U.S. Department
of Transportation
Federal Aviation
Administration

Advisory Circular

Subject: High Fidelity Flight Safety Analysis

Date: 10/15/2020
Initiated By: AST-1

AC No: 450.115-1

This Advisory Circular (AC) provides guidance and a comprehensive method for performing a high fidelity flight safety analysis in accordance with title 14 of the Code of Federal Regulations (14 CFR) § 450.115. A flight safety analysis is required for launch and reentry in accordance with § 450.113(a). AC 450.113-1, *Level of Fidelity*, provides guidance on when a high fidelity flight safety analysis is needed and how to determine the level of fidelity that is required. In situations when a high fidelity flight safety analysis is needed, this AC 450.115-1 provides guidance for performing that analysis in compliance with § 450.115(b). A high fidelity flight safety analysis may be required by § 450.115(b) for a particular phase or for all phases of flight. An operator's flight safety analysis method must account for all reasonably foreseeable events and failures of safety-critical systems during nominal and non-nominal launch or reentry that could jeopardize public safety, in accordance with § 450.115(a). In accordance with § 450.115(b)(1), the analysis must demonstrate that any risk to the public satisfies the safety criteria of § 450.101, including the use of mitigations, and account for all known sources of uncertainty, using a means of compliance accepted by the Federal Aviation Administration (FAA). The analysis must identify the dominant source of each type of public risk with a criterion in §§ 450.101(a) or 450.101(b) in terms of phase of flight, source of hazard (such as toxic exposure, inert, or explosive debris), and failure mode, in accordance with § 450.115(b)(2).

The FAA considers this AC an accepted means of compliance for complying with the regulatory requirements of § 450.115(b). It presents one, but not the only, acceptable means of compliance with the associated regulatory requirements. This AC assists with performing a high fidelity flight safety analysis. The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. The document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.

If you have suggestions for improving this AC, you may use the form at the end of this AC.

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1 PURPOSE.

This Advisory Circular (AC) provides guidance and a comprehensive method for performing a high fidelity flight safety analysis in accordance with title 14 of the Code of Federal Regulations (14 CFR) § 450.115. AST drafted AC 450-113-1, *Level of Fidelity*, to help an operator determine the level of fidelity of the analysis required by § 450.115(b). In situations when a high fidelity flight safety analysis is needed, this AC provides guidance for performing that analysis in compliance with § 450.115(b). A high fidelity flight safety analysis may be required by § 450.115(b) for a particular phase or for all phases of flight.

1.1 Analysis Scope.

An operator's flight safety analysis method must account for all reasonably foreseeable events and failures of safety-critical systems during nominal and non-nominal launch or reentry that could jeopardize public safety, in accordance with § 450.115(a). In accordance with § 450.115(b)(1), the analysis must demonstrate that any risk to the public satisfies the safety criteria of § 450.101, including the use of mitigations, and account for all known sources of uncertainty, using a means of compliance accepted by the FAA Administrator. In accordance with § 450.115(b)(2), the analysis must identify the dominant source of each type of public risk with a criterion in §§ 450.101(a) or 450.101(b) in terms of phase of flight, source of hazard (such as toxic exposure, inert, or explosive debris), and failure mode. In accordance with § 450.101(g), for any analysis used to demonstrate compliance with § 450.115(b), an operator must use accurate data and scientific principles, and the analysis must be statistically valid. Also in accordance with § 450.101(g), the method must produce results consistent with or more conservative than the results available from previous mishaps, tests, or other valid benchmarks, such as higher-fidelity methods.

1.2 Description of Methods.

To satisfy the requirements of § 450.115(c), an applicant must submit a description of the flight safety analysis methodology, including identification of:

- The scientific principles and statistical methods used;
- All assumptions and their justifications;
- The rationale for the level of fidelity;
- The evidence for validation and verification required by § 450.101(g);
- The extent to which the benchmark conditions are comparable to the foreseeable conditions of the intended operations; and
- The extent to which risk mitigations were accounted for in the analyses.

1.3 Level of Imperatives.

This AC presents one, but not the only, acceptable means of compliance with the associated regulatory requirements. The FAA will consider other means of compliance that an applicant may elect to present. Other means of regulatory compliance may be acceptable, but must be approved by the FAA Administrator in accordance with § 450.35(a)(1). In addition, an operator may tailor the provisions of this AC to meet its unique needs, provided the changes are accepted as a means of compliance by FAA. Throughout this document, the word "must" characterizes statements that directly follow from regulatory text and therefore reflect regulatory mandates. The word "should" describes a requirement if electing to use this means of compliance; variation from these requirements is possible, but must be justified and accepted by the FAA as an alternative means of compliance. The word "may" describes variations or alternatives allowed within the accepted means of compliance set forth in this AC. In general, these alternative approaches can be used only under certain situations that do not compromise safety.

2 APPLICABILITY.

2.1 The guidance in this AC is for launch and reentry vehicle applicants and operators required to comply with 14 CFR part 450. The guidance in this AC is for those seeking a launch or reentry vehicle operator license, a licensed operator seeking to renew or modify an existing vehicle operator license, and FAA commercial space transportation evaluators.

2.2 The material in this AC is advisory in nature and does not constitute a regulation. This guidance is not legally binding in its own right, and will not be relied upon by the FAA as a separate basis for affirmative enforcement action or other administrative penalty. Conformity with this guidance document (as distinct from existing statutes and regulations) is voluntary only, and nonconformity will not affect rights and obligations under existing statutes and regulations. This AC describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations.

2.3 The material in this AC does not change or create any additional regulatory requirements, nor does it authorize changes to, or deviations from, existing regulatory requirements.

3 APPLICABLE REGULATIONS AND RELATED DOCUMENTS.

3.1 Related Statute.

- 51 U.S.C. Subtitle V, Chapter 509.

3.2 Related Regulations.

The following regulations from titles 14 and 49 of the CFR must be accounted for when showing compliance with 14 CFR § 450.115. The full text of these regulations can be downloaded from the U.S. Government Printing Office e-CFR. A paper copy can be ordered from the Government Printing Office, Superintendent of Documents, Attn: New Orders, PO Box 371954, Pittsburgh, PA, 15250-7954.

- Section 401.7, *Definitions*.
- Section 450.35, *Means of Compliance*.

- Section 450.101, *Safety Criteria*.
- Section 450.103, *System Safety Program.*
- Section 450.108, *Flight Abort*.
- Section 450.113, *Flight Safety Analysis Requirements—Scope*.
- Section 450.117, *Trajectory Analysis for Normal Flight*.
- Section 450.119, *Trajectory Analysis for Malfunction Flight*.
- Section 450.121, *Debris analysis*.
- Section 450.123, *Population Exposure Analysis*.
- Section 450.131, *Probability of Failure Analysis*.
- Section 450.133, *Flight Hazard Area Analysis*.
- Section 450.135, *Debris Risk Analysis*.
- Section 450.137 *Far-field Overpressure Blast Effects Analysis*.
- Section 450.139 *Toxic Hazards for Flight*.
- Section 450.161, *Control of Hazard Areas*.
- Section 450.213, *Pre-flight Reporting*.

3.3 **Related FAA Advisory Circulars.**

FAA Advisory Circulars (will be available through the FAA website, http://www.faa.gov).

- AC 450.101-1, *High Consequence Event Protection*.
- AC 450.108-1, *Using Flight Abort Rule as a Hazard Control Strategy*.
- AC 450.110-1, *Physical Containment Flight Safety Analysis*.
- AC 450.117-1, *Normal and Malfunction* Trajectory Analysis.
- AC 450.123-1, *Population Exposure Analysis*.
- AC 450.137-1, *Distant Focusing Overpressure (DFO) Risk Analysis.*
- AC 450.139-1, *Toxic Hazards Analysis and Thresholds.*

3.4 **Technical Reports Related to High Fidelity Flight Safety Analysis.**

1. Allahdadi, Firooz A., Isabelle Rongier, Tommaso Sgobba, Paul D. Wilde (Eds.), *Safety Design for Space Operations*, Sponsored by The International Association for the Advancement of Space Safety, published by Elsevier, Watham, MA, 2013.
2. Anderson, John D., *Modern Compressible Flow: With Historical Perspective,* McGraw-Hill Education, dated 2003.

3. Baker, W.E., et al., *Workbook for estimating effects of accidental explosions in propellant ground handling and transport systems*, NASA Contractor Report 3023, August 1978, https://ntrs.nasa.gov/citations/19790002055.

4. Baker, W.E., et al., *Workbook for predicting pressure wave and fragment effects of exploding propellant tanks and gas storage vessels*, NASA Contractor Report 134906, September 1977, https://ntrs.nasa.gov/citations/19760012208.

5. Bonson, S.P. *Aerodynamic Characteristics for Debris from Space Shuttle External Tank*, dated May 23, 2012. https://arc.aiaa.org/doi/10.2514/3.57727.

6. Collins, Jon D., Randolph Nyman, and Isaac Lotatti, *Estimation of Space Shuttle Orbiter Reentry Debris Casualty Area*, AIAA Atmospheric Flight Mechanics Conference and Exhibit, August 2005, AIAA Paper 2005-6321. https://doi.org/10.2514/6.2005-6321.

7. Columbia Accident Investigation Board Report Vol. 1, NASA, Washington, D.C. August, 2003.

8. *Department of Defense World Geodetic System* 1984, NIMA TR8350.2, Third Edition, Amendment 1, National Imagery and Mapping Agency, January 2000.

9. Eck, M. and M. Mukunda, *On the nature of the fragment environment created by the range destruction or random failure of solid rocket motor casings.* Fairchild Space, Report FSC-ESD-217-88-426, July 1988, https://ntrs.nasa.gov/citations/19920005979.

10. Hoerner, Sighard F., *Fluid Dynamic Drag*, Published by the Author, Midland Park, New Jersey, 1965.

11. Global Reference Atmospheric Model (GRAM) Suite: https://software.nasa.gov/software/MFS-33888-1.

12. Iqbal, Naeem, Mark Salley, and Sunil Weerakkody, *Fire Dynamics Tools (FDTs) Quantitative Fire Hazard Analysis Methods for the USNRC Fire Protection Inspection Program*, NUREG-1805, Washington, DC, November 2004.

13. Julier, Simon J., and Jeffery K. Uhlmann, *A General Method for Approximating Nonlinear Transformations of Probability Distributions*, Technical report, RRG, Dept. of Eng. Science, University of Oxford, Nov 1996.

14. Kingery, C. N. and Bulmash, G., *Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst*, ARBRL-TR-02555, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1984.

15. Koppenwallner, G., *The Drag of Simple Shaped Bodies in the Rarefied Hypersonic Flow Regime*, AIAA 20th Thermophysics Conference Williamsburg, VA, 1985.

16. Kuo, Kenneth K. *Fundamentals of Solid-Propellant Combustion*, American Institute of Aeronautics and Astronautics, dated October, 1984.

17. Lambert, Jack D., *Computational Methods in Ordinary Differential Equations*, John Wiley & Sons, Chichester, 1977.

18. Larson, Erik W.F, and George M. Lloyd, *Application of Kernel Density Estimation to Impact Probability Density Determination for Risk Analysis*, 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando Florida, January 2010.

19. Manning, Ted A. and Scott L. Lawrence, *Fragment Acceleration Modeling for Pressurized Tank Burst, Journal of Spacecraft and Rockets*, Vol. 54, No. 3, May-June 2017. https://arc.aiaa.org/doi/full/10.2514/1.A33765.

20. Pike J. A., *Injury Scaling, Automotive Safety, Anatomy, Injury, Testing and Regulation*, Published by Society of Automotive Engineers, Inc., SAE, 1990.

21. Richardson, Erin, et al, Richardson, Erin, et al, *Monte Carlo Approach to Modeling the Breakup of the Space Launch System EM-1 Core Stage with an Integrated Blast and Fragment Catalogue*, dated December 8, 2014. https://ntrs.nasa.gov/citations/20150002599.

22. Risk Committee, Range Safety Group, Range Commanders Council, *Common Risk Criteria for National Test Ranges*, RCC 321-20 and RCC 321-20 Supplement, White Sands, NM 2020. https://www.wsmr.army.mil/RCCsite/Documents/321-20_Common_Risk_Criteria_Test_Ranges/321-20_Common_Risk_Criteria_Test_Ranges.pdf.

23. Snyder, M.W., *Analysis of Video Imagery of the Reentry and Breakup of the STS-31 External Tan*k, dated August 6, 2002. https://ieeexplore.ieee.org/document/576656.

24. Wilde, Paul D., and Chris Draper, *Aircraft Protection Standards and Implementation Guidelines for Range Safety*, 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando Florida, January 2010.

4 DEFINITION OF TERMS.

For this AC, the following terms and definitions apply:

4.1 Event Scenario.

A specific failure of a vehicle defined by its failure response mode and breakup list.

4.2 Fragment Class.

A fragment or set of fragments with similar characteristics that is defined by a representative fragment and the number of fragments it represents.

4.3 Hazard.

Any real or potential condition that could cause injury, illness, or death of people; or damage to or loss of equipment or property.

4.4 Hazardous Debris.

Any object or substance capable of causing a casualty or loss of functionality to a critical asset. Hazardous debris includes inert debris and explosive debris such as an intact vehicle, vehicle fragments, any detached vehicle component whether intact or in fragments, payload, and any planned jettison bodies.

4.5 **Intact.**

A vehicle or any detached motor that is substantially intact during ballistic flight, even though there may be some missing pieces.

4.6 **Malfunction Turn Failures.**

Events that can lead to the vehicle deviating outside of its normal trajectory bounds including all behavior ranging from gradual turns to rapid turns.

4.7 **Mission**.

The launch or reentry vehicle description and its intended operation, the flight profile, the flight safety system, and the flight abort rules under which the operation will be conducted.

4.8 **Monte Carlo Simulation.**

A simulation in which random statistical sampling techniques are employed to determine estimates for unknown values. Monte Carlo methods include computational algorithms that, for example, repeatedly sample from probability distributions that characterize input parameters (such as the weight, thrust, and drag of a vehicle) and perform physics-based simulations to obtain numerical results (such as a set of trajectories that characterize flight under normal or malfunction conditions).

4.9 **Uncertainty.**

The absence of perfectly detailed knowledge of input to the risk analysis models, but not in the definition of the models. 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).

5 OVERVIEW.

In accordance with § 450.115(a), an operator’s flight safety analysis method must account for all reasonably foreseeable events and failures of safety-critical systems during nominal and non-nominal launch or reentry that could jeopardize public safety. AC 450.113-1 can be used to determine the level of fidelity for flight safety analysis. Once an operator has determined that a high fidelity flight safety analysis is required, the method in paragraph 5.1 of this AC 450.115-1 can be used.

5.1 High-fidelity Flight Safety Analysis Method.

5.1.1 The first step in performing a high-fidelity flight safety analysis is to collect existing relevant input, and define and create input unique to the high-fidelity analysis. Input should include the following:

- Mission information identified in paragraph 6.1 of this AC.

- A probability of failure analysis that must be performed to comply with § 450.131; see AC 450.131-1 *Probability of Failure Analysis*.
- All vehicle normal and malfunction trajectories as specified in §§ 450.117 and 450.119; see AC 450.117-1 *Normal and Malfunction Trajectory Analysis*.
- The flight abort rules required by § 450.108; see AC 450.108-1 *Flight Abort Rule Development*.
- The vehicle break-up limits that are required by § 450.121(d)(2).

5.1.2 The second step is to identify hazards and hazard producing events. The operator should apply the flight abort rules and vehicle break-up limits to the normal and malfunction trajectories to obtain a set of failure events, in accordance with the requirements of § 450.108(f). These failure events, and all planned events, should be specified by state vectors that are defined by mean time of failure, position and velocity at the failure event point, and the probability of the failure occurring. An operator should follow the hazard identification analysis of paragraph 6.2 of this AC.

5.1.3 The third step is to develop a debris list, in accordance with the debris analysis requirements of § 450.121(a) and (b), which has two parts:

1. Characterization of the hazardous debris resulting from a hazard producing event using chapter 7 of this AC.
2. Quantitative description of the hazardous debris in terms of aerodynamic and harmful characteristics using chapter 8 of this AC.

5.1.4 The fourth step is to perform a risk analysis that computes individual risk, collective risk, risk to aircraft, and risk to any critical assets. Computing risk can be an iterative process if the computed risk exceeds the risk thresholds of § 450.101 and then additional mitigations are identified. To compute risk, an operator should perform the following steps:

1. Propagate the hazardous debris to impact to comply with § 450.121(c) using the procedure in chapter 9 of this AC.
2. Calculate a probability of impact distribution in accordance with § 450.117(a)(1) using chapter 10 of this AC.
3. Determine the population exposure to hazards resulting from hazard producing events using the consequence modeling approach of chapter 11 of this AC.
4. Compute risk using chapter 12 of this AC.

5.1.5 The fifth step is to use the results of the risk analysis to define flight hazard areas using chapter 13 of this AC. The operator should provide information to construct:

- Waterborne vessel hazard areas, i.e., Notices to Mariners (NOTMARs) in accordance with § 450.133(b),
- Land hazard areas in accordance with § 450.133(c), and

- Airspace hazard volumes, i.e., Notices to Airmen (NOTAMs), to comply with § 450.133(d) requirements.

5.1.6 The sixth step is to document all previous steps to comply with § 450.113(a).

6 MISSION DEFINITION AND HAZARD IDENTIFICATION.

For the flight safety analysis discussion, the term "mission" is defined to include the launch or reentry vehicle description, the flight profile, the flight safety system, and the flight abort rules under which the operation will be conducted. The hazard control strategy determination involves the description of all functional failures associated with reasonably foreseeable hazardous events that have the capability to create a hazard to the public, in accordance with the functional failure analysis required by § 450.107(b)(1). These hazardous events should be described in terms of the type of vehicle breakup. A discussion of types of vehicle breakups appears in paragraph 7.1 of this AC. When an operator uses flight hazard analysis as a hazard control strategy, a flight hazard analysis must identify, describe, and analyze all reasonably foreseeable hazards to public safety resulting from the flight of a launch or reentry vehicle, in accordance with § 450.109(b). The following subparagraphs address the factors and requirements for defining a mission, and the approach for identifying hazardous events that could create hazardous debris.

6.1 Mission Description.

Prior to the start of a flight safety analysis, several aspects of the mission should be described a manner that conveys an understanding of the launch or reentry vehicle, its performance, and its potential modes of failure. The objective and details of the mission must be identified in accordance with §§ 450.41(e)(4), 450.117, and 450.213(b). The flight safety analysis is constrained by a set of flight abort rules, if an operator is using this hazard control strategy, when flight abort is used in accordance with § 450.108 as a hazard control strategy for the flight or phase of flight of a launch or reentry vehicle to meet the safety criteria of § 450.101. In accordance with § 450.108(f), the mission description must include all flight abort rules and the specific steps that will be followed to implement a flight abort.

6.1.1 Defining the Vehicle/System.

Details of the vehicle configuration must be documented in accordance with § 450.45(e)(3), including all vehicle systems, such as structural, thermal, pneumatic, etc. In accordance with § 450.167, this also includes instrumentation used to track the position and velocity of the vehicle. Such instrumentation can include telemetry, GPS receivers, and transponders, as well as the associated tracking rates, and the accuracy of these data.

6.1.1.1 **Vehicle Propellants.**

For each of the vehicle's motors or stages, the type of solid or liquid propellant must be identified, in accordance with § 450.45(e)(3)(i) and should include the characteristics of these propellants. It may be appropriate to include propellant mass and density, rate of burning – at both operating pressures and ambient pressures, propellant shape within the motor for solid propellants, and previous flight history including potential variations in the thrust (average, maximum, and minimum) as part of the propellant identification required by § 450.45(e)(3)(i). The state of the vehicle and the accounting for all motors/stages should be specified by its mass properties as a function of flight time.

6.1.1.2 **Sources of Hazardous Debris and Trajectory Analysis for Malfunction Flight**.

The actions of the guidance and control systems that affect a vehicle's performance and responses must be quantified if those parameters meet the condition set in accordance with § 450.119(b)(3). This quantification should include details of the thrust vector control actions, attitude control thrusters, aerodynamic surfaces or fins. In accordance with § 450.119(a), the vehicle deviation capability in the event of a malfunction must be identified. This should be defined in terms of velocity turn data or malfunction turn trajectories, and should include turning capability over a range of thrust offsets and/or aerodynamic surface displacements, including the maximum values of these parameters. As applicable, turn data for failures such as nozzle burn through should be included, and solid rocket motor case burn through, or structural failure of an aerodynamic surface. For additional detail regarding trajectory analysis, refer to AC 450.117-1, *Normal and Malfunction Trajectory Analysis*.

6.1.1.3 **Trajectory Analysis Reports for Malfunction Flight.**

Non-nominal flight may lead to vehicle breakup. In accordance with § 450.119(b), the analysis must include descriptions of how the vehicle can fail (failure modes) and vehicle response to these failures. This should account for the effects of aerodynamic heating on the material properties and document the structural limits of the vehicle for withstanding aerodynamic and inertial loads. A Failure Mode and Effects Analysis (FMEA) and/or a Fault Tree Analysis (FTA) should be used to determine the potential vehicle failures and responses. These analyses should also be used to inform the failure probabilities estimated for each failure mode.

6.1.2 Defining the Mission Scenario.

To perform a high-fidelity flight safety analysis, it is necessary to define a launch or reentry mission in sufficient detail to meet §§ 450.41(e)(4), 450.117, and 450.213(b). This includes the mission objectives, a description of the launch or reentry vehicle, a description of the intended vehicle flight profile and potential variations, and identification of the locations and regions that will be affected by a normal mission.

6.1.2.1 **Launch and Reentry Mission Activities.**

Launch begins when hazardous pre-flight operations commence at a U.S. launch site that may pose a threat to the public. Hazardous pre-flight operations that may pose a threat to the public include pressurizing or loading of propellants into the vehicle, operations involving a fueled launch vehicle, the transfer of energy necessary to initiate flight, or any hazardous activity preparing the vehicle for flight. Hazardous pre-flight operations do not include the period between the end of the previous launch and launch vehicle reuse, when the vehicle is in a safe and dormant state, in accordance with § 450.3(b). A reentry mission includes activities conducted in Earth orbit or outer space to determine reentry readiness and that are critical to ensuring public health and safety and the safety of property during reentry flight. Reentry also includes activities necessary to return the reentry vehicle, or vehicle component, to a safe condition on the ground after impact or landing, in accordance with § 450.3(c).

6.1.2.2 **Mission Objectives and Constraints.**

An applicant must define the primary mission objectives and constraints in accordance with § 450.213(b). This includes a thorough description of the payload or reentry vehicle; including the class and function, physical dimensions and weight, payload owner and operator, intended payload operations during its lifetime, amounts and types of hazardous and radioactive materials in the payload, and the explosive potential of materials in the payload. For an orbital mission, mission objectives should also include the range of intermediate and final orbits of each vehicle upper stage and payload, and estimated orbital lifetimes, including the parameters defining parking, transfer and final orbits, approximate transit times to final orbit, and designated reentry site(s) for each object to be de-orbited.

6.1.2.3 **Mission-specific Description.**

In accordance with § 450.45(e)(3) must provide a written description of the vehicle or family of vehicles, which should include the model, type, configuration, and characteristics of the launch vehicle, or family of vehicles, proposed for launch or reentry. In accordance with § 450.45(e)(3), this written description includes, but is not limited to structural, thermal, pneumatic, propulsion, electrical, and avionics and guidance systems used in each vehicle, and all propellants. The description must include a table specifying the type and quantities of all hazardous materials on each vehicle and must include propellants, explosives, and toxic materials. For pressurized tanks and motors, it should include data specifying pressure versus flight time. For all periods of thrust, the description should include thrust versus flight time, with relevant uncertainties, and nozzle inlet, throat and exit areas. In accordance with § 450.45(e)(3) the vehicle description must include drawings that identify each stage, including strap-on motors; physical dimensions, which should include enough lengths, widths, thicknesses, angles of curvature to produce a fully dimensioned outer-mold line and relevant material response to external loads; location of all safety-critical systems; location of all major vehicle control systems, propulsion systems, pressure vessels, and any other hardware that contains potential hazardous energy or hazardous material. In accordance with § 450.117(d)(2), the applicant must submit quantitative input data, including uncertainties, sufficient to model the vehicle's normal flight in six degrees of freedom, which includes mass properties such as the nominal center of gravity and moments of inertia versus flight time with relevant uncertainties. In accordance with § 450.121(d)(2), the applicant must submit a description of the methods used to perform the vehicle impact and breakup analysis, which should include the vehicle's structural limits. For an unguided suborbital launch vehicle, the description should identify the location of the rocket's center of pressure in relation to its center of gravity for the entire flight profile. For a guided launch vehicle, the description must include a complete set of relevant aerodynamic coefficients, including uncertainties, sufficient to describe a 6 degree-of-freedom simulation for normal flight in accordance with § 450.117(d)(2).

6.1.2.4 **Intended Vehicle Flight Profile and Potential Variations.**

For each proposed vehicle flight profile, the flight azimuths, trajectories, associated ground tracks and instantaneous impact points must be defined for the duration of the licensed activity, including any contingency abort profiles, in accordance with § 450.41(e)(4). To comply with § 450.117(a), the trajectory data must include the nominal trajectory as well as sets of trajectories sufficient to characterize variability in accordance with § 450.117(a)(1) and uncertainty in accordance with § 450.117(a)(2) during normal flight. Variability should describe how the intended trajectory could vary due to conditions known prior to initiation of flight. Uncertainty should describe how the actual trajectory could differ from the intended trajectory due to random uncertainties in all parameters with a significant influence on the vehicle's behavior throughout normal flight.

6.1.2.5 **Trajectory Analysis Outputs and Abort Flight Profiles**.

The trajectory data should provide a fuel exhaustion trajectory that produces instantaneous impact points with the greatest range for any given time after liftoff for any stage that has the potential to impact the Earth. Vehicles using flight abort as a hazard control strategy require trajectory data or parameters that describe the limits of a useful mission in accordance with § 450.119(a)(3). Also, any contingency abort flight profiles should be defined. The trajectory analysis outputs required by § 450.117(d) should include the position, velocity, and vacuum instantaneous impact point for each second of flight, and the planned sequence of events or maneuvers during flight.

6.1.2.6 **Flight Mission Limits**.

Under § 450.119(c)(4)(iii), the description must also provide the trajectory data that characterize the limits of a useful mission, i.e., one that can attain one or more mission objectives. This should include specification of the worst wind conditions under which flight might be attempted, and a description of how the operator will evaluate the wind conditions and uncertainty in the wind conditions prior to initiating the operation.

6.1.2.7 **Wind Weighting**.

For an unguided suborbital launch vehicle, under § 450.111(b), the wind weighting safety system must describe how the launcher azimuth and elevation settings will be wind weighted to correct for the effects of wind conditions at the time of flight to provide a safe impact location.

6.1.2.8 **Affected Locations and Regions.**

The launch or reentry site should be defined, including any contingency abort locations. This includes the boundaries of the launch and landing (or impact) point locations for all mission hardware, including latitude and longitude, as well as identification of any facilities at the sites that will be used for pre- or post-flight ground operations. For all launch, reentry, or disposal sites, this should include all regions of sea, land, or air that contain, with 97 percent probability of containment, all hazardous debris resulting from normal flight events capable of causing a casualty, in accordance with §§ 450.133(b)(1), (c)(1), and (d)(1). Also, all areas of land that could be overflown by a normal mission, including variations and uncertainty in the trajectory, must be depicted in accordance with § 450.108(g)(3) whenever flight abort is used as a hazard control strategy.

6.1.3 Defining Flight Safety Systems.

In accordance with § 450.119(b)(4), a high-fidelity flight safety analysis must account for the potential for failure of a flight safety system (FSS), if any. An FSS may be required to control, contain, or mitigate hazards to satisfy the flight safety criteria of § 450.101. In accordance with § 450.101(c)(1), an operator can protect against a high consequence event in uncontrolled areas for each phase of flight by using flight abort as a hazard control strategy with an FSS that meets the requirements of § 450.108 if any reasonably foreseeable failure response mode could result in conditional expected casualties for uncontrolled areas, as defined in § 401.7, that exceed 1×10^{-2}.

6.1.3.1 **Mitigating Risk of a Flight Safety System.**

The FSS may need to be used for each stage of flight that poses a hazard in accordance with § 450.108(a), and its response should be correlated with the nature of the abort and the hazards to be mitigated. The FSS may result in termination of vehicle thrust by cutting the flow of propellants to the rocket engine, resulting in a landing or other non-destructive outcomes. This is usually the case for pilot initiation of the FSS. Alternately, it may be a destruct system that terminates thrust using charges to cut open the propellant tanks and disperse liquid propellants or to depressurize solid propellant motors, which will likely result in the breakup of the vehicle and potentially yield an explosion.

6.1.3.2 **Use of a Time Delay Analysis.**

The design of the FSS must include a time delay analysis, in accordance with § 450.108(d)(4). This analysis should establish the mean and uncertainty distribution for the elapsed time between the violation of a flight abort rule and the time when the flight safety system is capable of aborting flight for use in establishing flight safety limits. Considerations for the FSS design should include whether it is activated by remote command, e.g., a Missile Flight Control Officer (including a pilot), triggered by a premature separation system such as lanyard pull, or automatically triggered by an on-board autonomous flight safety system.

6.2 Identifying Hazards and Hazard Producing Events.

In accordance with § 450.109(b), if an operator conducts a flight hazard analysis for this phase of flight, the mission scenario must identify reasonably foreseeable hazardous events. This should include evaluating the hazards from hazardous debris if an undesirable situation occurs during flight, and quantification of the subsequent risk to people and assets. Following the identification of the hazardous debris hazard producing events, a thorough review should be performed to confirm that all events have been identified and that these events are reasonable and foreseeable for the specific launch or reentry vehicle and mission plan.

6.2.1 Vehicle Impact and Breakup Analysis.

The hazardous debris generating hazardous events must include the potential for structural breakup of the vehicle pursuant to § 450.121(b), which can include explosive events that occur during a malfunction due to aerodynamic, inertial, and heating loads acting on the vehicle. Destruct breakup of the vehicle resulting from activation of the flight safety system due to violation of a mission flight abort rule should also be considered under § 450.121(b). Potential events that could result in vehicle breakup while following a normal trajectory include: an explosion, rupture of a motor case or other pressure vessel, solid rocket motor burn-through, or structural failure due to loads (thrust, aerodynamic, inertial). Events that could lead to a vehicle deviating outside of its normal trajectory bounds are referred to as malfunction turn failures and include all behavior ranging from gradual turns to rapid turns resulting in a tumbling vehicle. They may also include gravity turns wherein the vehicle attitude is controlled to maintain a zero or near zero angle of attack.

6.2.2 Failed Motor Event Hazards.

Potential hazards from failed motor events should be identified. This includes inadvertent separation between stages of a vehicle or of a strap-on solid rocket motor. This should be addressed during normal flight and during a vehicle malfunction. The analysis should consider if any motors can fail to ignite during staging or fail to shut down at the planned event times.

6.2.3 Planned Jettisoned Hazardous Debris.

In accordance with § 450.109(b), if an operator is conducting a flight hazard analysis for this phase of flight, all reasonably foreseeable hazards to public safety for a planned mission must be identified. This can include planned jettisoned hazardous debris such as discarded stages, inter-stage hardware, hardware ejected prior to igniting a stage such as nozzle closures, support struts or rings, payload fairing pieces, and (for a sub-orbital launch) the payload. It can also include a planned intercept of the launch vehicle or vehicle payload with another launch vehicle or its payload.

6.3 Hazard Management to Minimize Public Risk.

The ideal way to manage risk and minimize the hazards in the region of a launch or reentry is to conduct the operation in a remote area. In that case, hazards can be isolated and risks to the public can be minimized or possibly eliminated. However, complete containment of hazards generated by even a suborbital vehicle is usually not possible, because populated areas tend to encroach on even the most remote sites, and areas at risk become too large to accommodate reasonable surveillance and access control measures. In these situations, a flight safety system often becomes necessary in accordance with § 450.108(c)(6) to protect the public from the potential hazards associated with a launch or reentry activity. A flight safety system may be destructive or non-destructive. A traditional flight safety system designed to terminate a vehicle's thrust and disperse its remaining propellants, resulting in falling vehicle breakup that results in inert fragments, is an example of a destructive system. Non-destructive flight safety systems include abort systems designed to render a vehicle non-propulsive, leading to potential recovery of an intact vehicle or its components. In either case, hazards to the public may still exist.

6.3.1 Risk Management of High Risk Areas.

Risk management often includes the evacuation of people from high risk areas or the sheltering of people to minimize their exposure to the hazards. This includes the development of hazard areas (or corridors) from which pedestrian, motorized vehicle, train, waterborne vessel, and/or aircraft traffic are cleared.

6.3.2 Minimizing Risk using Timing and Scheduling of Mission.

Another method often used to manage risk is to limit occurrence of a mission to a time when the risks are low. This includes restricting a mission to be initiated during favorable meteorological conditions during which dispersions of hazards will not reach populated areas, or the likelihood of causing casualties is sufficiently low to meet risk acceptance criteria. It also may include restrictions to specified times during the day or days of the week when population exposure is minimized.

6.3.3 Minimizing Risk by Modifying the Mission Profile.

If the risk to the public or critical assets cannot be mitigated by containment of the hazards, or sheltering of people, the operator should modify the mission profile. Modifications to the mission profile can include:

- Changing the launch azimuth to preclude or reduce the overflight of populated areas,
- Modification of the mission trajectory shaping (such as altitude as a function of downrange location) to mitigate the potential spread of the hazard,
- Adjusting the timing of planned debris events, such as jettisons,
- Placing limits on the allowable dispersions of the vehicle from the intended trajectory for which continued flight will be allowed (even if the vehicle has the potential to achieve a usable trajectory or provide the operator with useful data), or
- Restricting launch during adverse wind conditions.

