FLIGHT SAFETY CODE

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Amendment log

Version	Date	Contributor	Description
1.0	1 Sep 2001	ACTA Inc.	First version developed to align with the *Space Activities Act 1998* and its regulations.
2.0	1 Jul 2002	ACTA Inc.	Updated to align with the updated regulations for the *Space Activities Act 1998*.
3.0	31 Aug 2019	Shoal Group Pty Ltd & Asia Pacific Aerospace Consultants Pty Ltd	Revised the Flight Safety Code to align with the *Space (Launches and Returns) Act 2018* and the associated *Space (Launches and Returns) (General) Rules 2019* and *Space (Launches and Returns) (High Power Rocket) Rules 2019*.

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1 Introduction

1.1 Overview

1.1.1 The *Flight Safety Code* provides the methodology to assess that certain launch and return activities are safe under the *Space (Launches and Returns) Act 2018* [1] and the associated legislative instruments, specifically the *Space (Launches and Returns) (General) Rules 2019* [2] and the *Space (Launches and Returns) (High Power Rocket) Rules 2019* [3].

1.1.2 The *Flight Safety Code* provides a quantitative approach to ensuring that the risks associated with certain civil space and high power rocket activities in Australia are as low as reasonably practicable. The *Flight Safety Code* applies for applicants for Australian launch permits, high power rocket permits and certain return authorisations.

1.1.3 The *Flight Safety Code*'s risk hazard analysis provides methods to identify potential hazards during launches or returns that may cause harm to public health and safety, analyse the risks associated with these hazards, and develop measures to minimise those risks and ensure that they remain below the established launch safety standards.

1.1.4 This document and the attached appendices comprise the *Flight Safety Code*. It consists of two major parts:

- The launch safety standards, which provide standards for third-party casualty safety, asset safety standards for assets with catastrophic potential, restrictions to be applied to unproven vehicles overflying populated areas, and standards to be observed for drop zones and landing sites; and

- The risk hazard analysis methodology, which provides details of the inputs and the method to calculate casualty expectation for launch and return activities.

1.2 Further information

1.2.1 Further information is available at space.gov.au. To make enquiries, please email enquiries@space.gov.au.

2 Definitions

2.1 Defined terms

2.1.1 This *Flight Safety Code* uses a number of terms that are unique to the space launch industry and which have meanings of particular relevance to this code. These definitions do not override those set out in the *Space (Launches & Returns) Act 2018* [1].

Act: the *Space (Launches and Returns) Act 2018* [1].

Agency: the Australian Space Agency.

air-launched vehicle: a launch vehicle launched from an aircraft or air-based platform.

Australian launch permit: means a permit granted under section 28 of the Act.

asset risk: the risk to an *asset with catastrophic potential*.

asset with catastrophic potential: an asset that has the potential to cause a catastrophic chain of events with the potential to lead to casualties.

casualty area: an area surrounding a debris impact point where a person would become a casualty if they are within this area at the time of debris impact.

casualty expectation: the average number of casualties that can occur as a result of an event if the event were to be repeated thousands of times.

catastrophic chain of events: a chain of events following 'trigger debris' impact on an *asset with catastrophic potential* that has the potential to lead to casualties, as assessed by expert engineering analysis.

collective risk: the total casualty expectation from a launch or return.

controlled area: a drop zone area or landing site area.

debris: any material that poses a hazard if it falls to ground as a result of the intended or unintended break up of a space object or high power rocket.

debris footprint: the impact distribution for debris predicted to result from a particular event.

dispersion footprint: an area in which returned space objects or high power rockets, scheduled debris, or debris returns to land, defined by an impact probability isopleth or a standard deviation boundary.

downrange: the area in the direction of the nominal flight path of a launch vehicle.

drop zone: a three standard deviation dispersion footprint around the nominal impact point of scheduled debris.

expendable launch vehicle: a launch vehicle that uses disposable components to carry a payload into space.

Flight Safety Code: Flight Safety Code means the document of that name published by the Department of Industry, Innovation and Science, as in force from time to time.

hazard: a potential source of casualty or loss.

high power rocket: means an object of a kind prescribed by the *Space (Launches and Returns) (High Power Rocket) Rules 2019* [3]; that is:

(a) it is a rocket propelled by a motor or motors with a combined total impulse greater than 889,600 Newton seconds; or

(b) it is a rocket propelled by a motor or motors with a combined total impulse greater than 40,960 Newton seconds and is fitted with a system or systems that allow active control of its trajectory.

high power rocket permit: means a permit granted under section 38 of the Act.

impact probability: the probability of a space object or high power rocket, or debris, impacting on a location, area, facility or person.

impact probability isopleth: a line on a map connecting places of equal impact probability.

individual risk**:** the risk to a single person exposed to a launch or return, or a series of launches or returns.

instantaneous impact point (IIP): the point where a rocket in flight would impact the earth if propulsion ceased immediately. The IIP changes continually during powered flight. The IIP can also be used to describe the point where the debris footprint will impact the earth due to the break-up of a vehicle in flight.

landing site: a three standard deviation area around the nominal impact point for the return of a space objector reusable launch vehicle, including high power rockets.

launch: defined in the *Space (Launches and Returns) Act 2018* [1] as the launch of:

(a) a space object, means launch the whole or a part of the object into an area beyond the distance of 100 km above mean sea level, or attempt to do so; or

(b) a high power rocket, means launch the rocket into an area that is not beyond the distance of 100 km above mean sea level, or attempt to do so.

launch applicant: the applicant for a permit under the Act.

launch facility licence: means a licence granted under section 18 of the Act.

launch vehicle: means any technology designed to project objects into space or near to space, including expendable launch vehicles, reusable launch vehicles, high power rockets and all technologies requiring a launch permit or high power rocket permit.

nominal impact point: planned or intended impact point of scheduled debris or for the return of a space object or high power rocket.

overseas payload permit: means a permit granted under section 46B of the Act.

population centre: a person, group of persons or area of population, considered as a single entity for the purpose of the methodology of risk determination.

public: all persons except those directly participating in the launch or return.

re-entry: entry of a space object or high power rocket into the Earth's atmosphere.

return authorisation: means an authorisation given under section 46L of the Act for the return of a space object to a landing area in Australia.

reusable launch vehicle (RLV): a launch vehicle that includes the recovery of some or all of the component stages.

risk isopleth: a line on a map connecting places of equal risk.

Rules: means the rules made by the Minister under section 110 of the Act.

scheduled debris: planned or intended debris from a successful launch.

significantly populated area: a city, town or settlement, but not an isolated house or homestead.

space object: defined in the *Space (Launches and Returns) Act 2018* [1] as:

> (a) an object the whole or a part of which is to go into or come back from an area beyond the distance of 100 km above mean sea level; or
>
> (b) any part of such an object, even if the part is to go only some of the way towards or back from an area beyond the distance of 100 km above mean sea level.

standard person: a hypothetical object of cylindrical shape with a circular base of radius 0.3 metres and linear height of 2 metres.

successful launch: for the purposes of flight safety, a launch that does not suffer a malfunction that could pose a hazard to the public.

trigger debris: debris capable of triggering a catastrophic chain of events on an *asset with catastrophic potential* (see Section 3.2).

unproven vehicle: a launch vehicle that has not achieved five consecutive missions without a failure that could pose a hazard to public safety or property.

uprange: the area within the launch area and in the opposite direction to the nominal flight path of a launch vehicle

vacuum IIP: the IIP excluding atmospheric effects.

2.2 Acronyms and abbreviations

2.2.1 This *Flight Safety Code* uses a number of acronyms that are unique to the space launch industry and which have meanings of particular relevance to this code.

6-DOF: six-degrees-of-freedom.

BEI: Biodynamics/Engineering Inc.

DFO: distant focusing overpressure

EFFBD: enhanced functional flow block diagram

ELV: expendable launch vehicle

FAA: Federal Aviation Authority

FMEA: failure modes and effects analysis

FRM: failure response modes

FSS: flight safety system

G&C: guidance and control

HPR: high power rockets

IIP: instantaneous impact point

IIPR: instantaneous impact point rate

NEW: net equivalent weight of propellant in terms of TNT

RHA: risk hazard analysis

RLV: reusable launch vehicle

TNO: Netherlands Organisation for Applied Scientific Research

TNT: well-known explosive (acronym stands for Tri-Nitro-Toluene)

3 Launch safety standards

The party responsible for the launch or return of a space object or high power rocket is required to meet the following launch safety standards for risks posed to third parties.

3.1 Third-party casualty safety standards

3.1.1 The maximum third-party collective risk (the sum of casualty risks to all individuals in the public) on a per-launch basis:

$1x10^{-4}$ per launch

3.1.2 The maximum third-party individual risk on a per-launch basis:

$1x10^{-6}$ per launch

3.1.3 The maximum third-party individual casualty risk on a per-year basis:

$1x10^{-5}$ per year[1]

3.2 Asset safety standards

<u>Asset with catastrophic potential</u>

3.2.1 The maximum probability of *trigger debris* impact on an *asset with catastrophic potential* on a per-launch basis:

$1x10^{-6}$ per launch

3.2.2 The maximum probability of *trigger debris* impact on an *asset with catastrophic potential* on a per-year basis:

$1x10^{-5}$ per year[2]

<u>Trigger Debris</u>

3.2.3 Trigger debris is space debris of a particular shape, weight, velocity or explosive potential that is capable of triggering a catastrophic chain of events on an *asset with catastrophic potential*. Trigger debris is determined on the basis of expert engineering analysis commissioned by the launch applicant and agreed by the launch applicant and the owners of the relevant asset.

3.2.4 In the event the parties do not agree within a reasonable time, the Minister will determine such trigger debris based on expert engineering analysis (commissioned by the launch applicant) and cases put forward by the owner of the asset and launch applicant.

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[1] Note that this maximum third-party individual casualty risk per-year safety standard does not imply an absolute restriction on the number of launches per year. The number of launches able to be conducted per year on the same flight path will depend on how far the calculated maximum third-party individual risk per launch is below the $1x10^{-6}$ individual risk standard per launch (refer 3.1.2). For example, if the calculated maximum third-party individual risk per launch for a particular flight path is $2x10^{-7}$, up to fifty launches per year could be conducted on the same flight path.

[2] Note that this maximum probability of *trigger debris* impact on an *asset with catastrophic potential* on a per-year basis safety standard does not imply an absolute restriction on the number of launches per year, as described in footnote 1.

3.3 Unproven launch vehicle safety standards

3.3.1 An unproven launch vehicle may be restricted from flying in the vicinity of significantly populated areas.

3.4 Controlled area safety standards

3.4.1 A controlled area is an area for the intended impact of returned space objects or high power rockets, called a landing site, or for scheduled debris, called a drop zone. A controlled area is defined as a three standard deviation dispersion footprint around the nominal impact point for the return of a space object or high power rocket or for scheduled debris. The probability of impact within the controlled area is 0.997. The third-party casualty and asset risk safety standards also apply in controlled areas.

<u>Drop zones</u>

3.4.2 A drop zone is an area for the impact of scheduled debris from a space object or high power rocket. Scheduled debris may include jettisoned booster rockets, rocket stages, payload fairings, nose cone, or other debris which is scheduled to fall to ground as a result of a successful launch.

3.4.3 To meet the per-launch third-party individual risk standard, the launch should not proceed if a third-party individual may be within the area around the nominal impact point defined by the $1x10^{-6}$ individual risk isopleth during the time period for the drop. The launch should not proceed unless the area within the $1x10^{-6}$ individual risk isopleth is monitored and an all clear signal is given from the drop zone, unless the launch applicant can establish that pre-launch surveillance of the drop zone is not necessary because of adequate exclusion arrangements in the case of land drop zones, or because of sufficiently low likelihood of persons being in the drop zone in the case of marine drop zones.

3.4.4 The launch should not proceed unless individuals within the drop zone during the relevant period have been informed of the launch.

3.4.5 The Agency should be notified if an *asset with catastrophic potential* is within the drop zone.

3.4.6 The Agency should be notified of the location of actual drops upon completion of the launch.

<u>Landing site</u>

3.4.7 A landing site is an area for the planned return to the earth of a space object or a reusable launch vehicle, including high power rockets. To meet the per-launch third-party individual risk standard, the return should not proceed if a third-party individual may be within the area around the nominal impact point defined by the $1x10^{-6}$ individual risk isopleth during the time period for the return.

3.4.8 The return should not proceed unless third-party individuals within the landing site during relevant period have been informed of the launch and of the nominal impact point and the nominal impact time.

3.4.9 The Agency should be notified if an *asset with catastrophic potential* is within the landing site.

3.4.10 The Agency should be notified of the location of actual returns upon completion of the launch or return.

3.5 Flight safety system standards

3.5.1 A flight safety system should be installed on all vehicles to be licensed under the *Space (Launches and Returns) Act 2018* [1], unless otherwise authorised by the Agency.

3.5.2 A flight safety system is a risk mitigation method that detects an aberration in launch vehicle health or positioning and terminates flight in response. The system may be manually or autonomously activated and is a means of controlling the vehicle to minimise the risk to life and property.

3.5.3 The technology to be used in the flight safety system is not specifically stipulated. The launch or return applicant is free to choose the most appropriate flight safety system for their vehicle, however information about the system is required consistent with the *Space (Launches and Returns) (General) Rules 2019* [2] and *Space (Launches and Returns) (High Power Rocket) Rules 2019* [3].

3.5.4 The flight safety system should be operable throughout the entire powered flight phase and re-entry phase of a mission. It should be capable of terminating the flight when nominal flight conditions have been transgressed and be single fault tolerant (that is it will continue to operate even after a single fault occurs in the system). The system may be destructive resulting in the intentional break-up of a vehicle, or non-destructive such as engine thrust termination enabling vehicle landing or safe abort. The system may be manually operated or fully autonomous.

3.5.5 If the flight safety system is fully autonomous, it should incorporate at least one level of redundancy with a reliability requirement for successful operation of 0.999. If the flight safety system is to be activated manually, it should operate with a reliability of 0.998 with 95 per cent confidence. On any manually operated flight safety system, evidence is required that tracking and monitoring of the flight will take place.

3.5.6 Evidence is also needed to demonstrate that all flight-safety-critical systems are at least single fault tolerant; that is, they will incorporate one level of redundancy. This is required to prevent potential single point failures.

