can change during reentry due to aerodynamic stresses and aero-thermal heating, resulting in secondary fragmentation, melting, vaporization, or ablation. This not only affects the fragment drag characteristics, but the changes in the debris due to the heating affects (including fragment demise) and secondary breakup will need to be addressed in the risk computations. The purpose of the aerodynamic drag uncertainty debris dispersion model is to define the dispersions.

7.2.4.2 Data Sources

The primary source of data for fragment drag characteristics is data provided by the vehicle vendor for specific breakup modes (usually for destruct breakup; sometimes for other breakup modes). See also Section 7.1.

The most common data are the ballistic coefficients of the fragments. Since a fragment's ballistic coefficient varies with Mach number, values are often given that are average values for subsonic and supersonic speeds (where an average or representative ballistic coefficient is used for each of these regimes). In some cases, ranges of ballistic coefficient values are provided for each fragment or fragment group.

For some, usually well-defined, fragments the drag coefficient versus Mach number (along with the associated reference area) may be provided.

When drag characteristics are not provided, or the analyst wants to check the validity of the data, ballistic coefficients can be estimated based on a fragment's shape, size' and weight using standard formulas. For well-defined fragments the drag coefficient versus Mach number might be predictable using standard curves.

7.2.4.3 Modeling Considerations

The dispersions due to drag uncertainty are usually handled by defining the uncertainties in the fragment drag force.

a. If the drag is defined by a representative fragment ballistic coefficient, the uncertainty in the ballistic coefficient is used to define the dispersions. Since the drag force on a fragment varies significantly between supersonic and subsonic speeds, the appropriate ballistic coefficient should be used for these two regimes, and the uncertainty defined for each regime. For low ballistic coefficient fragments originating at lower altitudes where the atmosphere is dense, the drag force is high, and the velocity of a fragment is slowed rapidly to subsonic speeds such that it may be adequate to use the subsonic ballistic coefficient for the entire free-fall trajectory. The uncertainty in ballistic coefficient is typically defined by a range of values (from vehicle vendor data or engineering estimates) or may be defined by a statistical uncertainty or a probability distribution. Generally, the uncertainties (or a probability distribution) are not provided by the vehicle vendor and it is up to the analyst to estimate these.

b. If the drag is defined by drag coefficient curve (drag coefficient versus Mach number and associated reference area) the uncertainty in the drag will need to be defined in terms of the uncertainty in the drag coefficient. This may be in the form of lower- and upper-bound drag coefficient versus Mach number curves.

   The approach often used to define debris dispersions due to drag uncertainty is to propagate a fragment to impact using the best estimate of the ballistic coefficient and using the maximum and minimum, or statistically varied, ballistic coefficient values (or by using the best estimates and statistical variations on the drag coefficient versus Mach number data).

c. The resulting impact points can then be used to characterize the fragment dispersion due to drag uncertainty. Since the variation in a fragment impact point as a function of the drag traces along a curved line, often referred to as a debris centerline (Figure 7-2), the dispersions of the impact point lie along this line. This creates a challenge for the analyst as to how to model this “one dimensional” distribution, especially when combining this source of impact uncertainty with the other sources of impact uncertainty to characterize the total impact distribution. A conservative approach that has been used is to approximate the drag uncertainty dispersions by selecting an appropriate two-dimensional distribution to represent the one-dimensional curvilinear distribution.

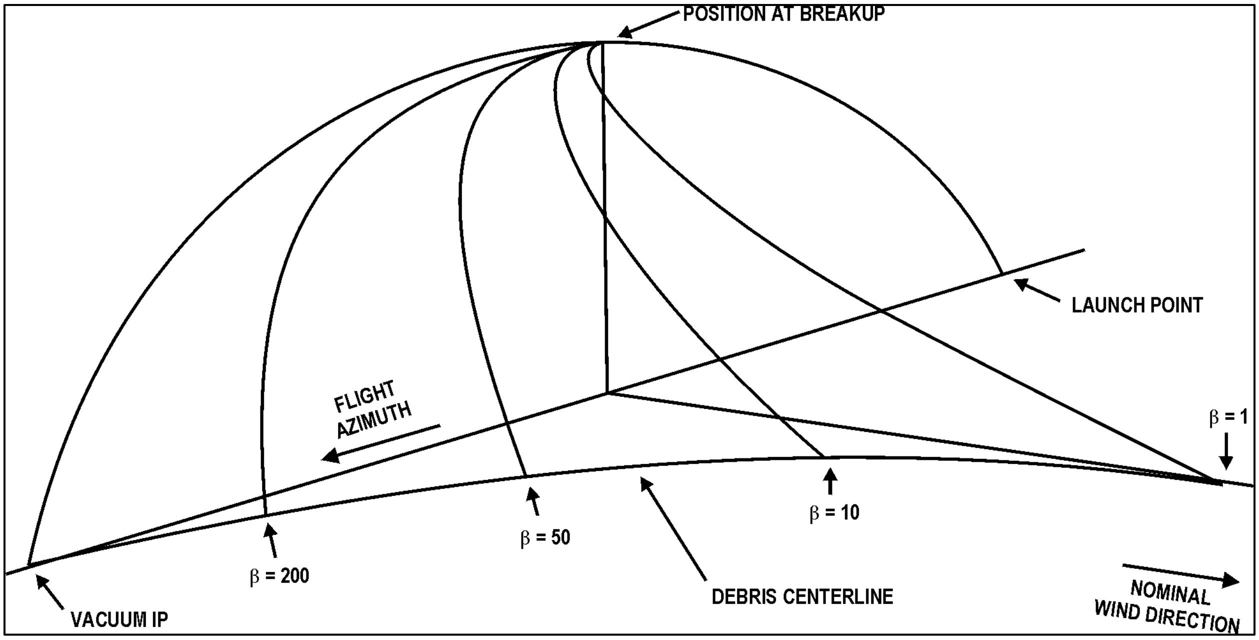

Figure 7-2. Debris Centerline Showing Variation of the Impact with Fragment Ballistic Coefficient (B)

d. An aerodynamic regime that may need to be considered when computing the impact points of fragments is the portion of the trajectory that is at very high altitudes where the atmosphere consists of individual molecules. Here the drag should be accounted for by using appropriate drag models for this regime.

7.2.5 Fragment Aerodynamic Lift Effects

7.2.5.1 Model Description

The location of a fragment during free fall or at impact can be significantly affected by the aerodynamic lift force acting on the fragment. For reasons similar to those discussed for aerodynamic drag (Subsection 7.2.4), the lift force on a fragment can usually only be roughly estimated. The uncertainty leads to uncertainty in the trajectory of the fragment during free fall and thus in dispersions at any given altitude or at impact. The purpose of the lift debris dispersion model is to define these dispersions.

7.2.5.2 Data Sources

The lift force on a fragment is usually defined by the lift-to-drag ratio, which is the ratio of the magnitude of the lift force to the magnitude of the drag force. Lift-to-drag ratios are not normally provided by vehicle vendors and therefore must usually be estimated by the analyst based on predicted fragment shapes.

7.2.5.3 Modeling Considerations

Fragment impact dispersions due to lift can be assessed by simulating fragment trajectories with and without the lift force. It should be emphasized that while the drag force always operates in a direction opposed to the velocity vector, the force normally called lift can operate in any direction perpendicular to the velocity vector, even downward, and the direction can rotate as the fragment falls. Thus, for fragments that can stabilize their orientation relative to the velocity vector, the larger dispersions should be accounted for by simulating trajectories with the lift vector stabilized in various directions. For fragments that will tumble during free fall or for which the direction of the lift vector is unknown due to the uncertainty in the fragment shape, the simulated trajectories should consider a rotating lift vector direction where the rate of rotation is varied. The impact points computed using the various assumptions on the lift vector can be used to define the limits on the impact dispersions in various directions, and these can be used in determination of debris containment or to define hazard zones. The impact points can also be used to estimate impact distribution statistics characterizing the impact uncertainty due to lift effects.

7.2.6 Wind Drift and Wind Uncertainty

7.2.6.1 Model Description

Wind is a significant factor affecting the trajectory of fragments during free fall. This is particularly true for fragments experiencing high drag (low ballistic coefficient). The wind causes a shift in the position of a fragment during free fall This shift is determined by the magnitude and direction of the wind as a function of altitude. Since the wind varies with both time and location, the wind profile can only be defined statistically. This uncertainty in the wind profile results in uncertainty in the free-fall trajectory of fragments and thus in dispersions at any given altitude or at surface impact. The purpose of the wind uncertainty debris dispersion model is to define these dispersions.

The modeling approach to account for fragment dispersions due to wind drift can vary depending on whether the analyst is demonstrating that fragments will be contained within prescribed boundaries, thus controlling the risks, or is performing a risk analysis for the case where debris cannot be contained. Containment can be managed by determining that the maximum debris dispersions will be contained under the maximum allowable launch wind, whereas a risk analysis will require that wind-induced impact dispersion statistics be developed. For containment analyses it may only be necessary to establish maximum allowable wind profiles while risk analyses will normally require defining the wind statistics.

7.2.6.2 Data Sources

The wind is usually defined in terms of a mean wind profile along with the associated uncertainties. For day-of-mission assessments, the wind profile is usually obtained from pre-mission measurements using weather balloons, towers, and radar profilers.

The wind is usually expressed in terms of the wind components in a local orthogonal coordinate system (such as an east-north system) as a function of altitude or in terms of the wind magnitude and direction as a function of altitude. In most cases, wind updrafts and downdrafts are ignored.

For monthly or annual wind data, the wind is generally defined in the following terms: mean wind profile; uncertainty in the wind defined by the standard deviations determined for each of the wind components at each altitude; and the correlation between the first two terms. In some cases, the wind statistics may also include the correlations between wind components at one altitude and those at other altitudes. Usually these correlations are only provided for the wind components at a given altitude and those at the immediately adjacent altitudes. Monthly or annual wind data statistics should only be used to characterize the variability of the wind. Wind uncertainty characterizes the temporal and spatial scatter that would remain given a wind profile obtained in the hours leading to launch. Wind statistics for a given location and time of the year are generated from many wind measurements (hundreds or thousands) taken over many years. These time-of-year wind statistics are used to perform planning risk analyses (i.e., for predicting risks for a launch planned for a future time).

Uncertainty should also be addressed for measured winds. Here the uncertainty is due to the uncertainty in the measurement of the wind (instrumentation error), the time elapsed between the wind measurement and the time of launch, and the spatial variation between where the wind is measured and where the launch vehicle flies. The uncertainties due to instrumentation error can be estimated based on the characteristics of the wind measuring system. The uncertainties due to time delay can be developed, for given time of year, by performing statistical analyses of measured winds taken at short time intervals (typically one- to six-hour intervals). Uncertainty due to special variation is difficult to define and is often ignored (the wind statistics for a given location are assumed to apply over segments of flight) or the wind data used are changed as the vehicle progresses along its trajectory. Measured wind and associated uncertainties are used to perform risk analyses during the countdown prior to a launch.

The following are common sources of wind data.

- Range Commanders Council (RCC) Range Reference Atmosphere data that is available for most of the test ranges.
- The Global Reference Atmospheric Model developed by NASA. This model can generate wind data for any given location on the Earth (latitude, longitude) using data from the Global Gridded Upper Atmosphere Statistics database (distributed as the Global Upper Air Climatic Atlas) and the RCC Range Reference Atmosphere data.
- NASA-developed statistical wind data.
- The Inter-Range Instrumentation Group wind statistics.
- The Air Force Environmental Technical Applications Center wind database covering various launch ranges.
- Data published for a given range (both individual soundings and statistical) from historical wind measurements taken at the range using various measuring systems, such as Jimsphere, Rawinsonde, and Windsonde soundings, and Doppler Radar Profiler measurements. (These data are also used as part of the database for the other wind data sources).
- National Oceanic and Atmospheric Administration data.

7.2.6.3 Modeling Considerations

Wind statistics can be used to define the uncertainties in the fragment position at altitude or at surface impact, to define percentile and maximum permissible wind profiles for given directions, or to generate random samples of the wind profile. Approaches for the computation of wind-created debris dispersions range from the computation of maximum surface impact dispersions due to winds in various directions to the development of impact distribution statistics or scatter plots.

a. Maximum dispersions are usually based on the worst wind conditions for which a launch would be conducted. In many cases these limiting winds are expressed as percentile winds; that is, winds in specified directions that would be exceeded a specified percentage of the time. Wind-corrected impact points generated using these wind profiles are used to define the limits of the fragment impact uncertainty area due to wind.

(1) Percentile winds may be planar or in a given general direction, such as a wind coming from the southwest, and do not necessarily represent a real wind condition.

(2) The maximum wind dispersion approach is often used for assessing the containment of debris and for defining caution and hazard corridors used to control the location and sheltering of people. The impact area defined by the maximum dispersion impact points could also be used to estimate a wind impact uncertainty probability distribution.

b. A wind covariance matrix can be used to compute the statistics of the debris impact uncertainty distributions directly or to generate random wind profiles and corresponding wind-corrected impact points (scatter plot) characterizing the impact distribution. The wind covariance matrix contains the variances of the wind components at each altitude, the correlation between the wind components at each altitude, and, if available, the correlations between wind components at a given altitude and other altitudes. It is important to include as much correlation data in the wind covariance matrix as possible to get the most accurate representation of the wind uncertainty and of the corresponding impact dispersions.

(1) The statistics of the debris impact uncertainty distribution can be computed using analytical models (such as partial derivatives) to relate impact (or altitude) displacements to the wind uncertainties defined by the covariance matrix.

(2) Random wind profiles can be generated from a wind covariance matrix using a procedure employing a decomposition of the covariance matrix, such as a Singular Value Decomposition or a Cholesky Decomposition. Scatter plots generated from the random wind profiles can be used to generate the statistics of the impact distribution and to define an appropriate impact distribution fit.

An approach that has been used to handle wind effects for debris risk analyses is to compute the risks for many possible wind profiles for the time period for which a launch is planned. The wind profiles can be actual measured winds or random wind profiles generated from a wind covariance matrix. The resulting risk estimates can be used to assess the likelihood that the risks for a future launch will meet acceptable risk criteria. A launch agency or range can use this information to decide if a launch should be restricted to a certain time of day or should be planned for a different time of the year when the likelihood of exceeding acceptable risk levels is reduced.

7.2.7 Free Flight of Inadvertently Separated Thrusting Motors

7.2.7.1 Model Description

Some launch vehicles carry thrusting motors that could separate and fly independently (free fly) to the time when the motor is destroyed or breaks up due to aerodynamic and inertial loads. In some cases, the motor may be allowed to fly intact to thrust termination or impact. Potential sources of free-flying motors include inadvertent separation of strap-on motors, early ignition and separation of upper stages, or ignition and separation of payload insertion motors. Normally jettisoned motors can have residual thrust that continues following separation. An inadvertent separation will likely affect the performance of the parent vehicle, including recoil from the detached motor or damage (or breakup) from the separation event, and this should also be considered in a risk assessment.

In many cases strap-on motors are required to carry an ISDS that automatically destroys the motor in the event of an inadvertent separation. If the ISDS activates immediately upon inadvertent separation, dispersions due to free flight are eliminated; however, to eliminate or mitigate fratricide of the parent vehicle, there may be a time delay in the activation of the system allowing seconds of thrusting flight prior to destruct, potentially resulting in significant dispersions. In some cases, the motors carry a termination system that must be activated by remote command from the RSO, and the time to destruct will depend on reaction time, signal transmission time, termination system activation time, and any intentional delays by the RSO.

The simulation of free flight trajectories for inadvertently separated thrusting motors involves significant uncertainty for many reasons:

a. the initial attitude and attitude rates of the motor just after separation are uncertain;

b. the vehicle may be turning off course or tumbling at the time of separation, thus adding additional uncertainty to the motor initial attitude and attitude rates;

c. the thrust magnitude and direction are often uncertain, particularly if the motor nozzle is gimbaled or is damaged during the inadvertent separation (due to contact with the parent vehicle);

d. the mass properties of the motor are uncertain and vary as the motor consumes propellant; and

e. the aerodynamic coefficients of the separated motor, particularly for large angles of attack, are uncertain, or are not available and need to be estimated.

The purpose of the dispersion model for free flight is to define the dispersions of the debris resulting from free-flying motor destruct/breakup. These dispersions are often the primary source of the overall dispersions of debris resulting from a free-flying motor.

7.2.7.2 Data Sources

Generally, the dispersions of a separated thrusting motor require 6 degree-of-freedom simulations of the motor to the time of destruct, aerodynamic and inertial loads breakup, or surface impact. Significant amounts of data are needed to perform these free-flight simulations. These data may be required for an undamaged motor and for various damage states of the motor.

The data normally required, including their associated uncertainties, are:

a. motor mass properties versus time;

b. motor aerodynamic coefficients as a function of angle of attack, roll attitude, etc.;

c. thrust magnitude versus time;

d. thrust direction (may be a function of time);

e. estimates of the initial attitude and attitude rates of the motor following separation; and

f. data defining when during free flight a motor will break up or be destroyed.

Some or all of these may be available from the vehicle vendor. Often some of the data will need to be estimated by the analyst, especially the uncertainties. Although aerodynamic coefficients are often available for the motor for low angles of attack, the extension to high angles of attack may have to be estimated based on data for similar motors or using computer tools developed to estimate aerodynamic coefficients. Initial attitudes and attitude rates, including their associated uncertainties, are particularly difficult to predict and will likely need to be roughly estimated.