7 HAZARDOUS DEBRIS CHARACTERIZATION.

In accordance with § 450.121(a), a flight safety analysis must include a debris analysis that characterizes the hazardous debris generated from normal and malfunctioning vehicle flight as a function of vehicle flight sequence. Normal flight-related hazardous debris events are due to planned jettisons such as spent stages, fairings, nozzle covers, and similar items. Vehicle breakup during on-trajectory normal flight can also occur due to aerodynamic forces, inertial forces, structural vibrations, thermal loads, and other effects that exceed the structural design limits of the vehicle. Malfunctioning vehicle flights that do not become orbital will result in vehicle breakup or intact impact. In this chapter, guidelines to develop hazardous debris lists or 'hazardous debris catalogues' for these vehicle breakup events are presented. The methods described here comply with §§ 450.121(b) and 450.121(d)(1), (2), and (5). In accordance with § 450.121(b), a debris analysis must account for:

- Each reasonably foreseeable cause of vehicle breakup and intact impact;
- Vehicle structural characteristics and materials; and
- Energetic effects during break-up or at impact.

7.1 Developing Hazardous Debris Lists for Range Safety Analyses.

Development of vehicle fragmentation characteristics given command destruct action, self-induced failure, or aerodynamic or aerothermal breakup is a statistically uncertain and semi-empirical process due to the myriad of potential outcomes. Vehicle designers understandably focus the majority of their engineering design time and expertise on optimizing nominal flight performance and vehicle loading within a normal range of thrust and angle of attack variations. When flight deviations become extreme to the point of vehicle mechanical failure, the mission is lost as far as the manufacturer and operator are concerned. However, the consequences of these potential failures are a primary concern for the protection of the public and for the assessment of associated risks. Hence, a quantitative description of the physical, aerodynamic, and harmful characteristics of hazardous debris are required by § 450.121(d)(5).

7.1.1 Characterizing Attributes of Hazardous Debris.

Due to the uncertainties in break-up, manufacturers and operators are inclined to produce conservative debris lists rather than develop thousands of sets of high-fidelity predictions. Explosive breakup and fragment accelerations are complex processes involving release of compressed gas energy, possible detonation of confined propellants, degree of propellant mixing, propellant deflagration combustion gas expansion, potential cryogenic liquid flashing, and impulse and drag effects on fragments. Accurate results from higher fidelity models pose the challenge of combining both flow dynamics and structural breakup integrated models. Higher fidelity models are inherently focused on narrow subsets of the solution space. Empirical data from test programs or observations from real-world failure events are essential data sets needed to validate or tune higher fidelity models or provide empirically defined initial conditions that are not explicitly modeled. Deterministic model simulations, field tests, and real-world failures constitute discrete samples of highly variable and uncertain processes. Ideally, a statistical modeling approach is desired to characterize the attributes of hazardous debris. Therefore, in accordance with § 450.101(g), the method must produce results consistent with or more conservative than the results available from previous mishaps, tests, or other valid benchmarks, such as higher-fidelity methods.

7.1.2 Debris Analysis Requirements.

In accordance with § 450.121(b), a debris analysis must account for (1) each reasonably foreseeable cause of vehicle breakup and intact impact, (2) vehicle structural characteristics and materials, and (3) energetic effects during break-up or at impact. All models should be based on considerations of the loads and structural response that could be expected during flight, including the combined effects of:

- Aerodynamic loads,
- Thrust loads,
- Effects of flight termination system action, such as ordnance,
- Explosion of solid rocket propellant in flight or deflagrations from solid rocket motors such as those that occur in a propellant burn-through,
- Secondary liquid propellant mixing and fireball expansion loads,
- Fracture mechanics, for example, from a failure of the pressurized liquid propellant tanks, overpressure of a solid rocket motor or losing a nozzle in a solid rocket motor,
- Breakup of rocket structural elements, such as interstages, avionics wafers, payload attachments and fairings that do not act as a confinement surface for an energetic propellant, and
- Fragmentation impact among structural elements during breakup.

Note: These processes generally occur as the mechanical failure progresses through high strain rates and non-linear plastic deformation of vehicle components. Vehicle manufactures possess the greatest amount of detailed information about the construction of their own launch vehicles. The analysis should bound the uncertainties involved. Debris catalogs are often a development that matures as knowledge of the vehicle matures. Initial assessments should err on the side of conservatism towards public safety, and higher fidelity models should be applied if necessary to demonstrate compliance with the quantitative risk criteria in § 450.101.

7.1.3 Comparing to Hazardous Debris Data for Vehicle Failures.

Actual failure events generally occur over broad ocean areas and most of the vehicle hazardous debris is seldom observed or recovered. When launch failures occur early in flight and the hazardous debris field is largely over land around the launch facility, (e.g., Titan 34D-9 at Vandenberg AFB), the ensuing accident investigation board generally focuses attention on investigation of the components that caused the launch failure (e.g., one solid rocket motor segment). The final accident report is often silent on the amount of total vehicle hazardous debris recovered. However, data does exist from some historic accidents and from some test campaigns. Debris catalog models must use results available from previous mishaps, tests – both for model accuracy and for assigning uncertainties around piece counts, sizes and imparted velocities in accordance with § 450.101(g). Small debris pieces generated during tests or accidents that may be hazardous to aircraft are of interest to debris list development but this class of fragment size may not have been collected or catalogued due to the difficulty in identifying and locating them or excessive time consumed attempting to collect them. Absence of such pieces in reported debris collections does not necessarily infer that these size classes were not generated, and, therefore the analysis should include uncertainties to account for ground rules applied in debris data collection campaigns.

7.1.4 Determining Population and Geographic Areas Affected by Hazardous Debris.

Range safety analysts are also charged in accordance with § 450.133(a) through § 450.133(d) with attempting to evaluate post-vehicle failure hazardous debris impact hazards and risks to people and structures on the ground, and to ships or aircraft operating in the launch area or under the launch flight path. To perform such analyses, the analyst needs to give reasonable consideration, in accordance with § 450.121(a) through § 450.121(c), to the total amount of launch vehicle hazardous debris generated and to estimate the numbers, sizes, shapes, masses, demise characteristics, drag characteristics, lift characteristics, and explosive potential for each fragment category.

7.1.5 Required Vehicle Information to Develop Breakup Hazardous Debris Lists.

Preparation of hazardous debris fragment lists resulting from failure-initiated vehicle destruction, planned jettison events, and intact impact events, should rely on several types of information. Ideally, empirical data defined from analysis of recovered hazardous debris is the most desirable. Such empirical data by itself is insufficient alone for the development of hazardous debris fragment lists because of the methods used to recover fragments after malfunctions usually only focus on the large, easily found pieces. The operator can use other information that could provide guidelines to assist in the development of hazardous debris fragment lists. Generally, this includes vehicle materials and methods of construction, and defining potential structural weaknesses. The following are typical sources of data that may be available:

7.1.5.1 **Vehicle Structural Description.**

Descriptions of the vehicle and payload, including scaled diagrams that show the general arrangement and dimensions of components. Three-dimensional (3-dimensional) Computer Aided Design (CAD) drawings are typically prepared during the design and fabrication of space vehicles. These digital 3-dimensional drawings could provide most of the geometric and mass information needed for generating a hazardous debris list.

7.1.5.2 **Propellant Tank(s), Engine(s) and/or Motor(s).**

Specifications of the engine and/or motor including case material (outer case, lining, insulation, thickness, density, strengths) should be provided, including descriptions of nozzles, steering mechanisms, propellant types and ingredients, propellant density, and propellant weights versus time in flight.

1. For solid motor propellant, the core radius (to outer edge of propellant), grain design, density, and internal pressure and web thickness versus time should be specified. For solid motor cases, lining and insulation, the thickness, density and material strengths, as well as the expected burst pressure should be specified.
2. For a liquid engines and associated tankage, the pumping and pressurization systems and associated stored energy, materials (thicknesses, densities, strengths), and pressurization, including expected operating pressures and burst pressures, should be specified.
3. For all tanks, engines, and motors, expected uncertainties around mass, dimensions, and material strengths should be specified.

7.1.5.3 **Flight Termination and Other Destruct Systems.**

Descriptions of destruct systems (command, automatic, separation), which includes descriptions of components and activation mechanisms, exact locations of all charges (beginning point, length, gap, ending point), descriptions of delays in activation of charges, and a discussion of whether, and under what circumstances, a destruct might ignite a non-thrusting motor.

7.1.5.4 **Trajectory Data.**

Trajectory data for a typical mission, which includes normal trajectories, malfunction trajectories, and event times (ignitions, steering programs, burnouts, jettisons). Trajectory data are used to obtain vehicle velocity, attitude or angle of attack, 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. Some vehicle breakup simulation models apply both internal and external pressure conditions to calculate fragment acceleration and maximum velocities. The external pressure is a function of vehicle altitude, which can be obtained from the vehicle trajectory data. Additional detail regarding trajectory data is available in AC 450.117-1, *Normal and Malfunction Trajectory Analysis*.

7.1.5.5 **Flight Abort Rules.**

Flight abort rules that define the allowable conditions for launch and activation of the flight safety system. These rules are detailed in AC 450.108-1, *Using Flight Abort Rule as a Hazard Control Strategy*.

7.1.5.6 **Vehicle Material Properties and Design Limitations.**

Knowledge of the vehicle's material properties, anticipated operating envelope, design limitations, and structural weak points (attachment points and points of transition between component geometries), and test results including the static and dynamic failure strengths of load-bearing components. Material properties should include, with associated uncertainties: density, yield and ultimate strengths, specific heat, thermal conductivity, and heat of fusion. Design limitations should include, with associated uncertainties: thicknesses, weld strengths, attachment types and materials, and margins of safety.

7.2 Effect of Type of Vehicle Breakup on Hazardous Debris List.

In accordance with § 450.121(b)(1), a debris analysis must account for each reasonably foreseeable cause of vehicle breakup and intact impact. The type of breakup affects the hazardous debris list and imparted velocities of those hazardous debris. There can be many failure modes for a vehicle and there can be multiple potential breakup modes for a given failure mode. The hazardous debris list depends on the breakup mode and not the failure mode. Vehicles can breakup due to many factors. In accordance with § 450.121(d)(1), an applicant must provide a description of all scenarios that can lead to hazardous debris. Some of the common breakup categories observed for vehicles are given below. It should be noted that newer vehicles have many different types of failures and breakup modes. It is the responsibility of the applicant to consider all the relevant failure and breakup modes for their vehicle whether that mode is listed here or not.

7.2.1 Catastrophic Explosion of a Motor or Engine.

An increase in chamber pressure inside a solid rocket motor that exceeds the ultimate strength of the motor casing can cause catastrophic explosions of that malfunctioning motor and generally lead to breakup of the vehicle. Liquid propellant engines may experience overpressure in the combustion chamber, turbopump failures, propellant leaks, or overheating that can result in an explosive event. The cause of the uncontrolled increase in internal pressures could be an internal anomaly or a malfunction in other parts of the vehicle. The main parameters that affect the hazardous debris list are (a) the location of the explosion, and (b) high net internal pressure (internal pressure—atmospheric pressure at that altitude) at the time of explosion. Typically, vehicle parts near the center of explosion break up into smaller pieces and have higher imparted speeds than hazardous debris away from the point of explosion. Solid rocket motor failures that result when the motor case burst pressure is exceeded can have significantly higher chamber pressures than when the same motor is destroyed by flight termination system (FTS) ordnance. Therefore, imparted hazardous debris speeds in these cases are typically higher than that for FTS induced breakup hazardous debris. Debris generation computer models should distinguish between vehicle components that comprise a containment structure for an explosive or energetic source (e.g., common bulkhead propellant tank, pressure vessel, ignited solid rocket motor) and those that do not because different assumptions apply to breakup and imparted algorithms for those cases.

7.2.2 Flight Termination System (FTS) Initiated Breakups.

When a vehicle malfunctions, the vehicle will either breakup inflight, impact the ground intact, or achieve orbital insertion. If unconstrained malfunction flight results in an unacceptable level of risk, then the vehicle may employ a flight abort system as a hazard control strategy and terminate powered flight in accordance with § 450.108(f)(2) to control risk. Thrust termination options include shutting down motors or inducing vehicle breakup using explosive charges. The breakup mechanism of the vehicle due to FTS destruct systems are different for liquid motors and solid propellant motors. The breakup hazardous debris characteristics also depend on the design and placement of the particular FTS system. FTS charges may be initiated automatically due to flight rules or manually by flight safety operators. It is also possible for them to be initiated during vehicle breakup due to other breakups such as aero breakup, aerothermal breakups, inertial and other structural breakups, and inadvertent stage separations. The breakup hazardous debris list and imparted speeds depend on the breakup mechanism and the time of flight. The aerodynamic forces, the amount of liquid propellant, the shape and thickness of the solid propellant casting, and the chamber pressure in currently burning solid rocket motors all affect the imparted speeds of the hazardous debris.

7.2.3 Aerodynamic Breakup.

Space rockets are designed to withstand nominal acceleration loads along the axis of the rocket and some small angles of attack. Higher angles of attack exert large bending moments on the rocket body, and they can break, typically near weaker parts of the vehicle, like mid-body construction joints, and inter-stages. Many rockets have mechanisms to initiate destruct systems when a stage gets inadvertently separated. Therefore, many of these aerodynamic breakups may initiate FTS destruct charges and produce hazardous debris effectively the same as FTS type breakups. However, if there is no FSS, or FSS just cuts off thrust without inducing breakup, then the rocket may break due to further structural loadings and the hazardous debris list would be much different from that due to an explosive FTS.

7.2.4 Structural Breakups.

Structural breakups can occur during normal trajectories as well as malfunction trajectories. Breakups on a normal trajectory are typically due to design or fabrication flaws. In this case, the vehicle breaks up due to excessive loads or vibrations experienced while traveling along the normal flight path. If the vehicle goes into a turn that results in a large angle of attack or results in a high rate of rotation during a malfunction in the lower atmosphere, it is likely to break up due to aerodynamic forces that exceed the vehicle Q-Alpha load limit. At high altitudes, with low atmospheric pressures or in a vacuum, a high rotation rate can break up the vehicle if inertial forces exceed the structural limit of the vehicle. The breakup hazardous debris list from these events can be unique to the vehicle design and nature of the forces that drive the breakup sequence. Many breakup events that are initiated by a structural failure can be quickly followed by a catastrophic explosion in a motor or can lead to initiation of an FTS destruct system. If that is the case, then the hazardous debris list may be substantially similar to that developed for the FTS event.

7.2.5 Aerothermal Breakup.

Aerodynamic heating can induce breakup of launch vehicles, stages, or reentry bodies, by virtue of both melting parts of the structure and weakening structural elements that are brought to high temperatures. Aerodynamic heating is proportional to velocity cubed, and therefore the heating rates are highly non-linear with respect to velocity. When objects reenter the Earth’s atmosphere either from an initial orbital condition, or from a loss of thrust or guidance failure during upper stage phases of flight approaching orbital velocity, reentry velocities are high enough to produce significant aerodynamic heating that may result in structural breakup and potential demise of fragments resulting from the breakup process. Atmospheric density and shape of the vehicle (i.e., stagnation radius) also affect aerodynamic heating rates and are factors that should be considered in an aerothermal breakup model. An important and complicating factor that has significant effect on aerodynamic heating induced breakup is the design and integrity of thermal protective layers or systems used on a reentry body. A controlled reentry of a system with a properly designed thermal protection system will result in an intact vehicle surviving the reentry heating regime. A damaged thermal protection system can result in breakup of the vehicle even under controlled flight, as was the case for the Space Shuttle Columbia, which shed approximately 90,000 hazardous debris pieces during a several minute reentry breakup phase (see reference [6] in section 3.4 of this AC). Alternatively, there are aerothermal loads that can compromise a vehicle or a vehicle component that can result in a very different debris scenario – an example of which would be the jettisoned Space Shuttle External Tanks, which broke apart due to aerothermal loads and burst abruptly into substantially fewer pieces than the Orbiter reentry. Reentry vehicles that contain residual liquid propellants may also experience an explosive event that further breaks up the reentry body.

7.2.6 Reentry Breakup Fragments by Material Type.

Fragments released from an aerodynamic heating breakup process can be used to define hazardous debris classes and conservatively applied to ground risk calculations by ignoring any further reentry demise as the fragments fall to the ground from the release altitude. When risks from reentry aerothermal breakup are high, demise of fragments during free fall should be evaluated. Aluminum fragments are most likely to reach melt temperature and demise due to the low melting point of aluminum. Titanium, stainless steel, and carbon-carbon materials are more likely to survive reentry heating. Material properties of reentry fragments are needed to perform reentry demise calculations. Reentry demise of fragments released from the breakup of a complex or large reentry body are often modeled as lumped mass objects with simple geometric shapes to support drag, stagnation radius, and heated area parameter allocations. Uncertainties and conditions under which lumped mass assumptions break down (larger objects, complex shapes, and multiple material types in one piece) should be evaluated. A hazardous debris risk analysis using aerothermal breakup defined fragments should recognize that demise during free fall can change the ballistic coefficient of the fragments, and therefore shift the ground impact point relative to an approach that ignores demise.

7.2.7 Partial Breakups and Shedding.

It is possible for a vehicle to break up partially resulting in separated intact stages and boosters still thrusting or capable of residual thrusting. These large pieces should be propagated using proper trajectory propagation methods as described in AC 450.117-1, *Normal and Malfunction Trajectory Analysis*, until reaching ground or secondary breakup. This progressive breakup should continue until all the hazardous debris can be considered as lumped masses that can be propagated using methods described in chapter 6 of this AC. It is also possible that a vehicle could breakup incrementally and shed hazardous debris along the way. For this case, main vehicle trajectory should be computed using the methods similar to vehicle propagation algorithms used for the full vehicle with proper consideration for change in thrust, mass, and aerodynamic characteristics of the malfunctioning shedding vehicle. Unlike hazardous debris lists for instant breakups, in addition to other required information, the shedding location of each hazardous debris also should be defined in the hazardous debris list for this case.

7.2.8 Other Vehicle Breakup Modes.

There are many types of space vehicles being designed and deployed and there will be new types of failure modes and breakup modes for these new vehicles. However, the principles used in developing hazardous debris lists for the above types of breakup modes are still valid for new vehicles.

7.3 Effect of Vehicle Structural Characteristics and Materials on Breakup Hazardous Debris List.

In accordance with § 450.121(b)(2), a debris analysis must account for vehicle structural characteristics and materials. Vehicle structural characteristics and materials can have significant effect on the breakup hazardous debris characteristics. Two main factors that affect vehicle breakup are: (a) type of loads applied to the vehicle, and (b) strength of the vehicle subassemblies. This information should be properly accounted for in the method and techniques used for generating a hazardous debris list. Specifically, in a high fidelity debris modeling approach these factors should be modeled directly. When applying an empirical or statistical model, a structural expert should evaluate if the new vehicle design data falls within the design range from which the empirical model is derived.

7.3.1 Breakup Hazardous Debris List by Design Features.

Some examples of structural characteristics that can affect breakup include connection between different stages of the vehicle. If a vehicle starts tumbling during a malfunction turn, then the vehicle will start experiencing high bending moments that may lead to breakup at weak cross sections along the rocket. Often, interstages are less robust than motor bodies, especially solid rocket motors. Therefore, the strength and design of the load bearing elements at interstages will influence how a vehicle breaks up. Similarly, the strength and design of the connections between a main rocket body and strap on boosters will affect how easily the strap-ons become separated during a mishap. Therefore, an applicant should consider all unique design features of the vehicle when the hazardous debris list is generated.

7.3.2 Breakup Hazardous Debris List by Material Types.

The type of materials used also affects the hazardous debris list. For example, composite materials used in modern space vehicles fracture differently from older metal structure designs. They also have different strengths, densities, and melting points. Therefore, it is important that the actual materials used to fabricate the vehicle be considered when developing the hazardous debris list.

7.4 Effect of Energetics in the Vehicle on Breakup on Hazardous Debris List.

In accordance with § 450.121(b)(3), a debris analysis must account for energetic effects during break-up or at impact. Energetic effects are additional velocities resulting from explosions or sudden release of internal compressed gas.

7.4.1 Effect of Motor Type**.**

Breakups of solid rocket motors are different from that of liquid propellant motors. Both types of motors can be in a single vehicle.

7.4.1.1 Solid Rocket Motors.

Hazardous debris lists from breakup of solid rocket motors will be affected greatly based on whether the motor is burning and pressurized at the time of breakup or not. If it is burning at the time, then the amount of internal pressure and the thickness of the remaining propellant grain affect the hazardous debris size as well as imparted speed at breakup.

7.4.1.2 Liquid Propellant Motors.

If there are liquid propellant motors in the vehicle, they have different effects on the hazardous debris list than that from solid propellant motors. For example, if the liquid propellants are stored in common bulkhead tanks with feed pipes that pass oxidizer through the interior of the fuel tank, or vice-versa, then this leads to greater initial mixing and greater explosive potential for the liquid propellants during breakup. If any of the liquid propellants are hypergolic, then estimating the explosive yield has more uncertainty. Mixing of hypergols is somewhat self-limiting because a reaction develops spontaneously on contact between the fuel and oxidizer liquid phases and that forces separation of fuel and oxidizer to limit the reaction. In addition, hypergols are toxic. Toxic fragments that contain these chemicals must be accounted for in accordance with

§ 450.139(c) since they can have an extended hazard area associated with release and atmospheric dispersion of the toxic chemical.

7.4.2 **Intact Impact.**

If a jettison body such as a spent stage or a malfunctioning space vehicle does not break up due to environmental forces or an FTS destruct system, then it will land intact on the ground. A hazardous debris list for an intact impact case has only one fragment. However, it can pose higher risk at the impact location due to secondary breakup and explosion upon impact. Due to its size, an intact component could cause a collapse of a complete building and mass casualties. The debris analysis should provide for how the intact vehicle could break up upon impact taking into consideration the explosive effects from any propellants in the vehicle. How a vehicle breaks up upon impact causes a bigger or smaller explosion depending on the ground hardness and mixing of propellant and oxidizer, or if a solid propellant is used, how it breaks up and explodes. The explosive effects may be defined as a TNT equivalent in the hazardous debris list. See paragraph 11.10.2. Intact impact of large parts of a vehicle can lead to release of toxic propellants, and the hazardous debris list should provide sufficient information to perform toxic release hazard analysis in accordance with § 450.139.

7.4.3 Effect of Phase of Flight at Breakup.

The configuration of a vehicle changes with the phase of a flight. For example, consider a space vehicle having a main solid propellant engine with attached solid propellant strap on boosters as the stage 1, a solid propellant stage 2, and a liquid propellant stage 3. Initially, only the main engine and the boosters may be thrusting. Breakup at this stage should reflect that fact (i.e., hazardous debris list for burning motors should reflect they are burning and hazardous debris list from stages 2 and 3 should reflect they are not burning). In the next phase of flight after strap-on boosters are spent and separated, breakup will reflect only hazardous debris from stage 1, stage 2, and stage 3 and other parts of the vehicle. In current practice, flight safety analysts prepare hazardous debris models for each part of the vehicle, (i.e., stage 1, strap-on boosters, stage 2, stage 3, and payload) and combine them to form the full vehicle hazardous debris list at a given phase of flight. When hazardous debris lists from different stages are combined, those lists also should be correspond to the correct burning status of those stages at that phase of flight.

7.4.4 Effect of Altitude of Breakup.

Multiple analyses at various altitudes are typically required, ranging from the launch point, to apogee, and back to ground (if sub-orbital). Traditionally, higher altitudes cause higher explosion velocities due to the expansion of pressurized vehicle gases into the lower pressures of the ambient atmosphere. There is a greater pressure potential through which to accelerate hazardous debris until these pressures equalize.

7.4.4.1 **Solid Propellant Motors**.

This velocity increase is particularly the case with solid propellant motors, where, the later flight time results in both lower ambient pressure and higher internal gas volume, as the solid propellant is depleted.

7.4.4.2 **Liquid Propellant Motors**.

Liquid motors experience balancing effects where higher altitudes are offset by depleted propellant, but the unique trajectories, structures, and propellant loadings ultimately drive the expected effects of higher altitudes on the hazardous debris catalog.

Note: The subsequent FSA (i.e., using these hazardous debris catalogs) should be capable of capturing how equally-jettisoned hazardous debris will travel exponentially farther near exo-atmospheric conditions, due to both the relief from atmospheric drag and the curvature of the Earth (ultimately to include some hazardous debris approaching orbital trajectories).

7.4.5 Effect of Propellant Loading at Time of Breakup**.**

As propellant depletes during ascent, gases that may either mitigate or exacerbate the hazardous debris catalog (particularly the explosion velocity) occupy the remaining volume of the motor. A solid propellant motor burns its propellant and replaces that volume with hot gas that is at the full pressure of the combustion chamber (typically about 1,000 psi). This phenomenon exacerbates the explosion velocity, producing higher-speed hazardous debris as the propellant is depleted. For example, in a space shuttle solid rocket booster (SRB) late in burn, rupture of that motor case could expand thousands of cubic feet of gas from 1000 psi to a low ambient pressure, accelerating fragments to near Mach-1 speeds on its way.

7.4.5.1 **Accounting for Volume, Pressure of Compressed Gases.**

Any hazardous debris generating model that is applied should account for the volume and pressure of compressed gases inside a solid rocket motor chamber when computing fragment explosion velocities as the propellant loading factor decreases (i.e., propellant is consumed) during burn.

7.4.5.2 **Accounting for Fracture Mechanics**.

A solid rocket motor breakup model should consider the fracture mechanics that apply to a sudden release of chamber pressure and the affect that has on the motor case and the remaining propellant web thickness. Several modeling approaches have been developed that estimate fragment velocities based on impulse and drag effects that evolve as internal compressed gases flow outward through gaps between solid rocket motor case and propellant fragments resulting from fragmentation of the motor. Examples are provided in references [7] and [9] in paragraph 3.4 of this AC.

7.4.5.3 **Accounting for Acceleration of Fragments following Combustion**.

Liquid propellant motors generally replace their propellant (kerosene, hydrogen, methane, oxygen, or similar) with ullage (helium, nitrogen, or similar) as the propellant burns. Even though this ullage is often inert, it is still a pressurized gas—and a pressurized gas, in a rupturing tank, propels fragments. Combustion during a rupture (which first requires adequate mixing of the fuel and oxygen) arguably occurs a fraction of a second after the fragments have departed (accelerated by merely the rupturing of the pressurized tanks), but some circumstances (particularly intact impact, and maybe other mid-air failure mechanisms) may mandate accounting for some further acceleration of fragments by a combustion or blast event; see references [3], [4], and [19] in paragraph 3.4 of this AC.

7.5 Steps for Developing Hazardous Debris Fragment Lists.

7.5.1 Explosive Breakups.

The following is a step-by-step procedure that should be used for developing a hazardous debris fragment list for an explosive breakup mode. Structural breakups and other malfunctions frequently lead to explosive breakups.

1. Acquire dimensioned drawings (3-dimensional CAD drawings with mass and dimensional data) of the total vehicle and major subsystems such as stages, interstages, nozzles, liquid engine assemblies, solid rocket strap-on motors, avionics bay, avionics components, propulsion and attitude control system components (small nozzles, pressurized tanks, propellant tanks and plumbing components), payload adapter assembly, payload, and payload fairing.
2. Acquire photographs of actual hardware assemblies and subassemblies. Photographs give a general feel for the extensiveness of items such as wiring harnesses, plumbing lines, mounting brackets, and miscellaneous small hardware.
3. Acquire flight hardware mass properties. Mass properties data should include masses of both subsystem components and the higher assemblies. Placement of subsystem components in terms of a vehicle reference system helps determine distance of individual components from the center of the explosion. Some mass properties may include masses of components that are distributed across the assembly such as paint, screws, washers, and adhesives.
4. Estimate the center of explosion realistically to match the design of the system.
5. Partition the vehicle construction into the following types of fragments or fragment sources:
    a. Liquid propellant tanks
    b. Solid rocket motors including case and propellant
    c. Skin and panel pieces (not part of liquid or solid propellant tanks)
    d. Struts and frame pieces
    e. Discrete components
    f. Piping and wiring harness pieces
    g. Miscellaneous small irregular shaped pieces
    h. Distributed material (adds to mass in items 3 and 4)

6. For liquid propellant tanks that break up with the vehicle, apply a semi-empirical engineering model. The model should be verified using either first principle high fidelity numerical methods, such as a coupled finite element code or advanced multi-phase multi-physics code, or information from test or accident history to generate a list of tank wall fragments. For most common motor designs, semi-empirical engineering tools are sufficient. For explosions in a tank with a common internal bulkhead and internal feed pipe, assume the explosion occurs inside the tank. If liquid propellants are housed in separate tanks without a common bulkhead, the center of explosion is considered to be external to the tanks in the inter-tank region.

7. For solid propellant motors that breakup with the vehicle, apply a physics-based algorithm or first principle high fidelity numerical method such as a finite element code to generate a list of motor case fragments and residual solid propellant fragments. Special consideration should be given to the aft motor segment and forward dome. The hazardous debris list and imparted speeds of the hazardous debris will depend on the net internal pressure and the remaining thickness of propellant grain. If using a finite element type code, the analysis should demonstrate that it can properly account for the variation in material strength properties with temperature, strain rate, pressure, and age of the propellant.

8. Use the vehicle drawings and descriptions to compute the surface area of one face of skin and panel type components. These will usually be associated with interstages, payload adapters, motor skirts, interior honeycomb or aluminum panels used to mount or isolate components, and trays to mount electronics (which may double as actively cooled heat sinks in some cases). For each type of skin or panel element, an operator should compute the mass per unit area. If hazardous debris fragment lists are to be applied to atmospheric reentry or hypersonic breakup where aerodynamic heating is a concern, material types should also be noted and may require additional final classifications of similar hazardous debris shapes and sizes by material type.

9. Estimate the number of fragments to assign to each skin and panel type assembly. This is recognized to entail significant uncertainty, since loading and fracture or failure mechanical analysis is rarely performed or available. Several guiding principles should be applied:

   a. The sum of the surface areas of the fragments should match the total un-fragmented surface area.

   b. The mass of each fragment should be computed as the surface area of the fragment times the mass per unit area, plus any prorated distributed mass to be added to these types of fragments (e.g., paints, adhesives, small fasteners, stiffening ribs, insulation, sound suppression foam, or other items that are deemed to be spread over large areas of other components).

   c. Assume that a range of fragment sizes are likely to be produced somewhat randomly from a statistical distribution. Historical events of large pressure vessels and combustion events of launch vehicles have suggested a log-normal distribution. The mean fragment length scale should be based on the length that would result in an ultimate strength exceedance from a 1D bending moment using the average tank skin thickness and the expected pressure on the material at break-up. The mode fragment length should be based on the average thickness, including stringer or support sections. Data has also suggested about a 1:1 to 1:5 variation in ratio of length to width. The skin or panel drawings may suggest some intuitive breakdown for fragment shapes or sizes if there are holes cut in the structure or regions of relatively thin wall or weaker construction separated by stronger structural rings, plates, or frame elements. An example would be hemispherical domes, which tend to be built stronger and are of a shape that results in less stress concentrations. These shapes tend to stay intact and fail along weld lines. Careful consideration should be given to capture the smallest credible fragment size, particularly down to a ballistic coefficient of ~1 pounds per square foot (psf), and/or mass greater than 0.4g, as those fragments create a hazard for aircraft and suspend in the atmosphere for significant fall-times. Characterizing fragments down to a ballistic coefficient of 3.0 psf is generally considered of high importance, as those have historically been in the range of hazards to persons exposed on the ground.

d. For panel and skin components close to the center of an explosion, assign relatively more small fragments and fewer large fragments. For panel or skin components farthest from the center of explosion only a relatively few large fragments should be considered unless the structure is very fragile.

e. Real fragments will have irregular shapes, but for risk analysis purposes simple shapes such as flat or curved plates, or rectangular cubes with uncertainties around drag, size and mass parameters, will serve as a reasonable approximation. If a more complicated shape is certain to survive, then parameters should be derived accordingly. When selecting fragment sizes, the geometry of the main assembly should constrain maximum fragment dimensions (e.g., a fragment dimension should not be greater than the height, width, or circumference of the parent piece).

10. Identify strut and frame pieces from vendor drawings and photos. These items may be somewhat integrated into the skin and panel structures as stiffening ribs and rings. Generally, both the top and bottom of stages, interstages, and payload adapters will terminate in a structural ring that provides stiffness, load transfer capability, sufficient material for fasteners to mount skin panels, and lift points. Alternatively, some struts and frame items may be part of open structural support systems that do not directly incorporate skin panels. Some pressurization tanks are mounted with support struts between tanks.

11. Identify discrete components from drawings and photos. These are items such as avionics boxes, tanks, small thruster assemblies, or other items that appear to be compact and of relatively robust construction. Typically, these types of components are predominantly individual avionics items grouped together on side walls of the vehicle or avionics trays. The assumption that avionics boxes and batteries survive a vehicle explosion intact may underestimate the number of small pieces that could result if the boxes break up. Tanks used to store pressurized gases and liquid propellants are also included in the discrete component’s hazardous debris group. Discrete components that are securely attached to skin or panel constructed items

may break loose and retain the attached panel segment as part of a discrete component.

12. Identify piping and wiring harness items from drawings and photos. Estimate the total length of tubing and wiring used in various diameter categories and a mass per unit length for each category.
13. Identify components that can best be described as small irregular shaped pieces that do not fit into any of the previous categories. These tend to be items like heavier duty mounting brackets, housings for springs that are part of stage separation hardware, and small compressed gas orbital maneuvering thrusters. Fragment shapes assigned to such pieces tend to be “boxes” or “cylinders,” even though some bracket assemblies have numerous openings and are more like a small 3-dimensional frame structure than a solid 3-dimensional structure.
14. Identify materials that are to be treated as distributed mass over other previously defined fragments. To conserve total vehicle mass within the fragment list and to recognize that actual fragments will be combinations of items represented as separate items in a parts list, items that cannot be identified with a specific discrete component should have their masses distributed among the other defined fragments. Items such as paint, insulation, and sound suppressing foam are typically applied to the skin and panel fragments and can be prorated to such fragments based on surface area calculations.