3.5.7 Evidence is needed to demonstrate that reusable launch vehicles incorporate a positive fail-safe re-entry system so that re-entry flight occurs under the conditions necessary to ensure that the risks to public safety do not exceed prescribed levels. The re-entry command may be autonomous with the uplinking of current meteorological data and need not include a person in the loop. The technology to be adopted is not stipulated, however information is needed to demonstrate effectiveness and reliability.

3.5.8 The activation of a flight safety system during flight will be the result of a failure mode, which will need to be assessed in the risk hazard analysis. The activation of the flight safety system will terminate thrust and possibly break up the vehicle. These actions are consequences of the failure mode and the break-up characteristics and debris impact patterns caused by activation of the flight safety system must be assessed during the risk hazard analysis.

4 Risk hazard analysis methodology

4.1 Introduction

4.1.1 This section provides a detailed description of the risk hazard analysis methodology that is required to be conducted as part of applications for certain launch and return activities in Australia.

4.1.2 Risk hazard analyses are required to identify, quantify and evaluate the risk to the public and assets with catastrophic potential from a potential launch or re-entry mishap, and to ensure that the launch safety standards specified in section 3 are not exceeded. The public includes all persons except those participating in the launch or re-entry.

4.1.3 The comprehensive identification of hazards is a major contributor to safety. The risk hazard analysis is based on the identification of potential hazards during launches or returns that may cause harm to public safety, an analysis of the risks associated with these hazards, and development of measures to minimise those risks and ensure that they remain below the established launch safety standards.[3]

4.1.4 The hazards under consideration for launch operations in Australia are the consequences of:

- debris striking persons either directly as inert debris or as explosive debris, and as overpressure effects in the event of that explosion; and
- the consequences of debris striking and triggering a catastrophic chain of events on an asset with catastrophic potential.

4.1.5 Rocket launches may also create toxic and distant focusing overpressure (DFO) hazards. These are not usually considered in the design of a mission, but are a consideration as part of the 'go – no go' decision on the day of launch. Procedures to determine if these are potential considerations for the launch are detailed in the International Association for the Advancement of Space Safety book, the *Safety Design for Space Operations*. [4]

4.1.6 The spent stages of expendable launch vehicles are to be treated as inert debris and appropriate hazard analysis is to be conducted to determine their potential effects on the public and assets with catastrophic potential.

4.2 Risk hazard analysis methodology overview

4.2.1 The risk hazard analysis methodology presented in this *Flight Safety Code* is a robust approach to quantitatively analyse risks related to launches and returns. This section and the following sections set out a step-by-step description of how to identify the risks and perform the calculations to quantitatively compute these risks.

4.2.2 The quantitative risk measure utilised in this risk hazard analysis methodology is known as the casualty expectation (E_c). The required inputs, the methods for calculating these inputs, and the method of calculating the casualty expectation for a launch or return is explained throughout the following sections and subsections.

[3] The FAA Flight Safety Analysis Handbook 2011 [5], and the associated Reusable Launch and Reentry Vehicle System Safety Process Advisory Circular 431.35-2A [23] is a useful guide identifying these hazards. Additionally, the Hazard Analysis of Commercial Space Transportation, Office of Commercial Space Transportation, Licensing and Safety Division, U.S. Department of Transport, May 1988, OCST-RD-RES01-88. Volume II [24] also identifies a number of hazards for consideration.

4.2.3 Casualty expectation is a calculation that expresses the collective risk of a casualty occurring (average number of casualties per-launch or return) to the population exposed to the debris hazard. The concept of collective risk is inherent in the calculation methodology. That is, the casualty expectation resulting from the calculations applies to the total population at risk rather than to an individual within that population. The casualty expectation equation can also be used to determine the risk to an individual exposed to the debris hazard through the use of individual risk isopleths.

4.2.4 A casualty is defined as either the serious injury or death of a person exposed to the launch or return.

4.2.5 Using casualty as the risk measure for the risk hazard analysis captures both fatality and serious injury. Casualty captures the dangerous effects of rocket launches or returns that result from direct impact of debris, overpressure from explosions, and toxic gases from burning propellants. Direct impact by non-exploding debris can cause both injuries and fatalities. There may be no fatalities from toxic gases, while there are hundreds of casualties. With overpressures, direct impingement on people close to the source can cause both injuries and fatalities, while broken glass from distant focusing of overpressure can produce many injuries, but few or no fatalities. If fatality is the only measure, consequences from toxic gas and distant breakage of glass can be overlooked and therefore not indicate the true consequence of the accident.

4.2.6 The risk hazard analysis methodology describes:

1. The broad inputs required for the E_c calculation;

2. The equation to calculate E_c and the steps required to use this equation, presented in subsequent subsections; and

3. The outputs required to demonstrate conformity with the launch safety standards described in section 3.

4.3 Casualty expectation (E_c)

4.3.1 Casualty expectation is a measure of risk. The risk calculations take into consideration the probability of the hazard due to various failure response modes, as well as the location of people with respect to the hazard and its effects.

4.3.2 The general definition of casualty expectation for a particular time interval (Δt) is:

$$E_{c,\Delta t} = (1 - P_f) \sum_i \left(P_i \sum_j \left(\sum_k P_{I,ijk} \times N_{f,j} \times A_{C,ij} \times D_{p,k} \right) \right)$$

Where:

Subscript i is the index for failure response mode;

Subscript j is the index for fragment group;

Subscript k is the index for population centre;

P_f is the probability of failure from any failure mode prior to the current time interval (note that if the vehicle failure rate is sufficiently low, the value of $1 - P_f$ is always near 1.0 and can be assumed to be 1.0 without significantly affecting the risk calculations) (**section 4.6**);

P_i is the probability of failure mode i occurring during the time interval (**section 4.6**);

$P_{I,ijk}$ is the probability of impact for failure mode i, fragment category j and population centre k (**section 4.9**);

$A_{C,ij}$ is the casualty area for failure mode i, fragment j (**section 4.10**);

$N_{f,j}$ is the number of fragments in fragment category j (**section 4.7**);

$D_{p,k}$ is the population density for population centre k (**section 4.8**);

4.3.3 The total collective E_c for the mission, or for a specified segment of flight, is computed by summing the E_c values for all applicable time intervals as follows:

$$E_c = \sum_{\Delta t} E_{c,\Delta t}$$

4.3.4 An overview of the process to calculate E_c is presented in Figure 1, Figure 2, Figure 3, and Figure 4, with explanatory descriptions presented in the following paragraphs.

4.3.5 Figure 1, Figure 2, Figure 3 and Figure 4 are enhanced functional flow block diagrams (EFFBD) with the following characteristics:

- White rectangles are activities that are required to be performed to calculate the casualty expectation and are comprised of an activity reference identification (top), activity description (middle), and the section reference in the *Flight Safety Code*;
- The grey ovals are inputs and outputs from the activity; and
- IT circle symbols are iteration loops, whereby the activities are performed repeatedly for the number of iterations required by the line connecting the IT circle symbols.

4.3.6 Figure 1 shows the process to calculate E_c broken down into three steps:

1. The applicant must prepare for the risk hazard analysis by understanding the flight vehicle characteristics and the proposed flight path to determine:
    - o Nominal flight trajectory;
    - o Flight vehicle failure response modes and debris characteristics; and
    - o Population centres at risk and associated population densities.
2. The applicant undergoes the iterative process to calculate casualty expectation by calculating:
    - o Probability of failure for the launch vehicle and failure response modes,
    - o Probability of impact for both scheduled and unscheduled debris, and
    - o Casualty area for the impact of the debris; then
    - o Then overlaying these over the described population densities.
3. The applicant produces the outputs required to demonstrate conformity with the launch safety standards, including total casualty expectation, and all required individual risk isopleths, probability of impact isopleths, and boundaries of controlled areas.

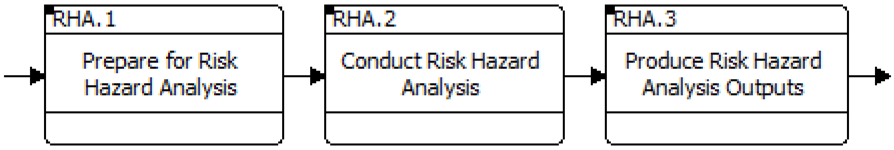

Figure 1. Risk hazard analysis calculation methodology enhanced functional flow block diagram (EFFBD)