7.2.7.3 Modeling Considerations

The many uncertainties in the free-flight trajectories for separated thrusting motors generally means that the dispersions need to be evaluated by simulating many free-flight trajectories, where the many uncertain parameters are randomly selected for each simulation. The state vectors at breakup, destruct, or motor impact can then be used to generate corresponding scatter plots for the motor or for its fragments. These can be used to compute the statistics of the impact dispersions, to generate an impact distribution histogram, or to compute risks for each impact point (after accounting for other sources of dispersion).

Other factors that should be addressed include the following.

a. Potential damage states of the motor. For example, a motor may have a nozzle with a fixed offset that would cause the motor to tumble, but damage resulting from the inadvertent separation event could result in damage to the motor nozzle that causes a change in the thrust direction and magnitude. The entire motor nozzle assembly including the throat could be knocked off, causing the thrust to nearly align with the motor centerline. Although the damaged conditions generally result in reduced thrust, the change in the thrust direction could result in greater dispersions than for an undamaged motor.

b. Breakup of the inadvertently separated motor due to aerodynamic and inertial loads or destruct action and accounting for this in the free-flight simulations.

c. Potential causes of side thrust. In some cases, the inadvertent separation of a solid propellant motor may be due to a burn-through of the motor case or the motor case could be punctured during separation, and the resulting side thrust and the effect on the motor normal thrust may need to be modeled in the free-flight simulations.

d. Scatter plot irregularities. Often the fragment impact point scatter plot resulting from free-flying motors is highly skewed or irregular. This presents a challenge for determining an adequate representation of the impact distribution. If the distribution cannot be modeled using a closed-form distribution function, it may be necessary to perform risk computations using a numerical characterization of the distribution or by computing risks for each of the random impact points.

7.3 Debris Distribution Models

7.3.1 Model Description

The subject of this section is the characterization of the overall distribution of fragment position during free fall and at surface impact accounting for all sources of position uncertainty. These fragment distributions are required for the calculation of impact probabilities. The focus of the discussion will be on the development of two-dimensional distributions used to compute the probabilities of fragment impact onto or near specified population centers or vehicles on the surface (ground or water), to define areas where aircraft will be at risk, or to compute rough estimates of the risk to specific aircraft. Subsection 7.3.5 will address the special considerations for developing three-dimensional distributions that may be needed to compute the probabilities of impact for specific aircraft (or a spacecraft) following a defined flight path.

7.3.2 Modeling Considerations

Impact distributions can be defined in various ways.

a. One method is to fit the combined (multiple dispersion sources) dispersion statistics, or the distribution of random impact points (scatter plots from Monte Carlo simulations) that account for multiple dispersion sources, with closed-form impact point distribution probability functions, such as bivariate normal distributions. A key advantage of this approach is that the closed-form distributions are very efficient for computing impact probabilities that can be important for assessing the risks for a large library of locations (occupied buildings, groups of people in the open, populated regions, valuable assets, etc.) and/or for timely assessments of the risks during a launch countdown. The shortcoming of this method is that the true distribution of impact points may have an irregular, skewed, or segmented pattern that may not be adequately represented with a closed-form function. The development of dispersion statistics and impact distribution functions is discussed in more detail in Subsection 7.3.3.

   A variation on this approach when a scatter plot is used is to define the impact distribution using a rectangular grid to define the impact space and to compute the probability of impact within each grid cell. The proability is found by counting the number of random impact points in the cell and dividing by the total number of points (the resulting impact distribution can be represented by a two-dimensional histogram). This results in a more accurate representation of the distribution but increases the data storage and computation time required to compute impact probabilities. The grid cell size is an important consideration since the smaller the cells the more accurate the representation of the impact point distribution, but if the cells are too small the impact probability in some cells may be under- or over-estimated due to under- or over-representation of impact points in the cells. Impact probability for a given location within a cell is computed by assuming a uniform probability of impact over the cell such that the impact probability is the probability of impact within the cell multiplied by the ratio of the area of the location to the area of the cell.

b. A second approach is to use random impact points that account directly for multiple sources of dispersion to define the impact distribution. In this case debris risk calculations would be performed for each of the random impact points. The resulting risk for each impact point is weighted by its relative probability and then the risks for all random impact points for the given failure scenario (failure mode, failure time, and vehicle breakup mode) are added to get the risk. This provides a good representation of where a fragment can impact. This approach usually requires that a very large number of impact points be generated to adequately represent all of the possible impact locations for a fragment and to get an accurate assessment of the risks. The probability of impact for a specific population center and the corresponding prediction of the risk could be significantly under- or over-predicted simply because the sample of impact points within and around the location are over- or under-represented. For example, holes in the scatter of impact points could lead to a prediction of zero risk for a populated building where it is clear that credible deviations in the vehicle trajectory prior to breakup or in the fragment free-fall trajectory could result in impacts on the building. The generation of random impact points that account for multiple dispersion sources is discussed in more detail in Subsection 7.3.4.

c. A third approach is a combination of the first and second approaches. Here, some of the sources of impact uncertainty are treated by generating random impact points, while others are treated by generating closed-form impact point uncertainty distributions about the random impact points. Impact probabilities and corresponding risks can then be computed for each impact point, but now using the closed-form impact distribution function to compute the impact probability for allocation. Again, the risks need to be weighted by the relative probabilities of occurrence of the random impact points. The advantage of this method is that the impact probability distributions about each impact point help to fill in the impact region to avoid under- or over-prediction of impact probabilities.

7.3.3 Impact Distribution Functions for Multiple Dispersion Sources

7.3.3.1 Model Description

The generation of impact uncertainty distribution functions to represent multiple sources of impact dispersion involves the combining of the statistics for the impact dispersions for each source or the generation of a distribution function that fits a scatter plot that accounts for multiple sources of dispersion.

7.3.3.2 Modeling Consideration

There are two basic approaches for developing impact distribution functions.

a. In the simplest form the generation of the combined distribution involves combining the maximum (or near maximum) dispersion for each dispersion source to get the resultant maximum. The combining of the dispersions is usually done by root-sum-squaring the maximum dispersion values, although a very conservative approach could involve adding these values. The combined dispersion needs to be calculated for various directions to establish a maximum dispersion contour.

  - If only a determination that debris is contained within prescribed range boundaries is required, the maximum dispersion contour may be all that is required.
  - If risks need to be computed, the contour will need to be assigned a statistical significance, such as interpreting it to be a 3-sigma dispersion contour, and a

probability distribution function that adequately fits the contour will need to be assigned.

b. The second method is to develop impact statistics for each dispersion source in the form of a mean impact point (defined by the impact point coordinates) and a covariance matrix. The covariance matrix contains the variances in each of two orthogonal directions (diagonal terms) and the covariance as the off diagonal terms. The mean and covariance matrix for the combined dispersion sources can then be computed by adding the coordinate values of the means and by adding the covariance matrices. This requires that an assumption be made that the impact dispersions from the various dispersion sources are independent of each other. It may be necessary to verify that this assumption will not result in unacceptable errors in the statistics of the combined distribution. The resulting mean and covariance matrix statistics can be used as the basis to define an impact distribution function having its mean at the computed mean impact point and its standard deviations along principal orthogonal directions where the standard deviations and principal axis directions are computed from the covariance matrix. The challenge for the analyst is to select an appropriate impact PDF that fits the statistics.

   If the statistics of an impact distribution are generated from a scatter plot that accounts for multiple sources of impact uncertainty (see Subsection 7.3.4), the statistics can include the mean, standard deviations, correlation coefficient, and higher moments of the distribution. These can be used to select a closed-form distribution function. The function can be compared with the scatter plot or scatter plot histogram to assess the goodness of fit.

7.3.4 Scatter Plots for Multiple Dispersion Sources

7.3.4.1 Model Description

As discussed above, the distribution of impact points for some or all sources of impact uncertainty can be represented by scatter plots (random impact points). The generation of scatter plots for computing impact dispersions, for each of the sources of uncertainty, are addressed in Section 7.2. The generation of scatter plots representing multiple sources of impact uncertainty are addressed here.

7.3.4.2 Modeling Considerations

Generating scatter plots that account for multiple sources of impact uncertainty requires that random trajectories be generated where random representations of each source of dispersion are accounted for in each impact trajectory simulation. Say, for example, that the sources of uncertainty to be treated are vehicle malfunction turn, fragment drag uncertainty, and wind uncertainty. The generation of each random fragment impact point will then involve a random simulation of the vehicle malfunction trajectory (or random selection of a malfunction trajectory from the set of trajectories provided by a vehicle vendor) to vehicle breakup to establish the breakup state vector, a random selection of the fragment ballistic coefficient, and a simulation of the fragment free-fall trajectory through a randomly selected wind profile. Each of these vehicle/fragment trajectory simulations will generate a single random impact point that accounts for all three dispersion sources.

A big advantage of generating random trajectories and impact points that account for multiple sources of uncertainty is that any correlation between the dispersions for the modeled dispersion sources are better represented.

7.3.5 Considerations for Three-Dimensional Models

7.3.5.1 Model Description

Clearance zones for aircraft to avoid impact by hazardous debris from a failed launch vehicle or from a debris-generating weapons test can be generated using two-dimensional debris distributions at the aircraft altitudes of interest, similar to those developed for surface impact. Since the purpose of the clearance zone is to define regions where aircraft are not allowed, two-dimensional distributions can be used to define horizontal plane (constant altitude) areas through which hazardous debris may fall. These, together with the time it takes for all hazardous debris to fall below the aircraft altitude(s), can be used to define the areas to be cleared and the time period that clearance is required. Using these two-dimensional distributions to compute the impact probability for a particular aircraft, however, generally results in an overstatement of the risk.

A three-dimensional debris dispersion model is needed to obtain a better estimate of the risk to a specific aircraft that is flying through a hazardous region (either inadvertently or intentionally, such as an aircraft providing launch support). (A three-dimensional model might also be required to assess the risks for a spacecraft with a known orbit.) Since the debris distributions will be continually changing as the fragments progress (rise and/or fall), and the location of an aircraft is continually changing, the dispersions for each class of fragments will need to be modeled as a function of time. The four-dimensional distributions (three dimensions to define location and one for the time) are needed to define the probability of a fragment being in a given location at a given time. This, together with information to predict the fall velocity of a fragment and the velocity of the aircraft versus time, can be used to determine the vulnerable volume of the aircraft. The two extra dimensions of the distribution (time and vertical position) make the generation of these distributions of debris more complex than the generation of two-dimensional distributions.

7.3.5.2 Modeling Considerations

A viable approach to define the three-dimensional distributions is to propagate fragments from the debris-generating event to a given time after the event using a Monte Carlo method where each fragment (or fragment group) is propagated many times, with the parameters characterizing the various sources of debris dispersion randomly selected for each Monte Carlo iteration. Thus, for example, a given fragment would be propagated for a random selection of the initial fragment state vector based on the uncertainties due to normal trajectory deviations (guidance and performance uncertainties); vehicle malfunction dispersions and velocities imparted at breakup; and for a random selection of the fragment ballistic coefficient and the wind profile acting during fragment free fall. Some of the sources of dispersion, such as wind or lift, could be handled analytically by computing the dispersions for given altitudes and combining these statistically with the dispersions generated through the Monte Carlo approach.

Following are comments on the general modeling approach and some important considerations.

a. The resulting three-dimensional scatter of fragment positions at a given time can be used to define the probability of the fragment being in a given location by either 1) binning the volume of concern and computing the probability of being in each bin using the number of samples in the bin, or 2) defining a three-dimensional PDF that adequately fits the random fragment locations. For computational efficiency the use of a PDF is preferable. A density function that has been assumed in past analyses is a trivariate normal distribution.

b. The distribution of debris and the debris velocities will change significantly as an aircraft passes through a debris cloud, and the aircraft can be impacted not only on top of the aircraft but also by the aircraft running into a fragment (see Figure 7-3). In fact, frontal impacts are usually more likely for aircraft traveling at high speeds (such as commercial airliners). Thus, the speed of the aircraft and the speed of the fragment must be accounted for. The fragment velocity can be defined as an average velocity for each bin, an average over all fragment locations, or an average over all fragments within altitude bands.

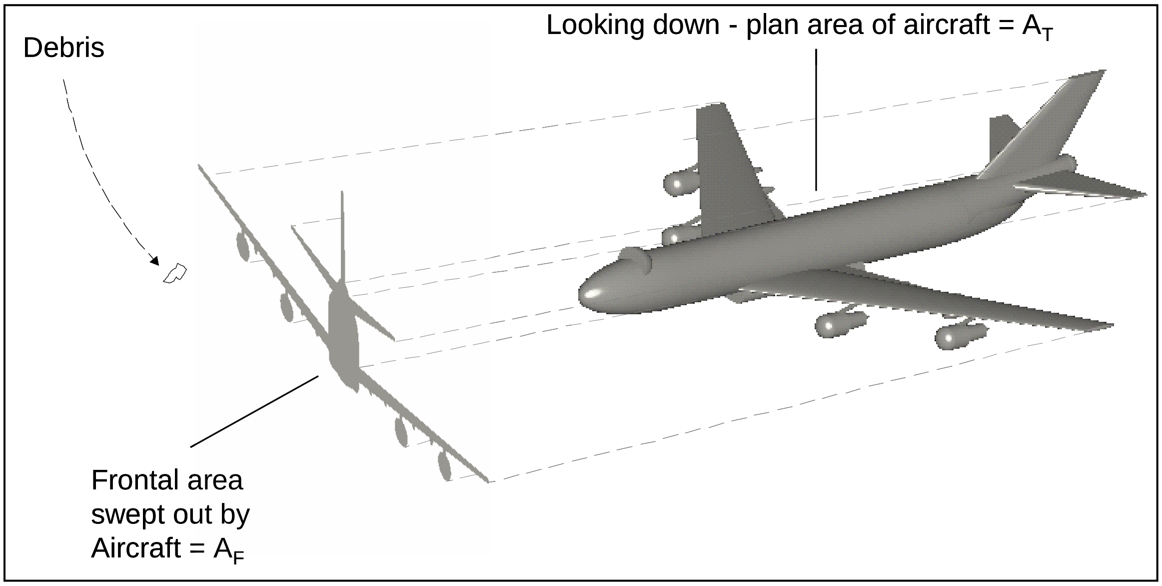

Figure 7-3. Aircraft Impact Geometry

c. Given the characterization of fragment position versus time and the velocity of the fragment, the probability of impact on an aircraft can be computed by segmenting the fall time of the debris into short time segments, computing the probability of fragment impact on the plan area or frontal area of the aircraft during the time step, and adding the probabilities over all time steps. This will need to be done for each fragment (or for each fragment group, accounting for the number of fragments in the group) and the results statistically combined to get the probability of one or more impacts by a fragment hazardous to an aircraft.

d. Previously published material shows how the areas of an aircraft can be used (in conjunction with the speed of the aircraft, etc.) to compute (1) the probability of impact for aircraft on specific trajectories through a debris cloud, and (2) probability of impact contours (Larson et al, 2005). Both of those products are useful in demonstrating compliance with the probability of impact requirements contained in the standard.

e. The AVMs presented in Chapter 6 account for the velocity of the fragment, the velocity of the aircraft, and the various areas of an aircraft. The casualty area or catastrophe area (A_{PROJ} in the following equation) given by the Chapter 6 AVMs must be modified as follows for use as a reference area (A_I) in standard probability of impact computations (much like the plan area of building is often used to compute the probability of impact on a building).

$$A_I = A_{PROJ} \frac{\sqrt{v_A^2 + v_d^2}}{v_d} \tag{7-1}$$

7.4 Impact Probability Models

7.4.1 Model Description

The purpose of this section is to discuss the approaches and considerations for using the distributions to compute probabilities of fragment impact onto populated locations and other assets of concern. The focus here is on the computation of impact probabilities for assets on the ground using two-dimensional characterizations of fragment impact distributions. The computation of impact probabilities for aircraft (or spacecraft) using three-dimensional fragment distributions is addressed in Subsection 7.3.5.

7.4.2 Modeling Considerations

For the purposes of this discussion, impact probability (P_I) is defined as a conditional probability: given a debris-generating event, the probability a specific fragment will impact a specified person, building, or other asset. The definition of impact is typically tied to the prediction of casualties or substantial damage, and thus does not necessarily imply direct physical contact. For an explosive fragment, impact includes whenever the fragment lands sufficiently close to a person or building to cause casualties or damage.

The approach to computing P_I depends on how the distribution of impact points is characterized (see Section 7.3).

a. If the impact distribution is characterized by an impact PDF, the impact probability is obtained by integrating the probability distribution over the area of concern. For people in the open, this is the area within which the people are located. For people in structures and other assets, this area will normally be the plan area of the structure or the plan area of a critical asset, with possible modification if the fragment has a steep angle of incidence at impact to account for side impacts on a building. As mentioned above, for explosive fragments the physical area occupied by people or by a structure needs to be expanded to include all locations where the blast loads can hazard the people or structure.

   (1) While the expanded area is considered for the calculation of casualties/deaths, the impact probability reported for fragments that explode upon impact is often based only on direct impact of a population center (e.g., directly hitting a building or impacting within the boundaries of a populated area).