7.5.2 Aerothermal Breakups.

Unlike an explosive event, aerothermal breakup will typically begin at a high altitude (e.g., 95km) and progressively shed an increasing number of fragments down to an altitude as low as 50km. This means fragments are shed from the body over time and space. If the reentry body is falling at a flight path angle that is nearly vertical, then the uncertainty in the hazardous debris impact location due to the shedding process is minimized, and the effect is mainly in the time differences of when hazardous debris pieces impact. This will be more important to predicting aircraft risk than ground risk. One approach that has been used with object oriented reentry breakup models is to estimate all reentry breakup hazardous debris to be generated at one time at an altitude of 78km. This is based on empirical observations that many different types of reentering satellites all seem to experience a major breakup event near the 78km altitude. Some reentry bodies contain propellant tanks that may have residual liquid propellant. Aerothermal heating may rupture these tanks due to heat transfer into the liquid and over pressurization of the tanks. In the case where a reentry explosion is predicted, the hazardous debris list development steps defined in paragraph 7.5.1 of this AC may be applied.

7.5.3 Small Hazardous Debris Hazardous to Aircraft.

Some hazardous debris may only be hazardous to aircraft and people on an aircraft, but not to people on the ground, whether in open areas, or sheltered in buildings, vehicles, or ships. This is mainly due to the closing speed between the aircraft and fragments. Due to the high closing speeds, fragments can impart significant collision impact energy to an aircraft. Hazardous debris that damages an engine, penetrates the fuselage to produce a loss of cabin pressure, or causes a fuel leak can lead to a plane crash killing all persons on board. The fragment list should contain all fragments capable of causing a casualty-producing event. Some aircraft vulnerability models consider dense fragments as small as 0.4g to be hazardous (see paragraph 11.8 of this AC). The closing speed is the relative velocity between the aircraft and the hazardous debris at impact. This is much higher than the impact speed of the same hazardous debris impacting a ground target for two reasons: (1) due to low air density at aircraft altitudes, terminal speed of hazardous debris is greater at aircraft cruise altitude than sea level, and (2) aircraft fly much faster than most debris terminal velocities, especially low ballistic coefficient debris.

7.6 Hazardous Debris Containing Toxic Material.

Upon impact, a liquid tank may not explode but instead break open and leak, or may explode but only partially consume the liquid propellants. Some liquid propellants used for rocket propulsion or spacecraft maneuvering, such as hypergolic propellants, are toxic to people. The possibility for this type of event should be evaluated to determine if there is a potential toxic hazard to people on the ground. If this hazard is considered credible, a flight safety analysis should evaluate the probability of the spill occurring over locations in the affected region, and the amount of liquid that could spill in accordance with § 450.139(c). This topic is covered in AC 450.139-1 *Toxic Hazards Analysis and Thresholds*.

8 AERODYNAMIC AND HARMFUL DEBRIS CHARACTERISTICS.

8.1 Ballistic Coefficients.

The equations of motion that propagate a fragment through the atmosphere apply force due to drag through the ballistic coefficient, β. This parameter indicates the relative importance of inertial and aerodynamic forces on a body in free fall. It is defined as:

$$\beta = \frac{W}{C_D A_{ref}}$$

where W is the fragment mass,[1] C_D is the drag coefficient, and A_{ref} is the associated aerodynamic reference area. Values of C_D and A_{ref} are obtained experimentally. The value of C_D varies as a function of speed v, usually given in terms of the Mach number $M = v/c$ where c is the speed of sound. The ballistic coefficient is nearly constant at low speeds ($M \leq 0.3$), and this is called the subsonic ballistic coefficient, β_{sub}.

8.1.1 Flow Regimes.

The earth's atmosphere contains three aerodynamic regimes: continuum flow at low altitudes, free molecular flow (FMF) at high altitudes, and a transitional regime. These are identified through the Knudsen number $Kn = \lambda / L$ where λ is the molecular mean free path and L is the characteristic body length. Applying a constant ballistic

[1] The ballistic coefficient is sometimes represented using weight instead of mass. This affects its usage in equations of motion, as the conversion factor is gravity. However, in English units, g = 1.0 lbf / lbm at sea level, so numerically, this factor may drop out.

coefficient derived for continuum flow (CF) to regions where free molecular conditions exist tends to underestimate the drag force. Therefore, accounting for drag force changes between the continuum and free molecular flow regimes typically reduces the size of the estimated impact dispersion areas. For larger debris, using a ballistic coefficient assuming continuum flow is usually an adequate model (except if the debris is traveling close to horizontally in the upper thermosphere or exosphere). However, for small debris, such as may be hazardous to aircraft, the effects of the flow regime can become important, especially if the debris spends significant time in the thermosphere or exosphere. The continuum flow regime is applicable where Kn ≤ 0.01, the transitional regime 0.01 < Kn < 10, and the FMF regime where Kn ≥ 10.

8.2 Drag Coefficient Estimates for Continuum Flow.

Two values used in the calculation of the ballistic coefficient are the drag coefficient and aerodynamic reference area. These should be defined in a consistent manner for a given shape. If experimental values are not known for a given fragment, then reasonably good estimates for use in β can be made by considering the shape of the fragment. Different conventions can be used for reference area, but the drag coefficient should correspond to the referenced area. This section provides tabular data that may be useful in assigning drag to various shaped fragments which are tumbling. To apply the tables 1 through 3 of this AC, the fragment should be approximated either as a sphere, a square box, a rectangular box, or thick/thin plate. The estimates for Aref are then be given by the area projected onto the direction of the flow. Experimental results of C_D for the four shapes are given in reference [10] of paragraph 3.4 of this AC. The tables show C_D at a set of specific Mach values M. To get values for other speeds, use piecewise linear fits without extrapolation. The fragments are assumed to be tumbling during free-fall.

8.2.1 Drag Coefficient Estimates for Spherical Objects.

For a sphere with diameter D,

$$A_{ref} = \frac{\pi D^2}{4}$$

Drag coefficients, as a function of Mach number, for subcritical flow are shown in Table 1. For supercritical flow, apply the ratio 0.14/0.47 to each drag coefficient in Table 1 to construct the associated table.

Table 1—Sub-Critical Drag Coefficients for Spheres

M	0.3	0.5	0.6	0.8	0.9	1.0	1.4	2	4	10
C_D	0.47	0.5	0.52	0.64	0.73	0.82	1.05	1.0	0.93	0.92

8.2.2 Drag Coefficient Estimates for Cylindrical Objects.

For a cylinder of length L and diameter D, $A_{ref} = \frac{\pi D^2}{4}$. For all values of L and D, the drag coefficients at M=0.3 are computed by:

$$C_D(M = 0.3) = 0.65\frac{L}{D} + 0.46.$$

When L/D=4, the drag coefficients as a function of Mach number are shown in Table 2. For coefficients C_D with other L/D ratios, apply the ratio $C_D(M = 0.3)/3.06$ to each drag coefficient in Table 2 to construct the associated table.

Table 2—Drag Coefficients with L/D=4 for Randomly Tumbling Cylinder

M	0.3	0.5	0.8	0.9	1.0	1.4	2	4	5	10
C_D at L/D=4	3.06	3.15	3.45	3.56	4.30	5.79	6.27	5.82	5.97	6.04

8.2.3 Drag Coefficient Estimates for Plate-Shaped Objects and Rectangular Boxes.

The dimensions of a rectangular object have the order $L_1 > L_2 > L_3$. For aspect ratios $L_2 > 5L_3$ and $\frac{L_2}{L_1} > 0.2$ use the values shown in Table 3, otherwise the box is a "Thin Plate" and presented in the next subparagraph. The reference area is given by:

$$A_{ref} = \frac{4}{\pi}\left(L_1L_2 + L_1L_3 + \frac{\pi}{2}L_2L_3\right).$$

Table 3—Drag Coefficients for a Randomly Tumbling Rectangular Box

M	0.3	0.8	1.0	1.4	2	3	4	6	10
C_D	0.75	0.78	0.92	1.05	1.06	1.09	1.09	1.12	1.17

8.2.4 Drag Coefficient Estimates for Thin Plate Shaped Objects with High Aspect Ratios.

The reference area for a thin plate is the same as for the general rectangular box, i.e. $A_{ref} = \frac{4}{\pi}\left(L_1L_2 + L_1L_3 + \frac{\pi}{2}L_2L_3\right)$. There are three cases to consider, where in each case apply the ratio $C_D(M = 0.3)/0.75$ to each drag coefficient in Table 3 to construct the associated table.

For $L_2/L_1 \leq 0.05$, at M=0.3 the drag coefficient is computed by

$$C_D(M = 0.3) = 1.27 - 6.35(L_2/L_1)$$

For $0.05 \leq L_2/L_1 \leq 0.1$, at M=0.3 the drag coefficient is computed by

$$C_D(M = 0.3) = 1.08 - 2.54(L_2/L_1)$$

For $0.1 \leq L_2/L_1 \leq 0.2$, at M=0.3 the drag coefficient is computed by

$$C_D(M = 0.3) = 0.903 - 0.76(L_2/L_1)$$

8.3 Drag in Transitional and Free Molecular Flow Regimes.

8.3.1 Reynolds Number.

A key parameter in these regimes is the Reynolds number,

$$Re = \frac{\rho v L}{\mu}$$

where μ is the absolute viscosity of the fluid. The Reynolds number is a dimensionless parameter that characterizes the ratio of inertial force and viscous drag force. There are two flow regimes: supercritical for Re >1 x 10^6, which corresponds to a smooth surface, and subcritical for Re <1 x 10^6 for a rough surface.

8.3.2 Drag in Free Molecular Flow Regime.

The drag coefficient depends on the wall temperature and the accommodation coefficient for the surface. With the conservative assumptions provided in reference [15] of paragraph 3.4 of this AC, the drag coefficient for a sphere in FMF can be computed as a function of Reynolds number:

$$C_D(Kn \geq 10) = 0.92 + 1.7exp(-0.1Re) \quad Sphere$$

and that for a stable thin plate by:

$$C_D(Kn \geq 10) = 1.83 + 1.12exp(-0.3Re) \quad Stable\ Thin\ Plate$$

while a tumbling thin plate is obtained by applying a factor 1.56.

8.3.3 Drag in Transitional Regime.

Values of CD in the transitional regime at a given altitude h, are computed using Gaussian interpolation between the CF and FMF regimes:

$$C_D(0.01 < Kn < 10) = \frac{1}{2} + \frac{1}{2}\left(\frac{h - \underline{h}}{\sqrt{2}\sigma_h}\right)$$

where $\underline{h}$ is the midpoint altitude between the upper CF and lower FMF altitude bounds. The standard deviation σ_h is 1/6th the distance between the two altitude bounds (treating the bounds as a 6-σ spread).

8.4 Lift uncertainty.

Lift uncertainty accounts for changes in the orientation of the body while on a free-fall trajectory. Lift force is always orthogonal to the drag force vector. Fragments generally tumble for at least a portion of flight during which the lift direction changes moment-by-moment. The effect of lift, like drag, is modeled with a coefficient C_L. Values of this coefficient should reflect the net effect of the tumbling and stable portions of flight. Because lift is uncertain, the ratio of the lift to drag is characterized as a one-sigma uncertainty, $(C_L/C_D)_\sigma$. Example values are given in Table 4 for different shapes.

Table 4- Example Values for Lift Uncertainty

Shape	$(C_L/C_D)_\sigma$
Spherical	0.00
Blunt	0.01
Intermediate	0.03
Flat plate or similar	0.05

8.5 **Required Information in the Hazardous Debris Model.**

In accordance with § 450.121(d)(5), a quantitative description of the physical, aerodynamic, and harmful characteristics of hazardous debris must be submitted.

8.5.1 For any given time of the flight, for any foreseeable nominal or malfunction trajectory, there should be a stochastic hazardous debris model from which flight safety analysis can extract a realization of a set of hazardous debris from the breakup event. It is customary to separate classes of hazardous debris models by breakup mode for all major vehicle systems associated with phases of flight (i.e., stages, boosters, and payload) and combine them as necessary depending on vehicle configuration. These hazardous debris models should capture the changes to the vehicle (including current mass of propellants, chamber pressure, temperature, velocity, angle of attack) and the breakup environment (altitude, ambient air pressure, temperature). It is common to define different hazardous debris lists that apply to different time ranges. Each such hazardous debris list represents a constant set of fragments that is unvaried during that time range. For example, one may generate ten hazardous debris lists for FTS breakups for the duration of active burning of a solid rocket motor.

8.5.2 A hazardous debris model should be specified for a given flight time range, for a given stage and for a given breakup mode. Typical hazardous debris lists contain hundreds to thousands of debris pieces. It is possible to have a general model that can output a full realization of all the hazardous debris with all the required properties. However, it is common to define a hazardous debris list as a list of hazardous debris groups where statistical parameters needed to generate a realization of hazardous debris in this group are specified. All the hazardous debris in the generated hazardous debris list should have the following information defined:

- Description of the hazardous debris group,
- Mass properties,
- Aerodynamic properties sufficient to define trajectory from the point of breakup until it is no longer a hazard,
- Statistical distribution of breakup-induced imparted velocities,
- Properties needed for aerothermal heating and ablation,

- Energetic properties: sufficient to define secondary explosions at impact, and
- Toxic properties: sufficient to estimate toxic hazards to people and environment immediately or long term.

8.6 **Consideration for Grouping Hazardous Debris to a Hazardous Debris Group.**

All fragments within a class should have similar material composition and produce the same type of hazard (inert, explosive, toxic, etc.). Further, each class should be constrained in terms of the variations of parameters important to aerodynamics and hazard produced as follows.

- The hazardous debris group should have a representative fragment mass. The group should constrain the ratio the minimum and maximum fragment masses to $\mathrm{W_{max}/W_{min}} < 2$.
- The hazardous debris group should have a representative mean projected area that is the extent of the fragment's hazard to people. The group should constrain the ratio of the minimum and maximum fragment areas to $\mathrm{A_{max}/A_{min}} < 2$.
- The hazardous debris group should have a representative ballistic coefficient, which is the geometric mean of the fragments in the group. The group should constrain the ratio of the minimum and maximum ballistic coefficients to $\max(\beta_{sub})/\min(\beta_{sub}) < 1.7$.[2] Fragments with β_{sub} less than or equal to 1.3 psf typically pose negligible public risks.
- The group should constrain the ratio of the maximum breakup-imparted velocity to minimum breakup-imparted velocity within the following bound:

$$\Delta V_{max}/\Delta V_{min} = 5/(2 + \log_{10} \beta_{sub})$$

8.7 **Description of the Hazardous Debris Group.**

For each hazardous debris group, the criteria used to include hazardous debris should be described.

8.7.1 Mass Properties.

For each hazardous debris group, a statistical model to describe the mass should be specified. The minimum level of information provided should include the mean plus and minus three-sigma, total mass, and the number of hazardous debris in the hazardous debris group.

8.7.2 Aerodynamic Properties**.**

Aerodynamic properties of the hazardous debris are needed to predict the propagation over the atmosphere until they become no longer hazardous. Minimum amount of properties that should be provided are described below.

- The group should have a representative nominal ballistic coefficient β, and plus and minus three-sigma uncertainty bounds that is represented by a lognormal distribution. Values should correspond to tumbling motion for an unstable fragment,

[2] In logarithmic space, approximately $\log_{10} \beta_{max} - \log_{10} \beta_{min} < 0.2$ or $\ln \beta_{max} - \ln \beta_{min} < 0.5$.

and for controlled motion for any duration of time that a fragment stabilizes with respect to its angle of attack. The nominal value should represent median subsonic ballistic coefficient βsub the hazardous debris group.

- The group should have a common representative mean lift coefficient to characterize the lift force. The group should have three -sigma uncertainty bounds of the lift coefficient corresponding to a tumbling fragment.
- βsub should have one or more C_D vs. Mach curves to convert to various Mach values that include supersonic flight. The C_D vs. Mach curve accounts for the fragment shape. Curves should correspond to tumbling motion for an unstable fragment, and for controlled motion for any duration of time that a fragment stabilizes with respect to the angle of attack. If stability is due to lift, then there should be an associated coefficient of lift C_L vs. Mach curve. A hazardous debris model should provide equations for the curves, or data points adequate for a piecewise linear description.
- An estimate of the axial, transverse, and mean tumbling areas of each fragment. If the fragment may stabilize under normal or malfunction conditions, the hazardous debris model should also provide the projected area normal to the drag force.
- An estimate of the ballistic coefficient corresponding to the axial, transverse, and tumble orientation for each fragment.
- The mean and plus and minus three-sigma axial, transverse, and tumbling areas for each fragment or fragment class.

8.7.3 Initial Velocity and Location**.**

Any additional velocity imparted on the hazardous debris due to any explosive effects should be specified. For instantaneous breakup of vehicles, all the hazardous debris can have the same initial state vector. However, for breakup cases that shed hazardous debris along the way, state vector for each hazardous debris group can be different.

8.7.3.1 The hazardous debris group should characterize the imparted speeds and directions relative to the pre-breakup center of mass motion. In-flight explosions or pressure vessel ruptures release energy with the potential to fracture the vehicle and disperse the resulting fragments.

8.7.3.2 The hazardous debris group should specify the magnitudes and directions of imparted velocity vectors and their associated uncertainty. For no preferred direction of the imparted speed, a Maxwellian distribution applies with speed defined as the maximum value equal to the 97th percentile. If there is uncertainty in the maximum value defined, then a statistical model for uncertainty of the maximum value should be specified. If velocity is not random, then a directed velocity model should be defined that specifies the distribution of directions and uncertainty in imparted velocity in those directions.

8.7.4 Aerothermal Heating Properties**.**

An aerothermal heating and demise model for the hazardous debris in each hazardous debris group should be defined for reentry or late ascent failure modes where falling hazardous debris can reach high enough velocity to cause melting in the hazardous debris. Aerothermal properties needed to support evaluation of component melting include: material type (to set melting temperature and heat of fusion), fragment stagnation radius, and heated surface area.

8.7.5 Energetic Properties.

8.7.5.1 **Propellants.**

Various types of propellant produce different hazards, so the amount and condition of loaded or residual propellants should be updated at the envisioned time of breakup.

8.7.5.1.1 Liquid propellants—such as Kerosene (“RP-1”) and Oxygen (“LOX”)—as individual constituents—may pose only a fire hazard, following an intact impact of a tank on the ground, with some additional hazardous debris hazard from the impact and rupture of the pressurized tank. Multiple constituents however, if landing as coupled or proximal items, may produce a combustive overpressure, and fragment speeds that are 1-2 orders of magnitude faster. Therefore, a hazardous debris catalog should account for the condition of these “hazardous debris items” (tanks) as they reach ground to perform the vehicle impact and breakup analysis of § 450.121(b).

8.7.5.1.2 Solid propellants can produce both explosive and toxic hazards, when impacting the ground and/or burning thereafter—while sometimes also modestly “burning back” as fragments fall (which reduces the amount reacting after contact with the ground). For these reasons, solid propellant hazardous debris catalogs are obligated in accordance with § 450.121(d)(5) to account for these predicted solid propellant fragment masses, counts, and mid-air burning conditions. For solid propellant hazardous debris, the following information should be provided:

- Mass of propellants
- Type of propellants
- Explosive energy in terms of TNT equivalent mass
- Burning status: burning now, can start burning during fall due to aeroheating, or contained (will not burn during fall)
- Equation and coefficients for burn rate at both motor pressure and ambient pressure; additional information is available in reference [16] in paragraph 3.4 of this AC.
- Snuff-out pressure

8.7.5.1.3 "Hypergolic" tanks, whether holding mono- or bi-propellants, may also survive a breakup and produce a several possible types of hazards on the ground (hazardous debris, overpressure, fire, and toxins). For these reasons, an operator should characterize any amounts of onboard hypergolic propellants in the hazardous debris catalog for their predicted condition (shielded tank in a stage, released tank as an individual hazardous debris item, a ruptured tank with mid-air dispersion).

8.7.5.2 **Other Energetic and Hazardous Debris**.

8.7.5.2.1 All remaining potential energies at time of ground contact (including batteries, intact propellant reservoirs, pressurized tanks, ordnance, compressed springs, elevated hardware temperatures, nuclear materials, toxins, chemicals, and any other potential hazard to humans or the environment) should be assessed.

8.7.5.2.2 Batteries can contain hazards from residual electrical charges or the ingredients within the battery that are released at rupture—in addition to batteries themselves being relatively high ballistic coefficient hazardous debris items.

8.7.5.2.3 Even a "depleted" propellant tank typically holds some residuals (typically ~2-5% of its capacity) that cannot be reliably burned during normal operation. These amounts can be unusually reactive, as they are nearer to the vapor state required for combustion. Therefore, hazardous debris catalogs should account for hazards posed by remaining propellants in "empty" tanks.

8.7.5.2.4 Inert gases (like helium, such as used for ullage) produce no toxic hazard, but may be contained in tanks that are many times higher pressure than other tanks on board (e.g., 5,000 vs. 100 psig). Similarly, hydraulic fluids (often a synthetic hydrocarbon), may be contained in tanks or reservoirs pressurized to high pressures (e.g., 2,500 vs. 100 psig), and any toxic effect may be negligible in comparison to other hazards. For this reason, stored pressure energy (i.e., a tank, tire, pneumatic cylinder, or otherwise) should be characterized within the hazardous debris catalog, for the potential overpressure hazard on ground.

8.7.5.2.5 Vehicles can contain hundreds of "ordnance items" such as contained energetic devices (cartridges, igniters, shape charges) designed to separate stages, deploy payloads, break bolts, cut electrical or fluid lines, jettison items, or destroy the vehicle itself (i.e. Flight Termination ordnance). When the vehicle—or its hazardous debris—reaches the ground, some of this ordnance may not have been rendered inert (fired and consumed), due to the stage at which the failure occurred, or due to the ordnance function being interrupted by the breakup itself. Unexploded ordnance can then remain as a hazard on ground, so the hazardous debris catalog should track these potential energy items and their expected condition during the various nominal and malfunction scenarios.

8.7.5.2.6 Other sources that are expected to produce non-negligible amounts of energy should also be included. An example is compressed mechanical springs, which can be used to isolate or stabilize onboard hardware, jettison stages or payloads, or otherwise, and may retain a hazard on the ground after the hazardous debris has come to rest, including if the item's retention hardware has been damaged. The size and pre-compression of these potential energy items should be tracked in the hazardous debris catalog, with their expected conditions during various nominal and malfunction scenarios.

8.7.5.2.7 Elevated temperatures of inert hardware (such as fractured nozzle components, hardware heated by plume radiation) can remain a burn hazard or an ignition source on ground after hazardous debris has come to rest. Residual temperatures above approximately 250°F have potential for igniting ambient ground brush or foliage, causing uncontrolled fires on the terrain around the hazardous debris footprint. Hardware temperatures above 130°F can cause burns to skin. For these reasons, any hazardous debris anticipated to retain elevated temperatures to ground should be tracked for that characteristic in the hazardous debris catalog.

8.7.6 Toxic Properties**.**

Any information that is needed for toxic effects of hazardous debris in accordance with § 450.139(c)(1) should be provided in the hazardous debris list. Toxins, chemicals, and heavy metals include a wide range of potential constituents on a vehicle. These can include residual hypergols, acids used for long-term reactions in payloads, lead used for ballast, or any other constituent that can pose a hazard to people or the environment—including if the hazardous debris is not recovered (such as chemicals or lead leaching into the soil or groundwater during the years following the mishap). Batteries have chemicals that affect long-term health of environment. If there are hazardous chemicals that can affect the impact area, then they should be identified. Some payloads may carry hazardous material, such as nuclear material, and any hazardous materials as defined in 49 CFR § 172.101 must be identified, in accordance with § 450.43(i)(1)(v), so that the Administrator can determine the need for any special analysis or safeguards.

8.7.7 Related to Hazard/Casualty Area of a Hazardous Debris.

An estimate of the mean area of each fragment that is the extent of a fragment's hazard to people should also be included.

9 PROPAGATION OF HAZARDOUS DEBRIS TO IMPACT.

A high-fidelity evaluation should compute the impact probability distribution for each class of fragments at the locations of hazarded people in accordance with § 450.135(b), and for specific assets that the operator is requested to evaluate. For this evaluation, the hazardous debris must be propagated following the vehicle termination event, or a jettisoned body from the moment of release, until it is no longer a hazard, as indicated under § 450.121(c). Each hazardous debris propagation under § 450.121(c) creates a trajectory that must account for significant forces acting on bodies in accordance with § 450.121(c)(1), and there should be a sufficient number of trajectories to account for uncertainty in breakup conditions and in external forces that effect the impact probability distribution. The set of fragment trajectories from each failure and planned event state vector may be computed to generate sample impact points that can later be fit with a functional distribution. The succeeding paragraphs discuss the data and parameters that should be accounted for, and general approaches for defining the propagator algorithm.

9.1 Atmospheric Data for Propagation.

The impact probability distribution for each class of fragments must account for the atmospheric conditions, in accordance with § 450.135(b)(4)(ii). The hazardous debris trajectories are influenced by wind and drag, in proportion to air density ρ, near the surface. Wind conditions can carry hazardous debris towards populated areas. The likelihood of high wind magnitudes can lead to high risk to surrounding populations or result in significant constraints on when a launch can occur. The minimum set of parameters that should be accounted for are air density, wind, and Mach number.

9.1.1 Air Density.

Air density is a function of altitude, geographic location, and time. For debris analysis, the spatial variation is important, especially the vertical profile of density. In the lower atmosphere, the temporal variation of density has no significant effect on impact locations, and the geographic variation effect is relatively small. Thus, average density models as a function of geographic location are generally sufficient up to around 300 km altitude. The high-altitude (above 300km) density model is very important when the vehicle is re-entering at a shallow angle (e.g., less than a few degrees from horizontal), and especially for very small reentry angles. In these cases, a model that extends to one million feet should be used. For steeper angles, the importance of density models above 300 kilofeet depends on the fragment characteristics. The density model at these altitudes also is more important as the fragment ballistic coefficient is smaller. For non-shallow trajectories for fragments relevant to debris risk (above 1 psf), the air density profile should extend from the surface up to about 400 kilofeet. Also, when implementing the air density model in the ballistic trajectory propagator, the potential for erroneous skipping at the “top” of a model should be considered (skipping can physically occur, but can also be a numerical aberration).

9.1.2 Air Density Models.

Since temporal variations in air density have insignificant effect on debris analysis (except for very shallow reentries), standard air density models can be used. For the lower atmosphere, a range reference atmosphere is commonly used in the launch or landing area. Below the exosphere, the Earth Global Reference Atmospheric Model from NASA (see reference [11] of paragraph 3.4 of this AC) should be used, as it provides sufficient data for the atmosphere. This dataset provides mean monthly historical values up to about 400 kilofeet, on grids of latitude and longitude that span the entire Earth. It has the accuracy and resolution adequate for debris analysis, but equivalent alternatives can also be used. For the exosphere, the density can vary significantly as a function of time due to space weather, but the COSPAR International Reference Atmosphere Model should be used as an average when temporal variability is not needed. It also contains references to models that account for temporal variation. When combining models, the result should be faired over a range of approximately 25% in altitude. Where air density is provided in more localized wind data or models (see section 9.1.5) the density from those sources may be used. A range reference atmosphere may also be used in the local area.

9.1.3 Mach number.

Mach number M is defined as $M = v/c$, where v is the ambient fragment or intact body speed with respect to the wind, and c is the speed of sound. If the speed of sound is not provided, then M can be computed using the air temperature T, e.g. $M = v \,/\, \sqrt{\gamma RT}$, where γ is the specific heat ratio, and R is the specific gas constant. For a good approximation, the atmosphere obeys the Ideal Gas Law, which is a direct relation between temperature, density, and pressure, for all altitudes for which drag should be accounted. Temperature data can be obtained from the same sources as air density data.

9.1.4 Wind.

Wind effects are very important for debris analysis, but wind above the jet stream (i.e., above 60,000 feet) usually has little effect. Appropriate application of wind is essential for compliance with § 450.135(a), as it is common for operations to be acceptable in some wind conditions, but not others. Section 450.135(a) provides two options: an analysis in planning that identifies limits on what conditions are acceptable for the operation or an analysis in the countdown that uses the best available data. For the launch or landing area (where the vehicle is traveling slower than two miles per second), local time-appropriate wind data or models should be used. Outside the launch or landing area, a three-dimensional statistical model should be used. Local data should only be used within 100 miles of the location it represents and should be faired with three-dimensional statistical model over approximately 50 miles horizontal distance and approximately 25% in altitude.

9.1.5 Local Wind Data for Countdown Analysis.

During the operation countdown, there are two options for wind data for areas where the vehicle is flying below hypersonic speeds.

9.1.5.1 The first option is to use measured wind data, from various measuring systems such as Jimsphere, Rawinsonde and Windsonde soundings, and Doppler Radar Profiler measurements. Data should be obtained within six hours of launch. The uncertainty in the wind forecast should account for the time delay between the forecast and the flight. This data is typically centered about a specific measurement location and thus depends only on altitude. This data should extend to at least above the top of the jet stream.

9.1.5.2 The second option is to use a wind forecast authorized by either the Department of Defense or NOAA (such as the North American Mesoscale (NAM) model or Global Forecast System (GFS)). Forecasts are usually sufficiently accurate for debris analysis for up to 72 hours, but should be verified by comparing newer forecasts to the forecast used in the countdown analysis. It is critical that the forecast computed for the planned operation time should be used. If localized weather events (including weather fronts or storms) are anticipated, the applicant must ensure the operational flight conditions are consistent with the forecast. The uncertainty in the wind forecast should account for the time delay between the forecast and the flight.

9.1.6 Local Wind Data for Availability Study.

If an availability study is performed to satisfy § 450.135(a)(1), then appropriate wind data should be obtained. The data set should include at least 100 wind profiles appropriate to the location of the operation within the same season of the operation (e.g., within 30 days of the launch date). Either data from the operation location (e.g., range) or from the NOAA Radiosonde database (https://ruc.noaa.gov/raobs/) should be used. An operator should either analyze every profile or a representative sample that includes the worst foreseeable conditions under which an operation might be attempted, as § 450.165(a) requires that the actual operational conditions be within the range of what has been determined to be acceptable. In accordance with § 450.135(c)(1), the applicant must submit a description of the methods used to demonstrate compliance with the safety criteria in § 450.101. In accordance with § 450.115(c), the applicant must include a description of how the operator will account for the conditions immediately prior to enabling the flight of a launch vehicle or the reentry of a reentry vehicle, such as the final trajectory, atmospheric conditions, and the exposure of people.

9.1.7 Non-local Wind Data.

A three-dimensional atmospheric model should be used for areas outside the local area. The NASA EARTH-GRAM model (discussed above) or its equivalent should be used, and should account for variability within the month of the operation. If doing a countdown analysis, a three-dimensional forecast model can be used.

9.2 Failure and Planned Event State Vectors.

All state vectors corresponding to failure and planned events required by § 450.117(d)(4) and § 450.119(c)(4) must be identified to conduct a hazardous debris risk analysis under § 450.135. Any time and spatial uncertainty in these state vectors must be also specified if it exists in accordance with § 450.117(d)(4)(iii). This information defines the starting points of the hazardous debris trajectories. These state vectors may be associated with intact vehicles, planned deployed objects, or vehicle breakup fragments. State vectors from FSS destruct action of the vehicle are discussed in AC 450.117-1, *Normal and Malfunction Trajectory Analysis*. The other most common sources are discussed in the subparagraphs below.

9.2.1 Self-Breakup State Vectors.

Vehicles on malfunction trajectories may experience sufficient external aerodynamic loads or internal inertia forces to cause the vehicle to come apart. The same is true for tumbling vehicles on ballistic trajectories when they survive until the end of powered flight since they could immediately start tumbling rather than remaining stable. Launch operators should determine vehicle breakup criteria limit ranges for each phase of flight, which should account for uncertainty in the thresholds. These ranges are often assumed to be represented by Gaussian distributions by default, although better informed understandings of the load limits may allow for other distributions to be used.

9.2.1.1 In general, a breakup state time is the moment when the stress related vehicle structural load criterion limit is exceeded. These breakup state vectors should be computed by interpolation between the time bounding malfunction trajectory initiation points.

9.2.1.2 The uncertainty in the breakup state vectors must be accounted for in the statistical trajectory set (paragraph 9.3 of this AC) in accordance with § 450.117(d)(4)(iii). The uncertainty in the criteria limit will result in a range of breakup state times and their associated breakup state vectors. Each breakup state vector can be assigned a probability based on the associated structural limit distribution probability value. However, the distribution of the breakup state times may be very non-Gaussian even when the criteria limit distribution is Gaussian. The uncertainty in the breakup state vectors must additionally account for failure state vector uncertainty if the vehicle or malfunction trajectory does not already do so.

9.2.1.3 This may be done by using the mean breakup state vector as the basis for the statistical trajectory. The mean state vector is where the 50 percent threshold is exceeded. The uncertainty in the state vector is then represented by one or more Gaussian covariance matrices that will be sampled during the setup of the based statistical trajectory set.

9.2.1.4 There are three common structural limit cases that should be evaluated. The first case is from aerodynamic forces. The aerodynamic breakup criteria should account for angle-of-attack α, i.e., the angle between the vehicle's roll axis and the velocity vector, and the external dynamic pressure q acting on the vehicle. The criteria breakup distribution is based on the dynamic pressure multiplied by total angle of attack (q-α) limits of breakup, or on a $q*\sin(\alpha)$ limit. Both of these limits are simplifications; if it is known from the design that more sophisticated quantification of structural limits is appropriate and have a significant effect on the breakup time, then those limits should be used. Structural limits should represent the upper bound of what the vehicle could survive. This type of breakup should be evaluated for vehicle malfunction trajectories, and for vehicle ballistic trajectories.