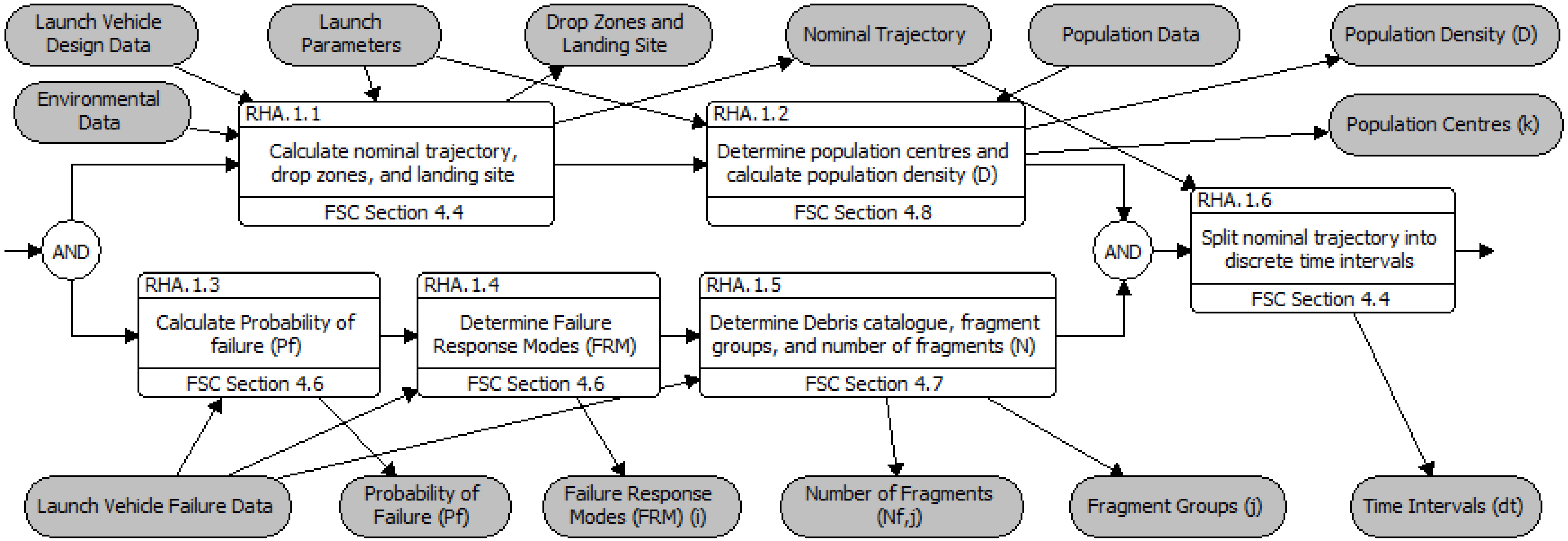

Figure 2. Prepare for risk hazard analysis EFFBD

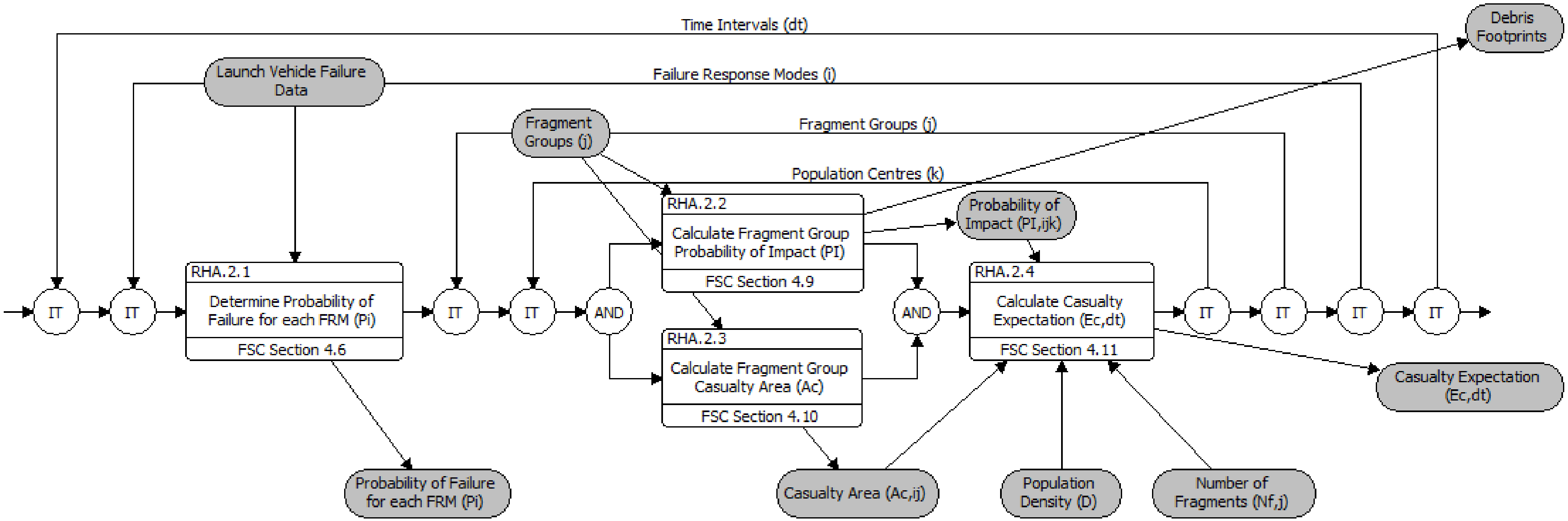

Figure 3. Conduct risk hazard analysis EFFBD

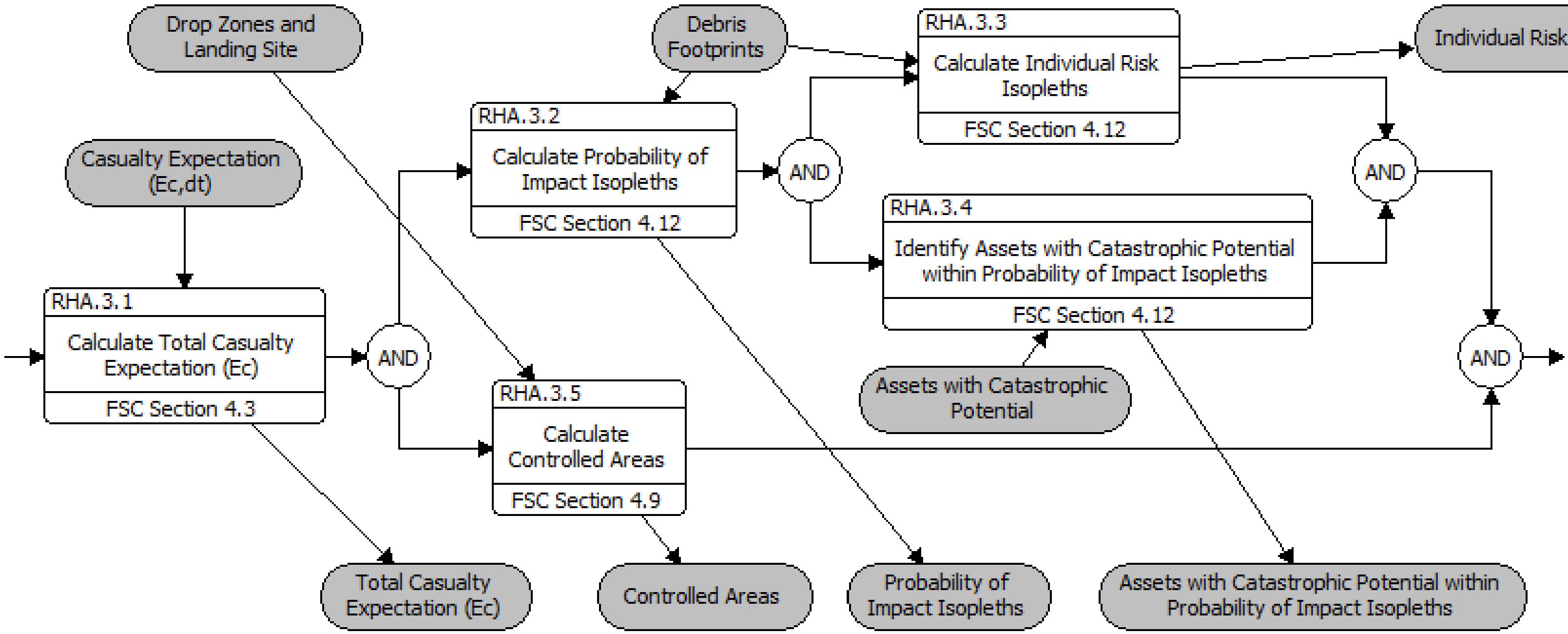

Figure 4. Produce Risk Hazard Analysis Outputs EFFBD

4.3.7 Inputs

Figure 1, Figure 2, Figure 3, and Figure 4 identify a number of broad inputs required for the casualty expectation calculation, including the following:

1. Information about launch vehicle, including:
    a. **Launch vehicle design data**: including information required by the Rules [2] [3], and all parameters required to calculate nominal trajectory (refer section 4.4);
    b. **Launch vehicle failure data:** including vehicle break-up models, vehicle failure modes and effects analysis (FMEA) and/or historical failure data (refer section 4.7).
2. Information about the mission, including:
    a. **Launch parameters** (including launch site, launcher azimuth, elevation, etc.);
    b. **Environmental data** (including wind models, pressure, temperature, etc.);
    c. **Population data** (including population centre locations, population centre areas, number of people, etc.);
    d. **Assets with catastrophic potential** (assets that have the potential to cause a catastrophic chain of events with the potential to lead to casualties).

4.3.8 Activities

To calculate casualty expectation, a series of activities need to be performed, some of which require iterative calculations. The activities are listed below with activity identifications shown in the figures as list headings. Further detail about how to conduct the activity are explained in the sections identified below.

RHA.1.1 Calculate nominal flight trajectory, nominal drop zone impact points, and nominal landing site impact point (**section 4.4**);

RHA.1.2 Determine population centres and population densities ($D_{p,k}$) (**section 4.8**);

RHA.1.3 Determine flight vehicle probability of failure (P_f) (**section 4.6**);

RHA.1.4 Determine flight vehicle failure response modes (i) (**section 4.6**);

RHA.1.5 Determine flight vehicle debris catalogue, break-up model, and fragment groups, and number of fragments in each fragment group (j and $N_{f,j}$) (**section 4.7**);

RHA.1.6 Split nominal trajectory into discrete time intervals (Δt);

For each discrete time interval (Δt);

RHA.2.1 Determine probability of failure for each failure response mode (P_i) (**section 4.6**);

Using the fragment groups generated in RHA.1.5, for each fragment group (j);

RHA.2.2 Calculate fragment group probability of impact ($P_{I,ijk}$) (**section 4.9**).

RHA.2.3 Calculate fragment group casualty area ($A_{C,ij}$) (**section 4.10**);

RHA.2.4 Calculate casualty expectation for Δt ($E_{c,\Delta t}$) (**section 4.11**);

RHA.3.1 Calculate total casualty expectation (E_c) (**section 4.3**);

RHA.3.2 Calculate probability of impact isopleths (**section 4.12**);

RHA.3.3 Calculate individual risk isopleths (**section 4.12**);

RHA.3.4 Identify assets with catastrophic potential within probability of impact isopleths (**section 4.12**); and

RHA.3.4 Calculate controlled areas (**section 4.9**).

4.3.9 <u>Outputs</u>

4.3.10 The activities conducted above are undertaken to calculate the casualty expectation. As indicated in Figure 4, the applicant is required to generate a series of outputs (described in detail in 4.3.11 and 4.13.12) to demonstrate that the launch safety standards described in section 3 are met.

4.3.11 As a guide, applicants should prepare a risk hazard analysis report and contour (isopleth) maps for the launch and return phases of each mission that present the impact probabilities and individual risk densities.

1. <u>Risk hazard analysis report</u> capturing all inputs, outputs, and assumptions used while conducting the risk hazard analysis to show consistency with the *Flight Safety Code* methodology.

2. <u>Casualty Expectation (E_c)</u> (total casualty expectation for the mission) and maximum third-party collective risk.

3. <u>Individual risk isopleths and controlled areas:</u> map showing each drop zone and landing site and the 1x10^{-6} individual risk isopleth. The individual risk isopleth is to be calculated on the basis of a person in the open.

4. <u>Probability of impact isopleths on assets with catastrophic potential and controlled areas</u>: map showing each drop zone and landing site and the 1x10^{-6} probability of impact isopleth for 'trigger debris' on a hypothetical object of the same physical dimensions as an asset with catastrophic potential. (Assets with catastrophic potential inside or in the vicinity of the 1x10^{-6} probability of impact isopleth for particular trigger debris should be identified, with separate maps for each type of trigger debris. In this context 'in the vicinity' means within 50 km.)

4.3.12 The approach described above provides a list of the inputs and activities required for the calculation of E_c. A more descriptive explanation of how to calculate E_c is provided in the following paragraphs.

4.3.13 The casualty expectation equation shown in 4.3.2 indicates how to calculate the $E_{c,\Delta t}$ for a particular instant in time. The equation is based on the probability (P_i) of a specific failure response mode i occurring during that instant in time (during that time interval (Δt)), and the probability that the fragments (called fragment category j) created from the failure (failure response mode i) impact on population k during the time interval ($P_{I,ijk}$).

4.3.14 The casualty expectation calculation also depends on:

- The number of fragments that are created in fragment category j by the failure mode i ($N_{f,j}$);
- The area where those fragments created by that failure mode i might impact and cause human casualty, known as the casualty area ($A_{c.ij}$); and
- The population density in that casualty area ($D_{p,k}$).

4.3.15 The equation also includes a finite probability $(1 - P_f)$ that a failure might occur prior to this particular time interval, although P_f is usually very small, hence $(1 - P_f)$ is generally close to 1 and this term can be assumed to be 1 without greatly affecting the calculations.

4.3.16 As can be seen from the above description of the E_c equation, a number of items need to be identified before the E_c can be calculated:

4.3.17 Probability of failure and probability of failure response mode: The probability of failure of the vehicle at each time interval (P_f) and the probability of failure response mode i (P_i) occurring during a specific time interval (Δt): This is accomplished by dividing the flight time of the vehicle into many very short successive time intervals (Δt). For each of these time intervals, all the potential failure modes of the vehicle are identified through engineering analysis and their probability of occurrence calculated. Potential failures include on-course failures (explosion or thrust termination), and failures causing deviation from course (off-course turns ranging from gradual to severe, failure to initially pitch over, gross guidance malfunction, etc.). If there is a flight safety system (person-in–the-loop or autonomous), it may activate and terminate thrust, and possibly break up the vehicle during the vehicle malfunction. This action must also be considered as a consequence of a failure mode and should be modelled to more accurately determine where debris would impact. A more detailed description about how to calculate the vehicle probability of failure (P_f) and the probability of failure mode i occuring during a specific time period (P_i) is found in section 4.6.

4.3.18 Number of fragments in a fragment group: All possible failure modes for each discrete time interval: For each of these failure modes, the behaviour of the vehicle as a result of these failures must be determined. Does the vehicle remain intact or does it break into smaller pieces? A vehicle break-up model is developed based on the structural integrity of the vehicle, the velocity of the vehicle at the time of failure and the type of failure (explosive or otherwise), the forces acting on the vehicle at the time of failure including any forces imparted by the failure mode, and any other factors to help determine how the vehicle will break up due to the failure. From the break-up model, fragment groups can be identified, including the number of fragments in each group. Each fragment can be considered a piece of debris and the sum of all fragments across all of the fragment groups comprise the debris catalogue for the particular failure mode. A more detailed description about how to develop a vehicle break-up model, fragment groups ($N_{f,j}$) and debris catalogues is found in section 4.7.

4.3.19 Probability of impact: Once the fragment groups and debris catalogues are identified, it is necessary to determine where each piece of debris will impact on earth. The area on earth where this debris will land is known as the debris footprint. The debris footprint is actually the probability of impact distributions for all categories of debris from a particular failure mode at a particular time interval. The debris footprint from the probability of impact is calculated for each failure mode for every time interval. A more detailed description about how to calculate the probability of debris impact ($P_{I,ijk}$) is found in section 4.9.

4.3.20 Casualty area: When the debris impacts the ground, there is a region around the debris impact point where a person would become a casualty if they were within that region. This is known as the casualty area. The casualty area is defined by the debris impact point as well as any adjacent area where the debris could cause a casualty through bouncing, skidding, exploding or other effects. A detailed description about how to calculate the casualty area for debris impacts from particular failure modes and fragments ($A_{c,ij}$) is found in section 4.10.

4.3.21 Population density: The final item needed to calculate E_c is the population density ($D_{p,k}$) in the casualty area. The population density can be determined by the ratio of the number of people in the area ($N_{p,k}$) to the size of the area ($A_{p,k}$). A detailed description about how to calculate the population densities in the relevant areas ($D_{p,k}$) is found in section 4.8.

4.3.22 Casualty expectation: Once all these factors have been identified for a particular failure mode i at a particular time interval (Δt), the corresponding $E_{c,\Delta t}$ can be computed for each fragment impact based on the casualty area and the population density at the point of impact. When all of the fragment impacts for all failure modes at time interval t are added together the result is the conditional $E_{c,\Delta t}$ given that a failure occurs during time interval (Δt).

4.3.23 The total collective E_c for the mission is derived by repeating the above process for all failure modes for all time intervals (Δt) for the entire flight profile. (Note that the $E_{c,\Delta t}$ for a specified segment of flight is a subset of the overall E_c. The total mission E_c is determined by summing the $E_{c,\Delta t}$ values for all time intervals).

4.3.24 Each element of the general E_c computation is described in greater detail in the subsequent sections.

4.4 Nominal flight trajectory

4.4.1 The starting point for the risk hazard analysis is a trajectory analysis. A trajectory analysis for the flight of the proposed launch vehicle must be undertaken to determine:

- The launch vehicle's nominal trajectory; and
- Each nominal landing site impact point and each nominal drop zone impact point.

4.4.2 A trajectory analysis must produce a nominal trajectory that describes the launch vehicle's intended flight path, position and velocity, where all vehicle aerodynamic parameters are as expected, all vehicle internal and external systems perform exactly as planned, and no external perturbing influences other than atmospheric drag and gravity affect the launch vehicle.

4.4.3 As an example, a common method for calculating a nominal trajectory involves developing a six-degrees-of-freedom (6-DOF) model of the proposed launch vehicle with all performance parameters set to their nominal values. A 6-DOF model has six degrees-of-freedom: three rotations (roll, pitch, yaw) and three translations (three axes of Earth-centred coordinate system). Executing a 6-DOF model through time in a trajectory simulation enables determination of the nominal landing site impact point or nominal drop zone impact point for each stage or component.

4.4.4 In general, a 6-DOF model must account for, but need not be limited to, the inputs defined in Table 1.

Table 1. Typical 6-DOF model input parameters

Category	Parameters
Launcher data, including	• Geodetic latitude and longitude • Height above sea level • All location errors • Launch azimuth and elevation
Reference ellipsoidal Earth model, including	• Name of the Earth model employed • Semi-major axis • Semi-minor axis • Eccentricity • Flattening parameter • Gravitational parameter • Rotation angular velocity • Gravitational harmonic constants; and • Mass of the Earth.
Vehicle characteristics for each stage, including	• Nozzle exit area of each stage • Distance from the rocket nose-tip to the nozzle exit for each stage • Reference drag area and reference diameter of the rocket, including any payload for each stage of flight • Thrust as a function of time • Propellant weight as a function of time • Coefficient of drag as a function of mach number • Distance from rocket nose-tip to centre of gravity as a function of time • Yaw moment of inertia as a function of time • Pitch moment of inertia as a function of time • Pitch damping coefficient as a function of mach number • Aerodynamic damping coefficient as a function of mach number • Normal force coefficient as a function of mach number • Distance from the rocket nose-tip to centre of pressure as a function of mach number • Axial force coefficient as a function of mach number • Roll rate as a function of time • Gross mass of each stage • Burnout mass of each stage • Vacuum thrust • Vacuum specific impulse • Stage dimensions • Weight of each spent stage • Payload mass properties • Nominal launch elevation and azimuth
Launch events, including	• Each stage ignition time • Each stage burn time • Each stage separation time
Atmosphere details, including	• Density as a function of altitude • Pressure as a function of altitude • Speed of sound as a function of altitude • Temperature as a function of altitude
Wind details, including	• Measurement of wind direction as a function of altitude • Wind magnitude as a function of altitude

Source: FAA Flight Safety Analysis Handbook, Version 1.0, 2011 [5]

4.4.5 A 6-DOF trajectory simulation calculates vehicle position, velocity and acceleration translation along three axes of Earth-centred coordinate system and rocket orientation in roll, pitch and yaw. A 6-DOF trajectory simulation also computes the translation and orientation of the rocket in response to forces and moments internal and external to the rocket including the effects of the input data described above.