   (2) The fragment impact probability distribution could be either a closed-form distribution, such as a bivariate normal distribution, or a segmented distribution defined by uniform probabilities of impact within grid cells, such as can be generated from a scatter plot.

b. If the random impact points from a scatter plot are to be used directly in risk calculations, the risks are computed for each point (i.e., the risks are computed based on the fragment impacting in its specific location). In this case the impact probability to be used for each random impact point is the probability that the particular impact point will occur (relative to all the other sample impact points for the given failure time and failure mode). The casualty/fatality expectation for a population center is then based on whether the fragment physically hit the center or, for explosive fragments, impacted sufficiently close to create risks due to the explosion loads or secondary debris.

   If a scatter plot is used to characterize the impact distribution for some sources of impact uncertainty and an impact PDF is used to represent the other sources of impact uncertainty, the risks are again computed for each random impact point but with a probability of impact computed by integrating the density over the area of concern. This impact probability times the probability of occurrence of the random point is then the net impact probability.

Although the probability of impact for each impacting fragment is all that is required to compute the associated risks, a total probability of impact may be desired in order to assess the likelihood of a fragment impact into politically or environmentally sensitive areas. This total probability of impact needs to account for all of the fragments created by the debris-generating event. A definition of total impact probability used at several of the ranges is the probability of one or more impacts.

With the above definition, the probability of impact for a given debris-generating event is given by the following general relationship:

$$P_I(1-or-more) = 1 - \prod_i \left(1 - P_I(i)\right) \tag{7-2}$$

where

$P_I(i)$ = Impact probability for the i^{th} fragment,

and the product is over all fragments generated by the event. This probability of impact will, of course, need to be multiplied by the probability of the debris-generating event and summed over all events in order to get the total probability of impact for a population center or the total for a mission.

7.5 Modeling for Explosive Fragments

This section discusses modeling issues specific to the computation of risks for explosive fragments. Subsection 7.5.1 discusses the modeling of explosive yields for fragments that can explode upon impact. Subsection 7.5.2 discusses the approach and issues associated with the calculation of risks for explosive fragments that can hazard a population center even when the fragment does not physically impact on the center.

7.5.1 Explosive Yield Models

7.5.1.1 Model Description

Failures of space launch vehicles often result in impacts of intact (or mostly intact) components containing liquid or solid propellants. When solid propellants are present, vehicle breakup can also produce multiple chunks of propellant as well as inert materials. When these propellant-bearing components and chunks impact (either the ground or an object) an explosion can occur. In addition, explosion of an intact vehicle may occur at the launch point, in the air, or upon impact of the vehicle. Explosive effects – a blast wave and ejected fragments – expand outward rapidly and can hazard a large area. The effects of these hazards must be characterized to produce a valid risk estimate.

A yield factor is usually an output of an explosive yield model. The yield factor for a given propellant explosion is the weight of TNT that would produce an equivalent explosive output divided by the weight of propellant. Although the yield factor concept is straightforward, a complication arises because different yield factors generally result depending on whether the explosive output is measured in terms of the peak overpressure or the positive phase impulse. (See Chapter 6 for an explanation of these terms). Once the yield factor is obtained, the yield itself (usually expressed as pounds of TNT) is the product of the yield factor and the propellant weight.

7.5.1.2 Data Sources

Several sources of information are available upon which yield models can be based, including the following.

a. Project Pyro (1968) provided test data for some models of liquid-propellant explosions for three combinations of oxidizer/fuel: liquid oxygen/RP-1, liquid oxygen/liquid hydrogen, and hypergols (nitrogen tetroxide/hydrazine). Propellant weights ranged up to 100,000 pounds for the cryogenic combinations and up to 1,000 pounds for the hypergolic combination. Models resulting from Project Pyro provide yield factors as functions of impact speed on hard and soft surfaces.

b. A more recent test program (2003) for liquid propellants conducted at the White Sands High Energy Blast Facility provided data for yield models of six propellant combinations: liquid oxygen/liquid hydrogen, nitrogen tetroxide/liquid hydrogen, nitrogen tetroxide/hydrazine, liquid oxygen/hydrazine, liquid oxygen/RP-1, and hydrogen peroxide/Jet A. Two types of testing took place: distributive mixing and drop. The distributive mixing tests were designed to produce the maximum mixing possible before ignition and were performed on all six propellant combinations. The drop tests were performed only on the liquid oxygen/liquid hydrogen combination in various tank configurations. The tanks were dropped onto a concrete pad from a tower. Maximum yields obtained from the High Energy Blast Facility tests are lower than those obtained for the three similar propellant combinations in Project Pyro.

c. Several organizations and individuals have produced models of explosive yield for solid propellants. Models have been developed for Class 1.1 and Class 1.3 solid propellants. Generally, Class 1.1 materials are those whose shock sensitivities are greater than that of TNT, while Class 1.3 materials have shock sensitivities less than that of TNT. Class 1.1 propellants are used in a few space-launch systems and some weapons systems (e.g., Minuteman II Stage III), while Class 1.3 propellants are used in many space-launch and missile system components. A 1991 model provided maximum yield factors for both types.

d. The more recent (1998) Propellant Impact Risk Assessment Team (PIRAT) project provided new yield factors for Class 1.3 HTPB solid propellants. The PIRAT project measured explosive propagation in samples in a series of tests, and modeled the results using a two-dimensional hydrocode. The code was used to predict yield factors for different diameter cylindrical motors with both side-on and end-on impacts, as well as for different chunk weights. Models based on PIRAT data predict yield factors as functions of motor diameter, impact speed and orientation (side-on, end-on) and propellant weight for motors or motor segments; and as a function of impact speed and weight for propellant chunks.

e. Another solid propellant impact yield model that has been used is based on a combination of PIRAT and empirical data (from tests and accidents).[224] This model provides the capability to compute yield factor uncertainty based on the observed scatter in the data and does not require knowledge of the orientation at impact for motor segments.

7.5.1.3 Modeling Considerations

The following issues should be considered.

- The characteristics of blast waves produced by explosions vary depending on the explosive material involved. The characteristics and behavior of blast waves as they expand outward from an explosion are well known for TNT. In addition, the interactions of TNT blast waves on humans and structures have been studied and documented. Consequently, it is convenient to estimate the explosive yield of rocket propellants in terms of equivalent weight of TNT (TNT yield). These equivalent yields are only approximate because the shapes and durations of the blast waves produced by propellant explosions often differ from those produced by TNT.
- A valid yield model should account for the propellant weight at impact, the impact speed, the configuration or orientation of the propellant, and the impacted surface material.
- Yield models for various propellants have been available for years. Models have been based on accidental explosion data, test program data, engineering judgment, and combinations of these.
  - Yields for liquid propellants vary with propellant type and the amount of mixing that occurs before ignition. Total mixing of all available propellants is unlikely because auto-ignition occurs within milliseconds of mixing, and the resulting explosion drives apart the unmixed portions.
  - Most liquid-propellant explosions are characterized as deflagrations rather than detonations.
  - When modeling liquid-propellant yield factors, some attention must be paid to tank configuration. Tests show a relationship between yield factor and propellant area-to-weight ratio.

NOTE	Impacting solid propellants may or may not explode, depending on propellant configuration (contained, uncontained, orientation), weight, and impact speed. Yields vary with these same factors plus the nature of the impacted surface.

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[224] Wilde, P. and M. Anderson. "Development of a Yield Histogram for Space Shuttle Blast Risk Analyses.", Paper presented during the JANNAF Safety and Environmental Protection Subcommittee Meeting, San Diego, 26-30 April 1999.

7.5.1.4 Model Uncertainty

Yields estimated from accidents and test programs often vary significantly from those predicted by models. In many cases, the causes of such variations are unknown. For liquid propellants, estimated yields vary depending on the volume of propellant mixing assumed to occur before ignition. Solid-propellant yield models based on PIRAT results are currently considered to be the best available despite the fact that the two-dimensional hydrocode used in the PIRAT analyses assumed infinitely long cylinders. The hydrocode only simulates fully loaded motors and does not model nearly spherical motors such as an inertial upper stage or a Star motor. The effect on yield factor of larger and larger bore-holes, resulting as propellant burns, is unknown. These and other factors can lead to considerable uncertainty in estimated yields.

7.5.2 Risk Computation for Explosive Fragments

7.5.2.1 Model Description

The calculation of casualty (or death) expectation for fragments that explode at impact requires special treatment since the impact explosion can cause casualties even if the fragment does not physically impact a person or a structure. Three potential causes of concern exist: blast loads (defined by the peak overpressure and impuse) can directly cause casualties to exposed people; blast loads can indirectly cause casualties through structural damage or collapse and window breakage; and secondary debris thrown out from an explosion can strike a person or structure.Thus, the risk computations should consider all of the possible impact points of an explosive fragment that are sufficiently close to a person, structure, or populated area (people distributed into various shelter categories) to create hazardous blast loads or impacting secondary debris.

7.5.2.2 Modeling Considerations

The predicted risks for an explosive fragment with a given explosive yield (usually defined by its TNT equivalency) will vary with the distance of the explosion from unsheltered people or from an occupied building due to the varying overpressure loads.It may also be necessary to consider the orientation of the explosion relative to buildings. A good way to address this is to compute the E_C for each potential impact location of the explosive fragment, as defined by the fragment impact probability distribution or the random impact points from a scatter plot. These would then be weighted by the probability of impacting in each location and summed to get the total casualty expectation for the given explosive fragment (given occurrence of the debris-generating event).

The process is illustrated in Figure 7-4 where a grid has been set up about a population center that extends out to the maximum distance that the overpressure loads are hazardous to the people or the building. The explosion is assumed to occur in each of the grid cells and the corresponding risk computed. The relative probability of impacting in the grid cell is computed by integrating the impact probability distribution over the area of the grid cell. The risks for each grid cell are then multiplied (weighted) by their corresponding impact probability and these are summed to get the total risk for the fragment.

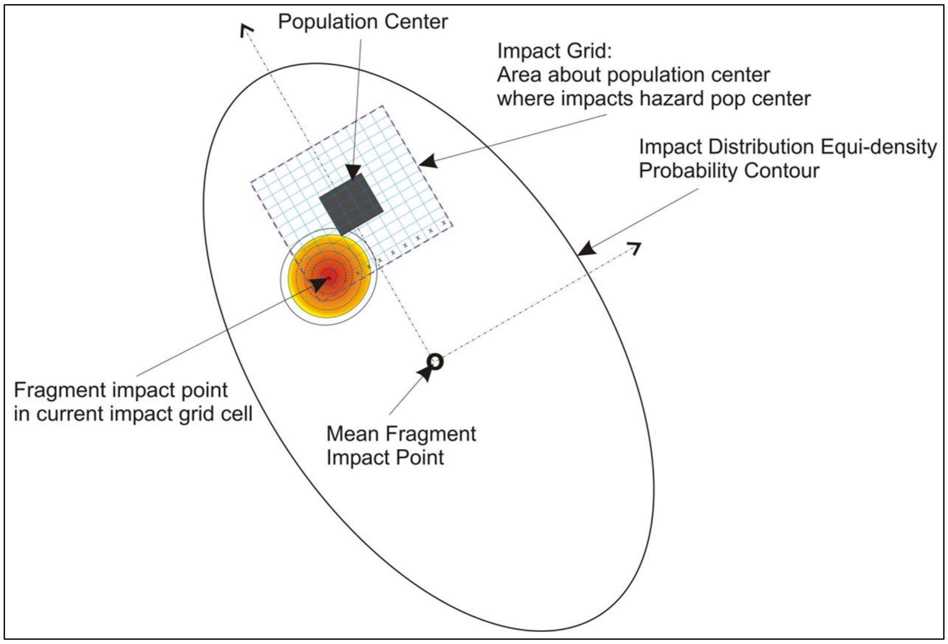

Figure 7-4. Procedure for Computing Risks Due to an Explosive Fragment

The calculation of casualties due to overpressure loads for a specific explosive event (location of the explosion relative to a populated site and explosive yield) is further discussed for unprotected people in Subsection 7.6.1.2 and for people in a building in Subsection 7.6.3.

A similar process may need to be performed for the secondary debris thrown out from an explosion (debris from the exploding vehicle fragment and/or the impacted surface). The secondary debris contribution to the risks becomes important when the debris can be thrown to distances beyond which the risks due to the overpressure loads are high.

7.5.3 New Propellant Characterization

Any propellant formulation that is novel to launch operations should undergo testing to establish potential yield and expected overpressure and impulse behavior for application in flight safety analysis models. Theoretical computations tend to over-estimate yields and data from other industries typically includes combustion with air, making specific testing necessary.

The testing of any new propellant should consider the following variables.

- The impact speed, up to a maximum credible speed given the safety system design.
- The credible propellant quantity contribution to the blast wave.
- Impact orientations – if necessary, a conservative simplification would be to test the maximum expected yield orientation.
- Tank or motor configurations and contained pressure, including potential for sympathetic detonations.
- The likely impact surface variability and its relative hardness.

All testing should have the following goals.

- Produce and collect pressure and impulse data necessary to determine the potential explosive yield or to produce an alternative predictive model.
- Collect data, including thermal or visual, to establish fireball size and formation.
- Collect any data that could be relevant to far field blast overpressure modeling, as referenced in Section 8.3, such as weather profiles and very far field pressure and impulse measurements to establish attenuation trends.
- Collect and document fragment information, including impact location, dimensions, weight, and shape classification.
- Test as closely to expected flight-like conditions as reasonably possible, including dimensions, scale, and mixture ratio.
- Produce statistically significant results for small-scale tests and perform multiple large-scale tests to establish confidence in trends.
- Ensure that the credible reaction potential is enveloped under both static and dynamic conditions, including for high-velocity impacts.

Test configurations can be novel or follow historic test programs that produced useful data. Historic liquid test programs have utilized the following test configurations. Examples of test programs[225] are listed in Subsection 7.5.1.2.

- Distributive Mixing Testing – small-scale characterization testing for bounding the potential explosivity.
- Confined by Missile Static Testing – used to scale up propellant quantity while keeping impact velocity low (< 10 ft/s).
- Confined by Ground System Testing – used to increase impact velocity while utilizing the same quantities of propellant as the Confined by Missle testing.
- High Velocity Impact Testing – often high speeds (> 200 ft/s) cannot be reached in the Confined by Ground System test fixture, so those tests are broken out.
- Sympathetic Detonation Testing – used to determine the credibility of detonation from one stage affecting either another stage or a booster or vise versa.

7.6 Vulnerability and Casualty Models

Vulnerability models are used to predict the level of damage to humans, structures, or vehicles due to the impact of a launch vehicle fragment or due to blast loads from an exploding fragment. Vulnerability models that may need to be considered are:

a. the direct impact of a fragment or secondary debris created by the fragment impact onto unsheltered people;
b. the impingement of blast loads on unsheltered people;

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[225] See the recent work by E.J. Tomei and James Nichols, TR-2019-00959

c. the direct impact of a fragment onto a structure;
d. the impingement of blast loads on a structure;
e. the direct impact of fragments onto ships, boats, and aircraft;
f. the impingement of blast loads on ships and boats.

The models for the direct impact of fragments, secondary debris, and blast loads on people are referred to as human vulnerability models. These models are used to predict the P_C or fatality due to these threats. These models are used not only to predict the casualties for unprotected people but can also be used to predict casualties for people in a structure or vehicle if the debris or blast load environment within the structure/vehicle can be defined.

The vulnerability models for structures and vehicles are used to predict damage levels that can be used both for estimating economic loss and as the basis for predicting the casualties to the occupants of the structure or vehicle.

This section discusses general approaches and the important considerations and factors for developing vulnerability models. Threshold levels defining lower bound levels of threat at which injury to a person or damage to a structure or vehicle will occur have been presented in Chapter 6. These threshold levels can be used to determine if the calculation of E_C or the calculation of damage to structures/vehicles will be required for a given threat (fragment impact or explosive loading) or to perform conservative risk analyses.

7.6.1 Human Vulnerability Models

Human vulnerability models are used to predict the P_C or fatality due to direct impact by a fragment, impact by the secondary debris created by the primary fragment impacting the ground, impact by the secondary structural debris created by the fragment penetrating into a building, or exposure to blast loads from an exploding fragment. These models are addressed separately for inert fragment/secondary debris impact and for blast loads.

7.6.1.1 Human Vulnerability to Inert Debris Impact

7.6.1.1.1 Model description

This model addresses human casualties that result from impact by inert (non-explosive) fragments. This includes (a) direct impact by a vehicle fragment, including impact by the fragment after it penetrates a structure; (b) impact by secondary debris created due to fragment splatter or cratering of the impacted surface; (c) secondary debris thrown out from an exploding fragment; or (d) impact by the secondary debris created by fragment penetration of or blast damage to a structure.

Casualties from inert debris result from one or more of several injury mechanisms.

- Penetration of the body by small, compact, high-speed fragments. Since this generally requires high velocities it is not expected to result from impacting launch vehicle debris since, except for very early flight times, the fragment velocities are not sufficiently high. It may result, however, from secondary debris from an exploding fragment or from secondary debris created by explosion loads acting on a structure. Penetration can be segmented into chunky penetration and piercing penetration.

- Laceration or penetration by ragged metal fragments and glass shards due to energy transferred to body organs and tearing of body tissues.
- Blunt trauma resulting from the acceleration of body organs or excessive body deflections. Blunt trauma includes localized blunt trauma from small fragments that can impact over critical organs, thus producing greater injuries.
- Crushing resulting from heavy fragments pinning body segments between the fragment and a rigid object such as the ground or a wall.
- Fragment impact causing a person to fall and strike the ground/floor, wall, or other object.