9.2.1.5 The second case is from inertial forces. One breakup criterion is when a vehicle has reached sufficient rotational speed in a vacuum or low-density atmosphere. The criteria breakup distribution is based on the rotation rate limits of breakup. The rotation rate accounts for yaw and pitch rates. This type of breakup should be evaluated for a vehicle malfunction trajectory. Another inertial force can be a buoyant force as a result of g-loads from the vehicle. This would present a force on any structures submerged in a fluid and may exceed attachment hardware limits. A third type of inertial force breakup is when g-loads exceed structural capability.

9.2.1.6 The third case is from aerothermal effects. An aerothermal induced breakup occurs when friction buildup leads to melting of portions of the vehicle. Sufficient time for melting can lead to aerothermal breakup during vehicle reentry from orbit, or if vehicle thrust termination occurs at sufficiently high altitudes and velocity. Since melting typically starts at altitudes centered about 75,000 feet when speeds reach about Mach 15, this case should be handled for all events that occur above 100,000 feet at speeds as low as Mach 10. The criteria breakup distribution is based on the altitude limits provided that a vehicle has exceeded a speed threshold. Although the altitude limits should include uncertainty, the speed threshold may be a single value. This type of breakup should be evaluated for a vehicle ballistic trajectory.

9.2.2 Thrust Termination Failure State Vectors.

The trajectory points of a randomly selected trajectory from the set of normal trajectories, or the nominal trajectory, are used to create a set of failure state vectors corresponding to thrust termination for an intact vehicle. The vehicle follows a ballistic trajectory after failure and self-breakup should be considered prior to surface impact for a vehicle that is tumbling. If self-breakup does occur, then the self-breakup state vector would replace the intact vehicle failure state vector for use in the risk analysis. The state vector uncertainty is added for the nominal trajectory case at thrust termination. The full set of trajectory points, or a subset of sufficient resolution, may be used. Since thrust termination failures can lead to potentially high consequence intact impacts, the analysis should identify the impact conditions in terms of speed and location. Thus, the sample rate of the failure trajectory should be at least four times higher than the tumble rate and high enough that velocity can be interpolated accurately to within 10%. Smaller limits down to 10 Hz may be necessary to meet § 450.119(b) for high speed vehicles, such as suborbital vehicles, or during abrupt maneuvers. State times that occur more often do not yield much benefit and so intermediate trajectory points can be filtered out.

9.2.3 Jettisoned Body State Vectors.

Planned deployment events jettison one or more bodies. These may be stages or other attached items, such as small doors or fins, the function of which has ceased. The risk from these bodies should be included in the debris risk analysis, in accordance with § 450.135(b)(3). Each originates from a planned event state vector that is determined during mission planning.

9.2.3.1 A body may be jettisoned from a trajectory randomly selected out of a set of normal trajectories, to account for state vector uncertainty. Alternatively, a single jettison state vector may be specified from the nominal trajectory, and its uncertainty accounted for using covariance data derived from the ensemble of normal dispersed trajectories, see paragraph 9.3 of this AC. The planned event state vector is computed through linear interpolation of time between bounding time trajectory points.

9.2.3.2 It is necessary to consider self-breakup of a jettisoned body during its ballistic fall. These bodies may be smaller than the main vehicle, but they can be large main stages that can still have points of weakness. Self-breakup of unpressurized sections may not be necessary to consider if they are more compact and have much higher structural breakup limits. Also, since these bodies are not powered in free-fall, they will not reach the speeds needed for inertial forces to be significant.

9.2.4 Intact Impact State Vectors.

A vehicle will impact the surface during powered flight if it survives a malfunction flight and does not achieve an orbital condition. Intact impacts only occur for a limited set of Monte Carlo simulations and may result in a sparse set of impacts in the tails of bivariate distributions. Uncertainty about the impact points differs for each impact point and should be evaluated. This should be computed in a way that ensures sufficient resolution to produce smooth and continuous individual risk contours, but should not be artificially smoothed. Intact impacts can be a significant contributor to risk results and should be accounted for using a statistically significant sample size (e.g., at least 30).

9.2.4.1 **Kernel Density Estimation Procedure of Impact Location Uncertainty.**

A Kernel Density Estimation (KDE) procedure is an example of an acceptable approach, which considers the distances between the neighboring impact points to determine the degree of smoothing needed. KDE works better with more impact points, but can be applied with as few as thirty. The points that are used in the KDE should come from the same type of events (i.e., the same failure mode and breakup type) and from failure trajectories within the same set. A KDE creates a smooth distribution from a collection of samples by applying a distribution about each sample (a kernel). The total distribution is then the sum of the individual distributions. Typically, a Gaussian distribution is used for each kernel.

9.2.4.2 **Impact Vector Based Uncertainty**.

An alternative approach is to compute uncertainty based on the velocity vector at impact. The magnitude of the horizontal component of the velocity vector can be scaled by a reference time (e.g., one to two seconds) to estimate an uncertainty in the impact location.

9.3 **Statistical Trajectory Set**.

Tumbling fragments, planned jettisoned hazardous debris, or an intact non-powered vehicle follow a ballistic trajectory. A ballistic trajectory's initial point is one of the failure or planned event state vectors discussed in paragraph 9.2 of this AC. A statistical risk analysis should employ a set of ballistic trajectories for each fragment class, which accounts for a set of fragments with similar characteristics, or a single body. Each trajectory in a set should account for all relevant sources of uncertainty of the event's state vector, and additional sources that affect the free-fall motion. At given times or locations, a trajectory set is described by a probabilistic distribution for use in a statistical risk analysis, or a hazard bound for a containment analysis. The trajectory set should account for uncertainty in ballistic coefficient β (i.e., drag), explosion or induced velocity (DV), lift, and wind.

9.3.1 Sampling Approach.

A trajectory set associated with an event state vector can be obtained from explicit rules of sampling. An example is the covariance sampling presented in the reference [13] of paragraph 3.4 of this AC. This sampling method is not random and follows specific rules and is appropriate for creating trajectories if the sources of uncertainty and subsequent trajectories nearly obey Gaussian statistics, (i.e., the skewness of the sampled points does not exceed roughly 0.15 throughout ballistic fall.) There are also other types of correlated random samples without the assumption of Gaussian uncertainty distributions. For more general statistics, the trajectory set should be created by performing a random Monte Carlo sampling of the state vector's sources of uncertainty. A typical number of Monte Carlo for ballistic trajectories for a given class of fragments is usually about 300-500 to create impact dispersions.

9.3.2 Uncertainty in Initial State Vectors and Ballistic Coefficient.

Event state vectors account for state vector uncertainty from the guidance and performance and any uncertainty involving its selection, when the event state vectors are set up (see paragraph 9.2 of this AC). The uncertainty in β typically can be characterized using a log-normal distribution. This sampling is done at the start of the ballistic trajectory. Guidelines for assigning beta are discussed in chapter 10 of this AC for usage when precise values are not known for a given fragment.

9.3.3 Uncertainty in Breakup-induced Velocity.

The most common modeling of DV assumes that there is no preferred direction. The uncertainty is then Gaussian in each direction, leading to a Maxwellian distribution in 3-dimensions. This approach is usually valid for propellant tank explosions. There are situations where the DV has a preferred directionality "directed-DV." At a given time, sampled fragments may form, for instance, a forward cone, hollow sphere, or a lateral torus or ring. An indication of what type of shape may form could be surmised by examining a plot of initial fragment speed vs directed angle off the vehicle's x-axis, or a computer-generated animation of the breakup. To define the sampling from a directed-DV event, in a precise manner, may require a fair amount of effort when there is no simple hazardous debris cloud shape, such as setting up a detailed finite element analysis program. This case may require describing the set of sampled fragments by a sum of many simple distributions. This sampling is done at the start of the ballistic trajectory. However, the uncertainty in vehicle orientation during that directional-hazardous debris event can also cause hazardous debris to occur in any direction, and so this uncertainty of final hazardous debris dispersion needs to be considered in accordance with § 450.121(c)(2)(iv).

9.3.4 Wind Uncertainty.

Wind uncertainty should be incorporated when using three-dimensional models of historical data (e.g., EARTH-GRAM) and when using measured data in the launch countdown. For historical data, the uncertainty should represent the wind variability that corresponds to monthly statistics. For measurement data, the uncertainty should statistically represent the potential change in wind conditions between the measurement and the time of the flight operation. Wind uncertainty should not be applied when using historical data samples in availability studies. When used, uncertainty data should be specified in altitude bands, with uncertainty given as a two-dimensional covariance. If correlation of uncertainty between altitudes is available, this data should be used. The time that the sampled fragment or intact body exists in the altitude band is used to convert wind uncertainty to the net position uncertainty for each band. The total uncertainty at a given time is the sum over all bands through which the sampled fragment or body passes.

9.3.5 Lift Uncertainty.

Uncertainty due to lift may be computed by a circular Gaussian distribution. The 1-σ radius is the difference in locations with and without lift force. Additional details are provided in section 8.4.

9.4 Ballistic Trajectory Generation.

Each ballistic trajectory should be created using a physics-based model that then utilizes the equations of motion accounting for the applied forces. Separate propagation models can be used for when fragments are in a vacuum, (i.e., above the given air density profile data), and when they are in the atmosphere. For motion completely in the vacuum, a fast method is to use Kepler's solution for a spherical Earth. The solution will propagate the fragment or intact body from its initial location to a desired lower altitude in one step. Additional iterations may be performed to achieve increased accuracy. The final location should be corrected for Earth oblations.

9.4.1 Otherwise, propagator algorithms are designed to propagate fragments in a series of small time steps. Position and velocity components are computed using acceleration and some of its higher derivatives. The size of the steps involves a tradeoff between runtime and accuracy. The time steps should be no larger than one second and should be adjustable to smaller values to account for rapid changes in direction and speed. There are two types of propagators: predictor, and predictor-corrector. A predictor will only move forward in time, without any knowledge of how much error is being introduced. A predictor-corrector will compute the error buildup between steps, and if too large will reduce the time step and restart the step. For ballistic trajectory generation, time steps of less than a tenth of a second lead to about the same results and runtimes for both types.

Exceptions are reentry cases where trajectories span large distances within the atmosphere before impact. For these, the error adjustment capability of the predictor-corrector usually shows a clear advantage of accuracy. For time steps closer to one second, predictors will run faster at a cost of accuracy compared to predictor-correctors, but are found to be sufficient for launch-to-orbit and non-orbital missions. These statements assume that the codes in question are robust and have been thoroughly tested to yield desired results.

9.4.2 Most propagators employ a version of a Taylor series expansion or Runge-Kutta algorithm. There are many versions of the Runge-Kutta algorithm as depicted in reference [17] of paragraph 3.4 of this AC. The various predictor-correctors have different starting mechanisms, step sizing logic, polynomial order, and error testing logic and thresholds. Both Taylor and Runge-Kutta series have an unbounded number of terms. For ballistic trajectories, the propagator should include at least up to fourth order terms.

9.4.3 All ballistic propagators should account for gravity, which in turn needs an Earth model to define the gravitational constant and Earth's shape. The WGS84 model should be used for all Earth constants; this model is described in greater detail in the reference [8] of paragraph 3.4 of this AC. For short range trajectories near the launch point, out to about two hundred miles, the Earth can be treated as a sphere. Otherwise, the oblateness of the Earth should be accounted for, which is specified by the J2 Earth moments. Neglecting the J2 term can lead to an error of several miles over tens of degrees of span. The next higher even moment, J4, tends to have a non-negligible contribution only for a highly elliptical ballistic trajectory that makes one or more passes around the Earth. The radius of the Earth at a local surface point should be computed using the radius of the Earth at the equator, at the poles, and applying the Earth model eccentricity correction for the local latitude.

9.4.4 In the atmosphere, propagators should account for drag force. For a tumbling body, drag is directed opposite to the direction of motion. If the position components are evaluated in the Earth's rotating frame, then the propagator should also account for the Coriolis and centrifugal pseudo-forces. To evaluate these forces, the Earth model rotation rate is needed.

9.4.5 State vectors consisting of position and velocity can be represented in many different coordinate systems. Propagator codes are generally in an Earth-centered EFG system, which may or may not be rotating with the Earth. At a given state time t_j, a propagator will start with position $\left(E(t_j), F(t_j), G(t_j)\right)$ and velocity $\left(\dot{E}(t_j), \dot{F}(t_j), \dot{G}(t_j)\right)$ and project them forward to time t_j+1.

9.4.6 The drag acceleration is given by

$$\vec{a}_{drag}(t_j) = -\frac{1}{2m(t_j)} C_D \rho v_{fluid} \vec{v}_{fluid} A_{ref}$$

where the fluid speed v_{fluid} is the fragment's speed with respect to the local winds, ρ is the local air density, and A_{ref} is the aerodynamic reference area. The gravity acceleration, with the J2 correction, is given by

$$a_{gravity}(t_j) = -g\left[1 - \frac{3}{2}J_2 \frac{A^2}{r^2(t_j)}\left(5\frac{G^2(t_j)}{r^2(t_j)} - 1\right)\right]\frac{x}{r(t)} \quad x = E(t_j) \text{ or } F(t_j)$$

$$a_{gravity}(t_j) = -g\left[1 - \frac{3}{2}J_2 \frac{A^2}{r^2(t_j)}\left(5\frac{G^2(t_j)}{r^2(t_j)} - 3\right)\right]\frac{x}{r(t)} \quad x = G(t_j)$$

The factor A is the Earth's equatorial radius, r, which is the distance from the gravitational center of the Earth to the center of gravity of the fragment. For a rotating frame, centrifugal acceleration is given by

$$\vec{a}_{centrifugal}(t_j) = -\vec{\omega} \times (\vec{\omega} \times \vec{r}(t))$$

where $\vec{\omega}$ is the Earth's rotation rate about the polar axis, and the Coriolis acceleration is given by

$$\vec{a}_{Coriolis}(t_j) = -2\vec{\omega} \times \vec{v}(t)$$

9.5 **Residual Thrust.**

A non-ballistic trajectory should be used for motors with residual thrust. Although the requirements do not explicitly mention residual thrust, it must be dealt with to meet requirement § 450.121(c)(1). There are several types of situations where a thrusting motor can survive vehicle breakup or termination. When a motor has non-negligible residual thrust, then a 5-DOF simulation should be used for essentially axisymmetric motors and a 6-DOF simulation for non-axisymmetric motors.

9.5.1 Free Flying Motors.

The first case is when an intact motor flies separately from the main body. This can occur when a motor detaches from its core vehicle and continues under full power until self-breakup or intact impact of the motor. A similar situation occur when an upper stage breaks up without destroying a lower stage. These should use the same type of analysis as with the powered core vehicle. This case is included in AC 450.117-1, *Normal and Malfunction Trajectory Analysis*. In some cases, residual thrust may present a negligible risk for casualty expectation, due to conditional probabilities which are discussed in AC 450.131-1, *Probability of Failure*. However, it should always be accounted for when performing assessments for flight abort, in accordance with § 450.108 and AC 450.108-1, *Flight Abort Rule Development*.

9.5.2 Partially Intact Motor.

A partially intact motor can also have residual thrust. This can occur when vehicle destruct system does not result in complete breakup of the attached motor. The destruct system is usually designed to break off the rear nozzle and front end of a motor, such that both ends have thrust but in opposite directions with a small net force from the remaining burning propellant. A partial destruct could yield a larger imbalance in thrust resulting in a net residual thrust T. A partially intact motor can result when a rocket motor nozzle throat fails and is ejected in the exhaust stream. The wider orifice diminishes the exhaust velocity and thus reduces the thrust. The motor propagates in a forward direction if the residual thrust acts along the central axis of motor towards the nose-end of the motor.

9.5.3 Stability of Unguided Motor.

For the motor to continue in stable flight and not tumble might require sufficient thrust force and stabilizing fins, or a thrust offset that produces a moment matched by aerodynamic moments – this is often achievable even for vehicles otherwise considered unstable at shallow thrust offset angles. A residual thrust that acts significantly off-axis usually leads to a spiraling motion of the motor. This is not as likely to be stable and may rapidly reach a tumbling state, especially if aerodynamic loads are negligible.

9.6 Directed Lift.

Some breakup scenarios can lead to release of objects with significant lift where a stable orientation can be maintained or reached during ballistic fall. An applicant should consider the directed lift of a hazardous debris body in a high-fidelity analysis when computing flight hazard areas in accordance with chapter 12 of this AC. Although the requirements do not otherwise explicitly mention lift, it should be dealt with to meet requirement § 450.121(c)(1). A body may also have oscillatory motion that shifts between a stable lift vector and a condition of instability. Neglecting the stable lift regimes can cause the analysis to estimate mean impact point significantly shifted from the true mean (if the body remains on a known heading), or significantly increase the dispersion around the mean impact point (if the heading of the body is uncertain). This effect is usually only relevant for large components designed for aerodynamic stability. Vehicle breakup could lead to motors or portions of motors that contain opposing pairs of wings or fins and experience a stable lift force during free-fall. The stability is likely to exist only for sufficiently high speeds, after which a transition to tumbling motion occurs. The lift vector need not be upwards, but could also be orientated laterally for a body not traveling horizontally (perpendicular to drag). A 6-DOF simulation should be used for a hazardous debris body that is stable and has non-negligible lift.

9.7 Progressive Breakup and Breakup Fragment Shedding.

If vehicle breakup occurs over a span of time, rather than at an instant in time, a set of ballistic trajectories should be initiated based on the core vehicle trajectory over that time span. This situation must be considered to meet requirement § 450.121(c)(2) and applies to planned body reentry from orbit. A progressive shedding of fragments may be due to aerothermal or aerodynamic effects while inside the atmosphere. The canonical example is the Space Shuttle *Columbia* reentry accident. *Safety Design for Space Operations*, (reference [1] of paragraph 3.4 of this AC) has an expanded discussion on this topic, including mathematical details, of shedding during a reentry event. During the breakup time span, ballistic trajectories should be initiated at a rate of about 1 Hz for each fragment class. A trajectory's initial state vectors are (interpolated) points along the nominal reentry trajectory. Each shed time should be assigned a probability of fragment release, and all probabilities sum to one for each fragment class. The probabilities may obey a distribution that is uniform, Gaussian, or a more general Beta distribution. The probabilities are applied during evaluation of risk associated with a fragment class at the given shed time. Planned reentry generally occurs over water where the focus is on risk to aircraft.

9.8 Hazardous Debris Demise.

Virtually any material, including metallic fragments, experiencing drag friction of enough severity and over a sufficient dwell-time will enter a state of ablation where the material melts. This situation should be considered for fragments descending into, or traveling through, the atmosphere at thousands of feet per second. Although the requirements do not explicitly mention hazardous debris demise, the situation must be dealt with to meet requirement § 450.121(c). The ablation activation time depends on fragment speed, air density, fragment ballistic coefficient, and type of material. The reference *Safety Design for Space Operations* (listed as [1] of paragraph 3.4 of this AC) has an expanded discussion, including mathematical details, of inert fragment demise during a reentry event. As the fragment loses mass, its drag coefficient will get smaller leading to an increase in drag and a slowing of motion. This changes the course of the ballistic trajectory. The ablation will end if the fragment speed reduction drops below the threshold required for demise. Although risks to people may be reduced due to slower impact speeds, different people and assets might be at risk due to the modified trajectory. Ignoring hazardous debris demise is not necessarily conservative.

10 IMPACT PROBABILITY DISTRIBUTION.

In accordance with § 450.121(c), an operator must compute statistically valid impact probability distributions, which should be computed for each predicted breakup location. For most ground or waterborne vessel risk analyses, distributions are 2-dimensional, associated with the impact points in which the statistical trajectories cross the surface. For an aircraft, one approach is to generate 3-dimensional distributions, associated with points along the statistical trajectories at a series of free-fall times of the hazardous debris clouds as the aircraft passes through a cloud. Another approach is to generate 2-dimensional distributions associated with the impact points in which the statistical trajectories cross the altitude level of the aircraft at a series of short progressing time spans.

10.1 Impact Probability.

A collection of statistical hazardous debris trajectories produces a set of impact points that intersect with a given altitude level. Mean sea level is used to compute risk to people in waterborne vessels. Mean terrain altitude is used to compute ground risks, which is typically the mean sea level for coastal launches. Specific altitude levels that depend on aircraft type are used to generate aircraft risk contours. For aircraft flying along specific flight paths, a range of altitudes may be needed. The impact points are separated into time blocks to deal with the transient nature of an aircraft flying at different altitudes.

10.1.1 For risk analysis computations, impact probabilities for people and assets should consider the number of impact points that hazard a site. The dispersion pattern formed by impact points should be fit to a single functional distribution that allows a minor amount of statistical information to be lost. If a single distribution cannot be used, a collection of simple distributions should be considered, such as a kernel density estimation (KDE) procedure as described in the reference listed as [18] of paragraph 3.4 of this AC. An alternative to a distributional fit is to use histograms of impact counts over the impact space, which can deal with diverse statistical patterns.

10.1.2 The criterion for employing functional distributions is that they can account for the first few statistical moments of the impact dispersion pattern. Every functional distribution employed should account for the first moment given by the mean and the second moment given by the variance. Functional distributions should also account for the moment of skewness and the fourth moment for patterns that exhibit excessive statistics in these moments. If higher moments are relevant, then either a collection of simpler distributions or a histogram should be constructed.

10.1.3 A statistical set of hazardous debris ballistic trajectories will likely be Gaussian if the sources of uncertainty applied during the Monte Carlo simulation are Gaussian, or near-Gaussian such as log-normal. Impact points may acquire skewness for long fall times and strong wind conditions. Monte Carlo state vector uncertainty sets may exhibit too much skewness, and more often too much kurtosis. Directed velocity explosion models tend to be non-Gaussian, such as forming a ring or torus, or possess no discernible pattern. Trajectories that involve residual thrust or directed lift are also likely to possess no discernible pattern.

10.2 Gaussian Distribution.

A Gaussian or “normal” distribution is usually appropriate when skewness and kurtosis are both small. Both values are 0 in an exact normal distribution. As a rule of thumb excessive skewness would be values outside the range [-1,1], and for kurtosis values outside the range [-3,3].

10.2.1 On a plane, a “bivariate” normal distribution is formed using the mean location $\left(\underline{x}, \underline{y}\right)$ and the associated 2-dimensional covariance matrix of the impact locations. The 2-dimensional distribution is the product of the two individual 1D distributions in which the standard deviation values $\left(\sigma_x, \sigma_y\right)$ are the eigenvalues of the 2-dimensional covariance matrix. The pair of 1D distributions are orthogonal along the principal axis, with direction provided by the eigenvectors of the 2-dimensional covariance matrix.

10.3 Skewed Distribution.

A Gaussian based distribution that accounts for skewness, is the Skew-Normal distribution. This is defined by a mean, covariance matrix, and an additional Shape parameter, α, that quantifies the amount of skewness.

10.3.1 Figure 1 presents a sampling of 1D skew-normal curves. The 2-dimensional skew-normal distribution cannot be reduced to the product of two 1D functions due to the nature of the shape parameters. For high skewness, the figure shows that the Gaussian distribution produces a tail in which zero probability exists.

10.3.2 Due to the nature of the shape parameter, solving for the 2-dimensional skew-normal distribution parameters involves an approach that requires the use of non-linear differential equations. A useful solution that applies to impact dispersions for the 2-dimensional distribution can be developed through a careful reading of the literature.[3] Issues that should be dealt with are employment of proper coordinates, and avoidance of common runaway solutions that go to an infinite value for alpha and are usually invalid.

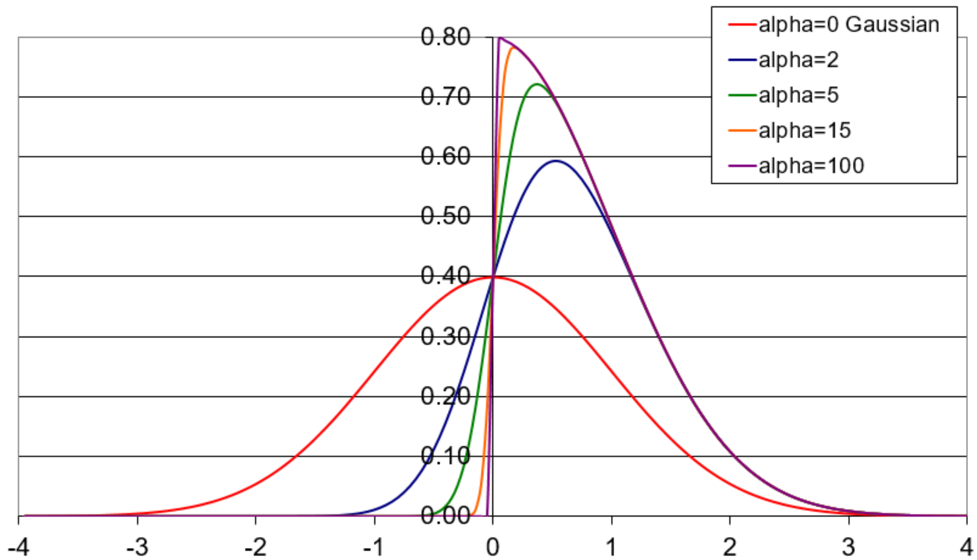

Figure 1—Comparison of Various Skew-Normal Curves

10.4 **Histogram Distribution.**

Impact probabilities are specified by first defining a surface grid. A histogram that specifies impact probabilities over a grid is constructed by determining the number of trajectories that pass through each cell. Cell sizes should be no larger than about one hundredth of the area of the dispersion pattern, which displays gradual differences between grid points. Otherwise, an iterative process may be needed to determine a suitably fine grid to attain the desired accuracy in computed risk. To obtain sufficient cell statistics, especially near the edges of the dispersion pattern, may require that the collection of trajectories have tens of thousands of samples. Due to long runtimes for trajectory generation, this type of approach is much less practical than the KDE in which runtime is proportional to the number of dispersions.

[3] *See* http://azzalini.stat.unipd.it/SN/index.html.

10.5 3-dimensional Impact Probability.

The collection of statistical hazardous debris trajectories produces sets of 3-dimensional cloud points at given free-fall times. Aircraft risk is computed by determining how much of the hazardous debris cloud the aircraft passes through between free-fall times and using the net probability inside the swept-out volume of encountering a fragment. Typically, a single mean probability value can be used since aircraft are much smaller than the hazardous debris clouds and as such, variations in hazardous debris impact probabilities will be insignificant. The total risk is the sum over all free-fall times. If only an aircraft analysis is being performed, then the trajectories only need be computed far enough until the cloud has fallen below the aircraft and is no longer a hazard.

10.5.1 The generalization of the 2-dimensional distributions to three dimensions is straightforward. The tri-normal distribution has mean $\left(\underline{x}, \underline{y}, \underline{z}\right)$ and standard deviation values $\left(\sigma_x, \sigma_y, \sigma_z\right)$ that are the eigenvalues of the 3-dimensional covariance matrix. The triplet of 1D distributions are orthogonal and along the principal axis, in which directions are provided by the eigenvectors of the 3-dimensional covariance matrix. The 3-dimensional skew-normal possesses the same solution process requirements and complexities as the 2-dimensional case but can be resolved in the same manner.

10.5.2 The 3-dimensional histogram approach uses cubes rather than cells. The set of cubes span the space through which an aircraft may pass, and will likely necessitate that the collection of trajectories has millions of members for those aircraft near the edges of the cloud dispersion pattern.

11 CONSEQUENCE MODELING.

A flight safety analysis must compute the predicted consequences of each reasonably foreseeable failure mode in any significant period of flight in terms of conditional expected casualties, in accordance with § 450.135(b). The hazardous debris may be inert, explosive, or toxic that endangers people who are unsheltered, in buildings, on or below deck of waterborne vessels, or in aircraft. For some cases, sufficient information is given to fully compute the consequence. Otherwise, the discussion will outline an approach and indicate what type of effort remains. The models presented in this chapter are in current use among many of the Federal ranges. If desired, the operator may employ its own models with proper justification.

11.1 **Types of Consequences.**

In accordance with § 450.135(b)(2), evaluation of risks requires computing the probability of consequence $p_{consequence}$ by examining the effects of the hazardous debris hazard on population centers. Analysis using population centers is further explained in AC 450.123, *Population Exposure Analysis*. Some of the $p_{consequence}$ values relate directly to requirement threshold levels that should not be exceeded for a high-fidelity analysis. Others are components of the risk values, to be discussed in paragraph 11.6.1 of this AC, that then relate to all the remaining requirement threshold levels.

11.1.1 The probability of consequence depends on the probability that hazardous debris impacts at or near the population center, and the probability that the impact results in a casualty:

$$p_{consequence} = p_{impact} \times p_{casualty}$$

11.1.2 There are several levels of effort that can be put forward to evaluate $p_{casualty}$, which differ by degree of conservatism.

11.1.3 The simplest and most conservative is to set $p_{casualty} = 1$ for all hazardous debris, and thus $p_{consequence} = p_{impact}$.

11.1.4 If using $p_{casualty} = 1$ results in meeting the risk criteria of §§ 450.101(a) to 450.101(b) then a less conservative and more complicated method to evaluate $p_{casualty}$ is not necessary.

11.1.5 Instead of setting $p_{casualty} = 1$ for all hazardous debris, it can be set only for selected fragments that pass specific hazardous debris filters, while everything else is rejected. Any hazardous debris on unsheltered people can be rejected if the impact kinetic energy is less than 11 ft-lbs and the mean impact kinetic energy per unit area at impact is less than 34 ft-lb/in^2. For sheltered people near windows, explosive consequences only need to be considered in the region where the overpressure exceeds 0.25 psig, for the purposes of the debris risk analysis required by § 450.135[4]. Several additional acceptable filters are given in the reference listed as [22] of paragraph 3.4 of this AC. Any hazardous debris on sheltered people can be rejected if the roof is struck with less than 17 ft-lbs. Explosive effects can be ignored for unsheltered people where the overpressure is less than 2 psig. For sheltered people hazarded by falling walls and roofs, the threshold is 1 psi. Finally, hazardous debris on aircraft can be rejected if its mass is less than 0.4 gram.

11.1.6 If the filters are not useful, then a probabilistic model-based evaluation of $p_{casualty}$ should be done. This would include a model for human vulnerability that considers the

[4] In accordance with § 450.137, a flight safety analysis must include a far-field overpressure blast effect analysis that demonstrates compliance with safety criteria in § 450.101. In accordance with § 450.137(b)(3), this analysis must account for the potential for broken windows due to peak incident overpressures below 0.1 psi and related casualties based on the characteristics of exposed windows and the population's susceptibility to injury, etc.

effects of the hazard on the human body. A valid model should account for the vulnerability of various body parts that dominate the risk. The type of consequence being performed will indicate which body parts should be considered. The degrees of injury to people and specific body parts can be separated into categories corresponding to the severity of the injury. A system that is used among many industries is the Abbreviated Injury Scale (AIS). This was originally published in 1971 to provide a taxonomy of injuries generated by road accidents, and has been refined several times since This publication is listed as reference [20] of paragraph 3.4 of this AC. There are 7 AIS levels that are defined in Table 4 of this AC. A "casualty" corresponds to AIS level 3 (or higher), which are serious injuries requiring hospitalization for recovery, or greater.

Table 5 – AIS Severity Levels

AIS Severity Level	Severity	Type of Injury
0	None	None
1	Minor	Superficial
2	Moderate	Reversible injury; medical attention required
3	Serious	Reversible injury; hospitalization required
4	Severe	Life threatening; not fully recoverable without care
5	Critical	Non-reversible injury; not fully recoverable even with medical care
6	Virtually Unsurvivable	Fatal

11.1.7 Evaluating the human vulnerability model at the casualty level can then be then fed into one of two forms that lead to a proper evaluation of $p_{consequence}$. The first representation is as an "effective" casualty area. As specified in § 401.7, effective casualty area means the aggregate casualty area of each piece of debris created by a vehicle failure at a particular point on its trajectory. The effective casualty area for each piece of debris is a modeling construct in which the area within which 100 percent of the population are assumed to be a casualty, and outside of which 100 percent of the population are assumed not to be a casualty. This area need not be a single connected region, but may be comprised of several disjoint sections. The effective casualty area, CA, is a factor in the probability of $casualty$ through $p_{casualty} = CA/A_{pop}$ where A_{pop} is the area of the population center. The effective casualty area must account for all relevant hazardous debris characteristics and the characteristics of a representative person potentially exposed to the hazardous debris hazard in accordance with § 450.135(b)(1). For reporting purposes, the effective casualty area needs to be computed for people who may be occupying an unsheltered casualty area in accordance with § 450.135(c)(3), as well as for a representative type of building, ground vehicle, waterborne vessel, and aircraft, assuming a representative impact vector, in accordance with § 450.135(c)(4).

11.1.8 The second way in which the potential for a casualty is usually characterized is by specifying a probability of casualty versus distance profile, i.e., $PC(d)$. The distance d is measured from the hazardous debris impact point, and the profiles that extend outward from that point may or may not depend on the hazardous debris' impact direction. The profile $PC(d)$ is not necessarily monotinically decreasing as d increases. To include all non-trivial risks for distant population centers, the profiles $PC(d)$ may need to go out far enough until the probability level drops below at least $1\text{x}10^{-6}$. A ramification of this is that a given population center can be reached by hazardous debris impacts with varying impact probabilities. To properly compute risk, the impact space should be broken down into cells where the probability of impact in each cell has small impact variation, which should be less than about 1/3rd of a standard deviation of the impact distribution. The $p_{consequence}$ on a site is then expressed as a sum over all the impact cells.

$$p_{consequence} = \sum_{n=0}^{N_{cells}} p_n^{impact} \times PC(d_n)$$

11.1.9 An effective casualty should also be computed to meet reporting requirements in §§ 450.135(c)(3) and (4), although it is generally not needed for computations that use the $PC(d)$ curves. For these cases, the effective casualty is evaluated as the integral of PC(d) over the area where PC(d) is at least 1%.