4.4.6 It is not a requirement of the risk hazard analysis to use a 6-DOF model. The applicant is free to use any model that is capable of accurately calculating the nominal trajectory, nominal landing site impact point and nominal drop zone impact points based on the necessary input parameters, including (but not limited to) those identified in Table 1. Note that the model used to identify the nominal trajectory, whether a 6-DOF model or otherwise, will generally be the model used in the subsequent casualty expectation calculations.

4.4.7 The nominal trajectory forms the basis to calculate casualty expectation, as defined in the subsequent subsections.

4.5 Mutually exclusive events

4.5.1 Because E_c is a function of the probability of failure and other potentially variable parameters, it also must have changing and mutually exclusive values at each failure time interval, Δt. Individual E_c calculations for each time interval are mutually exclusive because they are derived from mutually exclusive failure probabilities.

4.5.2 An extension of the mutually exclusive concept dictates that it is inaccurate to add the E_c of the first stage of flight to the E_c from the second stage of flight to get a total E_c because this ignores that a vehicle that fails during first stage cannot fail during second stage. The failure during the second stage can only occur when there is no failure during the first stage of flight. This problem is accounted for by the expression $(1 - P_f)$ in the E_c general equation and is best illustrated by using an event tree.

4.5.3 Consider a hypothetical mission involving a vehicle with three primary periods of flight (stage I, stage II and return from orbit) with the probability of failure during the first stage of 0.1, the probability of failure during the second stage of 0.1, and the probability of failure during re-entry of 0.05. In addition, assume that the average consequences in terms of casualties given a stage failure are:

Stage I failure: $E_c = 0.00015$

Stage II failure: $E_c = 0.00010$

Return from orbit: $E_c = 0.00005$

4.5.4 If the failures in the previous periods of flight were to be ignored in the event tree (see Figure 5), the probability of failure during stage II is 0.10 instead of the 0.09 as shown in the figure, and the corresponding probability of failure during re-entry is 0.05 instead of the 0.045 (as shown in Figure 5). If these probabilities are used and substituted into Figure 1, the total E_c becomes 27.5×10^{-6} instead of the correct value of 26.25×10^{-6}. (Note: The digits after the decimal point are shown here to help demonstrate the computation, but this type of analysis generally does not have an accuracy to warrant more than two significant figures; i.e. in this case, 26.25×10^{-6} becomes 26×10^{-6}.) The process shown above should really be done continuously through flight (e.g. you cannot fail at 100 seconds if you have already failed at 50 seconds). By ignoring the conditionality of the probabilities, the risks are always overestimated, although the effect is less as the estimated failure rate decreases.

Period of Flight			Comb-ined prob.	Conse-quence given the event (Ec given failure in the particular Stage)	Ec given period of flight
Stage I flight	Stage II flight	Return from orbit			
Stage I fails prob = 0.1			0.100	0.00015	15.0×10^{-6}
Stage I succeeds prob = 0.9	Stage II fails prob = 0.1		0.090	0.0001	9.00×10^{-6}
	Stage II succeeds prob = 0.9	Reentry fails prob = 0.05	0.0405	0.00005	2.025×10^{-6}
		Reentry succeeds prob = 0.95	0.7695	0	0
		Total			26.0×10^{-6}

Figure 5. Sample event tree to illustrate E_c computed with consideration of failure conditional upon success in the previous stage

4.6 Probability of failure (P_f)

4.6.1 The probability of each possible outcome can be divided into the probability of success (P_s) and the probability of failure (P_f) at a discrete time interval (Δt) during a launch event (e.g. first stage boost). The sum of these probabilities must be equal to 1.0 and can be expressed as:

$$P_s + P_f = 1.0$$

Where:

P_s is the probability of success; and

P_f is the value of the probability of failure (all failure modes).

4.6.2 If P_i represents the probability of failure mode i occurring during the discrete time interval, the probability of any failure mode occurring, P_f is defined by ΣP_i.

4.6.3 The probability of failure can be determined from historical records for mature launch vehicles or from comparative analyses and engineering failure mode analyses (e.g. failure mode effects analysis (FMEA)) for new launch vehicles. Although it is recognised that actual mishaps often differ from predicted outcomes, failure analysis nevertheless serves as a valuable tool for assessing the potential risk to public safety.

4.6.4 Launch vehicles can be classified into four categories when considering failure probability: new expendable launch vehicles (ELV), new reusable launch vehicles (RLV), mature ELVs and mature RLVs. The determination of failure probability is easiest with the mature vehicles because it can be based on statistics from the actual launch history of the vehicle itself. For new vehicles, the situation is different because there is no directly relevant historical data to rely on. In this case the development of the failure probabilities relies heavily on engineering analysis of the potential failure modes and their likelihood of occurrence. To account for the uncertainty due to the lack of actual flight experience, range safety organisations and authorities assessing the impact on public safety of launches and returns generally require more conservative estimates for the failure rates of new and unproven vehicles in order ensure adequate protection of people and property on and near launch sites and downrange flight paths of new vehicles.

4.6.5 The best basis for an estimate of the performance of a new vehicle is how other vehicles of its class have performed in the past, and this is the basis of the approach used here. It is also reasonable to separate ELVs and RLVs because the RLV will have redundancies and robustness in some systems that should either reduce the failure rate or provide less risky abort modes where recovery is a goal and because of the generally greater investment in quality control.

4.6.6 Use of the total failure probability of a vehicle alone is not sufficient for a risk analysis. While an estimate of mission failure probability is adequate from a mission performance standpoint, this is not adequate for the development of the public safety case. To accurately assess the impact on public safety throughout all phases of the flight, the failure probability for a risk analysis must be broken down into separate vehicle failure response modes for a sequence of time intervals. It is appropriate to use a mechanism such as an event tree to show all of the different responses and then allocate probabilities for each of the responses. There are two options for obtaining the conditional probabilities for the different responses:

- Generic probabilities based on the general experience of all vehicles over the last 10 to 20 years; or
- Probabilities based upon the manufacturer's own failure mode and effect analyses and reliability analyses.

4.6.7 Failure probability for a specified flight time interval divided by the length of the interval yields a failure rate, if the failure rate over that time period is assumed constant. Failure rate is frequently higher earlier in the flight, therefore the failure rate can decrease over the powered flight period. In that case, the integral of the failure rate over time is equal to the failure probability. If there is no direct evidence of this decrease, then a constant rate can be assumed. Note that the failure rate is determined over periods of powered flight only and not over coast periods. Therefore, if a launch operates for 500 seconds with 200 seconds of coast, the powered flight phase for failure rate considerations is 300 seconds. There can be event-related failures (staging, failure of an engine to start, etc.), and these should be given consideration not as rates but as discrete probabilities at those particular times. During an exoatmospheric coast phase the instantaneous impact point (IIP) on the ground does not move, therefore any failure during that time can be treated like an event-related failure, i.e. discrete.

4.6.8 The following models are to be used for all classes of vehicles. The following equation is to be used for calculating the failure probability[4] for ELVs, RLVs and returns.

$$P_f = \frac{ax + r}{x + n}$$

Where:

n is the number of launches of a vehicle;

r is the number of failures;

a is a failure probability assigned to a first launch[5]; and

x is an arbitrary factor that weighs the importance of general vehicle flight experience (past history of ELVs) against the actual flight experience of this particular vehicle (r failures in n launches).

4.6.9 An analysis of the actual failure rates for the first five launches of brand new launch vehicles since 1990 reveals that about 25 per cent of the new vehicles failed [6], therefore we will assign $a = 0.25$.[6] The parameter x is an arbitrary factor that weighs the importance of general vehicle flight experience (past history of ELVs) against the actual flight experience of this particular vehicle (r failures in n launches). The value x can have ranges from zero to infinity. If $x = 0$, no credit is given to past generic flight experience and if $x = \infty$, no credit is given to actual flight experience of the vehicle. We will propose $x = 4$ because it starts with the generic launch experience but allows the computed P_f to adapt fairly rapidly to actual flight experience. Therefore, for ELVs:

$$P_f = \frac{0.25 \times 4 + r}{4 + n} = \frac{1 + r}{4 + n}$$

[4] A failure for purposes of public safety must fall into the category of having a consequence that could lead to harm to people or property. Therefore, achieving a wrong orbit does not apply.

[5] The process is a Bayesian statistical process using a beta distribution and a 'normalization' factor, A. The equation could be written as $Pf = (r_0 A + r)/(n_0 A + n)$ where r_0 and n_0 are the 'prior' number of failures and launches respectively. The term 'prior' is a Bayesian term representing augmented data.

[6] The use of 0.25 is conservative, because a number of the new vehicle failures since 1990 have been mission failures where the vehicle reached orbit, but not the correct orbit. These mission failures do not affect public safety because they produced no debris impacts on earth. Data sourced from 'Maiden and Early Flight Failure Rates', Seradata Spacetrak Briefing, Seradata, August 2019 [6].

4.6.10 For RLVs, consideration may be given to the higher levels of redundancy and other features that establish high reliability and reusability, where the applicant can demonstrate that a new RLV will have reliability greater than a new ELV. For many years, the only RLV with extensive flights was the man-rated Space Shuttle that, during its operational life, had a failure probability based on number of failures, divided by number of launches of 1/135 for launch and 1/134 for returns. The Soviet Buran was successful during its one flight and the X-37 has been successful in its five flights to August 2019. In recent years, additional RLV activities have commenced with the flights of Spaceships 1&2, the New Shepard vehicle, and the landing of the first stages of the Falcon 9 vehicle. An analysis[7] of the flight history of all these RLV activities reveals an actual launch failure rate of 1.2 per cent and a return failure rate of 5.94 per cent. However, the bulk of the return failures were attempts by SpaceX to land its Falcon 9 first stages, which were done in controlled areas with no danger to public safety. If these return attempts are removed from consideration due to the fact that they did not endanger public health, the RLV launch failure rate remains 1.2 per cent, but the return failure rate drops to 0.61 per cent and these numbers are dominated by the Space Shuttle reliability figures.

4.6.11 It is assumed that, at the time of a first launch, no RLV can be proven to have the Space Shuttle reliability. However, to account for the expected higher reliability of RLVs, the method below describes how to calculate the failure probability of a new RLV between that of a new ELV and the Space Shuttle. Assume a lognormal probability distribution characterising the uncertainty in the estimate of the failure probability of the new RLV. Let the 5-percentile of the cumulative probability distribution be set at the 0.01 probability level (corresponding to a rough average of the launch and return probabilities for the Space Shuttle dominated launch and return failure rates above) and the 95-percentile set at the 0.25 probability (that of a new ELV).

4.6.12 The prior mean estimate of the new RLV failure probability is then calculated as follows:

Given that the 5-percentile ($\eta_{0.05}$) and 95-percentile ($\eta_{0.95}$) are 0.25 and 0.01, respectively, then:

lognormal median, $M = \sqrt{\eta_{0.05} \times \eta_{0.95}} = \sqrt{0.25 \times 0.01} = 0.05$

error factor, $K = \sqrt{\frac{\eta_{0.05}}{\eta_{0.95}}} = \sqrt{\frac{0.25}{0.01}} = 5$

standard deviation, $\sigma = \frac{\ln K}{1.65} = 0.9754$

mean, $m = Me^{\sigma^2/2} = 0.08$

4.6.13 Note that the mean is equal to the proposed value of 'a' for RLVs. The P_f equation to be used to calculate the failure probability for new RLVs becomes (using $x = 4$)[8,9]

$$P_f = \frac{0.08 * 4 + r}{4 + n} = \frac{0.32 + r}{4 + n}$$

[7] Analysis was conducted by Asia Pacific Aerospace Consultants Pty Ltd (APAC) to update the failure rate of reusable launch vehicles for this version of the Flight Safety Code. The analysis was based on the flight histories of the Space Shuttle, the Soviet Buran, the X-37, Spaceships 1 & 2, the Blue Origin New Shepard and the SpaceX Falcon 9.

[8] If one were to continue to adhere strictly to the Bayesian methodology, the update to a posterior estimate of P_f would be done with a lognormal instead of a beta distribution. However, the beta form is easier and within the accuracy requirements of the problem.

[9] For the experimental confidence for a proportion, r/n, see [25].

4.6.14 Note that, whereas the P_f equation given for new ELVs should be considered normative for P_f computation, the above equation for RLVs must be considered indicative and cannot be adopted until the applicant provides sufficient evidence that the proposed new RLV will indeed have reliability greater than that for a new ELV. Table 2, Table 3, and Table 4 show some scenarios that reflect how P_f could change with flight experience.