7.6.1.1.2 Modeling considerations

Historical models for human vulnerability to debris impact have been relatively simple models that predict casualty as a function of the fragment impact kinetic energy. These have often been expressed in terms of a single kinetic energy level above which a person is assumed to be a casualty. Common values that have been used range from about 11 ft-lbs for the casualty threshold to 58 ft-lbs for assured casualty. An improvement on this is models that provide the probability or severity of casualty as a function of fragment physical parameters such as kinetic energy, mass, mass density, area, impact velocity, shape, and various combinations of these parameters. Many of the early models in this area are based on data from impact tests with a variety of shaped impactors on humans (including both live subjects and, for higher energy impacts, cadavers), animals (live subjects and cadavers), and dummies. The highest fidelity models consider the detailed biomechanical phenomena of impact as a function of time for specified impacting fragments and impact conditions.

The modeling of human vulnerability is complex, and a detailed discussion of the various modeling approaches is beyond the scope of this supplement. Factors and considerations for developing human vulnerability models are as follows.

a. The model must quantify the level of injury delivered to an individual by the impact. As noted above, the simplest historical models have typically expressed an energy threshold (e.g., 11 ft-lbs) that, based on test data, represents the minimum impact energy where impacts have resulted in sufficient injury to require some level of prompt, professional medical attention, the minimum definition of a severe casualty. Fatal injuries within this standard are defined to be an injury that would, with high probability, be fatal to the individual assuming that no medical intervention is possible.
b. All of the relevant injury mechanisms (listed above) should be addressed.
c. The characteristics of the impacting fragment need to be addressed. The key parameters are the fragment mass, shape, density, deformability, orientation, and impact velocity (both magnitude and direction).
d. The characteristics of the human that is being impacted should be addressed. Key parameters are the body mass, exposed area, and susceptibility to injury. Two common categories used are adults and children. Further breakdowns can be considered, such as male or female and age categories. It should be noted that age and overall health play a significant factor. Survival of a given level of injury varies by a large amount between

elderly or infirm adults and robust, athletic adults in their prime, with susceptibility to the underlying injury varying by a factor of three or more.

e. The location of the fragment impact on the body is important. A breakdown of the body that has been used is the head (with special consideration for the eyes), thorax, abdomen, and limbs. Consideration also should be given to the location (front, back, side) of impact on the body and the offset of the fragment impact location relative to the center of gravity of the impacted body part.

f. More sophisticated models can consider fragility of individual organs or organ systems and parameters directly related to injuries, such as strain levels. Consideration of these factors, as well as anomalous injuries such as side-body impacts that can deliver stresses that rupture the aorta due to in-body stress concentrators, and *commotio cordis*, the stoppage of the heart by a blunt trauma impact so timed as to disrupt the normal cardiac rhythm, tend to be confined to research activities.

g. Body posture is another important factor since it affects both the body reaction and the exposed area. Common postures considered are standing, sitting, and prone.

h. Other considerations that may need to be addressed are the effect of a fragment impacting multiple body parts and impact by more than one fragment on a person.

The calculation of casualties requires that the level of injury considered to constitute a casualty be defined. For this standard the AIS has been selected as the method for defining level of injury. The AIS was originally developed for use by crash investigators to standardize data on frequency and severity of motor vehicle-related injuries. It has been extended to epidemiological research, trauma center studies to predict survival probability, patient outcome evaluation, and health care systems research. The general definitions used for the AIS allow injuries of different natures to fall into standardized categories. The AIS level selected as the minimum to constitute a casualty for debris risks is AIS level 3. The general definition of this level is reversible injuries; hospitalization required.

7.6.1.2 Human Vulnerability to Blast Loads

7.6.1.2.1 Model description

Human casualties can result due to exposure to blast loads (overpressure and impulse) resulting from the impact of an explosive fragment. The primary sources of impact explosions are vehicle fragments, intact stages, or an intact vehicle that contains liquid or solid propellants. The explosive yield is usually expressed in terms of equivalent pounds of TNT (TNT equivalency). Modeling to predict TNT equivalency is addressed in Subsection 7.5.1.

The primary injury mechanisms for blast loads are injury to soft tissue and injury due to whole-body translation[226]. The body parts most susceptible to soft tissue injury are the eardrums, lungs, gastro-intestinal tract, and larynx. Rupture of the lungs can lead to death. Whole-body translation can lead to casualty due to the impact of the body with a rigid object such as the ground/floor or a wall, resulting in blunt trauma, penetration, or crushing injuries.

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[226] Whole-body translation is the motion of a person due to the velocity imparted by the blast forces acting on a person’s body.

7.6.1.2.2 Modeling considerations

Following are considerations for modeling the vulnerability of humans to blast loads.

- Blast load human vulnerability models should consider both the effect of the peak overpressure of the blast wave and the impulse (the integral of the blast wave time history). The peak overpressure is the key threat for soft tissue injuries to the eardrums, lungs, gastro-intestinal tract, and larynx. The impulse leads to injuries due to whole-body translation.
- The potential for the occurrence of multiple injuries, which increases the likelihood of occurrence of a casualty, may need to be addressed.
- In addition to the threat from the overpressure loads from an exploding fragment there is also the possibility that fragments will be thrown out from the shattering of the hardware containing the exploding propellant or from the impacted ground, particularly if significant cratering occurs. The potential thrown debris will increase the risk to people within the throw range of the debris and may even result in a larger area threatened due to fragments thrown beyond the range of hazardous overpressure loads. Thermal (including firebrands thrown out) and toxic hazards resulting from an explosion may also need to be considered, although these hazards have generally not been addressed as part of debris hazard analyses. Toxic hazards are generally evaluated separately (see Chapter 8) and thermal hazards have not heretofore been considered for debris risk analyses.

Models for human vulnerability to blast loads have ranged from very simple models that assume that a person will become a casualty if exposed to an overpressure greater than a specified value, to the more recent OP-I functions that give the P_C or fatality as a function of P and I. These functions are portrayed as curves for various P_C levels plotted as a function of P and I.

7.6.2 Model for the Casualty Area for Inert Debris Impact in the Open

7.6.2.1 Model Description

Inert debris impacting into areas with unsheltered people hazards the people in one or more of the following ways (see Figure 7-5).

a. Fragment impacts a person directly during its initial fall to the ground.
b. Fragment impacts a person during its travel following a bounce off the impacted surface.
c. Fragment strikes a person during a slide or roll along the surface.
d. Fragment spatters at initial impact with pieces from the shattered fragment thrown out to impact a person.
e. Fragment creates a crater with ejected debris from the impacted surface being thrown out and impacting a person.

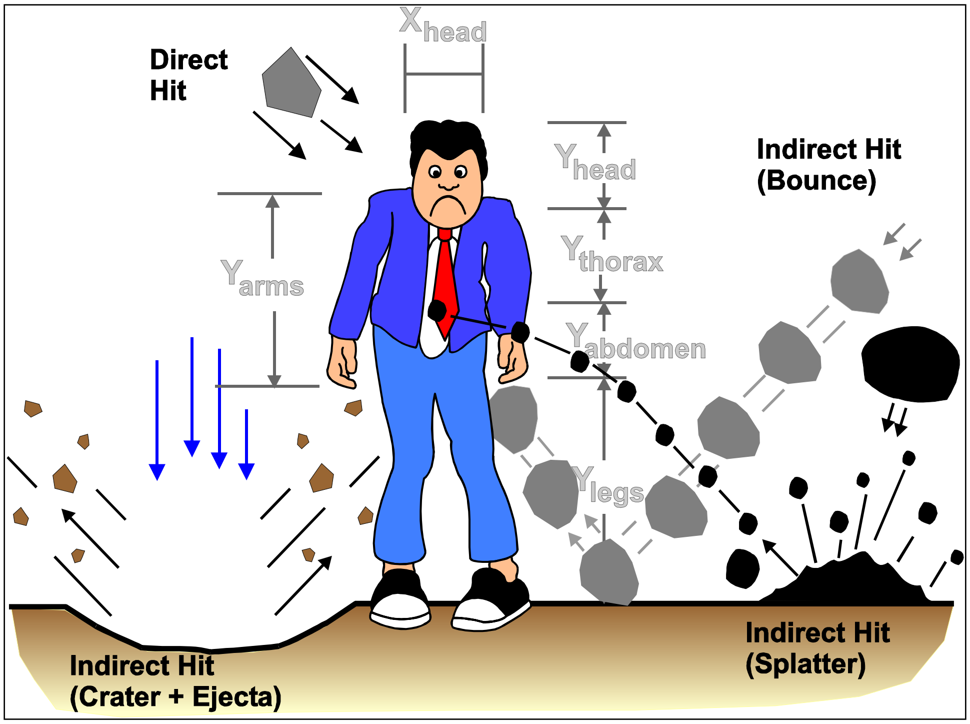

Figure 7-5. Hazards to an Unsheltered Person from Inert Debris Impact

The casualty area is the area on the ground about the impact point of a fragment within which an exposed person would be expected to become a casualty.

7.6.2.2 Modeling Considerations

The modeling of the casualty area for inert debris impact in the open requires an evaluation of each of the above listed phenomena. This involves modeling of the kinematics of the fragment's initial impact trajectory; bounces off the impacted surface and sliding or rolling along the surface; and the kinematics of the secondary debris resulting from splattering and cratering. It also involves modeling of the velocity and mass of the fragment or the secondary debris pieces at the locations during their trajectories where they could impact a person. Inert debris impacts can result from inert fragments created by the breakup of a launch vehicle; due to an intercept event; or from fragments thrown out from the impact of an explosive fragment (both debris from the shattered fragment and from the impacted surface). The casualty areas for debris thrown out from an explosion may only be of concern when the fragments can be thrown beyond the range where the P_C due to the overpressure loads is high.

Modeling considerations and factors include the following.

a. The casualty area should address the total area about the fragment impact point where a person could be located and be struck by the fragment or a secondary debris piece that has sufficient mass and velocity (or kinetic energy) to cause a casualty.

  (1) The P_C (AIS level 3 injury or greater) for a person at a given location can be based on the human vulnerability model for inert debris (see Subsection 7.6.1.1).

  (2) A simple, conservative approach is to assume that any impact by a fragment anywhere on a person constitutes a casualty (i.e., that the P_C is always 1.0), in

which case the casualty area would become the total area in which a person could be located and be impacted by the fragment or by a secondary debris piece.

b. Depending on the human vulnerability model used, the model for the casualty area may consider the part of the body that has been impacted. For example, the human vulnerability model could depend on whether a fragment impacts the head, thorax, abdomen, or a limb. The trajectory of the fragment and the trajectories of any secondary debris would need to be analyzed to determine the body part impacted for each location of a person.

c. Since there may be large uncertainty as to whether a fragment will splatter upon impact versus bouncing and/or sliding, the casualty area may need to be computed for each of these phenomena and the resulting casualty area obtained either by weighting each by their relative probabilities of occurrence and adding or by conservatively assuming that the one resulting in the larger casualty area applies.

d. The size and posture of a person needs to be defined. Usually for impacts in the open a person is assumed to be standing. To simplify the kinematic computations a cylindrical model of a person could be used. For a fragment that bounces, the portion of the bounce trajectory for which the bottom of a fragment is over the head of a person should not be included in the casualty area.

e. The bounce characteristics of the fragment need to be modeled. Usually this is expressed in terms of a coefficient of restitution[227] from which the rebound velocity of the fragment can be computed. Since it is difficult to determine the bounce characteristics for each impacting fragment, it may be necessary to estimate a coefficient of restitution to apply to all fragments or to all fragments having given general characteristics (for example, fragments consisting of uncontained solid propellant tend to have high bounce potential due to the rubbery nature of the fragments).

f. The impacted surface will affect the bounce and slide of a fragment. If the impact surface is known, the coefficient of restitution can be based on this surface; however, in general the impact surface is not known, and an average surface may need to be assumed, such as compacted soil. Variation of the coefficient of restitution with impact speed may also be a factor.

g. A fragment may slide upon impact. Usually slide characteristics are expressed in terms of a coefficient of friction that is used to estimate the slide distance. An average coefficient of friction may need to be estimated for all (or for specific categories of) fragments based on the assumed impacted surface. Generally, if a fragment will bounce following impact the amount of sliding between bounces will be a relatively small contribution to the total casualty area. For smaller fragments a slide into a person can only impact the foot or lower leg and thus may not constitute a serious injury.

h. Fragments might splatter upon impact. Modeling fragment splatter generally involves the definition of a maximum splatter range (or a probability distribution for splatter range), the number of splatter fragments, a mean splatter fragment size, and a mean fragment

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[227] The coefficient of restitution is the ratio of the rebound speed to the speed of approach in a collision. It is used here to compute the speed of rebound perpendicular to an impacted surface by multiplying it by the speed of approach perpendicular to the surface. In a perfectly elastic collision the coefficient of restitution has a value of 1.0.

weight. Experimental data and/or impact hydrocode simulations may be needed to develop estimates of the splatter parameters.

7.6.3 Structural Vulnerability Models

Structural vulnerability models are used to assess the damage to structures and to predict the casualties (or fatalities) for the occupants of these structures. This section is presented as two subsections, one for inert debris impacting a structure and one for blast loads acting on a structure.

7.6.3.1 Vulnerability Modeling for Inert Debris Impact on a Structure

7.6.3.1.1 Model description

Inert (non-explosive) debris from launch and test operation failures hazards people inside structures primarily due to the potential of the fragments to penetrate into the structure. The ability of a fragment to penetrate is primarily a function of its weight, shape, and speed at impact, although the material and density can also play a significant role. Since most debris will usually be falling vertically or near vertically at the time of structure impact, the primary hazard is from the debris penetrating through the roof and any ceiling of the structure, and potentially through one or more floors of the structure to hazard people on lower floors. If hazardous fragments can be impacting at shallow angles of incidence, it may be necessary to consider impacts on the sides of structures.

The source of the hazard from inert debris is the potential for the fragment itself to strike a person as well as the potential for the structural debris from the roof, ceiling, or floor(s) brought down by the penetration of the fragment to strike a person. The concept is portrayed for a three-story structure with a flat plywood deck roof in Figure 7-6.

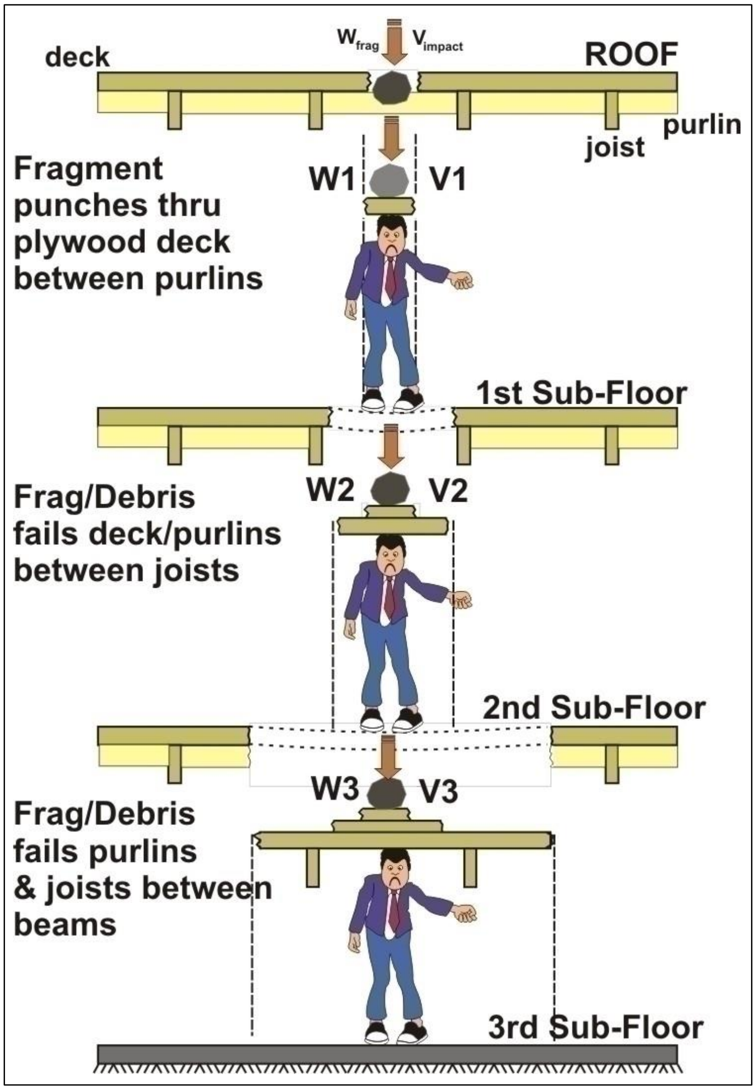

Figure 7-6. Example of Fragment Penetrating Multiple Floors of a Structure

The prediction of casualties within a structure involves a description of the characteristics of the fragments resulting from fragment penetration (weights, shapes, and velocities) and the application of human vulnerability models for inert debris as discussed in Subsection 7.6.1.1.

7.6.3.1.2 Modeling considerations

Vulnerability models for structures should be developed for various categories of structures to cover the range of structures that may be occupied and hazarded by the debris from a failed vehicle. This categorization can be simple or detailed depending upon the required accuracy of the risk analysis. In a more detailed approach, the type of roof and floors to be used to represent each structure category will need to be defined in order to assess the probabilities of penetration and the resulting debris environment (penetrating fragment and collapsing building structure) at each floor level.