11.2 Inert Hazardous Debris.

In accordance with § 450.135(b)(3), a debris risk analysis must model the casualty area, and compute the predicted consequences of each reasonably foreseeable failure mode in any significant period of flight in terms of conditional expected casualties accounting any impact or effects of hazardous debris. This section discusses the hazard cases where inert hazardous debris consequences arise, and provides guidelines for evaluating such consequence. Inert risk must be computed for people who may be occupying an unsheltered casualty area in accordance with § 450.135(c)(3), and people in buildings, people on or below deck in waterborne vessels, and people in aircraft in accordance with § 450.135(c)(4).

11.2.1 Although the discussion applies to inert consequences, in accordance with § 450.135(b)(3), the hazardous debris does not need to be inert but can also be explosive or toxic. This is because hazardous debris with small explosive or toxic risks may have higher risks by treating them as inert. In other words, the kinetic impact of the hazardous debris may pose more risk than if the fragment exploded or released toxic gases. Thus, for these cases risks should be computed both ways and the larger risks values applied against the risk thresholds.

11.3 **Unsheltered People**.

In accordance with § 450.135(b), the casualty consequence for inert hazardous debris impacts on unsheltered people must be represented by an effective casualty area. The hazardous debris list should include all fragments with an impact kinetic energy of at least 11 ft-lbs or a mean impact kinetic energy per unit area at impact of at least 34 ft-lb/in^2. The net effective casualty area may be based on a sum over much smaller areas.

11.3.1 The full hazardous debris hazardous area may be broken down in cells, and within each cell, the effective casualty area CA_{cell} is computed by

$$CA_{cell} = HA_{cell} \times p_{injury}$$

where HA_{cell} is the hazard area of the cell, which is the area of the cell, and p_{injury} is the probability of serious injury to a person in that cell of one or more specific body parts.

11.3.2 The probability of casualty is $p_{casualty} = \sum_{j=0}^{N_{cells}} CA_{cell_j}/A_{cell_j}$, and the probability of impact is computed separately, which and is evaluated over the population center area A_{pop}.

11.3.3 This probability p_{injury} depends on the body part(s) that are struck by hazardous debris, the type of person (male, female, adult, child), the impact velocity of the fragment, and the mass of the fragment. A partitioning of the body into parts where injury can at a minimum lead to a serious casualty, might include the head, chest, abdomen, legs, and thorax, but not arms. Hazard area cells may be associated with locations within which a particular body part is struck, and so do not need to be square but can assume any convenient shape.

11.3.4 The fragment shape also affects the degree of injury. To be conservative, fragments should be modeled as spheres, which tend to produce the highest probability of injury, although in some situations a plate shape may have higher risks. For a range of fragment masses, sample p_{injury} curves are shown in Figure 2 of this AC for vertical impacts to the head, in Figure 3 for horizontal impacts to the chest, in Figure 4 for horizontal impacts to the abdomen, and in Figure 5 for horizontal impacts to the legs. These curves are for localized blunt injury impacts for a typical person in the public. They only account for direct hits to the body and ignore any secondary injury to other body parts, such as if the person is knocked to the ground. For masses not shown in the figure, linear interpolation should be used between curves, and the bounding curves at the far left and right used instead of extrapolation. Small fragments may have a higher probability for skin penetration, while larger fragments for crushing. Larger fragments may also knock a person down causing secondary injuries when the person strikes the ground.

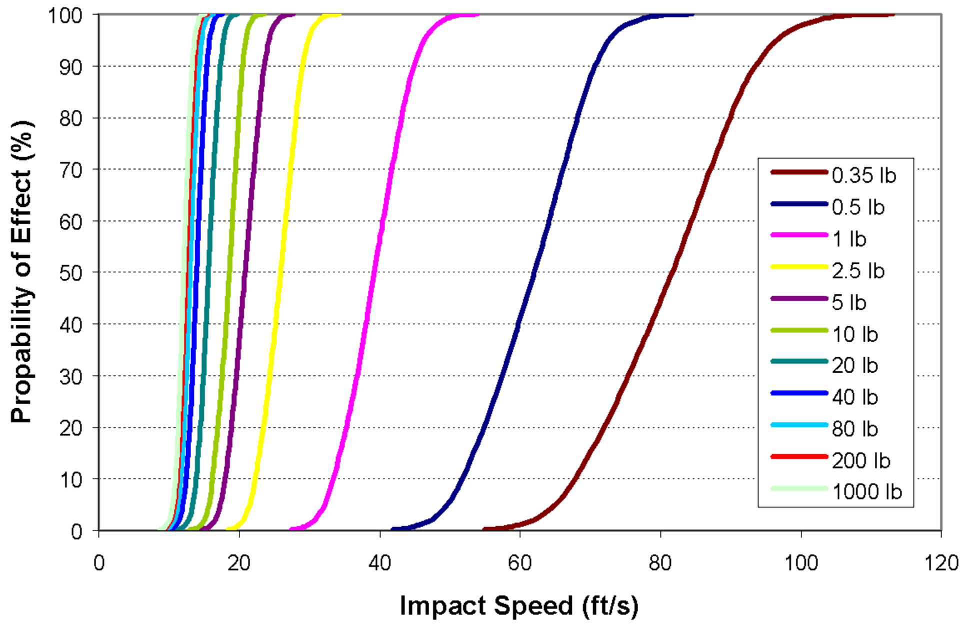

Figure 2—Probability of Casualty Curves for Non-Mission Essential, Vertical Impact to Head, Blunt Injury

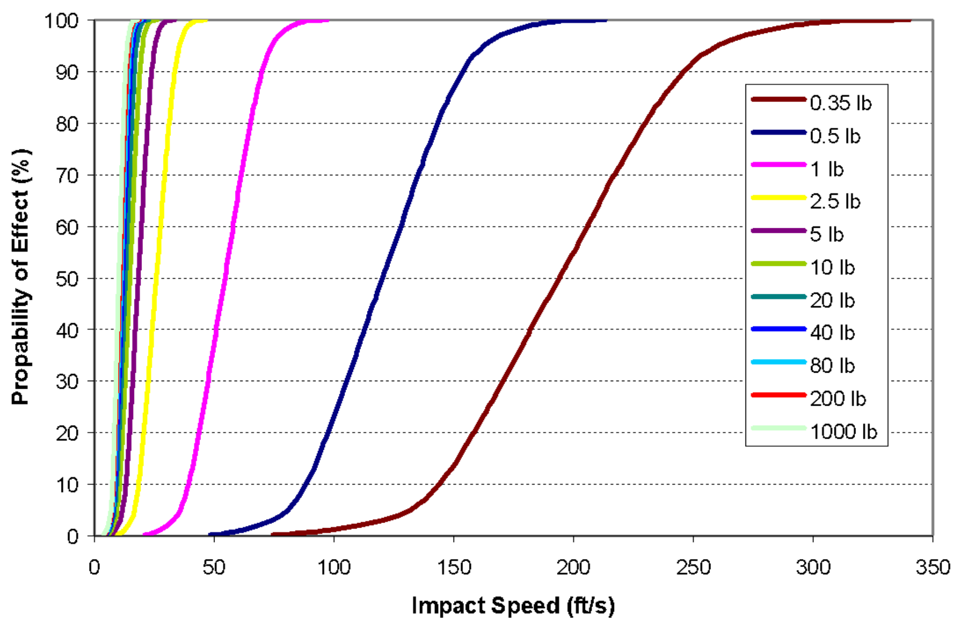

Figure 3—Probability of Casualty Curves for Non-Mission Essential, Sphere Impacting Chest, Blunt Injury

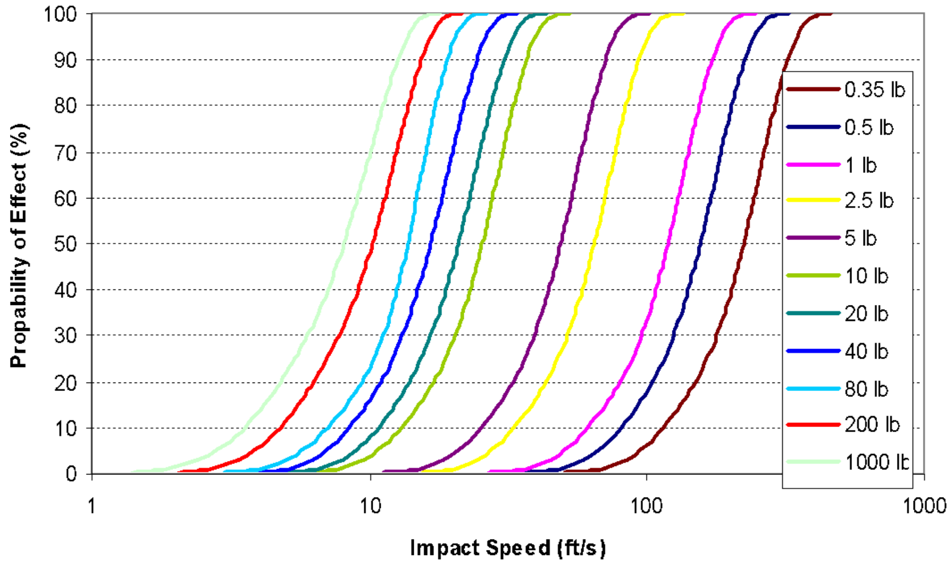

Figure 4—Probability of Casualty Curves for Non-Mission Essential, Sphere Impacting Abdomen, Blunt Injury

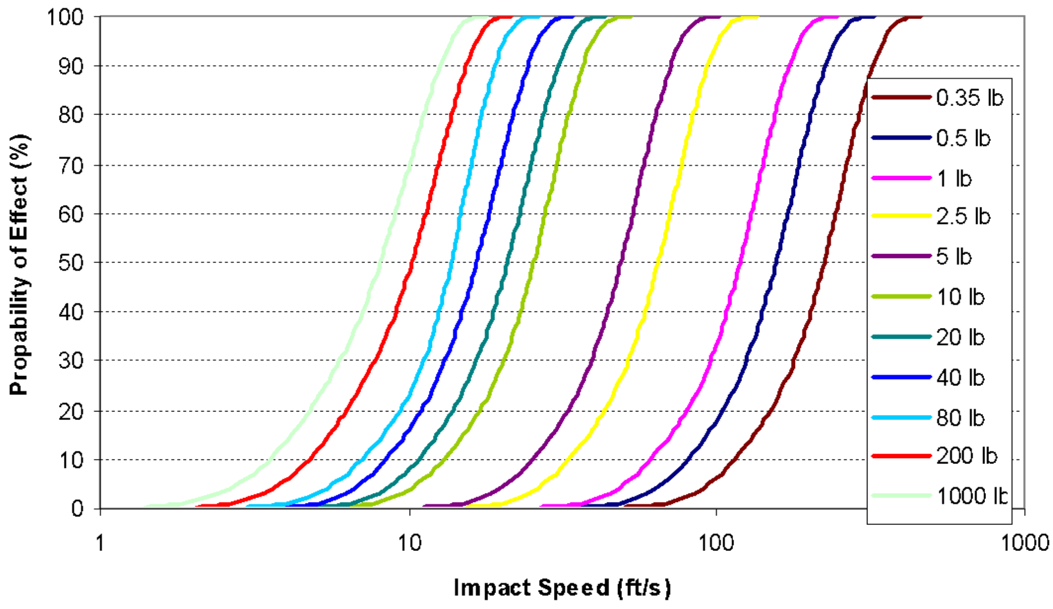

Figure 5—Probability of Casualty Curves for Non-Mission Essential Sphere Impacting Leg, Blunt Injury

11.4 Casualty Areas.

The casualty area, from which the "effective" casualty area is based, should include where a person could be standing to experience (1) direct impact of the fragment, (2) impact of the fragment during bouncing, (3) impact if the fragment due to skipping, sliding, rolling, or ricocheting, or (4) impact of fragment pieces if the fragment splatters. The hazard area should also account for the effect of terrain where feasible. Atmospheric drag and wind can be ignored when describing the fragment's motion during these phases.

11.4.1 Direct Hazard Area.

The local hazard area for direct impact should account for the radius of a standing person, about 1 foot, and the projected hazardous area of the fragment as it reaches the person. The fragment can be assumed to be spherical. The area should also account for the angle at which the fragment is traveling just prior to impact. For a person standing in any part of the direct hazard area, the path of the fragment should be tracked close enough to identify which body parts are struck to convert to the effective casualty area. For impact on a soft surface, it should be determined if the fragment buries itself into the ground, (i.e., more than half its radius is underground), before proceeding to consider fragment bouncing.

11.4.2 Bounce Hazard Area.

The local hazard area produced by a bouncing fragment could be computed by modelling the fragment as a sphere to get a conservative area. Modeling as a football, cube, or other shape will tend to lead to smaller areas, although the dynamics may be harder to capture. The contact with the Earth's or waterborne vessels' surface should account for a reduction in vertical speed based on the coefficient of restitution e for that surface: $v_{rebound} = e \times v_{impact}$. Conservative values as a function of the vertical component of the total impact speed are shown in Table 5 of this AC.

Table 6 – Coefficients of Restitution

Surface Type	Coefficient of Restitution	Vertical Impact Speed (ft/s)
Soft soil or water	0	$v_{impact} > 340$
Soft soil or water	$0.09 - 0.39(log_{10} - 2.301)$	$340 > v_{impact} > 200$
Soft soil or water	$0.2 - 0.0.845(log_{10} - 1)$	$200 > v_{impact} > 10$
Soft soil or water	0.2	$10 > v_{impact}$
Hard	0	$v_{impact} > 300$
Hard	$0.5\frac{log_{10}(300/v_{impact})}{log_{10}(300/40)}$	$300 > v_{impact} > 40$
Hard	0.5	$40 > v_{impact}$

11.4.2.1 The contact with the Earth's or waterborne vessels' surface should account for changes in the rotation rate of the fragment. During initial approach of the fragment, the angular speed can be assumed to be zero, which results in the angle of reflection equal to the angle of incidence. Conservation of momentum should be applied during contact with the surface to determine the post-bounce angular rate. The angular rate can be assumed to remain constant while the fragment is airborne and should be applied on subsequent bounces to compute the next angle of reflection.

11.4.2.2 The elliptical path, formed by the fragment's trajectory between bounces, should be tracked to identify which body parts are struck both during the ascent and descent to convert to effective casualty area. In the absence of data on the average height of exposed persons, a height of a 5 feet should be used when accounting for areas where a fragment bounce over a person's head and poses no hazard. The bouncing phase of the fragment should stop when the maximum rebound height drops below a threshold, such as 0.5 feet.

11.4.3 Slide and Roll Hazard Area.

When the fragment bouncing phase has ended, the motion of the fragment should be continued in the forward direction, accounting for the reduction in horizontal speed due to friction. The radius of the rolling fragment should be used to determine which body part(s) the fragment impacts. Obstacles such as trees, rocks, and similar items can be ignored if a bound is placed on the maximum distance that the fragment can travel once surface impact occurs. A typical bound is about a couple hundred feet.

11.5 **Probability of Casualty Area.**

In accordance with § 450.135(b)(4)(i), the vulnerability of people to debris impacts or effects must be represented by an effective casualty area. The hazard is due to fragments that penetrate the roof, causing potential injury to the people on the floor(s) below from the roof hazardous debris and the original fragment itself. The probability of casualty should be evaluated in the form $p_{casualty} = CA/A_{roof}$. The probability of impact is computed separately and is evaluated over the effective roof area. This area should include the projected radius of the fragment if casualty can occur when the fragment clips the edge of the building.

11.6 **Potential for Roof Penetration.**

Evaluation of the potential for roof penetration should consider the fragment's weight, projected area, angle of incidence, and impact vertical speed. The horizontal speed component of the velocity can be ignored. The construction of the building's roof and frame should also be considered such as dimensions, spacing of any joists or girders, and beam section properties. Figure 6 shows the layout of a typical wood roof and different impact configurations.

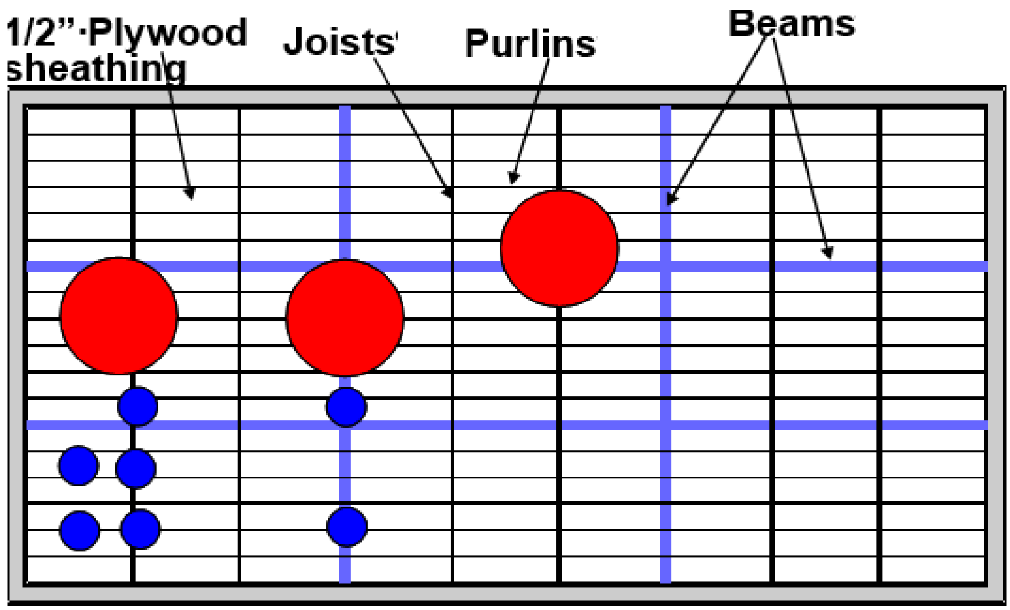

Figure 6—Illustration of a Wood Built-Up Roof

11.6.1 Hazardous debris that impacts the floor surface directly under the roof may penetrate the next floor level and cause potential injury to people two levels below the roof, and so on. Hazards tends to diminish the farther down a floor is from the roof. This means that risk values can be reduced by computing it for all floors in a building where people reside. However, it becomes more of a challenge to obtain accurate risk values for the lower floors beyond two or three down. As a tradeoff, risks can be evaluated for just some of the uppermost floors, and then to account for people in lower floors a conservative approach is to move them up to the lowest level that is being considered. It is acceptable to place everyone in the uppermost floor, although excessive risk might result and there might be greater chance that the thresholds are exceeded.

11.6.2 The sheltering model should account for variability of the fragment and building parameters. It can be assumed that a uniform impact probability distribution is applicable for the impact points on a roof. To avoid dealing with the orientation of a person as that person is struck, a conservative approach is to model only vertical head impacts. If extended roof hazardous debris, e.g., a beam, impacts a person, then its orientation should be accounted for when it strikes the head.

11.6.3 Typically, it is not necessary to evaluate individual buildings; instead, a small number of building classes can be defined to assess the protection afforded to sheltered persons. Unique buildings, particularly in the immediate launch vicinity, may need to be decomposed into sections corresponding to the representative buildings. If a specific building is not represented by a class, then a separate analysis needs to be performed on it. A representative building can be modeled without any bounds on the roof size. If the resultant effective casualty area is larger than the roof of the actual building it is being applied to, then the area should be cropped to that roof size.

11.6.4 The four roof classifications represented in Table 6 of this AC were analyzed for penetration by six ballistic coefficient classes for the hazardous debris. The hazardous debris were assumed to impact the roofs at terminal velocity and had weights ranging from 0.1 lb. to 10,000 lb. The resulting effective casualty areas for people in the top floor of the structures impacted by inert hazardous debris are shown in Figure 7 through Figure 10. Each figure provides the effective casualty area for a given roof-type as a function of fragment weight in each of the beta classes.

Table 7 - Representative Building Classes

Structure Roof Class	Building Description	Typical Construction	Conservative Glass/Floor Area Ratio
A	Mobile home and trailers; Temporary office trailers	Wood studs with plywood used for walls and roof	20%
B	Single residential units of all types, single family dwellings, duplex, apartments, town homes, condos	Un-reinforced masonry walls with wood stud roof	30%
C	Commercial buildings less than 15,000 ft^2 of all kinds, including retail, offices, restaurants, gas stations, strip malls	Metal stud and metal panel walls, steel moment resisting frame, metal panel roof	35%
D	Commercial buildings more than 15,000 ft^2 of all kinds, including retail, offices, warehouses, manufacturing, malls	Lightly reinforced concrete tilt-up walls with wood or metal decking over steel joists	10%

11.6.5 The effective casualty areas in the figures are based on many impact points over a roof for each fragment weight and roof type. In some cases, penetration will not occur every time, because the fragment is stopped by the joist supporting the surface. The average effective casualty area accounts for the contributions of those cases where there is no penetration.

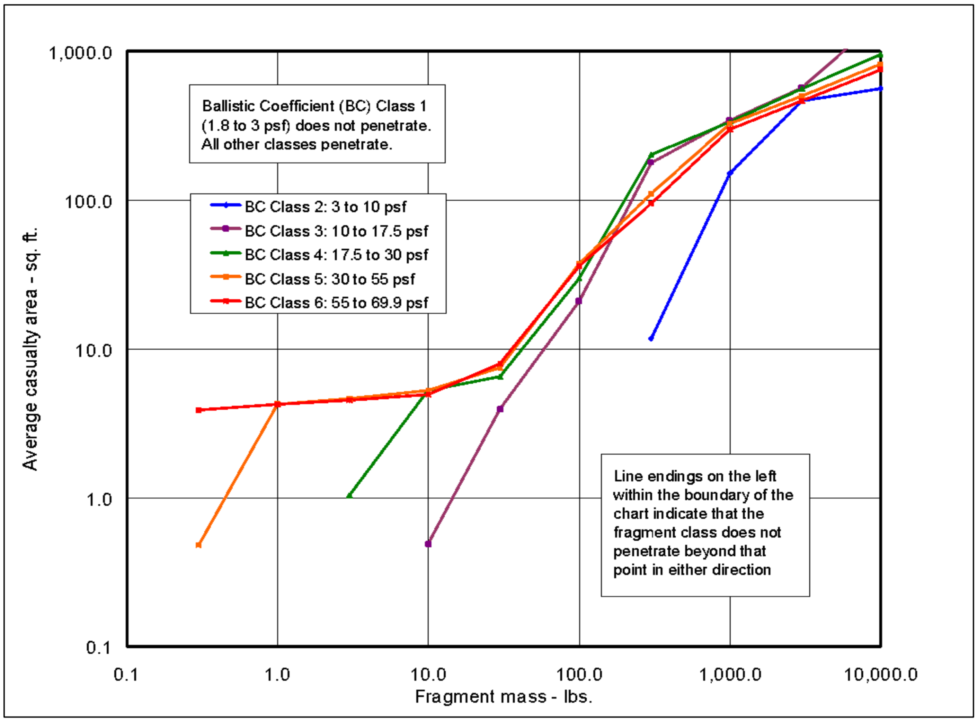

Figure 7—Effective Casualty Areas of Hazardous Debris Hitting a Light Metal Roof (Class A)

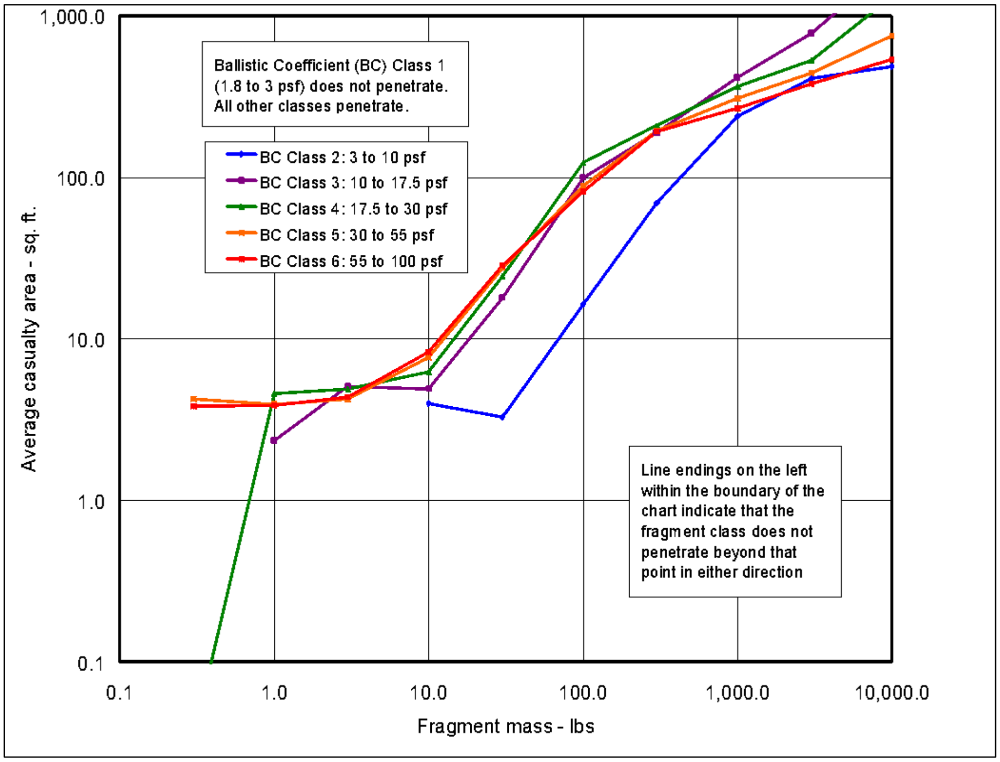

Figure 8—Effective Casualty Areas of Hazardous Debris Hitting a Wood Roof (Class B)

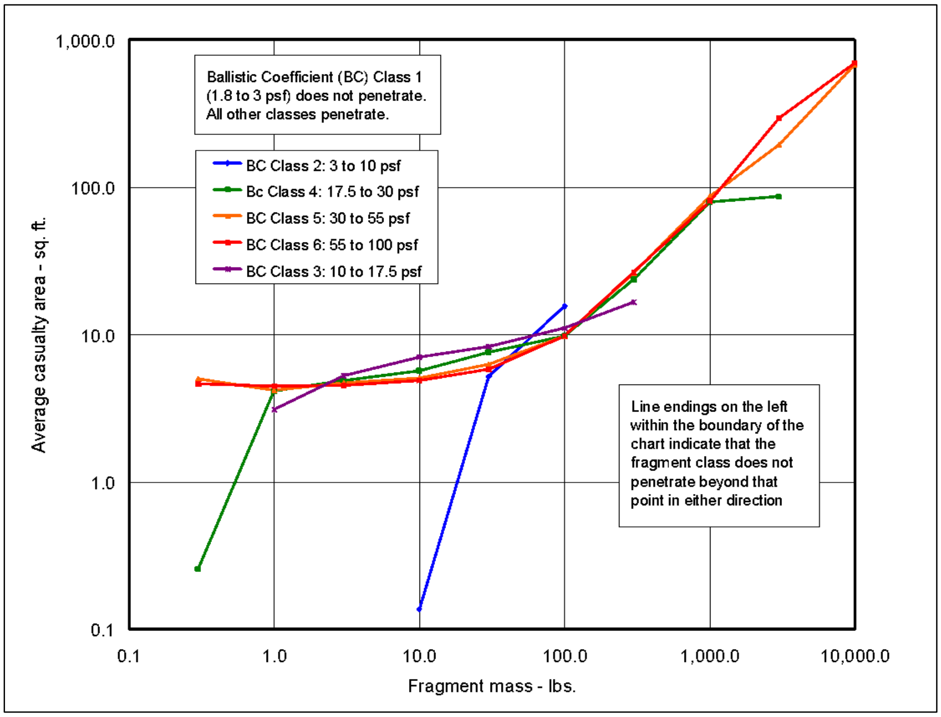

Figure 9—Effective Casualty Areas of Hazardous Debris Hitting a Composite Roof (Class C)

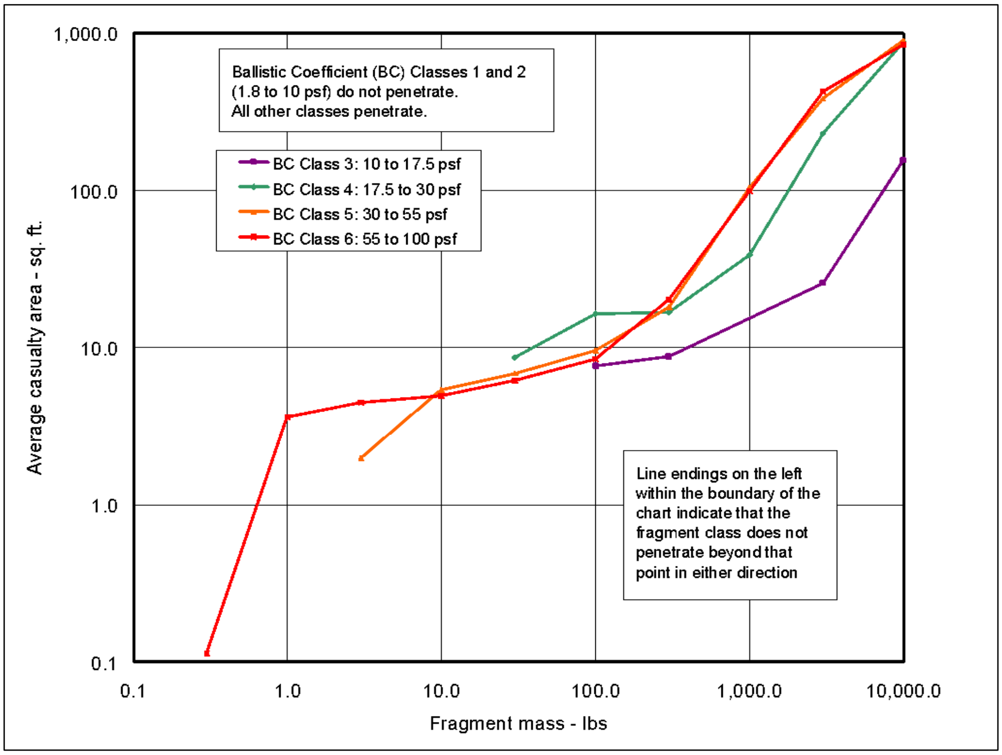

Figure 10—Effective Casualty Areas of Hazardous Debris Hitting a Concrete Reinforced with Steel Roof (Class D)

11.7 **People in Waterborne Vessels (Ships).**

In accordance with § 450.135(b)(4)(i), the vulnerability of people to debris impacts or effects from inert hazardous debris to people on ships must be represented by an effective casualty area. Effects from inert hazardous debris impacts in the water near the ships can be ignored. The probability of casualty is $p_{casualty} = CA/A_{ship}$, and the probability of impact is computed separately and is evaluated over the ship deck area.

11.7.1 Several sources of casualty should be considered for inert hazardous debris impacts on ships as described in the reference listed as [22] of paragraph 3.4 of this AC. The effective casualty area should account for injuries to people from direct strikes, deck penetration, hull penetration, and onboard fuel explosions. The most severe is a catastrophic event that is defined as one leading to a large number of casualties or a loss of ship. One catastrophic event that should be evaluated is a ship sinking due to hull penetration.

11.7.2 If the ship's hull is penetrated by hazardous debris and causes significant hull damage resulting in a catastrophe (e.g. sinking), and the estimated time to rescue the ship occupants exceeds the time they would be expected to survive without serious injuries, then the effective casualty area should be set to the maximum possible value, (i.e. to that of the ship area: $CA = A_{ship}$.) An inert fragment will penetrate the hull if it has sufficient impact kinetic energy and mass. If the speed of a ship is significant relative to the impact speed of a fragment, the impact velocity of the fragment relative to the ship may need to account for the ships speed.

11.7.3 Table 7 of this AC provides thresholds for hull damage based on the size of the ship. The effective casualty area should be set to zero if both criteria listed in the table are not satisfied for a given ship size, and then other sources of casualty should be evaluated.

Table 8 – Threshold Values for Significant Hull Damage

Ship Category			Penetration Criteria	
Length (ft)	Ship Types	Deck/hull Material	Minimum Mass (lbs)	Minimum Kinetic Energy (ft lbf)
< 25	Small fishing vessels and pleasure craft	One plywood layer: 0.75 inch	0.6	25
25-50	Small to medium size fishing vessels and pleasure craft	Two plywood layers: 0.5 and 0.75 inches	0.7	115
50-100	Medium sized fishing vessels and pleasure craft, tug boats	Two plywood layers 0.75 inch each	1.0	205
100-200	Large fishing vessels, pleasure craft, and coast guard patrol ships	Two steel layers: 0.1 and 0.2 inches	35	40,000
200-295	Large fishing vessels, pleasure craft, and coast guard patrol ships	Two steel layers 0.2 and 0.3 inches	115	71,000
> 295	Container ships, tankers, other cargo ships, pleasure cruise ships, military ships	Two steel layers 0.2 and 0.4 inches	6,300	1,250,000

11.7.4 Another catastrophic event is an explosion/fire from stored fuel being ignited by tank penetration or a collapsing deck. Ships tend to store fuel below the cabin or deck. A determination should be made of the total area A_{fuel} that could be penetrated leading to ignition and subsequent explosion of the fuel. If the fuel is ignited, then the effective casualty area should be set to the fuel storage area: $CA_{fuel} = A_{fuel}$.

11.7.5 An inert fragment will penetrate the deck if it has sufficient kinetic energy and weight.

11.7.6 Table 8 of this AC provides thresholds for deck damage based on the size of the ship. The effective casualty area should be set to zero if both criteria are not satisfied for a given ship size.