Table 2. P_f Computations for Several ELV Launch Sequences ($a = 0.25, x = 4$)

Condition	P_f before 1st Launch	P_f after last Launch
ELV succeeds on 1st launch	0.25	0.20
ELV fails on 1st launch	0.25	0.40
ELV succeeds on 1st 5 launches	0.25	0.111
ELV has one failure in 5 launches	0.25	0.222
ELV succeeds on 1st 10 launches	0.25	0.071
ELV has one failure in 10 launches	0.25	0.143

Table 3. P_f Computations for Several RLV Launch Sequences ($a = 0.08, x = 4$)

Condition	P_f before 1st Launch	P_f after last Launch
RLV succeeds on 1st launch	0.08	0.064
RLV fails on 1st launch	0.08	0.264
RLV succeeds on 1st 5 launches	0.08	0.036
RLV has one failure in 5 launches	0.08	0.147
RLV succeeds on 1st 10 launches	0.08	0.023
RLV has one failure in 10 launches	0.08	0.094

Table 4. Failure Probabilities for Vehicles

n	$r = 0$		$r = 1$		$r = 2$		$r = 3$		$r = 4$		$r = 5$	
	r/n	P_f	r/n	P_f	r/n	P_f	r/n	P_f	r/n	P_f	r/n	P_f
0	-	0.250										
1	0	0.200	1.000	0.400								
2	0	0.167	0.500	0.333	1.000	0.500						
3	0	0.143	0.333	0.286	0.667	0.429	1.000	0.571				
4	0	0.125	0.250	0.250	0.500	0.375	0.750	0.500	1.000	0.625		
5	0	0.111	0.200	0.222	0.400	0.333	0.600	0.444	0.800	0.556	1.000	0.667
6	0	0.100	0.167	0.200	0.333	0.300	0.500	0.400	0.667	0.500	0.833	0.600
7	0	0.091	0.143	0.182	0.286	0.273	0.429	0.364	0.571	0.455	0.714	0.545
8	0	0.083	0.125	0.167	0.250	0.250	0.375	0.333	0.500	0.417	0.625	0.500
9	0	0.077	0.111	0.154	0.222	0.231	0.333	0.308	0.444	0.385	0.556	0.462
10	0	0.071	0.100	0.143	0.200	0.214	0.300	0.286	0.400	0.357	0.500	0.429
12	0	0.063	0.083	0.125	0.167	0.188	0.250	0.250	0.333	0.313	0.417	0.375
15	0	0.053	0.067	0.105	0.133	0.158	0.200	0.211	0.267	0.263	0.333	0.316
20	0	0.042	0.050	0.083	0.100	0.125	0.150	0.167	0.200	0.208	0.250	0.250
25	0	0.034	0.040	0.069	0.080	0.103	0.120	0.138	0.160	0.172	0.200	0.207
30	0	0.029	0.033	0.059	0.067	0.088	0.100	0.118	0.133	0.147	0.167	0.176
35	0	0.026	0.029	0.051	0.057	0.077	0.086	0.103	0.114	0.128	0.143	0.154
40	0	0.023	0.025	0.045	0.050	0.068	0.075	0.091	0.100	0.114	0.125	0.136
45	0	0.020	0.022	0.041	0.044	0.061	0.067	0.082	0.089	0.102	0.111	0.122
50	0	0.019	0.020	0.037	0.040	0.056	0.060	0.074	0.080	0.093	0.100	0.111
75	0	0.013	0.013	0.025	0.027	0.038	0.040	0.051	0.053	0.063	0.067	0.076
100	0	0.010	0.010	0.019	0.020	0.029	0.030	0.038	0.040	0.048	0.050	0.058

Vehicles with Combinations of New and Old Subsystems

4.6.15 Vehicles change – they may switch, or add stages, or change guidance systems. This complicates the definition of flight experience per the definitions presented above. The most conservative approach is to consider that a vehicle subsystem change requires the vehicle to again be treated as a new vehicle with no flight experience. This can be used as the starting point.

4.6.16 If the applicant does change a stage, for example, but wants to claim successful flight experience for the rest of the vehicle, a subsystem failure probability model based on the vehicle prior to modification that allocates failure probabilities to subsystems and sums to the P_f as formulated as above must first be developed. This total P_f will now be different from the new vehicle P_f because the vehicle now has flight experience. The contribution of the various subsystems to the total P_f will be based on the previous flight experience and manufacturer FMEAs, etc. (see the example in 4.6.21).

4.6.17 Once the probability of failure contributions to the total P_f for the experienced vehicle have been determined for the various subsystems, these relative contributions to the total P_f are maintained in the next step.

4.6.18 The vehicle is now assumed to have a total P_f of a new vehicle (for example P_f = 0.25 for a new ELV). The probability of failure contributions of the various subsystems determined in the previous step are scaled so the sum of their probabilities of failure equals the new vehicle P_f (note that the relative contribution of each subsystem to the new total P_f remain the same as their relative contribution to the experienced vehicle P_f). The result is an allocation of the relative contributions to P_f of the various subsystems if the entire vehicle were considered a new vehicle. From this, the applicant can determine the allocation to the total probability of failure that would be given to the element that is new (the new stage or propulsion system, for example). The probability of failure of the new element resulting from this allocation is then substituted into the contributions to total P_f to produce a revised system failure probability for the modified vehicle (see the example in 4.6.21).

4.6.19 In the process of performing a risk analysis, the new element must reflect the higher failure probability rate.

4.6.20 This method can also be applied to RLVs that have the opportunity to test part of the system repeatedly before the first launch of the integrated system. Those parts of the system that have been proven can be assigned a lower failure probability, while those untested elements must conform to the general rules described above.

4.6.21 A simple example of this method is illustrated in Table 5. Assume a two-stage vehicle that has been launched many times and has an established failure probability equal to 0.04. Assume also, based on experience and manufacturer FMEAs etc., that the failure probability is allocated as follows:

1. Stage I propulsion P_f is 35% of the system P_f;
2. Stage II propulsion P_f is 35% of the system P_f; and
3. Guidance and control P_f is 30% of the system P_f.

Consider the case where the applicant chooses to change the Stage II propulsion. Table 5 provides a method for the calculation of the revised total P_f for the system.

Table 5. Revised Vehicle System Failure Probabilities

	Total Failure Probability, P_f		
	P_f, Orig. System = 0.04	P_f, All New System = 0.25	P_f, Modified System
Stage I Engine – 35%	**0.014**	0.0875	0.014
Stage II Engine – 35%	0.014	**0.0875**	0.0875
Guidance and Control – 30%	**0.012**	0.075	0.012
Revised Total Probability, P_f			**0.1135**

4.6.22 Another case is when a mature vehicle has an added new stage. Here, the first step assumes that the vehicle is entirely new and the probabilities are allocated accordingly. The second step goes back to the original vehicle and computes the allocation and resulting failure probabilities based on actual experience. In the final step, the numbers for the mature stages/systems are substituted into the model based on the new system. This produces a P_f model that has a lower failure probability than an all new vehicle, but has a higher failure probability than the original mature vehicle and allocates the higher failure rate to the new stage.

Allocation of response modes and determination of failure rate:

A risk analysis uses the failure rate of the vehicle, which normally varies with the stage of flight. If data about the vehicle that indicate otherwise are not available, the failure probability can be allocated evenly between each stage of flight unless the vehicle is part mature and part new as discussed above. The failure rate is generally higher at the beginning of stage operation because of the possibility of failure to start. Again if data are not available, a small percentage of the failure probability of the stage (e. g. 5 per cent) can be assigned to the start-up failure probability. The remaining failure probability of the stage can be distributed uniformly over the time of powered flight of the stage, unless there are data that indicate that the failure rate will not be constant.

4.6.23 The vehicle response due to the malfunction is important. If the failure initiates a turn that can move the vehicle off the nominal flight path, it will produce dispersions in the impact points of the intact vehicle or the vehicle debris into areas away from the nominal trajectory. These types of failures need to be accounted for separately from those failures that produce engine shutdown or other failures that do not cause deviations of the vehicle from the nominal flight path prior to vehicle break-up or initiation of free fall.

4.6.24 Example: Using the example from 4.6.21, assume the powered flight time of Stage I is 100 seconds and that of Stage II is 200 seconds. Table 6 gives the failure rate of the modified system in Table 5.[10]

Table 6. Vehicle Failure Rates

	Failure probability and failure rate
Failure probability for Stage I engine start-up	= 0.020 x 0.014 = 0.00028
Engine failure rate during Stage I operation	= 0.980 x 0.014/100 = 0.000137 failures/sec
Guidance and control failure rate during Stage I and Stage II operation	= 0.012/300 = 0.00004 failures/sec
Failure probability for Stage II engine start-up	= 0.020 x 0.0875 = 0.00175
Failure rate during Stage II operation	= 0.980 x 0.0875/200 = 0.000429 failures/sec

4.6.25 Table 6 defines the assignment of failure probabilities and failure rates between stages, but does not allocate between vehicle responses that stay within the trajectory plane versus those that deviate to the right or left. Assume that when the guidance and control fails it produces motion out of the plane of the trajectory 66 per cent of the time.

[10] This example does not take into consideration the discussion in section 4.5 where a failure in Stage II cannot occur if Stage I has already failed. Ignoring this produces a small conservatism in the results, but makes the mathematics easier.

4.6.26 The failure probabilities and failure rates are now allocated as shown in Table 7. This example demonstrates the computation and allocation of failure probabilities and failure rates for two different response modes. The particular allocations chosen are for demonstration only. These numbers should not be used in as the basis of computation by an applicant. The computation by the applicant should either be based upon vehicle history, FMEA or general launch vehicle experience.

Table 7. Vehicle Failure Rates and Probabilities Allocated Between Failure Response Modes

	Failure probability and failure rate	
	On-trajectory response mode (in-plane)	**Off-trajectory response mode (out of plane)**
Failure probability for Stage I engine start-up	0.00028 (from previous table)	0.0
Failure rate during Stage I operation	Engine + 0.33 of G&C failure rate $= 0.000137 + 0.330 \times 0.00004$ $= 0.00015$	0.666 of G&C failure rate $= 0.6660 \times 0.00004$ $= 0.0000266$
Failure probability for Stage II engine start-up	0.00175 (from previous table)	0.0
Failure rate during Stage II operation	Engine + 0.33 of G&C failure rate $= 0.000429 + 0.330 \times 0.00004$ $= 0.000442$	0.666 of G&C failure rate = 0.6660 x 0.00004 = 0.0000266

Generic allocation of failure mode probabilities:

4.6.27 Table 8 lists the historical failure rate for a number of vehicle failure modes based on all failures of launch vehicles over ten years (2009 to 2019).[11] The last failure mode listed in Table 8 describes a failure where the payload achieved orbit, but was not placed in the correct orbit. This is considered a launch vehicle failure; however, while it is a mission failure, this particular failure mode does not affect public safety and therefore it is not a failure mode that needs to be considered or included in calculating the probabilities of vehicle failure modes.

4.6.28 The numbers in Table 8 are intended to provide guidance as to what may be expected in terms of launch failure mode probabilities, but should not be used in a risk analysis for a vehicle unless there are no vehicle specific sources. If the historic failure mode data from the table are used, these historical failure percentages should be varied parametrically to determine whether the final results of the risk analysis are materially affected by the particular allocation of probabilities.

[11] The failure percentages in Table 8 were developed by Seradata using Spacetrak, their comprehensive database of launch failures from the actual launch history of all launch vehicles. [7]

Table 8. Probabilities of Various Vehicle Failure Modes Based on International Launch Vehicle Data (2009-2019)

Failure Mode	Vehicle Response	Percentage of failures
Engine failure to start	Vehicle has no thrust, forward acceleration ends	5.08%
Failure of engine to reignite	Vehicle has no thrust, forward acceleration ends	1.69%
Control system – loss of thrust vector control	Vehicle tumbles or turns away from the velocity vector at the time of the failure	3.39%
Guidance and control – loss of vehicle attitude reference	Either the vehicle moves in a different plane than the intended trajectory plane or takes on a new heading and moves stably in that direction	6.78%
Engine shutdown, loss of thrust	Vehicle stops accelerating, stays intact unless it is destroyed by flight safety system or breaks up aerodynamically	16.95%
Explosion somewhere in the liquid propulsion system	Vehicle loses thrust and breaks up with some high velocity fragments	13.56%
Solid rocket motor explosion	Vehicle loses thrust and can produce high velocity fragments	1.69%
Pitch attitude error, failure	Pitch attitude wrong, but vehicle remains in the original trajectory plane	5.08%
Stage, booster or payload separation failure	Hang-up of separation or preliminary separation can lead to various abort behaviours (aerodynamic break-up, explosions, etc.)	8.47%
Software error	Can lead to wrong orbital condition or affect the control system response	1.69%
Failure leading to improper orbital insertion	Not considered a failure mode that affects public safety	35.59%

Source: Seradata SpaceTrak Database [7]

4.6.29 If there is a flight safety system (person-in–the-loop or autonomous) it may activate and terminate thrust and possibly break up the vehicle during the vehicle malfunction. This action must also be considered as a consequence of a failure mode and should also be modelled to more accurately determine where debris would impact.

4.6.30 Any flight that is launched internally in the country or over another country has the potential for causing debris to fall on people. For launches of new vehicles, the following criteria must be met:

4.6.30.1 The pre-flight risk prediction for E_c that includes the analysis of failure mode probabilities across subsystems and flight phases must fall within the required launch safety standards.

4.6.30.2 An unproven vehicle may be restricted from flying in the vicinity of significantly populated areas. A significantly populated area includes a township or settlement, but not a homestead.

Unproven vehicles are those that have not achieved five consecutive missions without a catastrophic failure (a failure that could pose hazards to public safety or property).

4.6.31 A $P_f = 1.0$ can be adopted when calculating E_c for spent ELV stages being returned to Earth as the failure mode can be described as propulsion system shutdown.

4.7 Establishing a debris catalogue (j and $N_{f,j}$)

4.7.1 To compute the E_c it is necessary to develop a debris catalogue that identifies and characterises all debris that results from the destruction or break-up of a launch vehicle or a return vehicle. Generally there are two sources for obtaining a debris catalogue: 1) Obtain the debris catalogue developed by the manufacturer of the launch vehicle or return vehicle; 2) Develop the debris catalogue in conjunction with the manufacturer based on the various parts and components of the vehicle.

4.7.1.1 The vehicle break-up data must include all elements needed to characterise the fragments created by vehicle break-up, including number and size of fragments and their individual velocities and directions.

4.7.1.2 The data must include the various parameters required for risk analysis such as:

- Fragment ballistic coefficient;
- Aerodynamic characteristics;
- Weight;
- Projected area; and
- Imparted velocity at break-up.