Important considerations and factors that should be addressed for the development of the inert debris structural vulnerability models are as follows.

a. Materials, sizes, and spacing of the construction elements.
b. Location of the fragment impact on the structure roof relative to the structural elements (beams, joists, purlins, etc.).
c. Weight, shape, size, and velocity of the impacting fragment.
d. Area of the roof or floor that fails, ranging from a simple punch through of sheathing (shear failure) to the shear or bending failures of supporting joists, purlins, and beams.
e. Velocity of the fragment following penetration of the roof and of each floor (used to determine if the fragment penetrates the next floor level and to calculate the P_C if it impacts a person) and velocities of each structural debris piece that results from the penetration.
f. Computation of the probabilities of casualty for people struck by a penetrating fragment or by the resulting structural debris pieces by applying inert debris human vulnerability models (see Subsection 7.6.1.1).

For each combination of fragment and structure category the total area for each floor of a building within which a person may become a casualty (casualty area) or a fatality (fatality area) is defined. This casualty area is used in the calculation of the estimated number of casualties based on the density of people on a floor.

For each structure type it may be necessary to calculate casualty/fatality areas for a large number of fragment impact locations, weights, shapes, and velocities to obtain a model to address all cases of concern.

7.6.3.2 Vulnerability Modeling for Explosive Debris Blast Loads on Structures

7.6.3.2.1 Model description

Fragments that explode upon impact hazard people inside structures primarily due to blast loads (blast wave peak overpressure and impulse[228]) acting on a structure causing structural damage or collapse and window breakage, or blast loads acting directly on people inside a structure (due to open windows or other openings in the building). Casualties result from the flying/falling structural debris, flying glass propelled into the structure, and the blast wave entering the structure.

There are three ways explosive fragments can produce casualties inside buildings: detonation outside of a building that causes substantial structural damage; detonation (before or after penetration) upon impact with the building; and penetration of the structure without explosion (in which the vulnerability models for inert debris impact on a structure would apply). The P_C -causing impact outside of the building is by far the most likely occurrence. Therefore, the other two possibilities do not substantially contribute to the total risk calculation. This contribution to the risk may still need to be considered, particularly if the explosive yield of the fragment is small.

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[228] Impulse is defined as the integral of the positive phase of overpressure with respect to time.

7.6.3.2.2 Modeling considerations

The unique risk factor for explosive fragments is that they can impact a considerable distance (perhaps thousands of feet) from a structure and still contribute significantly to the risk. Thus, risk contributions need to be considered for impacts in an area that is much larger than the footprint of the structure itself (see Subsection 7.5.2). Unlike inert debris that usually only causes failure of the roof of a structure, blast loads can cause failure of walls, windows, and vertical support members in addition to failure of the roof.

Approaches and considerations for development of a structure vulnerability model for blast loads are as follows.

a. The blast loads from an impact explosion are a function of the explosive yield (usually expressed in terms of TNT equivalency; see Subsection 7.5.1) and the distance of the explosion from a structure. The contribution to the risk needs to be addressed for all fragment impact locations sufficiently close to a structure to experience hazardous blast loads.

b. The blast loads on a structure are also a function of the orientation of the structure relative to the blast front, and thus the model may need to also consider this.

c. Atmospheric conditions affect the propagation and attenuation of the blast wave and thus the blast loads acting on the structure. For explosions occurring close enough to a building to cause significant structural damage the atmospheric conditions tend to be a secondary issue. Blast loads on structures located at large distances from the explosion, which are significantly affected by atmospheric conditions, usually only pose risks due to window breakage. These risks are not generally handled as part of a debris risk analysis but instead are assessed as part of a DFO risk analysis (see Chapter 8).

d. The prediction of casualties within a structure involves modeling the level of damage to the structure including window breakage. It includes determination of the level of damage to the walls, roof, and other structural elements.

e. Blast load vulnerability models need to be developed for various categories of buildings covering the range of structures that may be occupied and hazarded by the debris from a failed vehicle. This categorization can be simple or detailed depending upon the necessary accuracy of the risk analysis.

f. For each structure category the type of roof, walls, floors, and other key structural elements will need to be defined. This should include the types of materials (e.g., wood, brick, metal, concrete block, reinforced concrete, etc.) and construction methods. The types (e.g., annealed, tempered, dual paned, blast filmed), numbers, and sizes of windows are also needed.

g. For a simplified approach it may be possible to estimate the P_C for a person in a structure based simply on the predicted level of structural damage and the number of windows broken. For example, empirical casualty data collected for accidental or terrorist explosions and for earthquakes could be used to relate the P_C to the level of building damage and the number of broken windows.

   The level of damage to a structure is sometimes expressed in terms of the percent structural damage.

h. A more detailed approach involves defining the debris and glass environments inside of a structure. This requires the modeling of the numbers, sizes, shapes, velocities, and directions of travel for the structural fragments to determine the areas hazarded. Also the numbers, sizes and throw distances of the glass shards from windows should be addressed.

   (1) Human vulnerability models (Subsection 7.6.1.1) can be used to determine the portions of the hazarded areas within which a person would be expected to become a casualty. This should account for the variation in the probability of a person becoming a casualty throughout the hazarded area and account for all fragments and glass shards that could impact a person at each location.

   (2) Flying glass becomes the dominant contributor to casualties whenever the potential impact locations of an explosive fragment are beyond the range where significant structural damage will occur.

7.6.4 Ship/Boat Vulnerability Models

7.6.4.1 Model Description

Risks to ships and boats can be an important consideration for some launch ranges, particularly those that launch out over the ocean. Although clearance of hazarded areas is the preferred method of reducing or eliminating the hazard to these vessels, there may be situations where there are ships or boats in the hazarded areas at the time of a launch. A launch decision may need to be made based on the level of risk (casualty/fatality expectation). Thus, vulnerability models may be required to perform the risk calculations.

7.6.4.2 Modeling Considerations

7.6.4.2.1 Inert debris

Modeling of the vulnerability of ships/boats to inert debris impact involves the vulnerability of people to direct impact by a fragment for the people in the open (on the top deck) and the vulnerability of people in structures for the people located in the deck house, in the superstructure, or below one or more decks.

a. The modeling approach for these is similar to those for land-based structures. Subsection 7.6.1.1 provides vulnerability models for humans impacted by inert fragments. Subsection 7.6.2 provides modeling of the total casualty area for inert fragment ground impact for people in the open accounting for secondary effects (although the secondary effects will be somewhat different for impacts on a ship/boat). Subsection 7.6.3.1 provides vulnerability models for inert debris impact on structures.

b. There are some additional issues that may need to be addressed for inert fragments.

   (1) The impact could result in the capsizing or sinking of the vessel, thus putting the entire crew at risk.

   (2) An impact could result in people being thrown overboard.

7.6.4.2.2 Explosive debris

Modeling of vulnerability for ships/boats for debris that explodes upon water impact involves consideration of many different sources of risk. These sources of risk are dependent on the type of vessel, how far the explosion is from the vessel, and how deep the water is where the ship is located.

a. First, the ship is exposed to the portion of the blast wave that is transmitted through the air. People on the top deck would be subjected directly to the blast loads. The blast wave could also damage or possibly collapse the deckhouse or superstructure and threaten the occupants due to the flying/falling debris. The blast wave could break windows resulting in flying glass (although windows on ships and boats will tend to be stronger and of materials that would make them less likely to break). If the blast loads are severe enough, the integrity of the ship or boat could be compromised, resulting in capsizing or sinking.

b. Additional sources of risk result from energy of the explosion that is transmitted into the water. The shock wave transmitted into the water (referred to as underwater shock) will travel through the water and could hit the side of the ship and/or reflect off the ocean floor and hit the underside of the ship. Because water has a higher density than air, this shock wave will reach the ship hull faster than the shock wave that travels through the air. The underwater shock could cause sudden motions of the vessel potentially injuring occupants. People who are standing could break their ankles or feet, people who are sitting could incur spinal injuries, and people that are standing or sitting could be injured by being thrown into bulkheads, walls, or decks. The underwater shock could also cause failure of the hull of the ship or boat, thereby causing the vessel to sink.

c. The explosion energy transmitted into the water will create a wave on the surface of the water, which could rock the ship or boat enough to knock crewmembers off of their feet or, if the wave is large enough, capsize the vessel. This surface wave travels slower than both the underwater shock and the air blast wave.

d. The combined effects of these multiple sources of casualties (air shock wave, underwater shock, surface wave) may need to be addressed. That is, the effect on the ship due to the underwater shock may affect the level of hazard posed by the wave action and/or by the air blast wave.

Vulnerability models may need to be developed for various types of ships and boats. Consideration should be given to the various construction methods (wood, fiberglass, steel, or a combination of these materials) and the various sizes, which could range from a relatively small recreational boat to a large cargo or cruise ship several hundred feet long and having several decks.

7.6.5 Aircraft Vulnerability Models

7.6.5.1 Model Description

The vulnerability of aircraft to debris impacts was under investigation at the time the standard was developed. Chapter 6 provides AVMs.

Historically, a conservative estimate was used to define inert fragments that could be hazardous to aircraft. The risk acceptability standard for aircraft assumed that an impact by a compact fragment greater than 1 gram results in a catastrophic failure of the aircraft. This fragment weight is considered to be the approximate minimum that is hazardous to an aircraft. Although the hazard posed by a 1-gram fragment is based on ingestion by an aircraft engine, the

1-gram criterion has been used to apply to an impact anywhere on an aircraft. This standard was initially applied for all types of aircraft and fragments of all sizes, shapes, and materials.

It has been recognized that an improved AVM is needed to avoid unnecessary conservatism in predicting the risks to aircraft and for defining the clearance areas for aircraft during launch or weapon test operations. Chapter 6 presents AVMs based on the findings. This section documents important considerations for the assessment of aircraft vulnerability.

7.6.5.2 Modeling Considerations

Modeling considerations and factors follow.

a. In general, the vulnerability of aircraft should be dependent on properties of the debris, the aircraft at risk, and the impact geometry, and should address the probability of outcomes of various severity levels caused by the impact on the aircraft.

b. The type of aircraft plays an important role in the severity of a fragment impact. It is important to consider the classes of aircraft of concern and develop vulnerability models appropriate to each type. Aircraft materials, locations of critical systems, and regulatory design requirements are important for assessing the vulnerability of an aircraft. Possible classes of aircraft may include air carrier, commuter aircraft, helicopters, private jets, private small craft, and military aircraft.

c. The characteristics for each class of aircraft of concern will need to be defined, such as the engines, projected areas, control systems, skin type, etc. Within each aircraft class it may be necessary to assess the variations in the aircraft characteristics and select representative aircraft models to use for the development of vulnerability models to be applied to the class of aircraft. Engineering data for the representative aircraft will be required to define both the external and internal components, including material types and thicknesses. In order to apply the vulnerability model to other types of aircraft within a class it may be necessary to define parameters to allow scaling of representative aircraft to the other aircraft in the class, such as fuselage dimensions, wing dimensions, and engine size/number.

d. The vulnerability models should consider the effects of debris of various sizes and effective densities impacting from various angles upon each section of the aircraft. The debris parameters to be considered include material type, shape, and weight.

e. All of the critical failure scenarios should be addressed, includingengine ingestion, secondary fragments generated by engine or propeller damage, windshield penetration, wing or tail penetration, fuel line or tank rupture, compromise of aircraft controls or control surfaces (including electrical or hydraulic system damage), and cabin depressurization such as may be caused by a fragment penetrating into the fuselage (potentially creating secondary debris). Both direct and indirect effects need to be addressed where indirect effects include such things as ejection of passenger(s) due to fuselage penetration and depressurization, casualties from a rapid altitude drop due to a depressurization event, and of course loss of control of the aircraft resulting in a crash.

f. Aircraft-induced aerodynamic effects may need to be considered. Examples of these effects include airstream deflection of debris so it does not hit the aircraft or an engine sucking in debris that would otherwise not impact the aircraft. This is only an issue for fragment densities well below the density of aluminum.

g. The development of comprehensive vulnerability models may necessitate detailed structural effects analyses using available structural dynamics codes, use of available penetration models, and evidence of effects from any available incident data (such as debris sucked into an engine). Models should be compared with empirical evidence where possible. Incident data can be collected that includes foreign object damage from FAA/Department of Transportation (DOT) and/or military databases.

7.7 Models for Casualty Area and Fragment Probability of Casualty

7.7.1 Model Description

Section 7.6 discussed vulnerability models for humans, structures, and vehicles. The concepts of casualty area and P_C was also introduced. The casualty area or the fragment P_C for an impacting fragment is used in the calculation of casualty (or fatality) expectation (see Section 7.8) by relating the impact of a fragment to the E_C given impact. The purpose of this section is to define and discuss these parameters and the approaches and factors that should be addressed.

Casualty area (A_C) is defined to be the area about the impact point of a fragment within which a person would be expected to become a casualty (AIS Level 3 or greater injury). It is a theoretical region within which 100% casualties are expected to occur and outside of which no one is a casualty. It usually accounts for the probability of a person becoming a casualty and therefore does not necessarily include the entire area hazarded by an impacting fragment. It is a weighted, or effective, area consisting of the sum of the products of sub-areas where the fragment could hazard a person times the corresponding probability that, if the person is located in the sub-area, he or she would become a casualty.

Fragment probability of casualty (P_{CF}), on the other hand, is the probability that a person in a given location will become a casualty given that a fragment from a given hazardous event hazards the location. It is sometimes used instead of a casualty area in the calculation of casualty expectation. This P_{CF} is not the same as the individual risk P_C referred to elsewhere in this standard, which is the total risk to an individual accounting for all hazardous events, all potential failure times, all debris generated by each event at each failure time, and the probabilities of occurrence of these events.

Casualty areas are often used to compute the risks to people for inert fragments, and P_{CF} is often used to compute the risks to people for explosive fragments, although this is not always the case and depends on the types of vulnerability models used. When casualty area is used for inert fragments it would be applied to:

a. the direct impact of an inert fragment or secondary debris created by the fragment impact into unsheltered people;

b. the direct impact of a penetrating inert fragment or debris created by the fragment penetration into people inside of a structure; or

c. the direct impact of fragments into ships or boats.

When P_{CF} is used for explosive fragments, it would be applied to:

a. the impingement of blast loads (peak overpressure and impulse) from an explosive fragment on unsheltered people;

b. the impingement of blast loads on a structure causing structural collapse and window breakage; and

c. the impingement of blast loads on ships and boats causing structural damage, window breakage, underwater shock, or wave action causing sudden motion of the ship or boat.

It is also expected that P_{CF} will be used for inert fragments impacting an aircraft.

7.7.2 Modeling Considerations

For an inert fragment impacting a given type of structure the A_C is the area inside of the structure (for a given floor of the structure) within which all occupants would become casualties (see Subsection 7.6.3.1). For inert fragments impacting a ship or boat, the A_C is either the area for unsheltered people (people on the top deck) or the area for sheltered people (people in the deck house or below one or more decks).

Because of variations in vulnerability in a normal population, not everyone exposed to given blast loads (peak overpressure and impulse) will become a casualty. The probabilities are summed (after weighting by the probability of impact at the location) over all hazardous impact locations.

The P_{CF} due to an explosive fragment for people in a given type of structure is a function of the damage to the structure (see Subsection 7.6.3.2).

a. One approach is to estimate the P_{CF} for people in the structure from the level of structural (and glass breakage) damage based on empirical data.

b. Another approach is to model the falling/flying debris and flying glass fragments within the structure and then use the human vulnerability models to predict the P_{CF}.

    (1) In this case the probability may need to be a function of the location within the structure (near an outer wall, in the interior of the structure, near a window, etc.).

    (2) If the environment inside of a structure is modeled, it may be determined that developing a casualty area would be a better way to compute the risks than using a P_{CF}.

Although this section addresses relatively complex methods for computing casualty areas and fragment probabilities of casualty, there is a very conservative approach that could be used that would not require complex modeling. This is to assume that anyone that is exposed to a hazard will become a casualty. In this case:

a. any unsheltered person within the total area hazarded by an inert fragment or the secondary debris would be assumed to be a casualty;

b. any person in a structure that is impacted by a fragment that can penetrate the structure would be assumed to be a casualty;

c. any unsheltered person exposed to a threshold hazardous overpressure (see Chapter 6) or greater would be assumed to be a casualty;

d. any person in a structure subject to a threshold hazardous overpressure (see Chapter 6) that could cause hazardous damage to the structure or its windows would be assumed to be a casualty; and

e. any person on a ship, boat, or aircraft that is impacted by a hazardous fragment or overpressure would be assumed to be a casualty.

If this approach, or some conservative variation thereof, is used and the risks are found to be acceptable, then the more complex models may not be needed.

7.8 Risk (Casualty/Fatality) Expectation Models

7.8.1 Model Description

Preceding sections have discussed the various models needed to perform risk analyses for the debris generated by in-flight launch vehicle and weapons test failures, intercept events and planned hardware jettisons. This section discusses the approach and the considerations for combining the output of these various models to generate risk estimates; expressed in terms of casualty expectations, fatality expectations, individual P_C and individual P_F.

Casualty expectation is defined as the expected number of casualties from a launch or weapons test. It is the mean number of casualties predicted to occur as a result of a launch/test operation if the operation were to be repeated many times. Fatality expectation is defined similarly. Individual P_C or P_F is defined as the probability of a specific individual becoming a casualty or a fatality.