Table 9 – Threshold Values for Ship Cabin and Deck Penetration

Ship Category		Penetration Criteria	
Length (ft)	Roof Material	Minimum Mass (lbs)	Minimum Kinetic Energy (ft lbf)
< 25	No roof assumed	n/a	11
25-50	1/2-inch plywood	0.055	23
50-100	3/4-inch plywood	0.137	75
100-200	0.10-inch steel	1.2	1,300
200-295	0.20-inch steel	4.4	7,800
> 295	0.3125-inch steel	10.0	16,000

11.7.7 The analysis should assume that the location of people on the ship or below deck is not coincident with that of the fuel storage area. The effective casualty area that accounts for both fuel explosion and casualty hazardous debris should be the sum $CA = CA_{debris} + CA_{fuel}$. Replace the sum with the ship area if the latter sum is smaller.

11.7.8 For unsheltered people, CA_{debris} is evaluated in the same method used in paragraph 11.1.1 of this AC. If the deck is not penetrated, then CA_{debris} includes the contributions from a direct hit, as well as bounce and roll. If the fragment penetrates the deck, then CA_{debris} only accounts for the direct hit and ignores the bounce and roll. For people below deck, Table 8 may be applied to determine if the hazard exists. Since ship decks tend to be strong material, the effective casualty area should be set to three times the projected hazardous area of the fragment $CA_{debris} = 3A_{fragment}$ to account for secondary hazardous debris if deck penetration occurs.

11.8 People in Aircraft.

In accordance with § 450.135(b)(4)(i), the vulnerability of people to debris impacts or effects to people in aircraft must be represented by an effective casualty area. An accurate method for aircraft risk examines the aircraft passing through the 3-dimensional hazardous debris cloud. Since the aircraft is in motion, there are a series of casualty areas where each is active for a short period of time, typically a few seconds or less. Each casualty area corresponds to that of the lateral cross-section of the volume that the aircraft sweeps out during the time the aircraft passes through the debris cloud. This area is a projected area, relative to the direction of travel of the aircraft. Chapter 10 of reference [1] in paragraph 3.4 of this AC provides additional discussion of the calculation of aircraft risk.

11.8.1 The application of vulnerability that leads from a casualty area to an "effective" casualty area comes from both the aircraft and the people on board. The term "aircraft vulnerability" refers to the combination of the two sources. The aircraft may be modeled as a rectangular box with top area A_{top}, front area A_{front}, and a side area A_{side}. The side area can be ignored because almost all fragments are likely to strike the front or top of the aircraft, and only graze the aircraft sides.

11.8.2 Applying aircraft vulnerability, the casualty area is reduced to the effective casualty area, and the corresponding volume swept out leads to a projected vulnerability volume. When the aircraft is moving through a hazardous debris cloud, the aircraft consequence probabilities should be summed over a series of snapshot times when both the aircraft and hazardous debris cloud are frozen. The projected vulnerable volume is the space that the aircraft's projected vulnerable area sweeps out during the time interval Δt between snapshot times,

$$VulV_{projected} = VulA_{projected} \times v_{rel} \times \Delta t$$

v_{rel} is the relative speed (magnitude of the velocity vector of impact) between the aircraft and the hazardous debris cloud:

$$v_{rel} = \left|\vec{v}_{aircraft} - \vec{v}_{debris}\right|.$$

The probability of consequence is the product sum

$$p_{consequence} = \sum_{j=1}^{N_{times}} p_{volume}(t_j) \times VulV_{projected}(t_j)$$

where p_{volume} is the probability of finding a fragment in the volume.

11.8.3 The vulnerable area of an aircraft depends on the fragment's mass, size, and shape. Models to compute $VulA_{projected}$ for aircraft are called the Probabilistic Aircraft Vulnerability Models (PAVM). A full discussion and details of the modeling process is given in reference [24] of paragraph 3.4 of this AC. The models consider potential hazardous debris damage and penetration of components of the aircraft, and apply human vulnerability models to evaluate serious injury for passengers. Rather than treat each fragment type individually, a conservative approach may be taken to model the hazardous debris fragments as steel cubes.

11.8.4 Above the maximum mass for which a PAVM is valid, the full size of the aircraft is used:

$$VulV_{projected} = (A_{top} \times v_{vertical}^{cloud} + A_{front} \times (v_{aircraft} + v_{horizontal}^{cloud})) \times \Delta t$$

The vertical cloud speed may correspond to a cloud that is either ascending or descending. For aircraft for which no PAVM applies, all fragments above one gram should be considered hazardous to the entire aircraft. PAVM modeling was not done for masses over 300 grams since the analysis becomes very complicated due to multiple aircraft components that can be damaged during the same event. Instead, the analysis should assume that any impact by a fragment with a mass over 300 grams is casualty producing.

11.8.5 Below 300 grams, PAVM models have been developed for several aircraft types. Figure 11 of this AC, presents curves of $VulA_{projected}$ for three classes of aircraft. These curves assume terminal velocity for the hazardous debris cloud fragments moving only in a vertical direction and aircraft flying only in the horizontal direction. For all other aircraft, all debris larger than one gram should be considered catastrophic. The reference [22] of paragraph 3.4 of this AC provides additional details on the proper use of these aircraft vulnerability models.

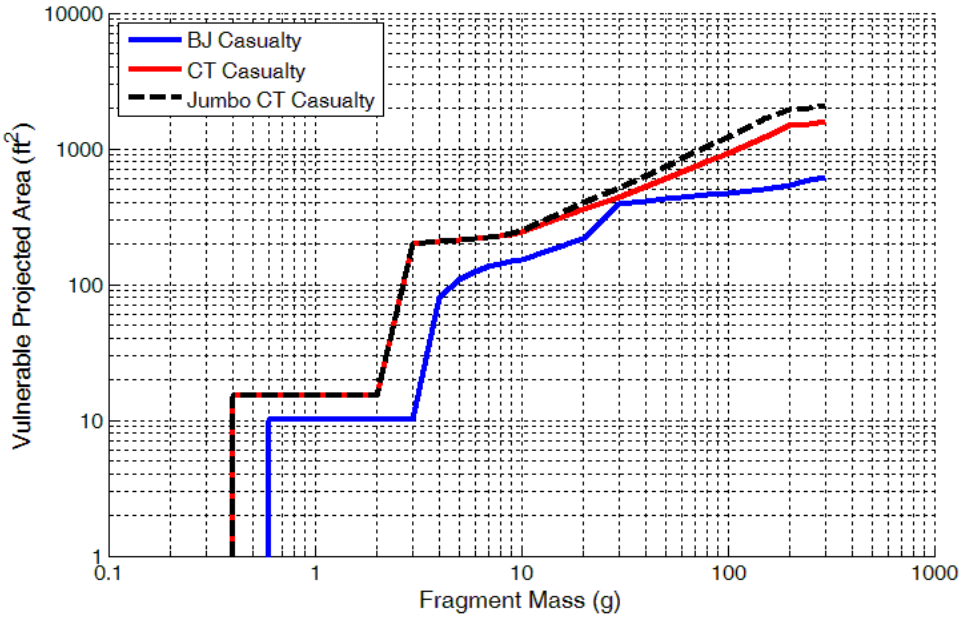

Figure 11—Sample Aircraft Vulnerable Projected Areas

11.9 Explosive Hazardous Debris.

In accordance with § 450.135(b)(1), consequences must be evaluated for all types of hazardous debris. This section discusses the hazard cases where explosive hazardous debris consequences arise, how to model explosions for risk analysis, and provides guidelines for evaluating such consequences.

- Explosive risk must be computed for unsheltered people, people in buildings, and people on or below deck on waterborne vessels. Explosive impacts on aircraft may be ignored, although treating the propellants as inert must be evaluated.
- Impacting vehicle stages, both solid and liquid motors, intact tanks, and major segments of solid propellant motors should be evaluated to determine whether they are expected to explode on impact. The explosion will cause a blast overpressure wave that may reach several thousand feet for large propellant weights. A general discussion of yield models exists in AC 450.137-1, *Distant Focusing Overpressure (DFO) Risk Analysis*.

11.10 **Yield Models.**

11.10.1 Characterizing the hazard from a blast wave that results from the impact of an explosive propellant fragment, requires the TNT equivalent yield of the explosive. Yield Y is the TNT equivalency of an explosive propellant weight w.

11.10.2 These parameters are related through a "TNT equivalency factor" $Y = F_{TNT}w$.

In general, the factor F_{TNT} may depend on propellant type, the type of surface that the propellant strikes, and the impact speed.

11.10.3 An accurate means to evaluate the consequences of an overpressure wave on people is to compute the peak overpressure $P(d)$ and impulse $I(d)$ of the blast overpressure wave at a distance d from the impact point.

11.10.4 To convert yield into these parameters, it is convenient to use the scaled distance $d_{scaled} = d/Y^{1/3}$.

11.10.5 The peak overpressure as a function of scaled distance may be obtained from Figure 12, and impulse as a function of scaled distance, in units of ft/lb1/3, may be obtained from Figure 13 of this AC. The reference listed as [14] of paragraph 3.4 of this AC provides further information.

11.10.6 These curves have been in use for decades by the Federal Ranges. A publication search may uncover various versions of updated curves that have been published since then, and with proper justification can be used as replacements to gain more accuracy.

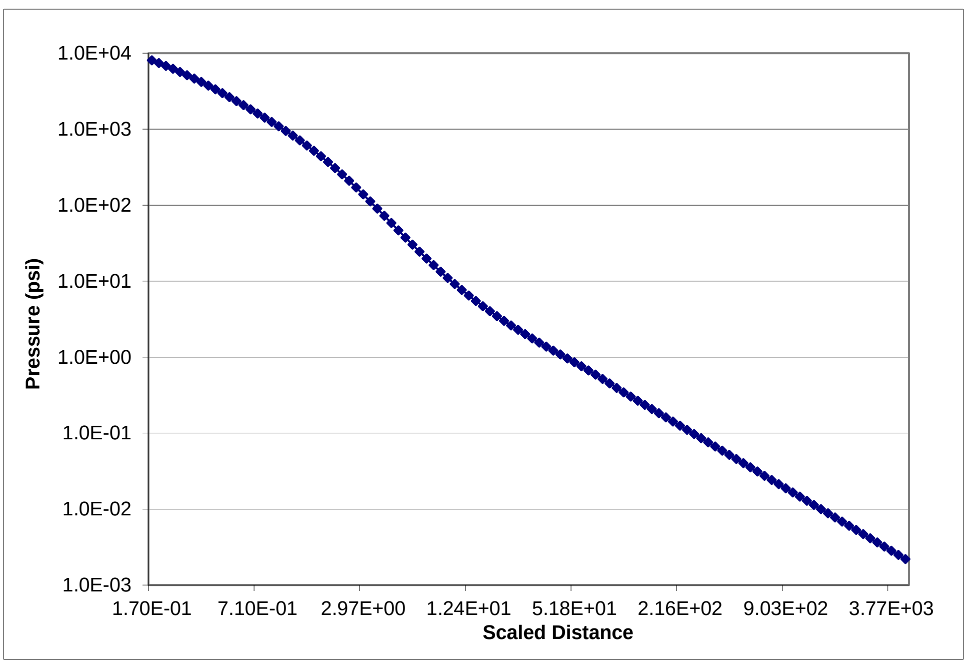

Figure 12—Peak Overpressure vs. Scaled Distance from Blast Waves

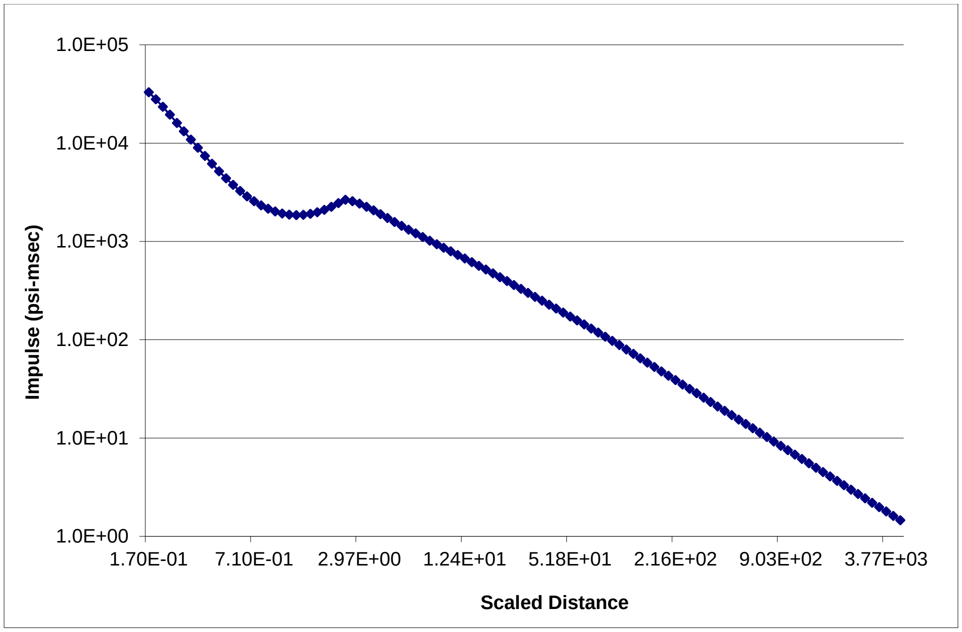

Figure 13—Impulse vs. Scaled Distance from Blast Waves

11.11 **Liquid Propellant Yield**.

Yield curves have been generated for most of the types of liquid propellant used by modern day rockets. For other propellants, the applicant should develop a model in compliance with § 450.101(g). These are shown in Figure 14 of this AC, where values of F_{TNT} are shown on the vertical scale. These curves are to be applied regardless of surface type.

> **Note:** The impact weight of the liquid tank should account for operator intentional venting of fuel that may have occurred during the failure event. Liquid propellant has two components, "fuel," (e.g. LH2, RP-1, A_50, or liquid methane, and "oxidizer," e.g. LO2 or N2O4). During venting, the motor is given a crack on its side allowing the fuel to leak, that usually starts from the time of failure. By design, the venting process does not change the oxidizer weight. On impact, yield should be computed by assuming that the ratio of fuel to oxidizer, $R = w_{oxidizer}/w_{fuel}$, is such that both components mix completely to creation an explosion. The effective propellant weight that gets converted into yield is only dependent on the remaining fuel: $w = w_{fuel}(1 + R)$.

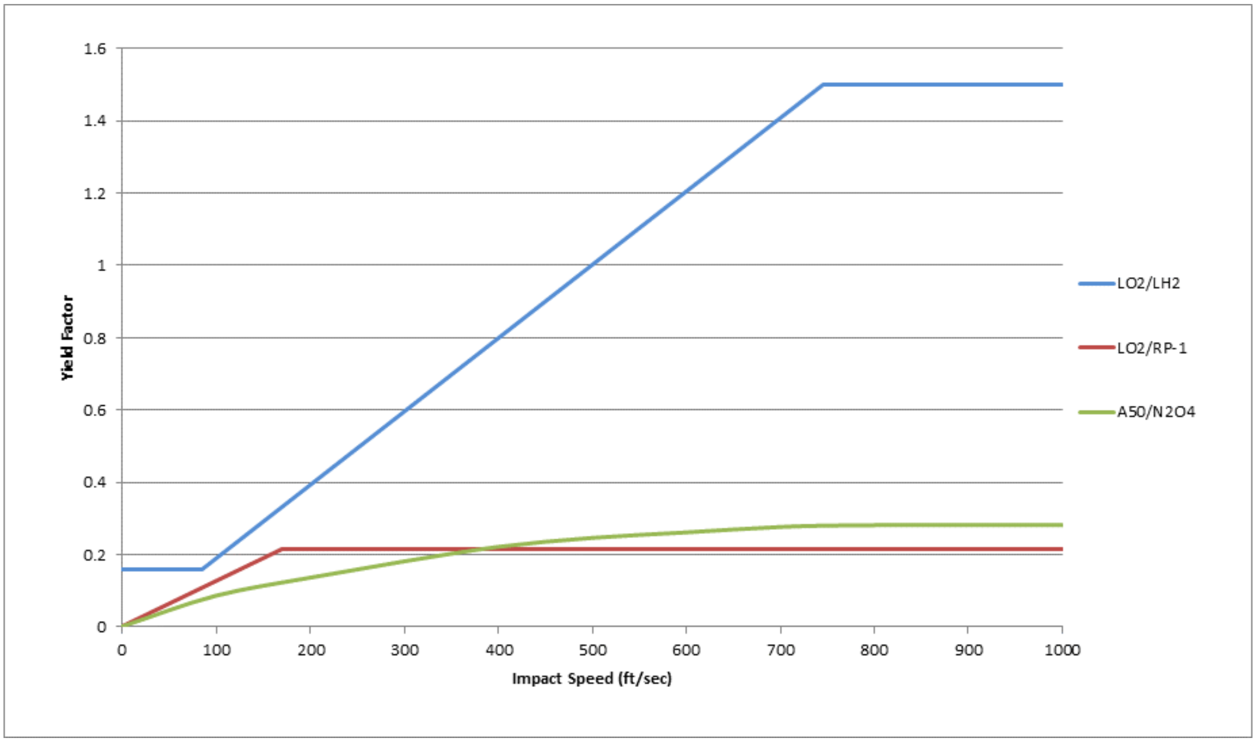

Figure 14—Yield Curves for Liquid Propellants on Hard Surfaces

11.12 **Solid Propellant Yield.**

Solid propellants relevant for flight safety analysis are typically represented in one of two categories: Hazard Division (HD) 1.1 detonable propellants, or HD 1.3 deflagration propellants. For other types of solid propellant, a conservative option is to apply the HD 1.1 model. The yield factors for solid propellant should account for the size and shape of the propellant, type of impact surface, total impact speed, and orientation at impact if applicable.

11.12.1 Uncontained propellant hazardous debris created during vehicle breakup should account for any loss of weight and change of shape during the ballistic fall due to burning. A determination should be made if the propellant is burning once ballistic fall commences, and if it snuffs out prior to impact. Snuff-out models depend on the propellant type and consider local air density and fragment speed. Fragments that are not initially burning may be assumed to remain non-burning during free-fall. The fragment weight and ballistic coefficient should be updated as burning occurs, and the ballistic trajectory should be based on the evolving weight and ballistic coefficient values.

11.12.2 For HD 1.1 impacts, yield factor F_{TNT} values for various surface types can be read from Figure 15. This plot indicates that the factor will either be 0 or 1.25. These curves make no distinction of whether the propellant is in a contained motor, its impact orientation, or uncontained hazardous debris created at vehicle breakup.

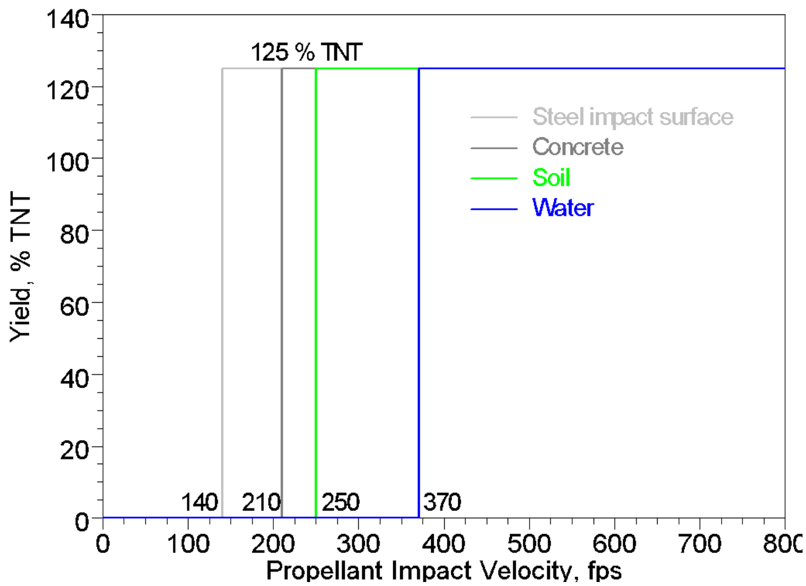

Figure 15—HD 1.1 Propellant Yield Model

11.12.3 For HD 1.3 propellant impacts, the appropriate yield model should account for the form of the solid propellant fragment. Three types of solid propellant fragments should be considered: contained motors, small uncontained chunks of hazardous debris created at vehicle breakup, or large uncontained pieces created at vehicle breakup that are shaped as a Cylindrical Annulus Sector (CAS).

11.12.4 Yield factors for intact motor segments that impact on sand in a side-on orientation may be obtained from the curves in Figure 16, where the segment sizes are measured by the lateral diameter of the motors. If the yield factor associated with the desired motors is not those presented in the figure or are not available, then the curves in Figure 16 can still be used. For other motor diameters between 41” and 146”, linearly interpolate between the nearest bounding curves. For diameters outside the range, use the closest bounding curve and do not extrapolate. For surface types other than sand or soft soil impact, adjust the impact speed by:

$$v = \frac{v_{impact}}{F_{surface}}$$

where $F_{surface}$ is 0.55 for steel, 0.78 for concrete, 1.00 for sand, and 1.61 for water.

11.12.5 Finally, for all intact motor orientations other than side-on, the conservative approach is to employ the side-on curves.

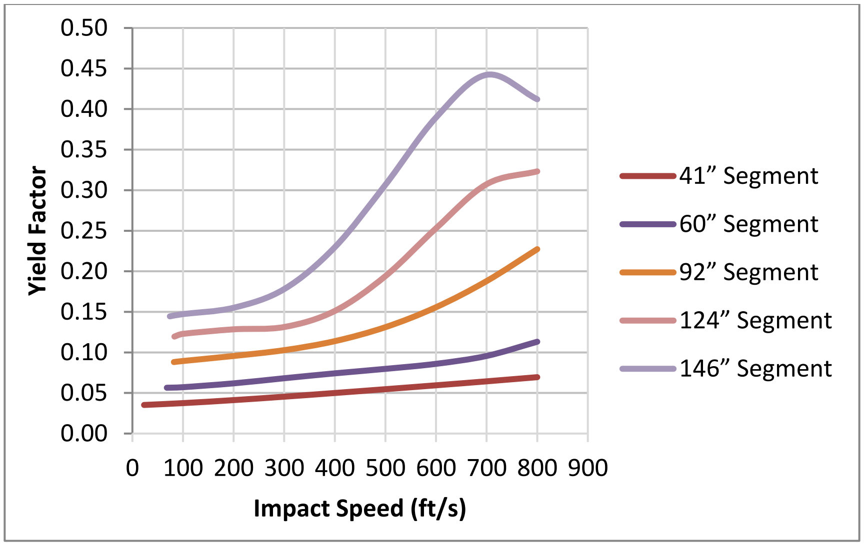

Figure 16—Yield Curves for Motor Segment Side-On Impacts on Sand

11.12.6 Propellant chunks may be modeled as cubed shaped. To get yield factors, Figure 17 of this AC can be used where the cube size is measured by the length of any of its edges. For other cube dimensions between 18” and 30”, linearly interpolate between the nearest bounding curves. For dimensions less than 18”, linearly interpolate using the 18” curve and zero values. Use the 30” curve for dimensions larger than 30” and do not extrapolate. For other surface types, apply the same impact speed correction as with the intact motors.

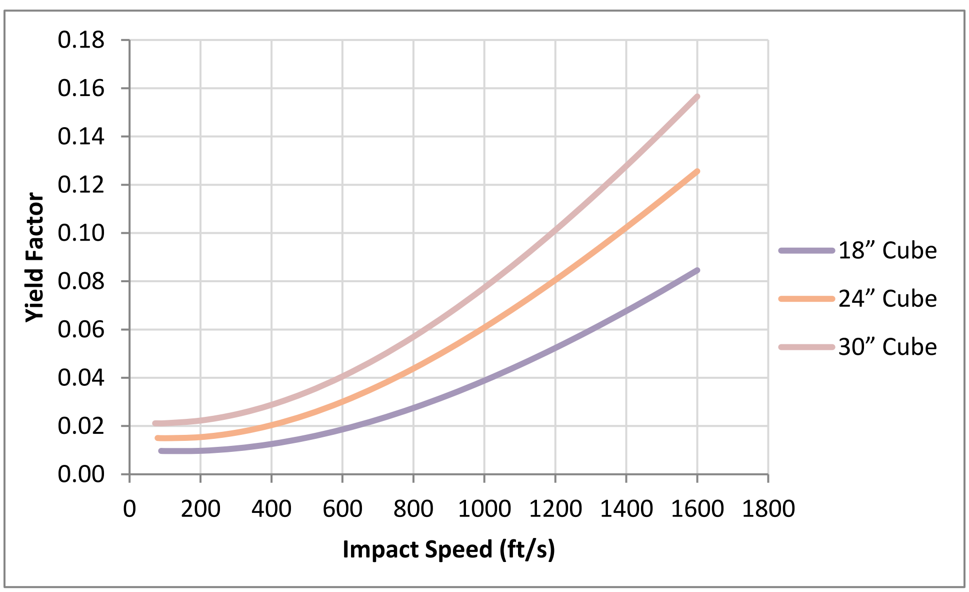

Figure 17—Yield Curves for Cube Chunks Impacting on Sand

11.12.7 The third shape case is impacts for uncontained propellant cylindrical annulus sectors. Apply the yield factors in Figure 18 for a CAS that subtend an angle of 120 degrees, and whose length is a half that of the origination motor. This means that the total propellant inside a motor will be modeled as six such CAS fragments. The diameters referenced in the figure's legend are those of the originating motor. For other surfaces and diameters, apply the same rules as given for the intact motor. For smaller lengths and subtended angles, but still forming a CAS, a conservative approach is to use the curves in Figure 18. For larger lengths and angles, the conservative approach is to use the intact motor yield factor curves, although the creation of such dimensions is unlikely.

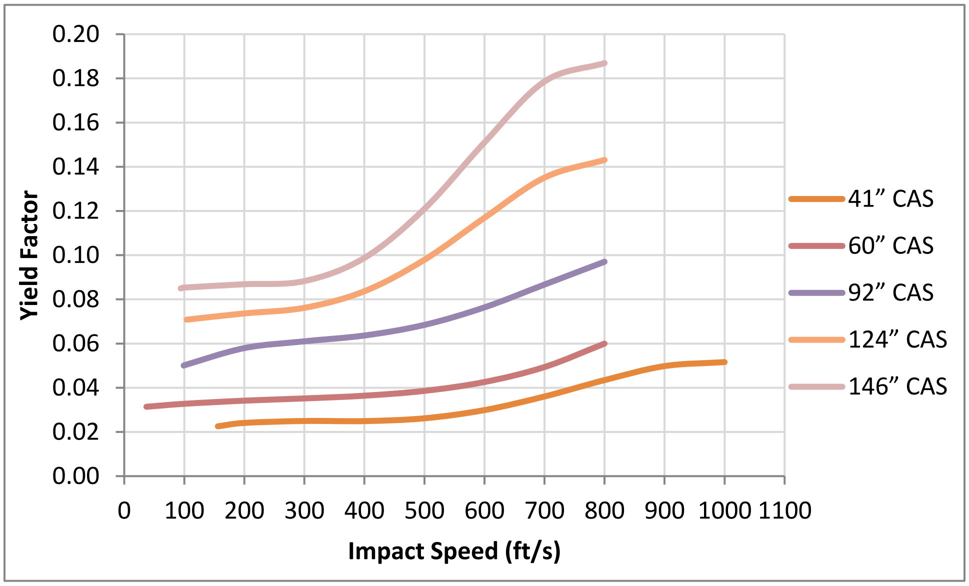

Figure 18—Yield Curves for 120° CAS Side-On Impacts on Sand

11.12.7.1 The curves in Figure 17 and Figure 18 are given in tabular form in AC 450.137-1, *Distant Focusing Overpressure Risk Analysis*.

11.13 **Sympathetic Yields from Multiple Motors**.

Several situations should to be considered when motors impact near one another during the same event. The first is when the motors have different propellant compositions. For that case, the yields should be computed separately, and never as a single yield with a combined impact weight from the motors.

11.13.1 A second situation is when one motor explodes on impact but at least one other motor, of the same propellant composition, remains intact. If the intact motor then explodes due to being struck by induced ejected hazardous debris from the exploding motor, then the yield from the initially intact motor should be computed separately from the others.

11.13.2 A third situation is when motors of the same propellant composition explode near each other. The first motor that explodes may cause a sympathetic reaction of the second motor, due to the shock wave, leading to its detonation at the same time. A single yield can be computed using a combined propellant weight if the shock wave pressure distance between the motors is small enough. An evaluation should be done, based on distance between the motors and structural properties of the second motor, to determine if the blast wave overpressure on the second motor exceeds its threshold for detonation. If insufficient information exists for such an evaluation, then a conservative approach is to combine the propellant weights and use this as a single yield.

11.14 Impacting Propellants for Unsheltered People.

Two types of events should be considered for impacting propellants to evaluate consequences for people that are not sheltered by a structure. First, a liquid tank on impact may explode and create a fireball. Second, on impact a solid propellant chunk or motor, or liquid tank motor, may create a blast overpressure wave.

11.14.1 Fireball.

When liquid tanks impact, they may create a fireball if they have sufficient fuel and impact speed. A fireball hazard should be represented as a probability of casualty versus distance curve, $PC(d)$. On impact, the liquid propellant will be consumed very rapidly, usually in at most a few seconds. This results in a fireball that grows to a maximum radius $r_{fireball}$ that is a well-defined border about an opaque region.

11.14.2 The maximum radius of the fireball depends on the type of liquid propellant. The following expressions may be used where the radii are given in feet, and W is the impact liquid propellant weight in pounds:

$$\begin{aligned} r_{fireball} &= 5.02W^{0.316} \quad LOX/RP-1\, r_{fireball} \\ &= 5.52W^{0.306} \quad LOX/LH-2\, r_{fireball} \\ &= 4.43W^{0.316} \quad Hydrazine \end{aligned}$$

11.14.3 For all liquid types that do appear in this list, a conservative model to use is the LOX/LH-2. If a person is inside the maximum fireball radius, then the person is considered a casualty. Outside, the probability of casualty is partly due to second degree burns, and diminishes by distance based on the fireball duration and emissivity of the fireball. When a person experiences 2nd degree burns over 20% of their body, the person is considered to be a casualty. The probability of casualty from the fireball will need to be combined with that from the blast wave created from the explosion (discussed in the next subparagraph).

11.15 Blast Wave Overpressure.

The threat from a blast wave should be represented as a probability of casualty versus distance curve, $PC(d)$. The blast wave should be treated equally in all directions, since there is no preferred direction, and can be quantified by peak overpressure and impulse as a function of distance. The probabilities of casualty and impact are correlated. The impact space can be divided into cells such that the probability of impact within each cell is close to uniform. The net probability of consequence for a given population center is the sum of

$$p_{consequence} = \sum_{n=0}^{N_{cells}} p_n^{impact} \times PC(d_n)$$

11.15.1 The sum should include all cells with $PC(d)$ above $1x10^{-6}$.

11.15.2 The blast wave injury to people is dominated by the effect on four body parts: the lungs, gastrointestinal (GI) track, larynx, and eardrum. Figure 19 presents probability of casualty curves for these body parts. The curves associated with the 50 percent casualty thresholds should be used to create the corresponding PC curves for a given impact event. A person may suffer one or more of the injuries. The following expression should be employed to obtain the total probability from all sources at a given distance "d":

$$PC(d) = 1 - \left(1 - p_{eardrum}(d)\right)\left(1 - p_{larynx}(d)\right)\left(1 - p_{GI\,Tract}(d)\right)\left(1 - p_{lungs}(d)\right)$$

11.15.3 For liquid tank impacts, use a probability of one inside the fireball radius and the blast wave probability outside the fireball radius.