4.7.1.3 Usually the data pertains to the debris that would result if flight termination action (destruct or thrust termination) were taken on the vehicle, but the debris generated by all other vehicle failure modes (including propulsion system explosion, pressure vessel rupture or aerodynamic break-up) also needs to be developed. The data may be refined by using specially developed break-up models. This is particularly true for the debris resulting from the pressure rupture or destruct of a solid rocket motor, where models have been developed to predict the sizes and weights of the resulting pieces of solid propellant and motor casing. Data for other modes of vehicle break-up, such as break-up due to an explosion of the vehicle, or due to aerodynamic and inertial loads acting on the vehicle, are usually estimated based on the flight termination break-up data.

4.7.1.4 Vehicle manufacturers often calculate vehicle break-up data and the resultant debris catalogue, particularly with respect to the activation of a flight safety system or a flight termination system. In some cases the vehicle manufacturer may have data for other break-up modes based on additional failure modes. The vehicle manufacturer is the first source for obtaining a suitable break-up model for the risk analysis calculations.

4.7.1.5 If there is no vehicle break-up data available from the vehicle manufacturer, or if the data is insufficient to properly conduct the risk analysis, a debris catalogue will need to be developed via in-depth engineering analysis of the vehicle and its fragmentation based on the various failure modes.

4.7.1.6 The starting point for this analysis is to obtain a detailed listing of the various parts and components that make up the vehicle from the vehicle manufacturer. This list is then used, with the aid of the manufacturer's structural engineers, to estimate the various pieces of debris that will result as the result of various failure modes. The parameters defining the debris fragments (ballistic coefficient, weight, projected area, etc.) are then computed based on the characteristics of the fragments. Velocities imparted due to an in-flight explosion are estimated using various software models. These models also attempt to predict the sizes and weights of the fragments resulting from an explosion, but usually the results need to be reviewed and refined to obtain a reasonable debris list. Consideration of the aerodynamic heating effects potentially leading to further fragment break-up or burn-up can also be considered for fragments with high velocities.

4.7.2 For the purpose of performing risk analyses, the debris fragments are grouped into 'fragment groups' consisting of fragments having similar characteristics. Average characteristics are then computed and applied to all fragments in the group.

4.7.3 An accurate debris catalogue is an essential and critical input into the risk hazard analysis calculations.

4.8 Population density ($D_{p,k}$)

4.8.1 Population data must be gathered for all locations that can potentially be at risk due to a launch or return. This includes populations both within and beyond the areas defined by the $1x10^{-6}$ individual risk isopleths. To enable the calculation of the individual risk isopleths (refer section 4.12), the applicant must gather the population data for as wide an area as possible to use within the risk hazard analysis. This should include the population data for the area around the launch site as well as a wide swath or area on either side of the nominal flight path. The best source of population data in Australia is the Australian Bureau of Statistics (ABS). Note that if the launch or return overflies other countries, the population data from those countries must also be obtained and included in the calculations.

4.8.2 There are typically two ways in which population data is presented: distinct population centres and population density. The use of population centre data has an advantage in these calculations in that it allows for consideration of sheltering. Sheltering can be treated by percentages of the population in each sheltering category (in the open, in light shelters, etc.).

4.8.3 More detailed population data is required nearer the launch or return site and in the uprange and downrange areas close to the launch or return site, often requiring data for individual buildings. As the distance from the launch or return site increases, the data can be defined in terms of towns, cities and large open areas. To account for the rural populations, the flight corridor is usually divided into large rectangular areas to pick up the spread-out rural population. The populations in the cities and towns are not included in the populations of those rectangular areas.

4.8.4 The alternate presentation of population data is population density. It is available in regions defined by ranges of degrees or minutes of latitude and longitude, and/or postcode regions. The advantage of using population density is that the entire population is accounted for. The disadvantage is that municipalities and other more densely populated areas are not efficiently defined and it is difficult to deal with sheltering.

4.8.5 The applicant should develop population centre data down to the smallest available size and then define open area population using the population density data with the population of the accounted for municipalities removed.

4.8.6 The population density of a distinct population centre or open population area k is calculated as follows:

$$D_{p,k} = \frac{N_{p,k}}{A_{p,k}}$$

Where:

$N_{p,k}$ is the number of people in population centre or open area population k; and

$A_{p,k}$ is the area of population centre or open area population k.

4.8.7 The population density must be calculated for all population centres and open area populations used in the risk hazard analysis.

4.9 Probability of impact ($P_{I,ijk}$)

Calculating three-sigma controlled areas from scheduled debris (spent stages, fairings, etc)

4.9.1 During most launches, certain elements of the rocket are jettisoned as the launch progresses. As each stage burns out, it is separated and follows a ballistic path to impact. In addition, certain other panels, fairings, etc. may be jettisoned. This scheduled debris happens with every successful launch and thus the mission must be planned carefully so that these items of debris do not create an unacceptable risk.

4.9.2 The procedure to compute the scheduled debris risk is as follows:

4.9.2.1 Define the state vector (position and velocity) of the scheduled debris at the time of jettison.

4.9.2.2 Determine the aerodynamic characteristics of the spent scheduled debris (drag coefficient, aerodynamic reference area, weight) and compute a drag corrected impact point. Tumbling can affect the aerodynamic characteristics of the object; therefore, consideration must be given as to whether the scheduled debris tumbles or stabilises at a particular attitude during descent.

4.9.2.3 Develop impact uncertainties of the scheduled debris based on the uncertainties in the vehicle state vector at the time of jettison (is the vehicle flying fast, slow, high, low, right or left?). Also consider any perturbation velocities that may be applied during jettison (e.g. any energy imparted due to explosive bolts used to separate a stage or fairing), the effect of winds and wind uncertainties and aerodynamic lift effects. This process should produce a standard deviation of impact uncertainty around a nominal impact point in the uprange and downrange direction, and another standard deviation of impact uncertainty around the nominal impact point in the crossrange direction. A more sophisticated analysis may produce an impact covariance matrix, representing the impact dispersions that may indicate some rotation of the dispersions relative to the downrange and crossrange directions, but this is normally of secondary significance.

4.9.2.4 Using the standard deviations computed above, assume a bivariate normal distribution with its mean at the nominal impact point, and with its two axes aligned respectively with the downrange direction and the (orthogonal) crossrange direction. Note that if the dispersion along the uprange-downrange direction is large, the uprange dispersion component will be smaller than the downrange component. If this is the case, the analyst has the option of adjusting the nominal impact point to make the distribution symmetrical in the uprange-downrange direction, or to use a different standard deviation for the uprange direction than that for the downrange direction.

4.9.3 The drop zone or footprint is to be calculated using the process above and by adopting three standard deviations (three-sigma) to around the nominal impact point of the returning vehicle. The three-sigma footprint describes the area where the vehicle will land with a 0.997 probability assuming that no major system failure has occurred.

Calculating probability of impact risk from scheduled debris (spent stages, fairings, etc)

4.9.3.1 Continuing from the process described above, if there is an island, offshore oil platform, or any other population centre that is potentially at risk due to scheduled debris, the impact probability can be computed by integrating under the bivariate normal distribution.

4.9.3.2 Figure 6 and the equation presented in Section 4.9.4 show the bivariate normal distribution; the area of the island, facility or population centre potentially at risk (A); and the equation for computing the probability of impact.

4.9.3.3 Referencing Figure 6, the probability of lying in a rectangle bounded by $x_2 < x < x_1$ and $y_2 < y < y_1$ is the volume bounded by the rectangle on the bottom and the surface on the top.

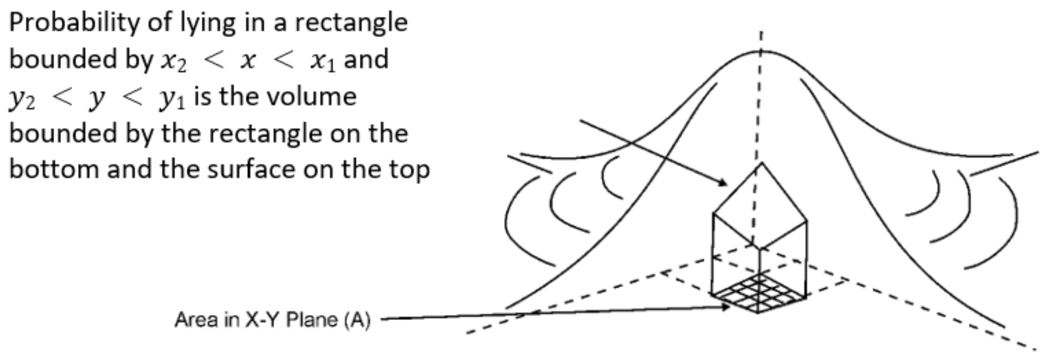

Figure 6. Bivariate normal distribution showing impact uncertainty and the area at risk [5]

4.9.4 The equation below is the calculation of the impact probability of a single object in an area, A, where the impact distribution is a bivariate normal distribution with the major and minor axes aligned along the x and y directions, respectively. The centre of the area, A, is at (x_A, y_A). Assume that x is in the downrange direction, and y is crossrange, positive to the left looking downrange. The mean for this distribution is assumed to be at the nominal impact location for the stage (or fairing or fragment), therefore the mean impact point for the distribution is $\mu_x = \mu_y = 0$ where μ is the mean impact point. For small values of the probability of impact P_I and few impacting scheduled debris, the individual P_I can be multiplied by the number of scheduled debris to get the total P_I.

$$P_I = \frac{1}{\sigma_x\sqrt{2\pi}} \int_{x_A-\sqrt{A}/2}^{x_A+\sqrt{A}/2} e^{\frac{x^2}{2\sigma_x^2}}\, dx \times \int_{y_A-\sqrt{A}/2}^{y_A+\sqrt{A}/2} e^{\frac{y^2}{2\sigma_y^2}}\, dy$$

4.9.5 When $\sqrt{A}$ is << than σ_x and σ_y, the equation above can be simplified to be:

$$P_I = \frac{A}{2\pi\sigma_x\sigma_y} \times e^{-\frac{1}{2}\times\left(\left(\frac{x}{\sigma_x}\right)^2+\left(\frac{y}{\sigma_y}\right)^2\right)}$$

4.9.6 The above process should be repeated for every jettison of scheduled debris (stages, fairings, etc.). Unless they are dropped together and have similar ballistic characteristics, the risks from each piece should be treated separately. When using this method, it is important to realise that different elements of scheduled debris (stages, fairings, etc.) cannot be grouped in the same bivariate distribution unless they have the same mean impact point and downrange and crossrange uncertainties. If they do not, a new distribution must be computed for each. However, two or more identical objects jettisoned at the same time with the same mean impact point can be treated together. The impact probability (for relatively small P_I) is simply the product of the number of objects times the P_I for one.

Calculating probability of impact risk by the corridor method

4.9.7 A relatively simple risk analysis procedure called the corridor method (derived from the concept of a flight corridor) can be used if the risks to be computed are downrange of the general launch area, do not involve return from orbit and do not involve actions due to range safety criteria that will distort the impact distributions. The elements of the corridor methodology are pictured in Figure 7.

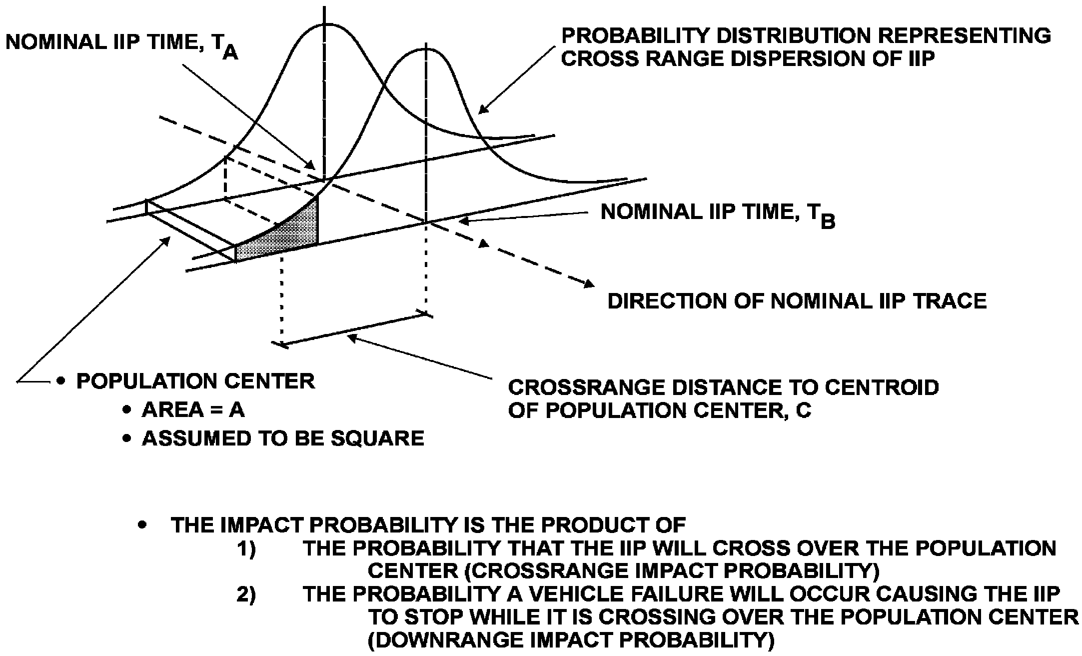

Figure 7. Diagram of the elements of the downrange corridor methodology [5]

4.9.8 The equations associated with the corridor methodology are as follows:

Impact probability on a population centre: $P_I = P_{I\,downrange} \times P_{I\,crossrange}$

Where:

$$P_{I\,downrange} = r_{failure} \times \frac{\sqrt{A_{pop}}}{r_{IIP}}$$

Where:

$r_{failure}$ is the failure rate;

r_{IIP} is the Instantaneous Impact Point (IIP) rate; and

A_{pop} is Population centre area.

The crossrange P_I is:

$$P_{I\,crossrange} = \int_{y_c - \frac{1}{2}\sqrt{A_{pop}}}^{y_c + \frac{1}{2}\sqrt{A_{pop}}} p(y)dy$$

Where:

$p(y)$ is the probability density function for crossrange dispersion for the particular fragment category.

4.9.9 The instantaneous impact point (IIP) is the point where a rocket in flight would impact the Earth if propulsion ceased immediately. The IIP changes continually during powered flight. In the case of the risk analyses described in this document, the IIP describes the point where the debris will impact the earth due to the break-up of a vehicle in flight, noting that the case of loss of thrust where the rocket does not break up is included in the debris footprint.