The basic equation for computing the casualty expectation for specific debris generating event, specific fragment and specific population center is:

$$E_C = \Sigma P_I (1/A) A_{Ci} N_i \qquad (7\text{-}3)$$

(used when the casualty model gives a casualty area, often used for inert fragments), or

$$E_C = \Sigma P_I \; P_{CFi} \; N_i \qquad (7\text{-}4)$$

(used when the casualty model gives a P_{CF}, often used for explosive fragments)

where the summation is over the number of shelter categories, and where:

E_C = Casualty expectation.
P_I = Probability of the fragment impacting so as to hazard the population center (Section 7.4).
A = Population center area.
A_{Ci} = Casualty area for the ith level of sheltering (see Section 7.7 for casualty area calculation).
N_i = Population in the ith level of sheltering.
P_{CFi} = P_{CF} for the ith level of sheltering (Section 7.7 discusses calculation of P_{CF})

The equation for fatality expectation is the same except that casualty area or P_{CF} is replaced by fatality area or fragment P_F.

Level of sheltering is the type of shelter afforded people, including no sheltering (in the open). The levels of sheltering can range from a simple model where everyone is assumed to be in the open or in a certain type of structure (defined by the building characteristics) to more complex models where people are allocated into multiple types of shelters, and a unique casualty area or P_{CF} is computed for each shelter type.

7.8.2 Modeling Considerations

An option sometimes employed to compute E_C, leading to a conservative (high) estimate of the casualty expectation, is to assume that everyone in a population center impacted by a fragment is a casualty. Then $E_C = \Sigma\, P_I\, N_i$.

Another option sometimes employed is to assume that all people within a population center are in the same level of sheltering, and the casualty area or P_C used is that for the selected level of sheltering. In this case the level of sheltering often selected is no sheltering, i.e., all of the people are in the open. Although assuming that all people are in the open may lead to a conservative estimate of the E_C, this is not always the case. Heavy inert fragments that can penetrate into a structure can pose a greater hazard (larger casualty area or larger P_{CF}) to people inside of the structure than if they were in the open. Also an explosive fragment can pose a greater hazard to people inside of a structure than if the people were in the open. Thus, making the assumption that all people are in the open (or in a selected type of structure) should be done with care in that it could actually result in an underestimation of the risk.

The other terms in the equation for casualty expectation require the development of a population library containing data defining population centers. The library consists of descriptions of where people are located, the area occupied, the number of people in each location, and definitions (or assumptions) of how these people are sheltered. The terms are as follows.

a. The location of people is defined in terms of the coordinates (usually latitude and longitude) of the centroid of the populated area.

b. The area, A, is the land area of the population center and is the area used in the calculation of P_I.

c. The allocation of the people by shelter category (where N_i is the number of people in the i^{th} category) can range from simply assuming that everyone is in the same type of sheltering to defining the number of people within each of several shelter categories (including unsheltered people).

    (1) The shelter categories can consist of a few basic categories for which vulnerability models are developed based on a representative structure description for each category.

    (2) For more detailed modeling, the shelter categories may consist of many structure types made up of specified wall, roof, and window characteristics, and may include a separate structure category for each floor of multi-story buildings. In some cases unique structure categories may be developed for specific buildings close to a launch site for which there is a special concern for the safety of the occupants (or a concern for the economic loss that could result from a launch accident).

Population libraries can range from relatively simple to very detailed. A basic population library might consist of cells defined by a grid covering the land area of concern. A common grid system used is a latitude-longitude grid. Comments regarding cell coverage are as follows.

a. Cells are typically a consistent size such as 1 degree in longitude by 1 degree in latitude.
b. For each cell the number of people and the assumed sheltering (such as everyone in the open) are specified. People could also be assumed to be distributed into various types of sheltering, perhaps by allocating a percentage of the people to each shelter type.
c. People are usually assumed to be uniformly distributed over each cell.
d. Cells can be used to define more detailed population distributions if the cell sizes are made smaller.

A more detailed population library distributes people into population centers where each center is defined by its location, area, and distribution of people by shelter category.

a. The population centers typically consist of small land areas close to a launch site, with more specific allocations of people to shelter types, and become larger and more generic as the location gets further from the launch site.
b. In the immediate launch area a population center may consist of a single building or a single floor of a multi-story building.
c. As the distance from the launch site increases the population centers become complexes of several buildings and/or populated open spaces, subdivisions of cities or towns, entire cities, or (for far distances) counties, states, or even countries.

Greater detail in the population data allows for more accurate predictions of the risk. As mentioned earlier, the level of detail used to allocate people into shelter categories can have a significant effect on the risk predictions, but greater detail requires more work to define the locations and sheltering of people and requires the development of more numerous and more complex shelter vulnerability models.

The basic equation for E_C presented in this section gives the risks to a given population center for the impact of a single fragment resulting from a debris-generating event. Each event is defined by a vehicle failure scenario, planned hardware jettison, or weapon system planned debris-generating event, where a vehicle failure scenario is a specific mode of failure occurring at a specific time of flight and resulting in a specific mode of vehicle breakup. This E_C is conditional in that it is the casualty expectation given that the debris-generating event occurs. To get the total conditional risk to the population center, the E_C values need to be combined over all fragments generated by the event. Then to get the actual risk for the debris-generating event, the population center conditional E_C needs to be multiplied by the probability of the event occurring. Finally to get the total risk to the population center the contributions for all debris-generating events (covering all flight times) need to be combined.

The total risk for a mission is the sum over all hazarded population centers.

Individual P_C can be computed directly from the total casualty expectation. It is usually computed separately for each population center since the probability can vary significantly from population center to population center. For a given population center the individual P_C is the total E_C for the population center divided by the number of people in the center. In some cases the individual P_C might be computed for each shelter category within a population center, possibly for each floor of a building. The maximum probability value over all population centers is typically used to get the individual P_C to determine if individual risk criteria are met. Individual P_F is computed similarly.

The probabilities of occurrence of the debris-generating events are important inputs to risk computations.

a. For planned events, such as a weapon system intercept or hardware jettison, it is the probability of achieving the event.
b. For failure scenarios, the probabilities are usually defined for short flight time intervals, and the probability is computed by integrating a failure rate (P_{fail} per second) over the time interval. A failure at a specified time during the interval (such as the mid-point time) is then used to represent a failure at any time during the interval.

The development of failure rates (for each of the credible vehicle failure modes) is a complex process and is beyond the scope of this standard, although methods have been developed by various launch ranges and other organizations (such as the FAA and NASA), and many of these are documented. The accuracies of the failure rates are very important to the accuracies of the risk predictions. Changing the failure rate uniformly (over flight time) for a given failure mode by a factor results in the corresponding risk prediction being changed by the same factor.

CHAPTER 8

Other Hazards

8.1 Introduction to Other Hazards

An FSA must evaluate all hazards to ensure a compliance with the risk acceptability criteria provided in Chapter 3 of the standard. The focus of the standard has traditionally been on the inert and explosive debris resulting from a range mishap, but other hazards can exist and sometimes pose significant risks. These other hazards typically include exposure to toxic propellants, glass breakage from far-field overpressure, and exposure to radiation. This chapter provides screening criteria and analysis considerations for hazard and risk assessments of these other hazards, as well as acceptable means to demonstrate negligible risk from other hazards by exclusion or containment.

8.2 Toxic Release Assessment

8.2.1 Scope

An FSA is used to establish launch commit criteria that protect all exposed people from any hazard associated with toxic release from a catastrophic[229] launch failure or a nominal launch and demonstrate compliance with the risk criteria of Chapter 3 of the standard. The analysis should:

a. account for any toxic release that will occur during the proposed flight of a launch vehicle or that would occur in the event of a flight mishap;
b. determine if toxic release can occur based on an evaluation of the propellants, launch vehicle materials, payloads, and estimated combustion by-products;
c. account for both normal combustion by-products and the chemical composition of any reactive materials;
d. account for any operational constraints and emergency procedures that provide protection from toxic release;
e. account for all people that may be exposed to the toxic release, including those on land and on any waterborne vessels, populated offshore structures, and aircraft that are not operated in direct support of the launch.

Detailed guidance for managing the risks from in-flight releases of toxic materials is provided in 84 Fed. Reg. 72[230] and in Chapter 5.1, Elsevier 2013.[231]

To ensure adequate protection from exposure to any toxic release, toxics must be identified and the risks either contained or managed to acceptable levels. A toxic release hazard analysis for launch vehicle flight should identify all propellants used for each launch and identify

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[229] "catastrophic" meaning that the vehicle is destroyed with or without FTS activation; not to be confused with "catastrophic risk" which implies that a large number of people are casualties.
[230] Toxic Hazards for Flight. 84 Fed. Reg. 72 (15 April 2019), pp. 15435-15436.
[231] Haber, J., J. Chrostowski, and R. Nyman. "Toxic Hazards" in *Safety Design for Space Operations*. San Diego: Elsevier, 2013. pp. 187-217.

whether each propellant is toxic or non-toxic as well as any other potential sources of release of toxic materials.

8.2.2 Analysis Products

The products of a basic toxic release hazard analysis for launch vehicle flight should include the following:

a. for each launch, a listing of all toxics used on all launch vehicle components and any payloads;

b. the chemical composition of each toxic and all toxic combustion by-products;

c. the quantities of each toxic and all toxic combustion by-products involved in the launch;

d. for each toxic and combustion product, identification of the toxic concentration threshold used and a description of how the toxic concentration threshold was determined.

8.2.3 Toxic Hazard Containment

A potential casualty distance for each toxicant and a toxic hazard area for the launch should be determined for a launch that uses any source of toxic substance. A potential casualty distance for a toxicant is the farthest distance from the launch point where toxic concentrations may be greater than the associated toxic concentration threshold in the event of a release during flight. A toxic hazard area defines the region on the Earth’s surface that may be exposed to toxic concentrations greater than the toxic concentration threshold of any toxicant involved in a launch in the event of a release during flight. The toxic hazard area can be determined from the potential casualty distances. A range should strive to contain the toxic hazard by evacuating people or by imposing meteorological constraints; however, if the hazard cannot be contained then a statistical risk management approach should be employed.

a. Toxic Hazard Area. Having determined the potential casualty distance for each toxicant, a toxic release hazard analysis should determine the toxic hazard area for a launch as a circle centered at the launch point with a radius equal to the greatest potential casualty distance for all the toxicants involved in the launch. If the toxic release does not originate at the launch point then the toxic hazard area should be adjusted or expanded accordingly. Containment is satisfied if:

    (1) there are no populated areas contained or partially contained within the toxic hazard area; and

    (2) no member of the public is present within the toxic hazard area during preflight fueling, launch countdown, flight, and immediate post-flight operations at the launch site.

b. Evacuation of the Toxic Hazard Area. For a launch where there is a populated area that is inside or partially within a toxic hazard area, containment may be achieved if the range evacuates all people from the populated areas at risk and ensures that no one is present within the toxic hazard area during preflight fueling and flight.

c. Flight Meteorological Constraints. Containment of toxic hazards may also be achieved by constraining the flight of a launch vehicle to favorable wind conditions or to times when atmospheric conditions result in reduced potential casualty distances such that any potentially affected populated area is outside the toxic hazard area. A range may reduce the potential casualty distances by imposing operational meteorological restrictions on specific parameters that mitigate potential toxic downwind concentration levels at any potentially affected populated area to levels below the toxic concentration threshold of each toxicant in question.

d. Containment Analysis Products. The products of a toxic release containment analysis for launch vehicle flight should include the following.

    (1) The potential casualty distance for each toxic propellant and combustion product and a description of how it was determined.

    (2) A graphic depiction of the toxic hazard area or areas.

    (3) A listing of any wind or other constraints on flight, and any plans for evacuation.

    (4) A description of how the range determines real-time wind direction in relation to the launch site and any populated area and any other meteorological condition in order to implement constraints on flight or to implement evacuation plans.

8.2.4 Statistical Risk Management

If toxic hazards cannot be contained as described, the range should use statistical toxic risk management to protect public safety. For each such case, a range should perform a toxic risk assessment and develop launch commit criteria that protect the public from unacceptable risk due to planned and potential toxic release. A range should ensure that the resultant toxic risk meets the collective and individual risk criteria requirements contained in Chapter 3 of the standard.

a. Toxic Risk Assessment. A toxic risk assessment should account for the following.

    (1) All credible vehicle failure and non-failure modes, along with the consequent release and combustion of propellants and other vehicle combustible materials.

    (2) Vehicle failure rates associated with credible toxic release modes.

    (3) The effect of positive or negative buoyancy on the rise or descent of each released toxicant in the atmosphere.

    (4) The influence of atmospheric physics on the transport and diffusion of each toxicant.

    (5) Meteorological conditions at the time of launch.

    (6) Population density, location, susceptibility (health categories), and sheltering for all populations within each potential toxic hazard area.

    (7) Exposure duration and toxic propellant concentration or dosage that would result in casualty for all populations.

b. Risk Management Products. When using the statistical toxic risk management approach the products of the risk assessment for launch vehicle flight should include the following.

(1) A description of the range's toxic risk management process, including an explanation of how the range ensures that any toxic risk from launch meets the risk criteria of Chapter 3 of the standard.

(2) A listing of all models used.

(3) A listing of all launch commit criteria that protect the public from unacceptable risk due to planned and potential toxic release.

(4) A description of how the range measures and displays real-time meteorological conditions in order to determine whether conditions at the time of flight are within the envelope of those used for toxic risk assessment and to develop launch commit criteria, or for use in any real-time physics models used to ensure compliance with the toxic launch commit criteria.

8.3 Far-Field Window Breakage

An FSA is also used to establish launch commit criteria that protect people from any hazard associated with far-field blast window breakage effects due to potential explosions during launch vehicle flight and demonstrate compliance with the risk criteria of Chapter 3 of the standard. The far-field blast window breakage analysis should account for DFO and any overpressure enhancement to establish the potential for broken windows due to overpressures and related casualties due to falling or projected glass shards. As with all hazards, containing the hazard is the primary goal but if containment cannot be achieved then a statistical risk analysis must be performed to ensure compliance with the risk criteria.

Detailed guidance for managing the risks from far-field window breakage is provided in 84 Fed. Reg. 72[232] and in Chapter 5.2, Elsevier 2013.[233]

8.3.1 Analysis Considerations

The analysis should account for:

a. the potential for DFO or overpressure enhancement given current meteorological conditions and terrain characteristics;

b. the potential for broken windows due to peak incident overpressures below 1.0 psi and related casualties;

c. the explosive capability of the launch vehicle on the pad at liftoff, at impact, at altitude, and potential explosions resulting from debris impacts, including the potential for mixing of liquid propellants;

d. characteristics of the launch vehicle flight and the surroundings that would affect the population's susceptibility to injury, such as shelter types and time of day of the proposed launch;

e. characteristics of the potentially affected windows, including their size, location, orientation, glazing material, and regional conditions; and

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[232] Far-field Overpressure Blast Effects Analysis. 84 Fed. Reg. 72 (15 April 2019), p. 15435.

[233] Haber, J., J. Chrostowski, and R. Nyman. "Distant Focusing Overpressure Risk Analysis." In *Safety Design for Space Observations*. San Diego: Elsevier, 2013. pp. 218-249.

f. the hazard characteristics of the potential glass shards, such as falling from upper-building stories or being propelled into or out of a shelter toward potentially occupied spaces.

8.3.2 Analysis Products

The products of a far-field window breakage analysis should include the following.

a. A description of the methodology used to produce the far-field blast overpressure analysis results, a tabular description of the analysis input data, and a description of any far-field window breakage mitigation measures implemented.

b. For any far-field window breakage hazard or risk analysis, an example set of the analysis computations.

c. The values for the maximum credible explosive yield as a function of time of flight.

d. The distance between the potential explosion location and any population center vulnerable to the far-field blast overpressure hazard. For each population center, identify the exposed populations by location, number of people, and window types and sizes.

e. Enforcement of any mitigation measures established to protect people from far-field window breakage hazards and any launch commit criteria established to ensure the measures.

8.4 Radiation Hazard Analysis Guidelines

8.4.1 General

An FSA should establish launch commit criteria that protect people from any hazard associated with radiation effects due to unconstrained directed energy or released radioisotope materials caused by equipment malfunction or vehicle flight anomalies.

8.4.2 Hazard Definition

The hazards to humans from radiation exposure can logically be divided into two categories: non-ionizing radiation and ionizing radiation. The electromagnetic spectrum of radiation spans extremely low-frequency energy wavelengths (10^{10} µm +) through high-frequency wavelengths (10^{-6} µm and smaller) with the visible light portion (0.4 – 0.8 µm) being most familiar. The effects of this energy on the human body are dependent upon exposure time and distance. The low-frequency, large-wavelength energies of the spectrum can be considered non-ionizing, since there is not a tendency to strip electrons from atomic structure as is the case for ionizing energies in the high-frequency, small-wavelength portion. The neutral zone of visible light provides a separation of these two hazards. The human eye has evolved to operate in this region and is less vulnerable to damage from energies of this portion of the spectrum. However, visible light can also present risk to the optic receptors and must be examined.

8.4.3 Non-Ionizing Radiation Hazards

On the ranges, non-ionizing radiation hazards are typically provided from sources that generally involve electromagnetic emissions from equipment such as radio and microwave devices that can include:

a. spacecraft/flight vehicle telemetry and communications systems;

b. radar systems;
c. satellite earth stations;
d. radio frequency (RF) generators;
e. cellular telephone base stations;
f. heat sealers (radiofrequency and microwave heat sealers);
g. lasers and laser pointers;
h. microwave communications transmitters and receivers;
i. non-destructive inspection and test equipment;
j. 60-Hz electrical power systems, power lines, substations, transformers, etc.;
k. ultraviolet radiators.