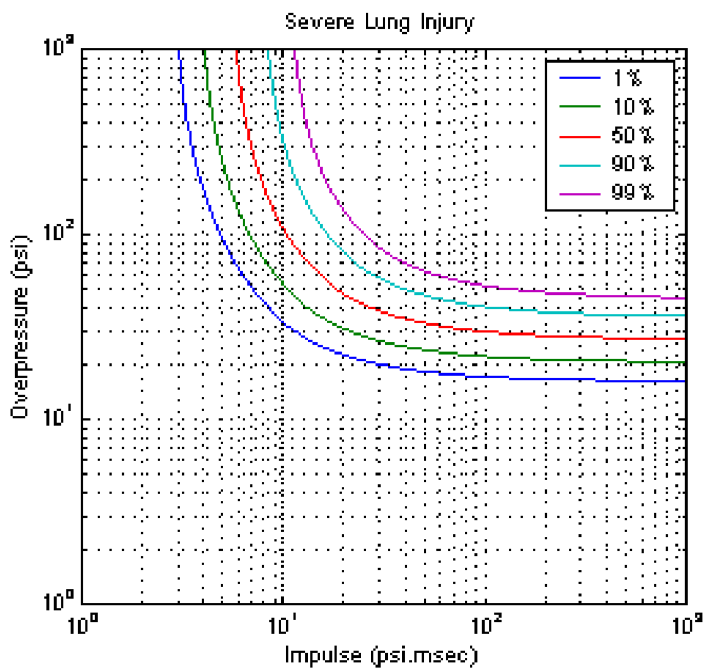

Figure 19—Probability of Serious Injury to a Lung

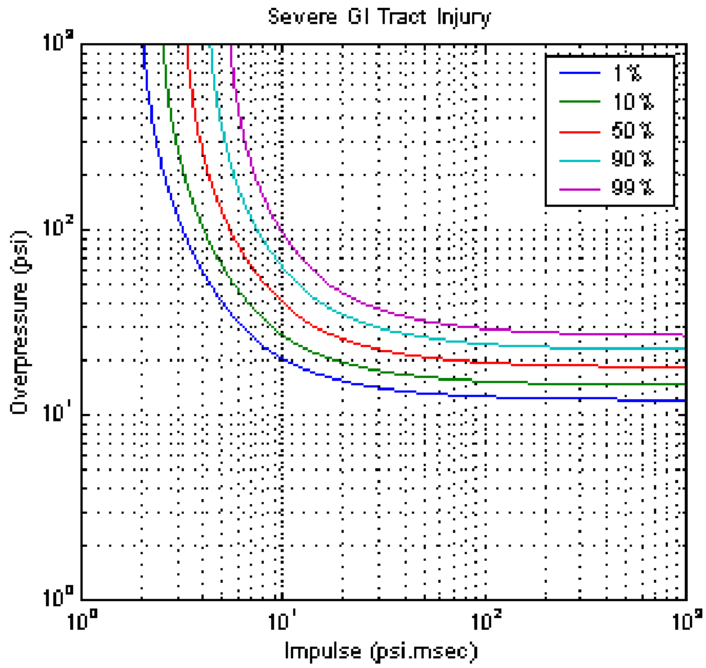

Figure 20—Probability of Serious GI Tract Injury

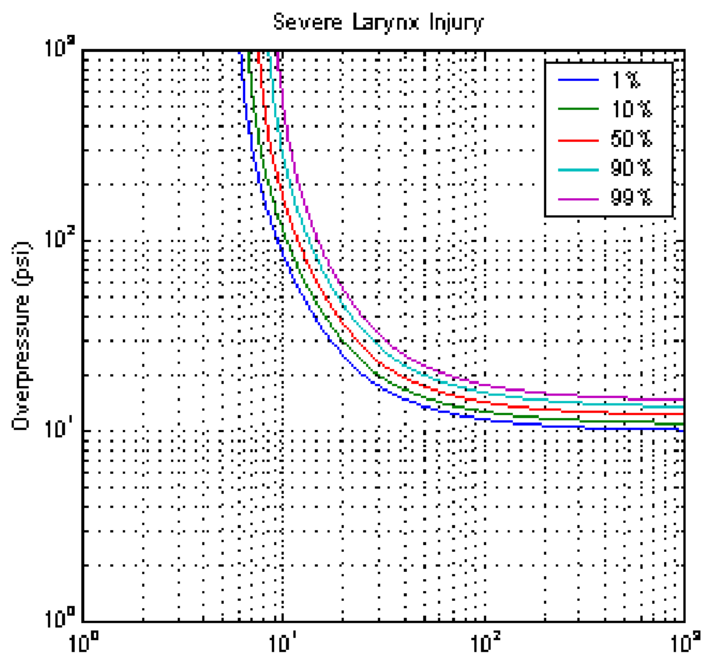

Figure 21—Probability of Serious Larynx Injury

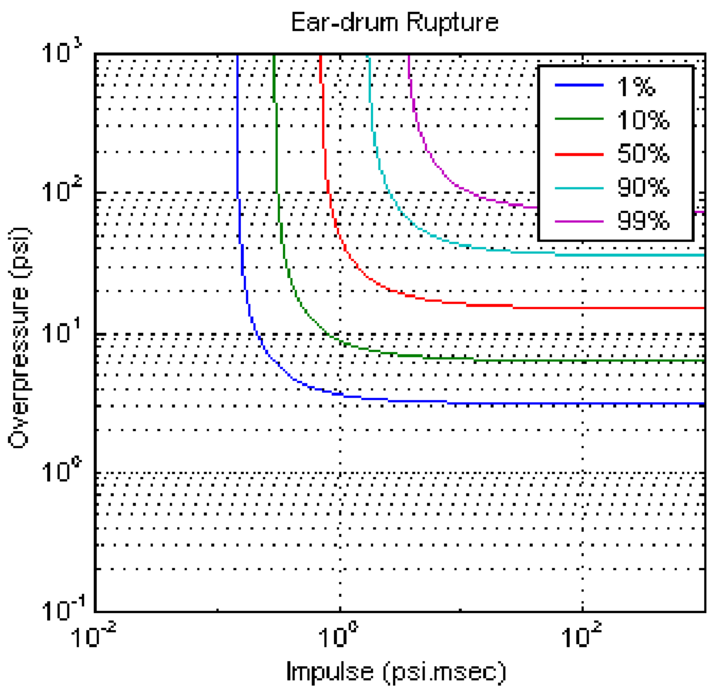

Figure 22—Probability of Serious Eardrum Rupture

11.16 **People in Structures.**

Three propellant fragment impact event scenarios should be considered for evaluating the potential for injuring people in structures. The first scenario is a liquid or solid propellant tank, or solid propellant fragment that impacts the roof of a building leading to its collapse. The second scenario is a burning piece of solid propellant fragment that penetrates the roof without exploding and creates a fire on the floor below. The third scenario is a liquid or solid propellant tank, or solid propellant fragment that impacts away from a building's roof and creates a blast overpressure wave that damages the wall and windows.

11.16.1 Roof Impact.

The hazard from a liquid or solid propellant tank, or solid propellant fragment, impacting on a roof should be represented as an effective casualty area for people on the floor below. The probability of casualty is $p_{casualty} = CA/A_{roof}$. The probability of impact is computed separately and evaluated over the area of the building roof A_{roof}. The effective casualty area depends on the type of roof and its size. General roof types that should be represented are wood, steel, and concrete. Table 6 of this AC presented a survey of buildings that fall into four general classes, A to D. The A Class is for lighter roofs of more temporary structures. The categories progress to the least vulnerable D Class - roofs of robust commercial structures. This simplified model does not address hazardous debris impacts on blockhouse-type structures.

11.16.1.1 A Monte Carlo simulation may be performed to sample impact roof locations, and account made if any joists or beams are at, near, or away from the impact points. Effective casualty area related curves as a function of yield, for these general roof types for a range of roof sizes, are shown in Figure 23, Figure 24, and Figure 25. Roof areas are in units of square feet, and the vertical axis is the ratio of the effective casualty area to the modeled roof area. Wood roof curves are a conservative selection for applying to roof types other than those shown. For a roof area less than 960 ft^2 the far-left curve should be used, and for areas larger than 86,640 ft^2 the far-right curve.

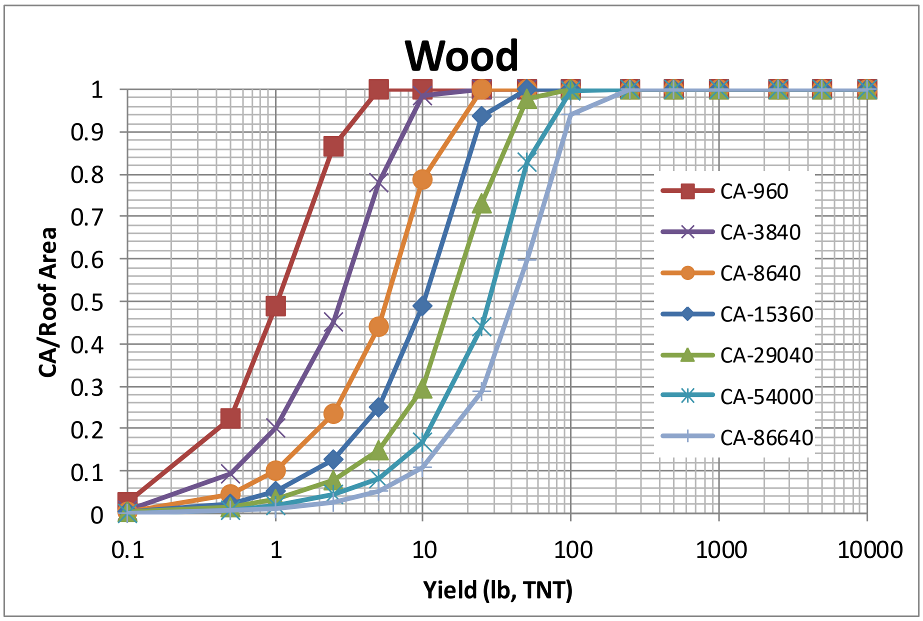

Figure 23 –Wood Roof Effective Casualty Area Ratio as a Function of Roof Area and Yield

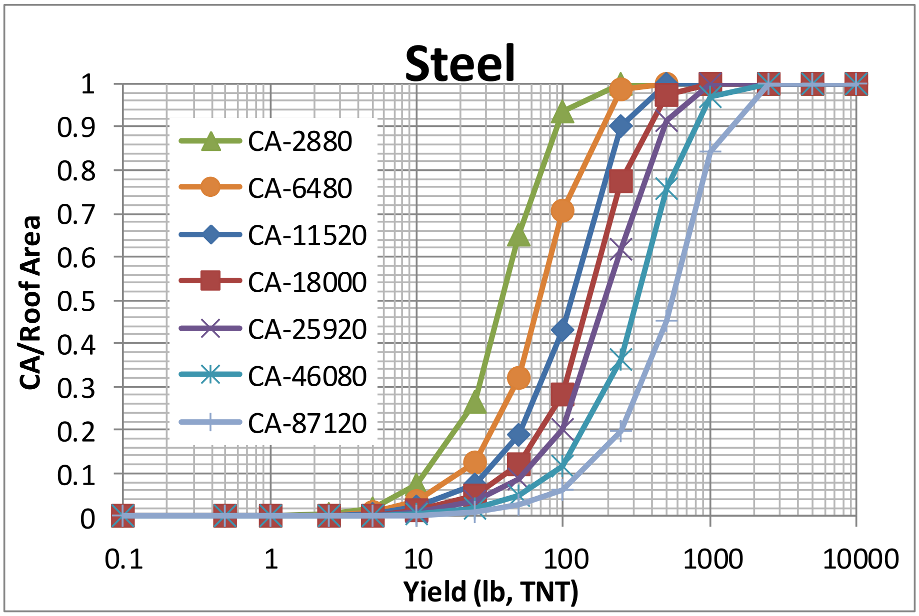

Figure 24—Steel Roof Effective Casualty Area Ratio as a Function of Roof Area and Yield

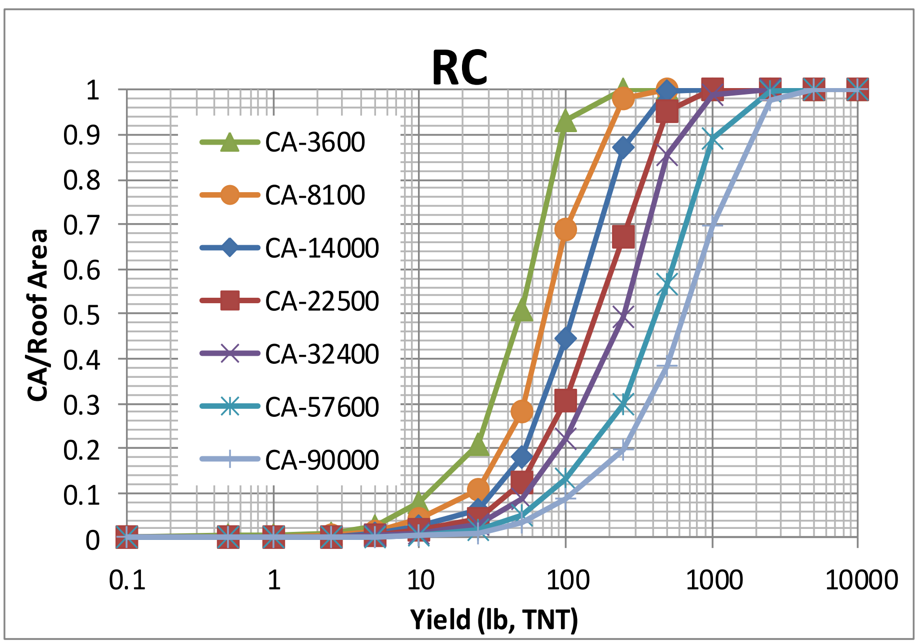

Figure 25—Reinforced Concrete Roof Effective Casualty Area Ratio as a Function of Roof Area and Yield

11.17 **Floor Fire.**

The following discussion presents the process for computing the effective casualty area for a fire resulting from a solid propellant fragment penetrating the roof and burning after impacting the floor. The probability of casualty is $p_{casualty} = CA_{fire}/A_{roof}$, and the probability of impact is computed separately and evaluated over the building roof area A_{roof}.

11.17.1 The flame from a stationary piece of burning propellant can be modeled in the shape of a cylinder whose base is the cross-section area of the solid propellant chunk, i.e. the fire area, and whose length is the flame height. The reference listed in [12] of paragraph **Error! Reference source not found.** of this AC provides further information. The flame over the burning propellant chunk forms a cylinder whose radius is that of the fragment, r_f.

11.17.2 For an HD 1.3 propellant type, the flame height in feet is computed by:

$$H_{flame} = 0.77\dot{Q}_{conductive}^{0.4} - 2.04r_f$$

where r_f is in feet, and the $\dot{Q}_{conductive}$ is the conductive heat flow rate away from the burning chunk.

11.17.3 The expression for computing the rate is:

$$\dot{Q}_{conductive} = \dot{m}4467A_f(1 - e^{-5.4r_f})$$

where $\dot{m}$ is the rate at which the mass of propellant burns in lbs/s, and A_f is the area of the propellant in ft2.

11.17.4 When a person experiences 2nd degree burns over 20% of their body, the person is considered to be a casualty. The conduction heat rate can be used to determine when a 50 percent probability of 2nd degree burn occurs. The reference for this information is [22] of paragraph **Error! Reference source not found.** of this AC.

$$P_{50\%} = \frac{1}{2}\left[1 + erf\left(-34.04 + 2.13\ ln\left(t \times q^{4/3}\right)\right)\right]$$

where t is time elapsed until depletion of propellant mass.

11.17.5 The quantity $t * q^{4/3}$ is referred to as the “heat load.” The heat flux q is in units of W/m2 and computed by:

$$q^{4/3} = t^{-3/8} \times \sqrt{5.38 \times 10^{-0,005r_f}}$$

11.17.6 Representative curves of floor fire effective casualty areas for 2nd degree burns as a function of heat load are given in Figure 26. The room is modeled as circular and the only room in the building. A conservative assumption was made that the people are trapped and cannot escape to another room or outside the building. The curves depend on the ratio of the flame height over diameter of the fire area, H/D.

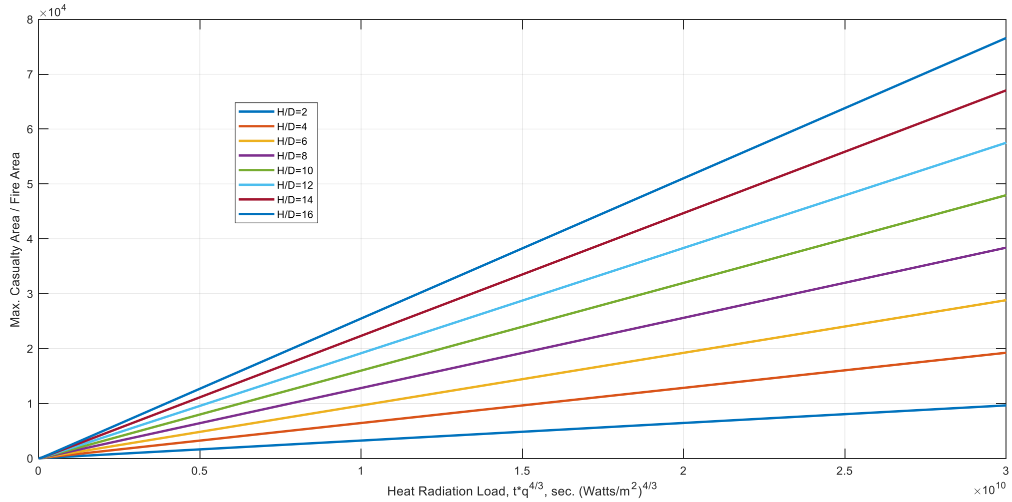

Figure 26—Normalized Casualty Areas vs. Heat Load

11.18 **Blast Wave Overpressure.**

The hazard from blast waves from propellant explosions, for impacts away from buildings and not on the roof, should be represented as curves of probability of casualty versus distance from the impact propellant impact point to the building's wall. The probabilities of casualty and impact are correlated. The impact space can be divided into cells such that the probability of impact within each cell is close to uniform. The net probability of consequence for a given population center is the sum of

$$p_{consequence} = \sum_{n=0}^{N_{cells}} p_n^{impact} \times PC(d_n)$$

11.18.1 The sum should include all cells with $PC(d)$ above $1\text{x}10^{-6}$.

11.18.2 The blast wave strikes the side of the building and both the breakup of the walls and windows should be evaluated for injury to people inside the building. The reaction of the building should consider both the peak overpressure and impulse of the blast wave. Walls of buildings will be subjected to different blast loading depending on the orientation of the building to the blast wave. To be conservative, shards produced by window damage should be modeled as entering the room without obstruction by drapes or other obstacles. The injury from both the wall and windows can occur together. At any given impact distance, the total probability of casualty of a person inside the building is given by

$$PC(d) = P_{wall}(d) + P_{window}(d) - P_{wall}(d)P_{window}(d)$$

11.18.3 Since analyzing every individual type of building is impractical, a small set of representative buildings may be evaluated instead. This requires defining classes of wall and window types. Table 6 of this AC contains a list of general building categories and their construction materials that may need to be evaluated. General wall types that should be represented are wood, metal, masonry, and concrete.

11.18.4 The degree of injury to people inside a building depends on the wall's level of resistance to the blast wave, the floor plan size of the building, and the characteristics of the hazardous debris that is generated when the wall is damaged. There are too many variables here to provide a suggestion for a conservative choice of what probability of casualty curves to apply for a building not accounted for by curves that are already on hand. Figure 24 presents an example of a series of curves that range in probability of casualty from 0.1% to 100% for a small wood structure that is common among houses. Similar curves may need to be created to describe other building types since those in Figure 27 are not necessarily the most conservative that such curves can be.

11.18.5 The red arcs that move from the lower left-hand side to the upper right-hand side correspond to specific impact yields and trace out the peak overpressure and impulse values as a function of the distance of the impact point to the wall of the structure.

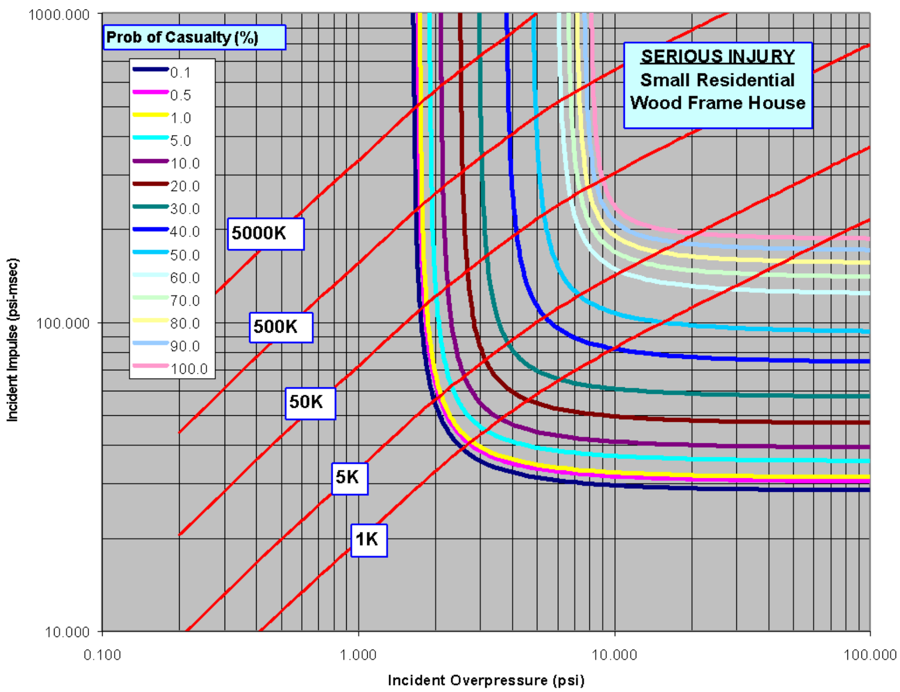

Figure 27—Probability of Casualty for a Small Wood Structure, ~2500 ft^2

11.18.6 For computing probability of casualty from window breakage, the rows of Table 10 present a survey of window types that the buildings are likely to have. Annealed windows are the most sensitive to blast waves while tempered windows are the strongest. Thus, it is conservative to treat all windows as annealed if more appropriate results are not available.

Table 10 – Generic Window Types

Glazing Type			Pane Size		
Annealed	Dual Pane	Tempered	Small	Medium	Large
x			x		
x				x	
x					x
	x		x		
	x			x	
	x				x
		x	x		
		x		x	
		x			x
		x	x		

1) Small = 0-10 ft**2; Medium = 11-20 ft**2; Large = >20 ft**2

11.18.7 An example of the probability of casualty curves for a large annealed window is shown in Figure 28. As with the wall curves, these are curves that are not the most conservative, and so other curves may need to be generated for the other window types.

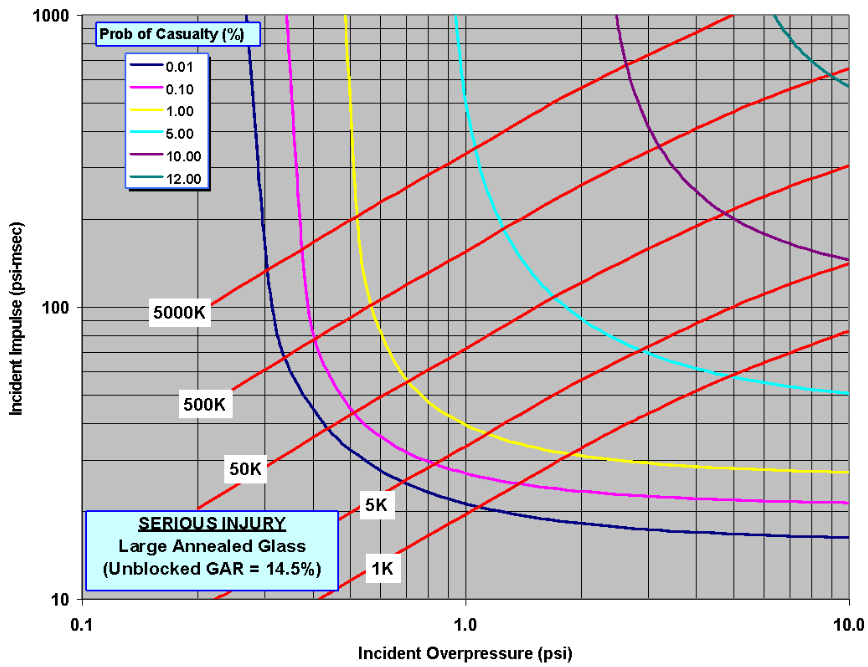

Figure 28—Large Annealed Windows (~5'H x 6'W x 0.232"T), GAR = 14.5%

11.18.8 The acronym GAR stands for Glass-to-Area ratio, which is defined as area of the glass in the window to the floor area: $GAR = A_{glass}/A_{floor}$. The curves are shown for a $GAR = 2.8\%$. For buildings with other GAR values, the probabilities from the curves can be rescaled through the general expression $P_{window}(d) = \frac{GAR^{building}}{GAR^{generic}} p_{generic}^{window}(d)$.

11.18.9 Note that the horizontal overpressure axis does not extend far enough to the right to reach large probability of casualty values. However, it is not necessary to plot out any farther since the wall probabilities have reached a value of one and the contribution from windows is no longer relevant.

11.19 People in Waterborne Vessels (Ships).

The casualty area and consequence analysis must account for the vulnerability of people to debris impact or effects, including effects of waterborne vessel upon the vulnerability of any occupants, in accordance with § 450.135(b)(4)(i). The total effective casualty area should be the sum of two sources. Further information on this topic can be found in the reference in [22] of paragraph 3.4 of this AC.

$$CA = CA_{ship} + CA_{water}$$

11.19.1 The first contribution corresponds to the relative area on the ship deck where people are seriously injured from an explosion of a propellant that impacts the ship. The second contribution is the area around the ship for propellant explosions in water impacts that lead to casualties on the ship. Both casualties refer to the same people on the ship, but to different impact locations of the propellant.

11.19.2 The probability of consequence is given by the sum

$$p_{consequence} = p_{impact}^{ship+water} \frac{CA_{ship} + CA_{water}}{A_{ship}}$$

which assumes that the ship sizes are much smaller than propellant impact dispersions. For ship impacts, the effective casualty area should be evaluated separately for people on the deck and those below deck. The effective casualty area for water impacts does not require such a distinction.

11.19.3 The effective casualty area for water impacts depends on how close the propellant explodes from the ship. Table 11 of this AC provides the maximum distance $r_{casualty}$ from the ship, as a function of ship length, that the propellant can impact and cause casualty. The yield values to apply for using the table should be computed for water surface impacts, and with side-on orientation for motor segments and CAS.

Table 11 – Water Impact Distances That Lead to Casualty

Ship Length (ft)	Minimum Yield (lbs-TNT)	Casualty distance (ft)
< 25	0.01	$37.5\ Y^{0.333}$
25-50		
50-100		
100-200	3.0	$20\ Y^{0.375}$
200-295		
> 295	10.0	$7\ Y^{0.44}$

11.19.4 Modeling ships as a rectangle, of length L and width W, the water effective casualty area is given by

$$CA_{water} = \pi r_{casualty}^2 + 2r_{casualty}(L + W)$$

which cover all locations where the edge of the blast overpressure wave can just reach the ship and cause serious injury.

11.19.5 For ship impacts and people below deck, Table 12 of this AC may be used to get the effective casualty area CA_{ship}. The yield values to apply in the table should be computed for steel surface impacts, and with side-on orientation for motor segments and CAS.

Table 12 – Ship Explosive Effective Casualty Areas for People Below Deck

Length (ft)	Yield (lbs-TNT)	Sheltered Effective Casualty Area (ft^2)
< 100	< 0.03	0
< 100	0.03 to 0.1	$10\ A_{ship}\ Y$
< 100	> 0.1	A_{ship}
>= 100	< 0.05	0
>= 100	0.05 to 0.5	$80\ Y$
>= 100	0.5 to 1.0	$[80\ Y, 2A_{ship}(Y - 0.5)]$
>= 100	> 1.0	A_{ship}

11.19.6 For ship impacts and people on deck, the blast overpressure wave profile should be applied. This profile may be reduced to an effective casualty given by the following equation, which is a sum over ring areas by the probability of casualty within the corresponding ring.

$$CA_{ship} = \pi \sum_{n=1}^{N_{rings}} \left(r_{ring}^2(d_n) - r_{ring}^2(d_{n-1})\right) \times PC(d_n)$$

11.20 **Toxic Emitters.**

11.20.1 An open-air solid propellant fragment burns with hazardous combustion products, while a liquid or hypergolic tank may explode or break open and leak toxic chemicals. In the liquid case, the exposed liquids will evaporate, and in either case, the gases will form a toxic cloud plume that is directed away from the impact point by the wind. High wind speeds create narrow plumes, while weak winds produce a wider cloud. Anyone who is exposed to the toxic cloud within a threshold distance from the spill, and the cloud's lateral span that is a function of distance, should be considered a casualty. A toxic release hazard analysis must be performed in accordance with § 450.139(c). This distance is based on the burn-time of the solid propellant fragment, evaporation rate of the liquid, time since the spill occurred, chemical type, and exposure time to the person. The threshold distance for people in buildings is less than for people in the open. People in buildings are not exposed to the same toxic level from the plume, compared to a person standing outside, because a smaller amount will seep in over the same period.

11.20.2 The probabilities of casualty for a population center and propellant impact are correlated. The impact space should be divided into cells such that the probability of impact within each cell is close to uniform. The net probability of casualty for a given site is the sum:

$$p_{consequence} = \sum_{n=0}^{N_{cells}} p_n^{impact}(PC = 1)$$

which applied the fact that the probability of casualty (PC) is either 1 or 0. The notation "$PC = 1$" indicates to only consider impact points whose plume reaches a population center.

11.20.3 A high-level discussion of the hazards from toxic clouds is given in Chapter 5 of reference [1] of paragraph 3.4 of this AC. The references at the end of that chapter can assist in determining the length and width of the plume. Other details that involve the nature of toxic chemicals are in AC 450.139-1, *Toxic Hazards Analysis and Thresholds*.

11.21 **Secondary Hazardous Debris Fragments.**

Secondary hazardous debris fragments are created when hazardous debris impacts the ground and then breaks into a set of smaller inert fragments. These situations must be considered when they pose a hazard to people or assets for splatter scenarios in accordance with § 450.135(b)(1). The secondary fragments may increase the hazardous area beyond that of the direct impact of the intact body or fragment, resulting in impact to more people. They may also increase the risks within the overlapping areas from direct impact and secondary hazardous debris. Examples of secondary fragments that should be considered include impacting (1) intact vehicles, (2) contained propellant tanks, and (3) inert fragments.

11.22 **Intact Impact Vehicle.**

Impact of an intact vehicle will cause a secondary-fragments field that is generally scattered in the direction of the impact velocity vector. Without obstructions, such as trees or hills, the scatter secondary-fragments field will fan out from the impact point. The length, width, and shape of the secondary-fragments field, and subsequent hazardous debris fragment list, depend on the impact angle, speed, and construction of the vehicle.

11.22.1 A basis for a list of secondary fragments should be evaluating similar events. There are few historical cases for launch or ballistic vehicles, which limits the sources that may be useful to other vehicles. Although not as directly applicable, there have been dozens of airplane crashes that produced secondary-hazardous debris scatter. Since creation of a proper secondary-fragments list from these cases is problematic, an acceptable alternative is to try to map out the hazardous scatter field and set probability of casualty as either 1 or 0. These selections should account for whether people are in the open or the type of building in which they reside. The probabilities of casualty for a site and intact vehicle impact are correlated. The impact space should be divided into cells such that the probability of impact within each cell is close to uniform. The net probability of consequence for a given population center is the sum, which applied the fact that PC is either 1 or 0.

$$p_{consequence} = \sum_{n=0}^{N_{cells}} p_n^{impact}(PC = 1)$$

11.23 **Intact Propellant Tank Secondary Hazardous Debris.**

When intact liquid or solid propellant tanks survive until impact, there should be an evaluation of the hazards due to the blast wave, from any explosion, and subsequent secondary fragments from breakup of the motor’s shell. The imparted velocity of the secondary fragments should be determined by considering the impulse of the blast wave. Blast waves from propellant explosions are strong enough to eliminate any influence of the impact angle and give no preferred direction for the ejected fragments. Some explosions may result in secondary fragments traveling several thousand feet.

11.23.1 The hazardous debris fragment lists from the secondary fragments are not the same as when vehicle breakup occurs while in flight. Properties of the fragments, such as the mean and distribution of sizes, weights, and areas should be constructed. The weights and areas are used to compute ballistic coefficients of the fragments. The mechanism of the propellant explosion for a surface impact has different physics than from the vehicle’s destruct system. At present, there are no recommended models for this purpose.

11.23.2 The risk from the secondary hazardous debris may be determined through a Monte Carlo analysis. The individual event scenario events select different characteristics of the fragments from the distributions, (i.e., speed, direction, and weight). Each event scenario should trace the trajectory of all ejected fragments. Atmospheric drag and wind can be ignored when generating these trajectories. For various distances away from the impact point, statistics should be kept of the probability of casualty.

11.23.3 The consequence for a breakup of an impacting propellant tank should be represented as a probability of casualty versus distance curve, $PC(d)$. The explosion tends to overwhelm the pre-impact conditions, leading to the fragments being thrown equally in all directions as a function of distance. The probabilities of casualty and impact are correlated. The impact space should be divided into cells such that the probability of impact within each cell is close to uniform. The net probability of consequence for a given population center is the sum of

$$p_{consequence} = \sum_{n=0}^{N_{cells}} p_n^{impact} \times PC(d_n)$$

11.23.4 The sum should include all cells with $PC(d)$ above $1\text{x}10^{-6}$.

11.24 Inert Fragment Splatter.

The impact kinetic energy of inert fragments with sufficient impact speed and weight, may have enough equivalent TNT yield to explode into a collection of shards. This situation may be handled through the same type of Monte Carlo analysis as with the propellant tank impacts. Secondary fragments from single impact inert fragment usually travel no more than a few tens of feet, compared to thousands of feet for the propellant tanks. Thus, instead of probability versus distance curves, the results of the Monte Carlo analysis can be reduced to small effective casualty areas about the impact point.

12 RISK COMPUTATION.

The objective of a launch or reentry mission risk analysis is to demonstrate that collective and individual risks are below acceptable levels as specified in § 450.101, not necessarily to quantify the precise risk levels. Such risk analyses can be conducted using a low fidelity analysis or using a higher fidelity analysis. A higher fidelity analysis will allow for greater flexibility in acceptance that the analysis results comply with the risk acceptance criteria. This results from the increased accuracy, and reduced uncertainty, of the predicted risks.

12.1 How Risk is Expressed.

Risk is defined in § 401.7 as a measure that accounts for the probability of occurrence of a hazardous event to persons or property. If there is more than one possible outcome of an event, the total risk associated with the event is determined as the logical sum over all possible outcomes of the products of the probability of each outcome and its associated consequence. The total risk for a launch or reentry mission is the logical sum of the risk over all potential hazardous events that can pose a hazard to people or property. Risk can be lowered by reducing the probability of an event occurring or by reducing the consequences of the event. For example, planning a mission that avoids flight operations over populated areas can decrease or eliminate the hazard to people (and property) and thereby reduce the risk. The process for computing the measures of risk are discussed in this section.

12.1.1 The hazardous debris risk for a mission are expressed in several forms. These are:

- The expected average number of human casualties for a mission, often referred to as the casualty expectation, E_C. The E_C for hazardous debris is the sum of the risk over all potential hazardous debris generating events that can pose a hazard to people or property.
- The maximum risk to an individual resulting from the launch mission, referred to as individual risk. This is the maximum risk over all individuals exposed to the launch hazardous debris hazards, and addresses the people located in all population centers and all vehicles.
- The Conditional Casualty Expectation. This is defined as the expected number of casualties that could occur from each foreseeable failure mode (hazardous event) occurring in any one-second period of flight, given that the response mode has occurred.