4.9.10 The corridor method effectively calculates the probability of impact on a population centre as the product of two factors:

- Downrange impact probability; and
- Crossrange impact probability.

4.9.11 The downrange impact probability is the probability that a vehicle failure will cause the IIP to stop while it is crossing over the population centre as defined by the first equation in 4.9.8. The crossrange impact probability is the probability that the IIP will cross over the population centre as defined in the second equation in 4.9.8. Figure 7 shows that the crossrange impact probability is a normal distribution with its peak centred along the track of the flight path or flight corridor.

4.9.12 The *FAA Flight Safety Analysis Handbook*, Version 1.0 [5], provides appropriate equations for calculating the probability of debris impact on populated areas and can be used as a source of further information.

4.9.13 In using the method described in 4.9.8, caution should be used as it could easily underestimate the crossrange effects of debris. If the crossrange standard deviation is based on the normal variations in the guidance and performance of the vehicle, it will be ignoring any velocity imparted to the debris from any explosion or other energy release in the break-up and also any malfunction/tumble behaviour of the vehicle prior to break-up or abort. Therefore, some perturbation analysis must be performed beforehand to produce crossrange uncertainties due to perturbations to the debris, and perturbations due to malfunction behaviour. The standard deviations due to these perturbations can be included with the guidance and performance dispersions by using the root-sum-squared method. If the results indicate marginal risk acceptability, it may be wise to consider performing a more robust debris footprint methodology that can simulate the actions of the range safety abort system.

4.9.14 A simpler version of the corridor method uses only the vacuum impact points (impact points assuming no wind or atmospheric effects) and groups all of the casualty areas of all the fragments into a single casualty area (refer section 4.10). This will produce approximate results that can be used in mission planning, but is not suitable and should not be used for a final casualty expectation prediction.

Calculating probability of impact risk by the footprint method

4.9.15 The footprint method is an alternative to the corridor method, and is defined in the *FAA Flight Safety Analysis Handbook* [5] as a method of calculating the probability of impact risk on a population. The footprint is a mathematical probabilistic description of the scatter of debris resulting from a vehicle break-up at a particular time in flight. It is a basic building block of numerous risk analyses performed for many launch vehicles. The initial conditions are described by position (x, y, z), velocity (Vx, Vy, Vz), and time of occurrence. The debris from the break-up is divided into categories based on ballistic coefficient (β), velocity induced from the break-up event, and the casualty area (refer section 4.10) associated with impact.

4.9.16 The ballistic coefficient is an important debris parameter that indicates the relative importance of inertial and aerodynamic forces on a body in free fall. The ballistic coefficient, often referred to as beta (β), is defined as

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

Where:

W is the weight of the debris;

C_D is the drag coefficient; and

A_{ref} is a reference area associated with the drag coefficient.

4.9.17 Since drag coefficients are typically derived experimentally, the A_{ref} can be set by the experimentalist, but A_{ref} is often equal to the area projected on to the direction of the flow. The drag coefficient is a non-dimensional value defined as:

$$C_D = \frac{2F_D}{\rho A_{ref} V^2}$$

Where:

F_D is the total (friction and form) drag force;

ρ is the density of the fluid the object moves through (air in the case of launch vehicle debris); and

V is the velocity of the object relative to the fluid.

4.9.18 The location of mean impact points of the fragment groups are dominated by their ballistic coefficients and the wind. Higher ballistic coefficient debris tends to impact far downrange, relatively uninfluenced by the wind. Low ballistic coefficient debris will slow down rapidly, falling more directly below the break-up point or being carried in the direction of the wind. This is illustrated in Figure 8.

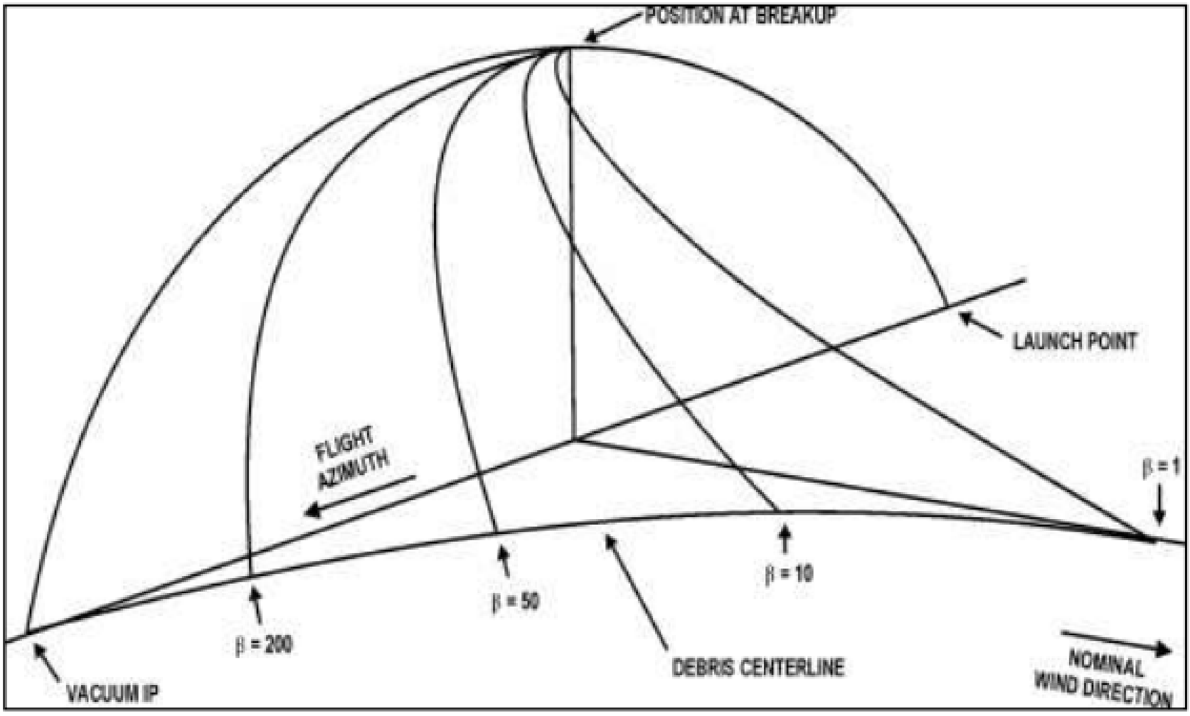

Figure 8. The influence of ballistic coefficient and wind on debris impact [8]

4.9.19 Several launch vehicle failures under the same conditions (time in flight, failure mode, wind conditions, etc.) would not be expected to produce exactly the same impact locations and consequences due to the inherent variability in such factors as the debris generated, or the size of the impact explosions.

4.9.20 The impact points for each piece of debris within the various groups/categories are uncertain due to the effects of five sources of dispersion: induced velocity, wind uncertainty, ballistic coefficient uncertainty, lift uncertainty, and state vector uncertainty. The state vector uncertainty can be due to both uncertainty in the nominal guidance, and performance and any aberrant vehicle behaviour before the break-up. These sources of impact point dispersion lead to the impact distributions for each of the debris categories as shown in Figure 9.

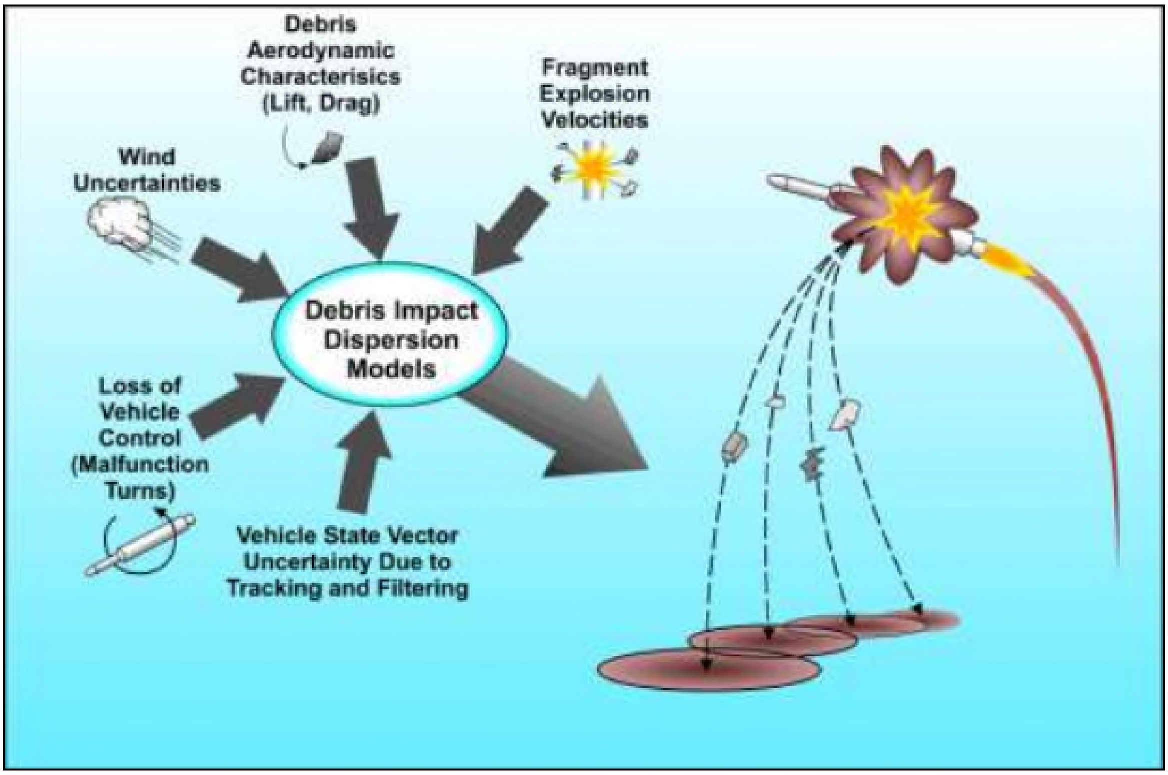

Figure 9. Contributions to debris impact dispersion models [5]

4.9.21 The 'disks' illustrating the impact dispersions in Figure 9 are often represented by bivariate normal (binormal) probability distributions. Therefore, each debris footprint is typically modelled as a series of bivariate normal distributions representing the impact uncertainties of each of the debris categories. Each of these distributions is dependent on the number of fragments in the group, the average weight of the fragments in the group, and a projected area of the average fragment when it impacts.

4.9.22 The footprint approach facilitates numerical simulation of scenarios because a footprint can represent a single accident: a possible outcome due to a failure mode occurring at a failure time. The footprint approach is built from thousands of these scenarios where each scenario has a probability, has a failure time, and represents some vehicle behaviour at that time. The primary challenge for a debris risk analysis is to be able to define a set of scenarios that describe all of the possible conditions sufficiently to produce a valid determination of risk.

<u>Calculating probability of impact risk by Monte Carlo method</u>

4.9.23 An alternative, more computationally intensive, and more general approach to calculating downrange probability of impact and risk involves using a Monte Carlo method.

4.9.24 Baeker, Haber and Collins [9] provide a procedure that follows a Monte Carlo methodology described as follows, and depicted in Figure 10:

- Establish the nominal trajectory and the normal deviations around the trajectory due to variations in performance and steering.
- Compute the malfunction turn behaviour of the vehicle if it goes into a tumble turn, normally assuming that the turn can be in any direction. Do this every several seconds of flight as necessary, and for different thrust offset angles ranging from minimum to maximum. Assign a

probability distribution to the likelihood of the magnitude of the thrust offset angle, given that the vehicle is in a malfunction turn.

- Determine the maximum product of dynamic pressure and angle of attack allowable by the structural design of the vehicle.

- Develop a debris list by category of ballistic coefficient.

- Start a simulation and, for a given time increment, randomly select a failure response mode or thrust offset angle and fly a malfunction turn until vehicle break-up or violation of abort criteria (the abort criteria can be based on vehicle attitude, violation of an abort limit line by the IIP or other). At break-up, calculate the drag-corrected trajectories of each debris category using a randomly selected wind profile (generated by varying the wind using the mean wind and a wind uncertainty model).

- Repeat this process many times for that initial failure time and collect the impact data in separate groups for each debris category. Develop mean and impact covariances for each debris category to form a bivariate normal distribution. The bivariate normal distribution is of the same form as that used for the impact dispersion of empty stages (refer to Figure 10).

- Compute the impact probability for each population centre and the corresponding casualty expectation (refer Section 4.11). All of these calculations are weighted according to the failure probability during that interval. The casualty expectations are stored for each population centre.

4.9.25 The above sequence is repeated for each flight time interval. The method is valid both for the downrange and launch area calculations. The total casualty expectation is the sum of the casualty expectations from each time interval.