These non-ionizing hazards tend to affect the most vulnerable parts of the human body; namely the eyes and the skin, as directed energy exposure can cause both photochemical and thermal damage to biological tissue.

Energy collimated in laser beams poses a particular hazard capable of spanning long distances with potential to threaten personnel unrelated to the operation (e.g., airline pilots flying near the area, workers on distant elevated platforms or buildings). Lasers are used in a wide variety of tactical applications, such as rangefinders, designators, illuminators, laser pointers and markers, direct-fire simulators, disruptors, and dazzlers. Lasers can even produce hard kill effects when sufficient energy dwells on the target. Lasers are also used in communications systems, lidar, guidance and landing systems, and underwater detection and imaging systems. Depending upon a laser beam's energy density and wavelength at the point of exposure, Class III and Class IV laser exposure can result in permanent injury despite autonomous physiological aversion responses, such as blinking.

High-energy lasers (HELs) represent a special subset of Class IV lasers for which direct beam exposure poses a lethal risk and even diffuse reflections can pose eye or skin hazards. The HELs may also pose a fire or similar catastrophic damage hazard to materials exposed to the beam. The specific hazards for missions involving HELs must be assessed on a case-by-case basis.

Procedural controls for containing the beam, the volume through which it propagates, and any laser surface danger zone resulting from the termination of the beam at the target and surrounding area form the backbone of protection for mitigating risks of Class III and Class IV laser exposure on the range.

8.4.3.1 Screening and Safety Procedures

Each Service maintains a program to characterize Class III and Class IV military exempt lasers through a laser hazard evaluation that is summarized in terms of wavelength, energy, divergence, and the resulting nominal ocular hazard distance (NOHD) and nominal skin hazard distance in the Laser Safety Review Board letter. For outdoor testing or training of Class III or

Class IV lasers, the Military Handbook (MIL-HDBK) 828[234] series provides authoritative safety guidance for DoD ranges. The military handbook provides guidance for understanding the hazardous volume around the beam and the surface danger zone with intersecting surfaces as well as guidance for establishing a safe buffer zone. The MIL-HDBK-828 also informs that that Class III and Class IV lasers shall be treated as direct fire weapons, which establishes an operating context for safely employing lasers that ensures "the public be protected from the risk of death, injury, illness, or property damage from the use of lasers by DoD activities," as mandated by DoDI 6055.15.[235] It is important that participants use proper laser eyewear protection with the correct optical density for the wavelength of the laser. Proper attire or shielding to protect against skin damage may also be required.

8.4.3.2 Risk Analysis Guidelines

The preferred method of ensuring range safety in the employment of outdoor Class III and Class IV lasers is by containment of the hazardous laser energy so that non-participants and critical infrastructure are not exposed to hazardous laser energy. This may include propagation of the laser beam within the NOHD through exclusive-use airspace and clearance of surface danger zones, which should be cleared of all non-participants. In the case of HELs, there is no safe direct exposure, so all personnel should be kept out of the danger volume and the effective NOHD of diffuse reflections must be added to the hazard containment pattern.

The goal of a Probabilistic Risk Analysis (PRA) is to quantitatively assess the risk of specific mishaps resulting in harm or damage to the surrounding public and infrastructure that may be exposed. The PRA should result in an understanding of the boundaries beyond which the risk of exposure to hazardous laser energy does not exceed that which one would normally expect in the course of normal life activities.

8.4.4 Ionizing Radiation Hazards

Ionizing radiation sources can affect the human system by stripping electrons from atomic structures, and thus causing alterations in the DNA that can ultimately lead to life-threatening cancers. Sometimes difficult to detect, particles of radioactive substances can enter the human body via multiple pathways through the respiratory, skin, digestive, and circulatory systems.

8.4.4.1 Screening and Safety Procedures

The DOT regulations on transportation container design test and qualification provide protection from release of radioisotope materials in many accident conditions. Following these basic procedures, monitoring worker exposure, and limiting access to these sources is often sufficient. However, in the case of a major radiological source that may be scheduled for launch, there is no DOT-approved vessel to completely contain the radioisotope material in the event of a launch abort.

Major radiological sources are determined based upon the particular isotope's A_2 value. Values for sources can be found in the 1996 edition of Regulations for the Safe Transport of

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[234] Department of Defense. "Range Laser Safety." MIL-HDBK-828C. 31 March 2017. May be superseded by update. Retrieved 16 October 2023. Available at https://quicksearch.dla.mil/qsSearch.aspx.

[235] Department of Defense. "DoD Laser Protection Program for Military Leaders." DoDI 6055.15. 25 August 2023. May be superseded by update. Retrieved 16 October 2023. Available at https://www.esd.whs.mil/Directives/issuances/dodi/.

Radioactive Material.[236] Should the inventory exceed the A_2 value for that radionuclide it is considered a major source and more extensive safety review and security protocols become necessary.

For launch approval of major radiological sources the range must comply with the requirements of applicable Presidential directives and National Security Council memoranda, such as Presidential Directive/National Security Council Memorandum (PD/NSC) 25[237] and more recently National Security Presidential Memorandum 20.[238]

8.4.4.2 Risk Analysis Guidelines

For small radioisotope sources a specific, formal risk assessment may not be required other than a hazard analysis that identifies the dangers of exposure and provides procedural mitigations. For major radiological sources scheduled for launch, PD/NSC-25 dictates that a thorough risk assessment must be accomplished to include pre-launch, ascent, and any potential orbital maneuvers prior to escape from Earth.

A risk assessment for major radiological sources scheduled for launch should include an extensive analysis of all potential accidents that can release any quantity of radioisotope from the system. A detailed probabilistic risk assessment for major radiological sources should provide subsystem failure probabilities that sum to a total launch failure probability, apportioned through the phases of pre-launch, ascent, staging, and escape orbit transfer. Event sequence diagrams often provide a means to estimate the conditional probabilities leading to accident outcome conditions that describe the effects a particular accident scenario may have on the radioisotope source. By understanding the potential threat to the source material, the potential release quantity and particle size distribution can be modeled for meteorological dispersion and ecological uptake. Sensitivity and uncertainty analyses in the risk assessment are used to provide an overall estimate of worst-case release and latent cancer fatalities given an accident.

This major radiological source risk estimate is provided to the decision maker for evaluation and approval or disapproval. Since each mission is unique, hazard assessment methodology can vary. For the most part the need for a critical evaluation drives state-of-the art modeling techniques and often extensive testing of any hazardous systems that may threaten the radioactive source. Air Force Manual 91-110[239] has additional requirements regarding radioactive source use and for launch approval of major radiation sources, but relies on the PD/NSC-25 process to provide risk acceptance.

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[236] IAEA. *Regulations for the Safe Transport of Radioactive Material: 1996 edition*. Vienna: IAEA, 1996.

[237] Zbigniew Brzezinski. “Scientific or Technological Experiments with Possible Large-Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space.” PD/NSC-25. 14 December 1977.

[238] President Donald Trump. “Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems.” NSPM-20. 20 August 2019. Retrieved 17 October 2023. Available at https://www.govinfo.gov/content/pkg/DCPD-201900558/pdf/DCPD-201900558.pdf.

[239] Secretary of the Air Force. “Nuclear Safety Review and Launch Approval for Space or Missile Use of Radioactive Material and Nuclear Systems.” DAFMAN 91-110. 24 February 2022. May be superseded by update. Retrieved 17 October 2023. Available at https://static.e-publishing.af.mil/production/1/af_se/publication/dafman91-110/dafman91-110.pdf.

APPENDIX A

Glossary

3-sigma: Three times the standard deviation, typically referenced to the mean value.

Abbreviated Injury Scale (AIS): An anatomically based, consensus derived, global severity scoring system that classifies each injury in everybody region according to its relative importance on a 6 point ordinal scale.

Acceptable risk: A predetermined criterion or standard for a maximum risk ceiling that permits the evaluation of cost, national priority interests, and number of tests to be conducted.

Accumulated risk: The combined collective risk to all individuals exposed to a particular hazard through all phases of an operation. Guidance Information: For the flight of an expendable orbital launch vehicle, risk should be accumulated from liftoff through orbital insertion; for the flight of a suborbital launch vehicle, risk should be accumulated from liftoff through the impact of all pieces of the launch vehicle, including the payload.

Aggregated risk: The accumulated risk due to all hazards associated with a flight. Guidance Information: For a specified launch, aggregated risk includes, but is not limited to, the risk due to debris impact, toxic release, and distant focusing of blast overpressure.

Aleatory uncertainty: The kind of uncertainty resulting from randomness or unpredictability due to stochasticity. Aleatory uncertainty is also known as variability, stochastic uncertainty, Type I or Type A uncertainty, irreducible uncertainty, and objective uncertainty.

As Low As Reasonably Practicable: That level of risk that can be lowered further only by an increment in resource expenditure that cannot be justified by the resulting decrement in risk. Often identified or verified by formal or subjective application of cost-benefit or multi-attribute utility theory.

Automatic Destruct System: A destruct system that self-activates under certain failure conditions, such as when vehicle breakup is sensed via a lanyard pulled or a break-wire separated or when data or communications links are lost. Often automatic destruct system activates destruct charges on the break-point stage (usually the weakest part of the vehicle) and all lower stages.

Background Risk: Risks voluntarily accepted in the course of normal activities.

Basis of confidence: The foundation for a users’ trust or belief that software will perform its intended function in a right, proper, or effective way. Typically refers to a specific document containing the results of IV&V efforts, testing, and/or comparisons with either real world data or results produced by other validated models.

Best available: The most accurate and/or realistic information available when a risk assessment is performed.

Best practice (1): A management idea that asserts that there is a technique, method, process, activity, incentive or reward that is more effective at delivering a particular outcome than any other technique, method, process, etc. The idea is that with proper processes, checks, and testing, a project can be rolled out and completed with fewer problems and unforeseen complications.

Best practice (2): An acceptable level of effort that represents the best choice available given the circumstances.

Binning: The allocation of data points into bins according to the value(s) associated with the data point. For example, for data points defining a location in space (latitude, longitude, altitude) it is the placement of each point into its appropriate bin where the bins are the 3-dimensions cells defined by a 3-dimensional grid (each cell is defined by the latitude, longitude and altitude values defining the cell boundaries).

Carcinogen: Any substance that produces cancer.

Casualty: A serious injury or worse, including death, for a human. For the purposes of this standard, serious injury is defined as AIS level 3 or greater except where prior general practice at the range has been to protect to a lesser level of injury than AIS level 3, such as eardrum protection.

Casualty expectation: See *Expected Casualties*

Catastrophe: Any event that produces a large numbers of casualties or has a severe impact on continued range operations.

Clarity: An EPA TCCR principle of uncertainty characterization; the assessment is free from obscure language and is easy to understand. Brevity and plain English are employed; technical terms are avoided; simple tables, graphs, and equations are used.

Clearance Zone: An area or volume from which objects at risk (people, ships, aircraft, etc.) are to be restricted or eliminated in order to control the risks.

Coefficient of restitution: The ratio of speed of separation to speed of approach in a collision.

Cold trajectory: The vehicle follows the planned profile but, due to low performance of a motor, arrives at the various points in the profile late. This can also be described as moving slower and not flying as far downrange as nominal predictions at any given time in flight. The decreased performance does not necessarily produce an unacceptable trajectory.

Collective risk: The total risk to all individuals exposed to any hazard from an operation. Unless otherwise noted, collective risk is the mean number of casualties (E_C) predicted to result from all hazards associated with an operation. Collective risk is specified as either for a mission or per year. The collective risk should include the aggregated and accumulated risk.

Collision Avoidance (COLA): The process of determining and implementing a course of action to avoid potential on-orbit collisions with manned objects or with other specified orbiting objects. The process includes the determination of wait periods in either the launch window or spacecraft thrust firings based on validated CAs or risk analyses and accounts for uncertainties in spatial dispersions and arrival time of the orbiting objects and/or launch vehicle.

Compounding conservatism: An analysis approach that results in extremely conservative results by making a series of conservative assumptions (See *Conservatism).*

Conjunction Assessment (CA): The process of determining the point of closest approach of two orbiting objects, or between a launch vehicle and an orbiting object, in association with a specified miss distance screening criteria or the corresponding probability of collision. Associated with the closest approach assessment is the closest approach distance, the times of launch or orbital firing that would result in the closest approach, and meeting the miss distance or collision probability criteria.

Conservatism: As used in risk analysis modeling, conservatism is a set of modeling assumptions that exaggerates the risk by overstating event probabilities, hazard probabilities or consequences. Conservatism refers to the degree of overstating risk.

Consistency: An EPA TCCR principle of uncertainty characterization; Conclusions of the risk assessment are characterized in harmony with other government actions.

Containment: The launch safety strategy/process of minimizing risk by keeping hazardous operations within defined hazard areas that are unpopulated or where the population is controlled and adequate protection can be provided to highly valued resources; to isolate a hazard from populations and highly valued resources.

Credibility: The quality that makes something (as a witness or some evidence) worthy of belief; credible.

Critical Asset: A resource requiring protection. It normally includes property/infrastructure that is essential to protect the public health and safety, maintain the minimum operations of the range, or protect the national security or foreign policy interests of the United States.

Neighboring operations personnel: Persons not essential to the specific operation or launch currently being conducted, but who are required to perform safety, security, or other critical tasks at the range. To be treated as NOP they must be notified of a neighboring hazardous operation and either trained in mitigation techniques or accompanied by a properly trained escort. The NOP do not include individuals in training for any job or individuals performing routine activities such as administrative, maintenance, or janitorial. The NOP may occupy safety clearance zones and hazardous launch areas and need not be evacuated with the GP. The NOP should be included in the same risk category as MEP.

De manifestis: A level of risk that is instantly recognized by a person of ordinary intelligence as inherently unacceptable.

De minimis non curat lex: {Latin} The law does not concern itself with trifles - often shortened to *de minimis*.

De minimis threshold: The level of mishap risk below which a hazard does not warrant any expenditure of resources to track or mitigate.

Debris impact risk: The potential for injury, death or property damage resulting from the impact of falling debris. (Separate from explosive or toxic debris risk.)

Decision Authority: The range commander or senior official designated by the range commander to make risk decisions on his or her behalf.

Deflagration: An explosion where the propagation of the explosive reaction into the un-reacted material is by heat and mass transfer. In a deflagration, the propagation rate is always less than the speed of sound in the un-reacted material.

Depressed trajectory: The actual trajectory profile is lower than expected.

Detonation: An explosion where the propagation of the explosive reaction into the un-reacted material is by shock compressive heating. In a detonation, the propagation rate is at least as fast as the speed of sound in the un-reacted material.

Diffraction: A description of how overpressure wave fronts bend around structures and objects

Diffusion: Dispersion of gasses or particulates by atmospheric turbulence.

Discrete complementary cumulative distribution: The complementary cumulative distribution is one (1) minus the cumulative distribution, i.e. $1-F(x)$. The word “Discrete” is used to refer to the fact that x in the distribution can only have integer values.

Discretionary function: A deed involving an exercise of personal judgment and conscience. Also *“discretionary act”*; Not an implementation of a hard and fast rule. Relates to “Discretionary Function Exclusion” of Federal Torts Claims Act.

Distributive mixing test: A liquid propellant explosive test used to study the effects of initial surface area contact between fuel and oxidizer propellant components on the blast yield produced in an explosion. The configurations used in these tests permit the ratio of the initial surface area of contact to the total propellant weight to be precisely controlled.

Distant focusing: An atmospheric phenomenon that can produce greatly enhanced overpressure due to sonic velocity gradients with respect to altitude.

Endoatmospheric: Within the Earth’s atmosphere; generally considered to be those altitudes below 100 km.

Energetic materials: Materials that can burn or explode when subjected to a heat source or shock loading.

Epistemic uncertainty: The kind of uncertainty arising from imperfect knowledge. Epistemic uncertainty is also known as incertitude, ignorance, subjective uncertainty, Type II or Type B uncertainty, reducible uncertainty, and state-of-knowledge uncertainty.

Exoatmospheric: Outside the Earth’s atmosphere; generally considered to be those altitudes above 100 km.

Expected casualties: The mean number of casualties predicted to occur as a result of an operation if the operation were to be repeated many times. This risk is expressed with the following notation: $1E-7 = 10^{-7} = 1$ in ten million operations.

Expected fatalities: The mean number of fatalities predicted to occur as a result of an operation if the operation were to be repeated many times. This risk is expressed with the following notation: $1E-7 = 10^{-7} = 1$ in ten million.

Explosive yield: The energetic measure of a given quantity of explosive material, such as solid propellant. It is generally expressed in terms of equivalent weight of TNT since the energetic yield of TNT (defined by the overpressures and temperatures created) is well documented.

Failure modes: How a vehicle, system or component might fail.

Far-field overpressure: An overpressure occurring at a significant distance from an explosion that may be enhanced by atmospheric effects.

Fatal injury: any injury that results in death within 30 days of the accident.

Fragmentation: The breakup of an in-flight vehicle into fragments (components of the vehicle, pieces of the structure, chunks of solid propellant, miscellaneous hardware, etc.) typically caused by explosive loads, aerodynamic and inertial loads, activation of an FTS, intercept with another vehicle, or impact on a surface.

Federal Tort Claims Act: A statute that limits federal sovereign immunity and allows recovery in federal court for tort damages caused by federal employees, but only if the law of the state where the injury occurred would hold a private person liable for the injury 28 USCA 2671-2680. Also FTCA.

Fidelity: The accuracy of the representation when compared to the real world.