12.2 **Risks to Population Centers and Protected Objects.**

12.2.1 Casualty Expectation.

For population centers, the casualty expectation E_C for a specific population center and hazardous debris resulting from a specific hazardous debris generating event is a function of the characteristics of the population center (footprint area, structural types and associated shelter categories and associated population) as discussed in AC 450.123-1 *Population Exposure*, the probability of impact of a fragment on a population center (see Chapter 10 of this AC), and the effective casualty areas or probabilities of casualty for each population center (see Chapter 11 of this AC). The E_C for a fragment class is obtained by multiplying the E_C per fragment by the number of fragments in the fragment class. The total casualty expectation for a population center hazarded by hazardous debris is the accumulation of these values over all fragment classes and all hazardous debris generating events.

12.2.2 The basic equation for casualty expectation $E_{C_{ijk}}$ for fragment class i, population center j, and the kth generating event (jettisoned hazardous debris or a given failure mode occurring at a given failure time), is given by

$$E_{C_{ijk}} = p_k^{failure}\, p_{ij}^{impact}\, N_{F_i} \sum_{l=1}^{l=N_{pops}} p_{ijl}^{casualty} N_{P_{jl}}$$

where $p_{failure}$ is the probability of occurrence for the hazardous debris generating event, NF is the number of fragments in the fragment class, N_P is the number of people in the population center, p_{impact} is the population center impact probability, and

$p_{casualty}$ was discussed in Chapter 11. The total casualty expectation for a given population center j is the sum $E_{C_{Pop\ j-Total}} = \sum_{ik} E_{C_{ijk}}$. The total casualty expectation for the mission is the sum over all pop centers.

12.3 **Probability of Hazardous Debris Generating Event.**

The probabilities of occurrence, P_{F_k}, for the hazardous debris generating events are computed using the failure rates developed as described in AC 450.131-1, *Probability of Failure*. They include hazardous debris jettisons (for which the probability is usually near one), applicable failures (loss of thrust, explosion, malfunction turn) resulting from discrete event failures (stage ignitions, stage shutdowns), and applicable malfunction failures occurring at specific times during the stages of flight. The probabilities for discrete event response modes are equal to the failure rate times one second, since discrete events are assumed to occur over a one second interval. Vehicle stage failure response mode probabilities are computed for short time intervals of flight, with time intervals selected such that the risk can be computed for a given time during a time interval (usually the mid-point time) that is considered representative of the risk at any time during the interval. Time intervals need to be sufficiently short such that the hazardous debris footprint for a given time interval sufficiently overlaps that of its adjacent time intervals to represent a continuous footprint. The failure probability for a given stage response mode occurring during a given time interval is computed by integrating the failure rate for the response mode over a time interval:

$$P_F = \int_{t_A}^{t_B} R(t)$$

where R(t) is the response mode failure rate (probability of failure per second).

12.4 **Probability of Impact.**

The computation of the probability of impact p_{ij}^{impact} for a given hazardous debris class i on a given population center j, is dependent on fragment type. Development of an impact probability distribution is discussed in Chapter 9. For an inert fragment impacting a population center, p_{ij}^{impact} is obtained by integrating the impact probability distribution for the fragment class over the area of the population center.

12.4.1 A population center is a populated place with a known location at launch time. This includes people in the open at a specified location, occupied buildings/structures, and vehicles. Vehicles could include road vehicles (cars, trucks, busses), trains, and waterborne vessels (aircraft are normally protected by clearing them from aircraft hazard corridors during a mission). Road vehicles can be accounted for by determining road traffic density at “population centers” placed at multiple locations along roads. Generally, the risks to trains, waterborne vessels, and aircraft are controlled (mitigated) by defining hazard areas or corridors (such as NOTMARS and NOTAMS, see Chapter 13) and controlling their locations during a launch such that the risks are sufficiently small and considered to be acceptable.

12.4.2 Hazard areas, including NOTMARS and NOTAMS, are designed to protect these populations. However, if a train and/or a waterborne vessel will be in a hazardous area, and its location(s) during the operation are known, risks to their occupants need to be included in the risk analysis in accordance with § 450.135(b)(4)(i). They should also be included during a launch countdown risk analysis when it is known that a train or a waterborne vessel has violated its hazard area, with the projected location of the train or waterborne vessel used to compute the risk.

12.4.3 While it is unusual for an aircraft to be in a hazard corridor, and it is likely not possible to define a fixed aircraft location, it may be necessary to assess the risks to aircraft in accordance with § 450.133(d) traffic through a hazard corridor during a launch countdown. This would require a special analysis to compute the impact probability, which should involve the use of 4-dimensional hazardous debris distributions (3 dimensions in space, plus time).

12.4.4 For an explosive fragment hazarding a population center, the probability of impact needs to consider that the fragment need not physically impact the center to cause casualties. This could also be the case for a liquid propellant tank creating a fireball, or secondary hazardous debris from an exploding tank or motor. An explosive fragment can impact the ground outside the boundaries of a population center, such that overpressure loading (peak overpressure and impulse) at the population center are sufficient to cause casualties (see paragraph 12.2 of this AC). This can occur for people who are unprotected (in the open) or within a structure. Thus, for explosive hazardous debris, the area around and including a population center should to be overlaid on a grid and impact probabilities computed for each grid cell. Casualty expectation $E_{C_{ijk}}$ will then need to be computed for an explosive fragment impact in each of these cells (with the probability of impact for each cell obtained by integrating the impact probability distribution for the explosive fragment over the area of the cell), and the resulting $E_{C_{ijk}}$ values for the cells summed over all cells.

12.4.5 The concept is illustrated in Figure 29. In this figure, the area encompassing the population center is gridded to create "impact cells." The grid extends out from the population center to include all the area within which the explosive fragment could impact and significantly contribute to the E_C for the center. An explosive fragment is shown as impacting in a specific cell, with the rings denoting decreasing levels of overpressure loading with distance from the impacted cell centroid. E_C for the population center is computed (using the consequence model for explosive hazardous debris, see paragraph 12.2 of this AC) for the impact occurring in the cell, using the cell impact probability p_{ij}^{impact}. This is then repeated for all impacted cells and the results summed to obtain the total E_C for the population center.

12.4.6 For a large population center, often referred to as a region, where there are various shelter levels (including people in the open) distributed over the region, a second grid should be defined that partitions the population center into grid cells (call this the population grid). The reason for this is that the overpressure loads for a given explosive fragment impact location can vary significantly over the population center. In this case, the E_C should be computed for an explosive fragment impact in each "impact cell" for each of the cells in the population grid, and these values summed to get the total E_C for the impact cell. This is then repeated for all impact cells and the results summed to get the total E_C to the population center for the explosive fragment.

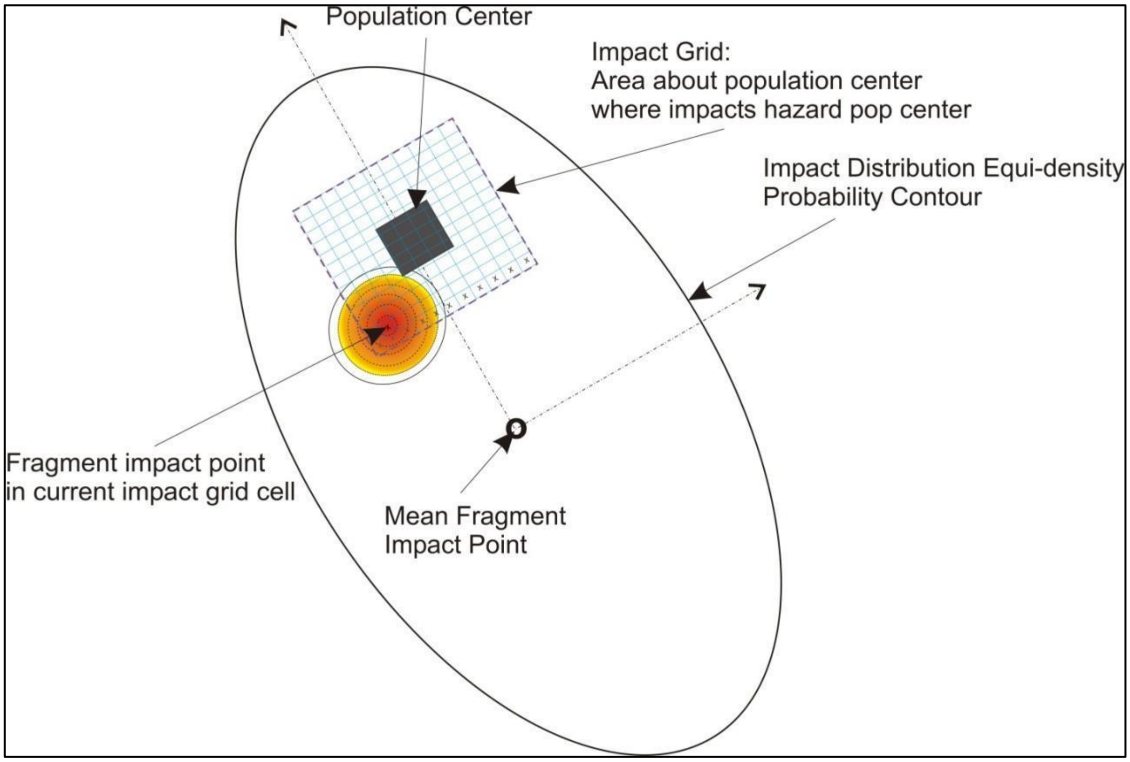

Figure 29—Calculation of the Risk to a Population Center Due to the Impact of an Explosive Fragment

12.5 Individual Risk.

Mission individual risk is the probability of any single individual becoming a casualty, evaluated over all fragment classes and hazardous debris generating events. In accordance with §§ 450.101(a)(2) and 450.101(b)(2), the risk must meet the FAA individual risk criterion. For a specific population center and shelter type, to compute the mission individual risk, divide the mission E_C by the total population:

$$P_{CI_j} = \frac{E_{C_{Pop\ j-Total}}}{N_{Pop_j}}$$

The largest probability over all population centers and shelter types is then compared with the threshold values in § 450.101(a)(2) and 450.101(b)(2).

12.6 Conditional Casualty Expectation.

The FAA has established consequence criteria, specified in requirements § 450.101(c), which state: An operator must protect against a high consequence event in uncontrolled areas for each phase of flight by:

1. Using flight abort as a hazard control strategy in accordance with the requirements of § 450.108;
2. Ensuring the consequence of any reasonably foreseeable failure mode, in any significant period of flight, is no greater than 1×10^{-3} conditional expected casualties; or
3. Establishing the launch or reentry vehicle has sufficient demonstrated reliability as agreed to by the Administrator based on conditional expected casualty criteria during that phase of flight.

12.6.1 The consequence should be measured by the casualty expectation in uncontrolled areas (defined in § 407.1) for any failure mode occurring during any significant period of flight, with an important threshold at 1×10^{-3} set in § 450.101(c)(2).

12.6.2 Since E_{C_k} includes the probability of occurrence for hazardous debris generating events $p_k^{failure}$, the E_{C_k} are the contributions to the total mission casualty expectation accounting for the probability that the hazardous debris generating event has occurred. Thus, to obtain the casualty expectation CE_{C_k} for the hazardous debris generating event given that the event has occurred, (i.e., is conditional on the event having occurred), the probability of the event $p_k^{failure}$ needs to be removed as shown below:

$$CE_{C_k} = \frac{E_{C_k}}{p_k^{failure}}$$

12.7 Aggregate Risk.

Accumulated risk is the combined risk to all individuals that are exposed to hazards, such as that due to impacting hazardous debris. It accounts for all hazardous events that could occur for a launch or reentry mission, including all phases of the mission.

12.7.1 Collective risk represents the total risk to all individuals exposed to all the hazards that could result from a mission. It provides a measure of the risk to everyone potentially exposed. In the launch and reentry industry, risk is usually quantitatively expressed in terms of expected casualties (E_C, also referred to as “casualty expectation”). E_C is the expected average number of human casualties incurred per launch or reentry mission. When the human casualties contemplated are limited to just those incurred by members of the public, E_C for a mission measures the public safety risk of conducting the mission. E_C is usually computed separately for each of the hazards, and these are added to obtain a conservative estimate of total collective risk.

12.7.2 In general, aggregated risk, collective and individual, must account for the three principle launch hazards: hazardous debris (which includes inert and explosive debris), far-field overpressure blast effects (which is commonly referred to as distance focusing overpressure (DFO)), and toxic release, in accordance with §§ 450.101(a)(1) and (a)(2). The total casualty expectation is generally estimated by summing the total (accumulated) casualty expectation from each of the hazards posed by a mission. Although this AC only addresses methods for computing the risk for hazardous debris, the total casualty expectation for the hazardous debris hazard will need to be combined with the values computed for DFO and toxic release to obtain the aggregate risk to be compared with FAA risk criteria per § 450.101(a)(1)(i).

12.7.3 The total collective risk results for a mission should include:

a. A list of the maximum individual probability of casualty for the top ten population centers and all centers that exceed 10 percent of the individual risk criterion in accordance with § 450.135(c)(5)(iii),

b. A list of the probability of loss of functionality of any designated critical asset that exceeds one percent of the criterion, and

c. A list of the conditional expected casualty for each failure mode for each second of flight under representative conditions and the worst foreseeable conditions in accordance with § 450.135(c)(5)(iv), unless an operator demonstrates compliance with § 450.108(c)(6).

12.8 **Analysis.**

In accordance with § 450.135(a)(1), there are two options for an applicant, either to perform sufficient analyses prior to the day of the operation accounting for all foreseeable conditions within the flight commit criteria (an availability study), or to run an analysis in the countdown for the operation. Per § 450.135(c)(1), an applicant must submit a description of how the operator will account for the conditions immediately prior to enabling the flight of a launch vehicle or the reentry of a reentry vehicle, in particular:

1. Final trajectory
2. Atmospheric conditions (especially wind)
3. Exposure of people

12.8.1 Availability Study.

Thus, if an availability study is performed, which could be weeks or months ahead of the operation, the variability in the range of all input data should be accounted for. This involves running the risk analysis with a variety of these inputs that span the range of what is possible for the operation. The range of parameters should consider other flight commit criteria or hazard controls. Each combination of these variety of inputs is a potential scenario for the operation. The appropriate application of atmospheric data for an availability study is discussed in section 9.1 of this AC. Population data variability should consider seasonal, temporal, and operation-related (including any observers and visitors variations, as discussed in AC 450.123-1, *Population Exposure*. The trajectory variability should consider the variation in mission profile due to variation in mission objectives, atmospheric conditions, and the operation timing (e.g., launch window). If some scenarios do not meet the risk requirements of § 450.101, then in accordance with § 450.165, an operator must establish and observe flight commit criteria that identify and preclude initiation of the operation each condition necessary prior to initiation of the flight operation. Specifically, this includes the monitoring of the meteorological conditions necessary to be consistent with any safety analysis, as required by

§ 450.165(a)(2), and any hazard controls derived from any safety analysis required per § 450.165(a)(7).

12.8.2 Countdown Analysis.

Alternatively, operators may choose to perform a risk analysis during the countdown, during the hours leading up to a mission. In accordance with § 450.135(a)(2), a risk analysis during the countdown must use the best available input data, including flight commit criteria and flight abort rules. Thus, a countdown analysis is one where the uncertainties in conditions are reduced to the minimum feasible. A primary difference between a planning analysis and a countdown analysis is that a countdown analysis will use updated normal trajectory data (if different from best estimate planning data), updated population exposure data, and wind data based on the latest wind forecast or wind measurements (weather balloon, weather towers, sonars) made during the countdown. In some cases, the duration of the flight initation window may result in significant differences in predicted risks. In all cases, all risks to the public must satisfy the criteria in § 450.101 and must be met at the time of initiation of the flight operation, not simply the average risks in the flight initation window.

13 FLIGHT HAZARD AREA DEFINITION.

In accordance with § 401.7, a flight hazard area is a region of land, sea, or air that must be surveyed, publicized, controlled, or evacuated in order to ensure compliance with the safety criteria in § 450.101. A flight safety analysis must include a flight hazard area analysis, in accordance with § 450.133(a). The concept of a hazard area can be broadened to include lower and upper altitudes, leading to the concept of a hazard volume. Hazard volumes are important for aircraft risk because hazardous debris at altitude transits to the ground over a period of time, and the dispersion, which is impacted by meteorological conditions, and the aerodynamic characteristics of hazardous debris. Flight hazard areas are publicized prior to a mission, and areas are surveyed, controlled, or evacuated, to control public risk, in accordance with § 450.161(c).

13.1 Sources of Hazards.

Consideration of hazards, and the consequences produced is part of performing a standard risk assessment. Protecting people from hazards can be approached by specifying where people can or cannot be, through measures of tolerable acceptance, mitigation, or through exclusion. Sources of hazards include planned hazardous debris events, in accordance with § 450.133(a)(1), as well as hazardous debris or other hazards that could result from all reasonably foreseeable malfunction failure modes. Planned hazards include expended and dropped stages, and jettisoned equipment (such as de-spinning devices) or ballast. Unplanned hazards include motor explosions leading to air blast and inert hazardous debris, burning or explosive hazardous debris, and hazardous debris that results from aerodynamic breakup or activation of a flight safety system. An operator must submit a description of the methodology to be used in the flight hazard area analysis in accordance with § 450.115(c), to satisfy § 450.133(e)(1).

13.2 Flight Hazard Areas.

Flight hazard areas are based on ensuring the risk to a protected entity (people, waterborne vessels, aircraft) meets the individual risk criteria in §§ 450.101(a)(2) or (b)(2) in accordance with §§ 450.133(b)(2) and 450.133(c)(2); meets the collective risk criteria in §§ 450.101(a)(1) or (b)(1) in accordance with §§ 450.133(b)(3) and 450.133(c)(3); or meets the aircraft risk criteria in §§ 450.101(a)(3) or (b)(3) in accordance with § 450.133(d)(2). Implicit in such calculations is an understanding of what could be at risk. For waterborne vessels, this might include whether small fishing boats, large fishing boats, cargo vessels, oil tankers or cruise ships could potentially be in a region. The class of vessel potentially at risk affects the vulnerability of people on a vessel. Vulnerability characterization of people at risk can be defined at various levels of fidelity. An example of a conservative, low level fidelity characterization of vulnerability is one in which compact fragments that are 1 gram or larger are treated as hazardous to aircraft. Higher fidelity models consider the characteristics of impacting fragment in assessing the associated probability of a casualty.

13.3 Examples of Specific Flight Hazard Areas.

- Exclusion Zones: An exclusion zone is a hazard area or volume within which a protected entity must not be present to ensure compliance with § 450.161(a). Exclusion zones may be stipulated because the risk to people in the open is unacceptable and can only be mitigated by excluding their presence. Exclusion in some cases may be the simplest approach to risk mitigation.
- Warning Areas: A warning area is a lower risk hazard region than an exclusion zone, in which exclusion is not enforced. Warnings are publicized to ensure awareness and to promote voluntary exclusion pursuant to § 450.161(c).

13.4 Contour Grids and their Durations.

A common step in defining a flight hazard area is to set up a gridded region within which to compute risk contours. This gridded region is typically used for people on land, on waterborne vessels, and in aircraft. Aircraft grids should be defined at the altitude of specific aircraft types to be evaluated. A gridded region may contain one or more grids. Contours are based on risk values at a set of grid vertices. These vertices are the corners of grid cells that exist within the boundaries of the grids. Each grid is typically shaped as a rectangle and specified by its outer boundaries and cell sizes. The total number of grid cells has a large effect on computer runtimes; an excessive number of cells may be undesirable.

13.4.1 There are several considerations when defining grid dimensions. The guiding principle is that they must contain 97% of all debris resulting from normal flight events capable of causing a casualty to satisfy requirements §§ 450.133(b)(1), 450.133(c)(1), and 450.133(d)(1). The grid dimensions should contain the casualty producing IIPs, at the grid altitude level, of the normal trajectories. They should also contain most, but not necessarily all, the casualty producing IIPs of the failure and planned event IIPs. The IIPs are used to create impact dispersions (see chapter 9 of this AC).

13.4.2 Several techniques can be applied to generate containment areas from calculated impact dispersions. Acceptable techniques include binning the impacts (empirical distribution or a 2-dimensional histogram) as discussed in paragraph 10.4 of this AC; kernel density estimators reference [18] of paragraph 3.4 of this AC; or using parameterized distributions such as a bivariate normal distribution or other distributions as discussed in paragraphs 10.2 and 10.2.1 of this AC. Scatter plots may assist in selecting the appropriate choice. Histogram-based approaches will result in discrete contours, while other approaches will yield continuous contours. Each approach has its advantages and disadvantages in terms of computational cost and accuracy. For example, two-dimensional histograms generally require many more samples to estimate the likelihood of low probability events than histograms. The analysis should include some justification as to the applicability of the specific approach adopted.

13.4.3 Not all the IIPs may be within the 97% containment level of the dispersions. Alternatively, the 97% containment level may reach far beyond any the IIPs. Thus, it may be necessary to display the 97% containment levels to ensure that grid boundaries meet the requirements. A grid cell should not be so large that it contains over 99% of the casualty producing impact dispersions that overlap it, and more desirably under 10%, to avoid issues of accuracy.

13.4.4 In the case of bivariate normal distribution for a single fragment, the "sigma" level corresponding to a confidence level CL=97% is $2.64 = \sqrt{-2ln(1 - CL)}$. If a normal flight event generates more than one fragment, then the containment should be the 97% confidence containment of all resulting fragments.

13.5 Development of NOTMARs.

Flight hazard areas applicable to waterborne vessels must be generated for regions of sea that must be surveyed, publicized, controlled, or evacuated in order to comply with the safety criteria in § 450.101 (§ 450.133(b)). Hazard areas and durations of applicability are used to develop Notices to Mariners (NOTMAR), which are provided to authorities and disseminated to waterborne vessel operators for navigation and traffic management guidance.

13.5.1 A range of waterborne vessel types that could be present in the hazard area should be used for hazard evaluation purposes. Each vessel type will be assigned to a specific grid(s) to compute risks. Casualty producing impacts to waterborne vessels result from blast and inert hazardous debris. At each grid vertex, the probability of casualty to an individual is computed by applying the waterborne vessel consequence models discussed in paragraph 11.7 of this AC. In accordance with § 450.133(e)(2)(iii), two sets of contours must be drawn that correspond to individual risk thresholds as provided in requirements §§ 450.101(a)(2) or (b)(2). The first set is the 1×10^{-6} individual probability of casualty contours for all selected waterborne vessel types, to represent the threshold for a member of the public. The second is the 1×10^{-5} individual probability of casualty contours for all selected waterborne vessel types, which represents the threshold for neighboring operations personnel. In accordance with § 450.161(a), an operator must publicize, survey, control, or evacuate the area within these contours prior to initiating flight of a launch vehicle or the reentry of a reentry vehicle to ensure compliance with § 450.101(a)(2) or (b)(2).

13.5.2 Each set of contours should be enveloped by a polygon, which does not have to touch any of the contours, as it is common practice to add a buffer zone. When there are islands of contours, separate disjoint polygons may be created. Simpler polygons are preferred to avoid placing unduly complex requirements with which waterborne vessel operators should adhere.

13.6 Development of NOTAMs.

In accordance with § 450.133(d), flight hazard volumes applicable to aircraft must be generated for regions of airspace that must be surveyed, publicized, controlled, or evacuated to comply with the safety criteria in § 450.101. Aircraft hazard volumes are used to develop NOTAMs. These hazard volumes and durations of applicability are provided to the FAA. The FAA develops NOTAMs, which restrict air traffic operations, to protect the public from planned or inadvertent hazardous debris from a mission. NOTAMs should not be excessively conservative or geometrically complex.

13.6.1 A range of aircraft types that could be present in the hazard area should be used for hazard evaluation purposes. Each aircraft type will be assigned to a specific grid(s) to compute risks. At each grid vertex and altitude associated with a specific aircraft type, the probability of casualty to an individual is computed by applying the aircraft consequence models discussed in paragraph 11.8 of this AC. In accordance with § 450.133(e)(2)(v), representative 1×10^{-6} and 1×10^{-7} probability of impact contours are drawn for all debris capable of causing a casualty to persons on an aircraft, regardless of location.

13.6.2 Each set of contours is enveloped by a polygon which does not have to touch any of the contours as it is common practice to add a buffer zone. When there are islands of contours, separate disjoint polygons can be created. Simpler polygons are preferred to avoid placing unduly complex requirements with which aircraft operators should adhere.

13.6.3 In addition to these contours, aircraft hazard volumes are defined by a range of altitudes that apply to the selected aircraft. This should be from ground level to the highest relevant altitude, which is typically 60,000 feet.

13.7 Development of Land Hazard Areas.

In accordance with § 450.133(c), flight hazard areas that apply to unsheltered people must be generated for any region of land that must be surveyed, publicized, controlled, or evacuated to comply with the safety criteria in § 450.101. Land Hazard Areas (LHA) are developed with a similar methodology to NOTMARs. Near shorelines, LHAs often border NOTMARs. LHAs are disseminated to the land controlling authorities to ensure surveillance, crowd control, and road traffic management.

13.7.1 LHA-based contours are designed to protect people in the open. Casualty producing events result from blast, toxic releases, and inert hazardous debris events. At each grid vertex, the probability of casualty to an unsheltered individual is computed by applying the consequence models discussed in paragraphs 11.3 and 11.11 of this AC. In accordance with § 450.133(e)(2)(iii), two set of contours are drawn that correspond to the individual risk thresholds provided in §§ 450.101(a)(2) and (b)(2). The first set is at the $1x10^{-6}$ probability level for all applicable shelter types that could house a member of the public. The second set at the 1×10^{-5} probability level for all applicable shelter types that could house neighboring operations personnel. An enveloping polygon is drawn about each set of contours. The polygons do not have to touch any of the contours as it is common practice to add a buffer zone. When there are islands of contours, separate disjoint polygons may be created.

14 SATISFYING APPLICANT SUBMISSION REQUIREMENTS.

A completed high-fidelity flight safety analysis must be sufficiently documented to show that related 14 CFR requirements have been met. Top-level requirements of § 450.115 must be applied to each of the flight safety analysis requirements. For each flight safety analysis requirement, the submitted material should clearly specify the scientific principles and statistical methods used to communicate that a high fidelity analysis has been performed. This will require descriptions of all methods applied, specification of analysis assumptions, justifications and underlying scientific principles, to meet the standards expected of a high-fidelity flight safety analysis in accordance with § 450.101(g). In addition, the analysis should confirm that each appropriate risk threshold specified in § 450.101 will not been exceeded given the flight commit criteria and flight abort rules employed. In accordance with § 450.115(b)(1) the results must demonstrate that any risk to the public satisfies the safety criteria of § 450.101, including the use of mitigations, accounting for all known sources of uncertainty. The application should explain how uncertainty in risk predictions were accounted for, as well as note how risk mitigations were accounted for. In accordance with § 450.115(c)(4), an applicant must provide evidence for its validation and verification (V&V) of the suitability of the submitted material as required by § 450.101(g).

14.1 Nominal and Failure Trajectories.

Advisory Circular 450.117-1, *Normal and Malfunction Trajectory Analysis*, discusses the usage of trajectories by placing them within the context of a flight safety analysis. Various types of trajectories must be generated to comply with §§ 450.117(d)(2) and 450.119(c)(3) requirements. The generated trajectories should be written to data files or spreadsheets that contain:

- Time histories of the vehicle position, velocity, orientation, and associated IIPs,
- Clearly defined coordinate system for each time history parameter,
- Clearly marked units for each data parameter,
- Notation indicating whether using a right-handed or left-handed coordinate system, and
- If relevant, notation indicating whether using an Earth fixed (ECR) or Earth rotating (ECI, inertial frame) coordinate system, or any other coordinate system.

14.2 Failure and Planned Event State Vectors.

Trajectories are used to create a set of failure and planned event state vectors that account for each foreseeable cause of vehicle breakup, including breakup caused by flight safety system activation, inadvertent separation, or by impact of an intact vehicle. The set of failure and planned event state vectors should be written to data files or spreadsheets that specify:

- Nominal state time for on-trajectory cases,
- Vehicle failure and breakup times for malfunction turn cases,
- Position and velocity vectors for hazardous debris modeled with 3 degrees-of-freedom during ballistic fall,
- Orientation of hazardous debris body and angular velocity vector if modeled with 5 degrees-of-freedom (DOF) for axisymmetric bodies or 6 DOF for non-axisymmetric bodies during ballistic fall,
- Clearly defined coordinate system of each state vector parameter,
- State vector failure probability, or identification of failure mode to assign failure probability to each state vector,
- Identification of breakup mode to assign hazardous debris fragment list to state vectors,
- State vector position-velocity covariance, or identification of data source, if state vector uncertainty is not accounted for in trajectories from which the state vectors are selected, and
- Clearly marked units for each data parameter.

14.3 Breakup and Jettisoned Hazardous Debris.

Paragraph 7.5 of this AC presents the creation of vehicle hazardous debris fragment lists for all foreseeable causes of vehicle breakup. Ballistic or near-ballistic hazardous debris may create a hazard at any time during flight and so it must be clearly characterized to comply with § 450.121 requirements. Such hazardous debris may be partitioned into classes that represent one or more fragments, in which case the rules used to create appropriate groups must be documented under § 450.121(d)(5). Generated hazardous debris fragment lists should be written to data files or spreadsheets that define each item by:

1. Nominal value and statistical uncertainty bounds of the ballistic coefficient,
2. Statistical uncertainty in lift coefficient,
3. Mean and statistical uncertainty in break-up induced velocity of a Maxwellian distribution, or detailed speed and direction distributions for a directed DV case,
4. Projected fragment hazard area as the direct reach of the fragment on a person or building,
5. Total weight, and constituent inert and propellant weights,

6. Identification of Mach-CD table to apply for tumbling motion and identification of Mach-CD table to apply for any stable motion,
7. For propellant motors or fragments:
    a. State times corresponding to time-dependent parameter values,
    b. Time history of propellant weight,
    c. Identification of liquid or solid propellant type,
    d. Indication if propellant or motor is burning at release,
    e. For exposed solid propellant fragments: parameters used to compute change in burning propellant weight and size,
    f. For contained motors: propellant consumption rate if burning at release,
    g. For fuel venting motors: initial ratio of fuel/oxidizer and time history of fuel weight,
8. For potential inert aerothermal demise: material type and information needed to compute aerothermal ablation; for composite fragments with multiple material types, provide information to identify only those portions that may lead to aerothermal demise, and
9. Clearly marked units for each data parameter.

14.4 Probability of Failure.

Advisory Circular 450.131-1, *Probability of Failure* discusses how to create failure probability or rate profiles for use in computing unconditional risks. Profiles are created for each foreseeable failure mode to comply with § 450.131 requirements. The profiles can be written to a data file or spreadsheet in a tabular form that clearly indicates the time span over which to apply each failure rate or probability. Each failure probability or rate profile should be accompanied by a graph as a function of time and a plot of cumulative failure probability.

14.5 Requirements for Flight Hazard Areas.

Chapter 13 of this AC discussed the generation of land, waterborne vessel, and aircraft flight hazard areas to comply with § 450.133 requirements. Each of the associated protected zones require a 97 percent confidence of containment for all hazardous debris impacts in accordance with §§ 450.133(b)(1), 450.133(c)(1), and 450.133(d)(1). Inside hazard areas, the risk threshold levels for people cannot be exceeded for individual risk in accordance with § 450.101(b)(2)(i). Geographical coordinates of flight hazard areas should be graphically documented, and the coordinates and duration times provided. Reference AC 450.161-1 *Surveillance and Publication of Hazard Areas or Aircraft and Ship Hazard Areas* for additional information.

14.6 Hazardous Debris Propagation and Impact Distributions.

Chapter 7 of this AC discussed taking each failure and planned event state vector that may cause a hazard and propagate it to the ground. Resulting hazardous debris impact distributions must be statistically valid in accordance with § 450.121(c), accounting for all foreseeable sources of impact dispersion to comply with § 450.135(b) requirements. Under § 450.121(c)(2), sources of impact dispersions must include, at a minimum, uncertainties in atmospheric conditions; debris aerodynamic parameters, including uncertainties; pre-breakup position and velocity, including uncertainties; and hazardous debris velocities imparted at breakup, including uncertainties. If the data sources are not easily available, then the data should be written to data files or spreadsheets. Chapter 9 discussed how to define a hazardous debris cloud and impact functional distributions to comply with § 450.135(b) requirements. Since cloud distributions are typically an internal product of the risk tool, and generally not written out to file, descriptions of final dispersions are not required. However, the methods of definition are required in accordance with § 450.123(c)(1).

14.7 People and Assets.

Chapter 10 of this AC discussed how to define exposure areas that hazard people and assets to comply with § 450.123 requirements. Population centers and asset sites should be written to data files and/or spreadsheets with the following considerations:

1. Mean latitude/longitude location for surface sites and stationary waterborne vessels, otherwise a time-based path for a moving object (waterborne vessel, aircraft) that covers the duration of the mission.
2. Size:
   a. Floor plan area for surface site,
   b. Top area and length for stationary waterborne vessel,
   c. Rectangular dimensions for moving waterborne vessel, or
   d. Top and front areas for aircraft.
3. Value of asset.
4. Population as a function of time of day, week, month, or year:
   a. Number of unsheltered people,
   b. Number of people in each shelter type, and specification of roof type, wall type, and window type,
   c. For waterborne vessels: number of people on deck and separately below deck, and
   d. Number of people in aircraft, and identification of aircraft type.

14.8 Consequence and Risk.

Chapters 10 and 11 of this AC discussed the details for performing a consequence analysis to comply with § 450.101(c) requirements. In addition to the risk measures specified in the requirements, in accordance with § 450.135(c)(4), the applicant must provide the computed effective casualty areas for unsheltered people for each fragment class under § 450.135(c)(3). Most of the consequences covered in chapter 11 of this AC should have computed effective casualty areas, while some cases involving propellant explosions should be dealt with the preparation of probability versus distance curves.

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