Flight commit criteria: See *Launch Commit Criteria*

Flight Safety System (FSS): Includes airborne and ground safety systems, tracking safety system, and telemetry data transmission systems that must meet flight safety and customer requirements, as well as established reliability and single point failure requirements (*See also Flight Termination System* and *Range Safety System*).

Flight Termination System (FTS): The airborne portion of the FSS. An FTS ends the propulsive flight of a vehicle and consists of the entire system on an airborne vehicle used to receive, decode, and execute a flight termination (this includes automatic destruct system, ISDS, and ground command signals). It includes all wiring, power systems, and methods or devices (including inadvertent separation destruct systems) used to terminate flight (*See also Flight Safety System* and *Range Safety System*).

Focus factor: The ratio produced by dividing the peak incident overpressure experienced under actual atmospheric conditions by the peak incident overpressure predicted under standard atmospheric conditions without winds.

Generalized Energy Management Steering: Boost velocity control is achieved by burning all boost propulsion stages to burnout, shaping the trajectory to use all the energy, without thrust termination.

General public: All people not declared MEP or NOP. This includes the public plus range personnel not essential to a mission, visitors, press, and personnel/dependents living on the base/facility.

Handover: The transfer of flight safety control of a vehicle from one RSS to another. Control may be transferred manually by the RSO or automatically based on achieving some predetermined conditions.

Hazard: Any real or potential condition that can cause injury, illness, or death of personnel, or damage to or loss of equipment or property.

Hazard threshold: The lowest level at which adverse outcomes are expected to appear.

Hazard area: A geographical or geometrical surface area that is susceptible to a hazard from a planned event or unplanned malfunction.

Hazard volume: A geographical or geometrical volume of airspace that is susceptible to a hazard from a planned event or unplanned malfunction.

Hazardous operation: Those activities that, by their nature, expose personnel or property to dangers not normally experienced in day-to-day actions.

Hot trajectory: The vehicle follows the planned profile but, due to higher than expected performance (thrust) from its motors, arrives at the various points in the profile early. This can also be described as flying further downrange and moving faster than nominal predictions at any given time in flight.

Hydrocode: A computational tool capable of modeling the behavior of continuous media over a wide range of speeds. It can also be adapted to treat material strength and a range of rheological models for material behavior. It considers the effects of external and internal forces on a predefined mesh of cells that represent the system being studied.

Immediately dangerous to life and health: The maximum level to which a healthy individual can be exposed to a chemical for 30 minutes and escape without suffering irreversible health effects or impairing symptoms. Used as a “level of concern” (See: level of concern).

Impact: The impingement of a fragment on a surface, a structure, a person or a vehicle.

Inadvertent Separation Destruct System (ISDS): A specialized form of ADS located on vehicle components that automatically activates when an off-nominal dislocation of the component from the main vehicle is sensed. There is often a built-in delay included, in hope that the separated component will be sufficiently displaced at charge activation to preclude damage to the main vehicle.

Individual risk: Individual risk is the risk that a person will suffer a consequence. Unless otherwise noted, individual risk is expressed as the probability that an individual will become a casualty due to all hazards (P_C) from an operation at a specific location. Guidance Information: If each person in a group is subject to the same individual risk, then the collective risk may be computed as the individual risk multiplied by the number of people in the group. In the context of this document, individual risk refers to the probability that the exposed individual will become a casualty as a result of all hazards from a mission.

Informed decision: The “informed decision” principle is used in tort claims against the U.S. Government. The Federal Tort Claims Act (FTCA) enjoins the U.S. court system from second-guessing decisions made by properly authorized government officials in determining the acceptability of operational risks. A key test under the FTCA requires that the decision-making official be fully advised and informed of the known risks. Failure to fully advise the decision-making authority of known risks can result in liability of the U.S. Government or its officials.

Involuntary activity: No choice was made by the person affected that placed them in a position of increased risk; or the activity participated in or the item used was one that is generally done or used by more than 99% of the population.

Launch commit criteria: Hazardous or safety-critical parameters, including, but not limited to, those associated with the launch vehicle, payload, ground support equipment, FSS, hazardous area clearance requirements, and meteorological conditions that must be within defined limits to ensure that public, launch area, and launch complex safety can be maintained during a launch operation.

Launch Mission: For the purposes of flight safety analyses, a launch mission begins with lift-off, ends at orbital insertion, and includes impacts from all planned debris released prior to orbital insertion (or final impact for a suborbital mission). A launch mission includes any flight of a suborbital or orbital rocket, guided or unguided missile, and missile intercepts. See Subsection 4.2.5 for details on defining a launch mission for risk assessment.

Launch Wait: A specified launch window period during which a range or range user shall not initiate flight in order to prevent collisions with on-orbit manned objects or other protected orbital object.

Level of Concern: The concentration in air of an hazardous substance above which there may be serious immediate health effects to anyone exposed to it for short periods.

Lift-off: For the purposes of flight safety analyses, lift-off occurs during a launch countdown with any motion of the launch vehicle with respect to the launch platform (which includes a carrier aircraft), including any intentional or unintentional separation from the launch platform.

Lofted trajectory: The actual trajectory profile is higher (lofted) than expected.

Manned spacecraft: a spacecraft that is either currently occupied or intended to be occupied. Includes spacecraft en route to, and in support of, manned missions.

Maxwellian distribution: A one-dimensional probability density function defined by a single parameter. In the Range Safety context, the Maxwellian distribution is important because of the following relationship: Suppose the velocity components v_x, v_y, and v_z are independent Gaussian, distributed random variables with zero mean and a common variance (σ^2), then the magnitude of the vector **v** with components v_x, v_y, and v_z follows a Maxwellian distribution.

Mishap: An unplanned event or series of events resulting in death, injury, occupational illness, or damage to or loss of equipment or property or damage to the environment.

Mission: A flight test or operation. It may include multiple vehicles or all phases of the flight beginning with liftoff/launch. See Subsection 4.2.4 for details on defining a mission for risk assessment.

Mission-essential: Those persons and assets necessary to safely and successfully complete a specific hazardous operation or launch. The ME individuals may include persons in training to perform the specific mission currently being conducted, but excludes those in training for other critical tasks. ME personnel are informed of the hazards associated with the operation and trained in mitigation techniques appropriate to the hazard level. The range commander or mission director (or their designees) should identify the ME personnel in training and justify their designation as ME.

Mission rules: Rules that define safety constraints and conditions and establish the boundaries within which the safety team operates. The lead safety organization develops the mission rules and briefs the range user to ensure a complete understanding of the intent and application of them. Mission rules are documented and become part of the range safety plan.

Monte Carlo analysis: A numerical analysis method that uses repeated sampling of random values from known (or postulated) distributions to estimate an unknown distribution.

Nominal Ocular Hazard Distance (NOHD): The distance along the axis of the laser beam beyond which the irradiance (W/cm^2) or radiant exposure (J/cm^2) is not expected to exceed the appropriate maximum permissible exposure; that is, the safe distance from the laser.

Orbital Insertion: Orbital insertion occurs when the vehicle achieves a minimum 70 nm perigee based on a computation that accounts for drag.

Outrage factor: The components of perceived injustice regarding public perception of imposed risk; i.e. Is the risk voluntary? Is the risk fair? Is the risk familiar? Who has control of the risk? Is the responsible party open and responsive? etc.

Overpressure: The pressure caused by an explosion over and above normal atmospheric pressure. It can be significantly affected by the atmospheric conditions, particularly the temperature and wind profiles.

Probabilistic modeling: A process that employs statistical principles and the laws of probability to quantify the variability and uncertainty in a quantity. The results of probabilistic models typically express the ratio of the outcomes that would produce a given event to the total number of possible outcomes.

Probability of casualty: The likelihood that a person will suffer a serious injury or worse, including a fatal injury, from a hazardous event. This risk is expressed with the following notation: $1\text{E}{-7} = 10^{-7}$ = 1 casualty in ten million. Operations.

Probability of fatality: The likelihood that a person will die within 30 days from a hazardous event. This risk is expressed with the following notation: $1\text{E}{-7} = 10^{-7}$ = 1 fatality in ten million operations.

Prudent person: See *Reasonable Person*

Q-Alpha: The product of the dynamic pressure and the angle-of-attack for an in-flight vehicle. The dynamic pressure is a function of the velocity of the vehicle relative to the air mass and the local density of the atmosphere ($1/2 * \text{density} * \text{velocity}^2$). In still air, the angle of attack is usually the angle between the longitudinal axis of the vehicle and the velocity vector of the vehicle.

Range Safety Officer (RSO): Range Safety Officer is a generic term used in this document to designate the individual or individuals responsible for making range safety decisions, particularly flight termination decisions. During real-time, the RSO is delegated the authority to execute the range commander’s range safety policies and has sole responsibility for making range safety decisions. Other commonly used designations include missile flight safety officer and missile flight control officer.

Range Safety System (RSS): The ground-based portion of the FSS. An integrated system of hardware, software, and human operators that is necessary to provide mission safety support. Includes instrumentation and communication infrastructure needed to fulfill safety’s flight control responsibility. *See also Flight Safety System* and *Flight Termination System*

Reasonable care: As a test of liability for negligence, the degree of care that a prudent and competent person engaged in the same line of business or endeavor would exercise under similar circumstances - Also termed due care; ordinary care; adequate care; proper care.

Reasonable person: A hypothetical person used as a legal standard, especially to determine if someone acted with negligence. The reasonable person acts sensibly, does things without serious delay, and takes proper but not excessive precautions. Also termed *Reasonable Man* or *Prudent Person.*

Reasonableness: An EPA TCCR principle of uncertainty characterization; the assessment is based on sound judgment. The components of the risk characterization are well integrated into an overall conclusion of risk that is complete, informative, well balanced and useful for decision making. The characterization is based on the best available scientific information. The policy judgments required to carry out the risk analyses use common sense given the statutory requirements and guidance from higher authority. Appropriate plausible alternative estimates of risk under various candidate risk management alternatives are identified and explained.

Reentry Mission: Reentry missions include both controlled and uncontrolled reentries. In this context, a controlled reentry mission begins with the final commitment to enter the atmosphere from orbit (or otherwise from outer space) and ends when all vehicle components associated with the reentry come to rest on the Earth (or are otherwise secured). For example, a controlled reentry mission could begin with the final command to commit the vehicle (or object) to a perigee below 70 nm and end when all vehicle components come to rest on the Earth. An uncontrolled reentry mission begins when the object naturally decays to a perigee below 70 nm and ends when all vehicle components associated with the reentry come to rest on the Earth. The reentry of upper-stages and payloads are separate reentry missions per the US Government Orbital Debris Mitigation Standard Practices and DoDI 3100.12. In this context, reentry missions do not occur during suborbital flights because a reentry mission separate from the launch mission can occur subsequent to orbital insertion only. See step b of Subsection 4.2.4 for details on defining a reentry mission for risk assessment. .

Residual mishap risk: The risk that remains after all approved mitigations have been implemented.

Risk: Risk is a measure that accounts for both the probability of occurrence and the consequence of a hazard to a population or installation. Unless otherwise noted, risk to people is measured in casualties and expressed as individual risk or collective risk.

Risk analysis: A study of potential risk under a given set of conditions. Risk Analysis is an activity that includes the complete array of tasks from data gathering, identification of hazards, estimation of associated risks, and verification of results.

Risk management: Risk management is a systematic and logical process to identify hazards and control the risk they pose while considering practicalities and trade-offs.

Risk Profile: A plot that shows the probability of N or more casualties (vertical axis) as a function of the number of casualties, N (horizontal axis). It is discrete (not fractional) and is the complementary cumulative distribution of the histogram representing the aleatory uncertainty of number of casualties. The mean of the histogram is the E_C. In addition, the sum of the values of the $P[\geq N]$ over all N is equal to the E_C.

Safety: Relative protection from adverse consequences.

Sensitivity: The degree to which the model outputs are affected by changes in a selected input parameter.

Sensitivity analysis: The computation of the effect of changes in input values or assumptions (including boundaries and model function form) on the outputs. The study of how uncertainty in a model output can be systematically apportioned to different sources of uncertainty in the model input. By investigating the “relative sensitivity” of model parameters, a user can become knowledgeable of the relative importance of parameters in the model.

Serious injury: Any injury that: (1) requires hospitalization for more than 48 hours, commencing within 7 days from the date the injury was received; (2) results in a fracture of any bone (except simple fractures of fingers, toes, or nose); (3) causes severe hemorrhages, nerve, muscle, or tendon damage; (4) involves any internal organ; or (5) involves second- or third-degree burns, or any burns affecting more than 5% of the body surface.

Ship Accident: A "ship accident" occurs if the water-borne vessel is involved in an accident that results in loss of life, personal injury that requires medical treatment beyond first aid, or complete loss of the vessel. This definition is consistent with the level of protection afforded people involved in a "boat accident" as defined in current regulations.

Sigma: Standard deviation.

Spacecraft Critical Cross-Sectional Area: The maximum cross-sectional area of vulnerable surfaces of a manned spacecraft in the direction that the spacecraft is traveling relative to the hazard.

Spacecraft Vulnerable Area: The entire surface area of a manned spacecraft that would hazard human life if any portion of it was breached. For a cylindrical shaped spacecraft the vulnerable area would be the surface area of the cylinder rather than its cross-sectional area or projected area to a debris density flux.

Statistical risk management: Risk management that makes use of probabilistic modeling, formal risk analyses, and risk acceptability criteria.

Suborbital Mission: A suborbital launch mission is any flight of a launch vehicle, rocket, or missile that does not achieve orbital insertion. The per-mission requirements for launch are intended to apply from lift-off until landing or final impact for a suborbital mission, including all planned debris impacts.

Suborbital Rocket: A rocket-propelled vehicle intended to perform a suborbital mission whose thrust is greater than its lift for the majority of the rocket-powered portion of its flight.

Substantial damage: Relating to aircraft vulnerability means damage or failure that adversely affects the structural strength, performance, or flight characteristics of the aircraft, and that would normally require major repair or replacement of the affected component.

Susceptibility: The quality or state of being open, subject or unresistant to some stimulus, influence or agency.

TCCR: EPA principles of uncertainty characterization; see *Transparency*, *Clarity*, *Consistency*, and *Reasonableness*.

TNT equivalent: The explosive yield of a material expressed in terms of the weight of trinitrotoluene (TNT) that will produce an essentially equivalent yield. TNT equivalent, or "TNT equivalency", is used to characterize explosions since the overpressures and temperatures produced by TNT are well documented.

Toxic hazard area: A generic term that describes an area in which predicted concentration of propellant or toxic byproduct vapors or aerosols may exceed acceptable tier levels; predictions are based on an analysis of potential source strength, applicable exposure limit, and prevailing meteorological conditions; toxic hazard areas are plotted for potential, planned, and unplanned propellant releases and launch operations.

Toxic release hazard analysis: Analysis to ensure people are not exposed to concentration thresholds for each toxicant involved in a launch or in the event of a flight mishap. Results are used to establish flight commit criteria that protect people from a toxic release casualty.

Toxicant: A substance that can cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological or reproductive malfunctions, or physical deformities in any organism or its offspring. The quantities and length of exposure necessary to cause these effects can vary widely. *See also Toxic Substance*

Toxic substance: A chemical or mixture that may present an unreasonable risk of injury to health or the environment. *See also Toxicant*

Toxics: A generic term for the toxic propellants and combustion by-products resulting from a nominal launch vehicle flight or catastrophic launch abort.

Transparency: An EPA TCCR principle of uncertainty characterization; explicitness in the risk assessment process. It ensures any reader understands all the steps, logic, key assumptions, limitations, and decisions in the risk assessment, and comprehends the supporting rationale that leads to the outcome.

Uncertainty: The absence of perfectly detailed knowledge. Uncertainty includes incertitude (the exact value is unknown) and variability (the value is changing). Uncertainty may also include other forms such as vagueness, ambiguity, and fuzziness (in the sense of border-line cases).

Uncertainty analysis: An investigation of the effects of lack of knowledge or potential errors on the model and when conducted in combination with a sensitivity analysis allows a model user to be more informed about the confidence that can be placed on model results.

Validation: Refers to the set of activities that ensure that the software that has been built is traceable to customer requirements. The validation process determines whether the mathematical model being used accurately represents the phenomenon being modeled and to what degree of accuracy. This process ensures that the simulation adequately represents the appropriate physics by comparing the output of a simulation with data gathered in experiments and quantifying the uncertainties in both.

Variability: Observed differences attributable to true heterogeneity or diversity. Variability is the result of natural random processes and is usually not reducible by further measurement or study (although it can be better characterized).

Verification: Refers to the set of activities that ensure that software correctly implements a specific function. The verification process determines whether a computer simulation code for a particular problem accurately represents the solutions of the mathematical model. Evidence is collected to ascertain whether the numerical model is being solved correctly. This process ensures that sound software-quality practices are used and the software codes themselves are free of defects and errors. It also checks that the code is correctly solving the mathematical equations in the algorithms and verifies that the time and space steps or zones chosen for the mathematical model are sufficiently resolved.

Voluntary activity: The person affected made a choice that knowingly placed them in an increased position of risk compared to the rest of the population. This includes career and job choices. Examples: repetitive motion injuries, recreational boating, etc.

Vulnerability relationship: A model of the relation of hazard level compared to the probability or degree of an adverse outcome.

Worst-case: A semi-quantitative term referring to the maximum possible exposure, dose, or risk, that can conceivably occur, whether or not this exposure, dose, or risk actually occurs in a specific population.

APPENDIX B

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