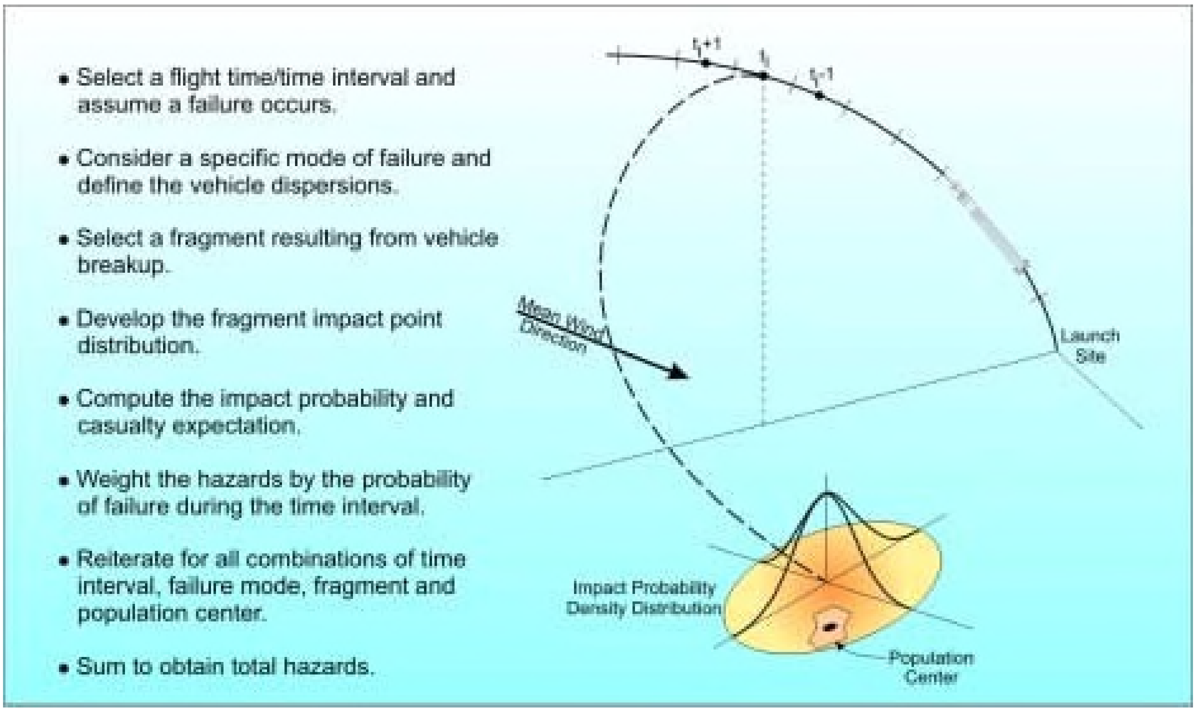

Figure 10. Monte Carlo iterative procedure to compute risks [9]

4.9.26 This method is recommended for the launch area risk calculation, as launch area risks are the most difficult to compute. At this time in flight, the IIP is not moving rapidly downrange and consequently the corridor method of risk analysis is not appropriate. Moreover, the abort criteria play a very important part and are used to restrain the motion of the vehicle not only laterally but also from moving back toward the launch site. Therefore, the analysis must model aborts in multiple directions.

4.10 Casualty Area (A_c)

4.10.1 When debris impacts, there is a region on the ground in which a person who is present will become a casualty. The area that defines this region where a person will become a casualty is known as the casualty area. A person can become a casualty both outside and inside a shelter because of:

- Direct impact from debris;
- Being struck inside the structure from debris created by the fragment (e.g. roof failure);
- Direct overpressure and impulse from an explosion of vehicle or propellant; and
- Debris effects internal to a structure on occupants due to a nearby explosion of a vehicle or propellant (e.g. flying glass shards caused by the explosion).

4.10.2 Debris characteristics that affect the casualty area are cross-sectional area, impact velocity, weight, impact angle, drag coefficient, and explosivity. Also, knowledge of the number of fragments is essential, since it is normally assumed that each fragment will land sufficiently far away from any other to make the likelihood of two fragments striking the same person very unlikely. It is also assumed that explosive fragments can have much larger casualty areas.

4.10.3 The issues to be considered when calculating casualty area include the effects of inert debris falling vertically and/or ricocheting, explosive debris, debris fragment size and number (debris catalogue), horizontal and vertical cross-sectional area of the 'standard person', angle of impact, and calculation of the composite or effective casualty area. All of the above debris scenarios will depend on the type of launch vehicle failure; for example, the debris casualty area for a launch vehicle impacting intact can be expected to be significantly less than for an in-air explosive failure. Four underlying assumptions to be adopted are that:

1. The debris catalogue converts the total non-volatile mass of the launch vehicle (including payloads) into fragments that are potentially casualty producing;
2. All fragments with weight and impact velocity above a specified threshold, either striking a person directly or glancing a person will result in death or serious injury;
3. No individual debris casualty areas overlap; and
4. The dimensions of a 'standard person' are 0.3 metres in radius and 2.0 metres in height.

4.10.4 The preferred methodology for calculating casualty area is addressed in a more comprehensive manner in Appendix 1.[12]

[12] The preferred A_c casualty area is explained in detail in Appendix 1, which was by ACTA Inc in 2002, and updated by Shoal Group Pty Ltd and Asia Pacific Aerospace Consultants Pty Ltd in 2019. This methodology is fully self-contained A_c for applicants to readily calculate A_c. The methodology is presented in detail in Appendix 1.

4.10.5 The equation for calculating Casualty Area A_c is expressed as follows:

$$A_c = A_{c\,(inert)} + A_{c\,(explosive)}$$

Where:

$A_{c\,(inert)}$ is the area affected by inert debris. This comprises a basic component $A_{c\,(basic)}$ which is made up of debris falling vertically and diagonally, and a ricocheting or skid component F_{skid}, (see Appendix 1 for further information on F_{skid}).

$A_{c\,(explosive)}$ is the area affected by explosive debris. This contribution to casualty area by explosive debris is calculated from converting propellant weights into equivalent TNT weights and using an explosive overpressure threshold of 25 kPa (overpressures of up to 65 kPa will be considered on a case-by-case basis).

4.10.6 $A_{c\,(basic)}$ can be calculated as a circular area encompassing the sum of the radius of a 'standard person' and the radius of the fragment (vertically falling debris), plus the projected area encompassing the radius of a person, plus the radius of the fragment multiplied by the tangential height of a 'standard person' (diagonally falling debris).

The equation for calculating $A_{c\,(basic)}$ is:

$$A_{c\,(basic)} = \pi\left(r_p + r_f\right)^2 + 2\left(r_p + r_f\right) h \tan\alpha$$

Where:

r_p is the radius of the "standard person";

r_f is the radius of a circular fragment;

h is height of the "standard person" (2 m); and

α is the impact angle as defined in Figure 12.

Figure 11 and Figure 12 provide a diagrammatic clarification of how $A_{c\,(basic)}$ is determined:

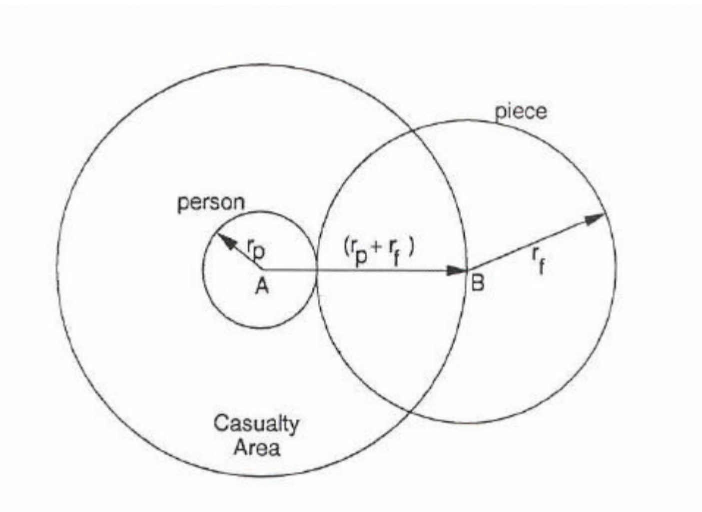

Figure 11. Debris falling vertically [10]

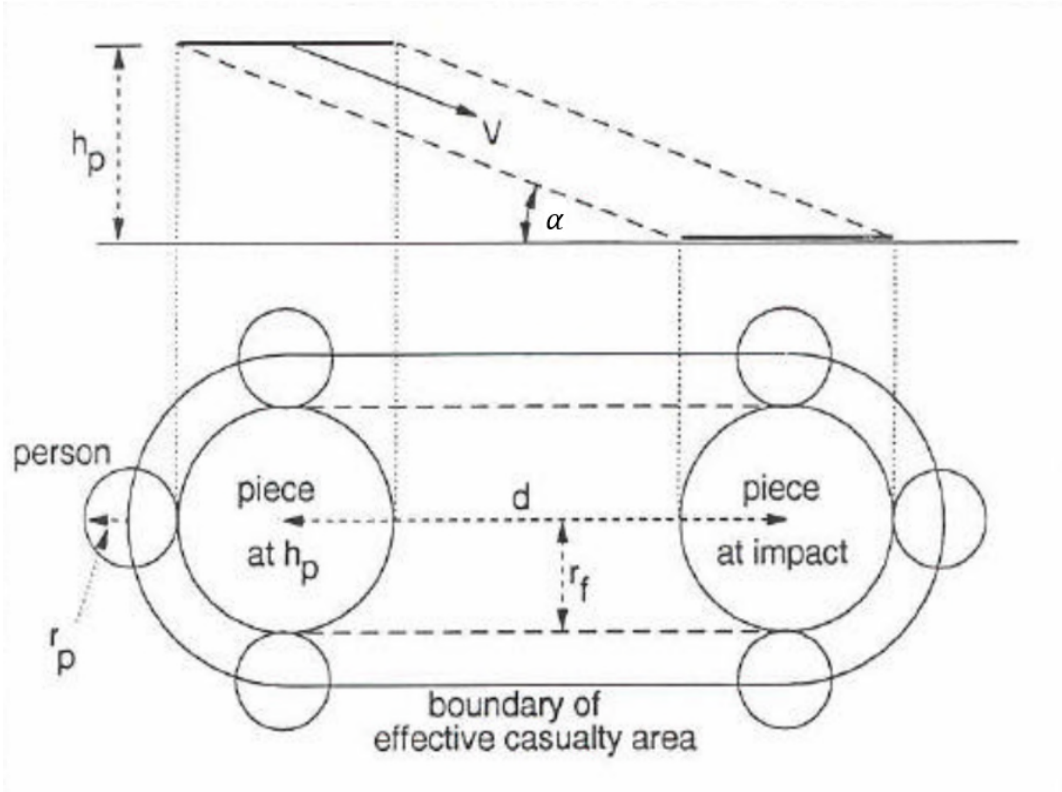

Figure 12. Debris falling diagonally [10]

4.10.7 F_{skid} represents the adjustment to the casualty area resulting from ricocheting or skidding fragments. This component of A_c is addressed in the *FAA Flight Safety Analysis Handbook* [5]. The handbook provides the basis for calculating F_{skid}. The handbook shows that the project area of the debris fragment increases by a median factor of 4.36 as a result of ricocheting or skidding fragments. Scenarios for factors such as altitude of the failure or type of terrain (pavement, soft ground) have a marked effect on the Ec computation, and are discussed in detail in the handbook.

Incorporating F_{skid}, the $A_{c\,(inert)}$ equation becomes:

$$A_{c\,(inert)} = \pi\left(r_p + \sqrt{\frac{F_{skid}A_p}{\pi}}\right)^2 + 2\left(r_p + \sqrt{\frac{F_{skid}A_p}{\pi}}\right)h\tan\alpha$$

Where:

A_p is the projected area of the fragment. For a circular shaped fragment, A_p is defined as:

$$A_p = \pi\, r_f^2$$

Where:

r_f is the radius of a circular fragment as defined above.

4.10.8 The *FAA Flight Safety Analysis Handbook* [5], also addresses the explosive debris contribution to the casualty area, and this is summarised below.

$A_{c\ (explosive)}$ can be calculated from the equation:

$$A_{c\ (explosive)} = \pi R_e^2$$

Where:

$$R_e = K \times (NEW)^{1/3}$$

Where:

R_e is the radius (m) for the explosive casualty area;

K is a distance scaling factor (m/kg$^{1/3}$); and

NEW is the net TNT equivalent weight (or yield) of the propellant (kg).

4.10.9 The factor K is addressed in a number of publications. Two references provided by the US FAA are US DOD 6055.9-STD, *DOD Ammunition and Explosive Safety Standards* (August 1997) [11] and Chemical Propulsion Information Agency Publication 394, *Hazards of Chemical Rockets and Propellants* (30 June 1985) [12].

4.10.10 All the required equations, tables and graphs necessary for completing the calculation are provided in the methodology at Appendix 1 – Methodology for calculating casualty area $\boldsymbol{A_c}$.

4.11 Casualty Expectation for discrete time interval ($\boldsymbol{E_{c,\Delta t}}$)

4.11.1 As stated in section 4.3 the casualty expectation is the primary measure of the risk of a launch or return. Calculation of the casualty expectation requires the debris catalogue, probability of impact, casualty area and population density as described in the previous sections.

4.11.2 Following the methodology for calculating:

- Debris catalogue, and number of fragments ($N_{f,j}$) (**section 4.7**);
- Population density ($D_{p,k}$) (**section 4.8**);
- Probability of impact ($P_{I,ijk}$) (**section 4.9**); and
- Casualty Area ($A_{C,ij}$) (**section 4.10**);

the casualty expectation for a particular scenario (failure mode i, fragment group j, population centre k, and time interval Δt), can now be calculated by using the following equation:

$$E_{c,ijk,\Delta t} = P_{I,ijk} \times N_{f,j} \times A_{C,ij} \times D_{p,k}$$

4.11.3 The above equation represents the $E_{c,ijk,\Delta t}$ from one particular scenario. To obtain the total casualty expectation $E_{c,\Delta t,}$ from all failure response modes, and resultant fragment groups on all population centres for the single time interval (Δt) all failure modes, fragment groups, casualty areas and affected population densities for that single time interval must be calculated. The following equation describes how to calculate the casualty expectation for a single time interval Δt:

$$E_{c,\Delta t} = (1 - P_f) \sum_i \left(P_i \sum_j \left(\sum_k E_{c,ijk,\Delta t} \right) \right)$$

4.11.4 This method must be applied to all potentially affected population centres to obtain the total casualty expectation for each discrete time interval.

4.11.5 The entire launch vehicle flight or return is comprised of multiple discrete time intervals. To calculate the total casualty expectation for the entire mission, all the $E_{c,\Delta t}$ from the discrete time intervals must be summed together (refer section 4.3). This can be expressed in the following equation:

$$E_c = \sum_{\Delta t} E_{c,\Delta t}$$

4.11.6 The total mission casualty expectation is the sum of the individual casualty expectations from each of the discrete time intervals. This is the casualty expectation that must be compared to the launch safety standards to ensure that the public risk for a launch or return is within the safety thresholds in order for the launch or return to proceed.

4.12 Probability of impact isopleths and individual risk isopleths

4.12.1 Probability of impact isopleths are contour lines on a map connecting places of equal probability of impact. Probability of impact isopleths show the geographic distribution of impact probability on a map. The isopleth areas will change with the area of the people or place at risk, with the size of the debris fragments, and with the number of debris fragments. For example, the 1×10^{-6} probability of impact isopleth for impact on a person for a spent stage represents a boundary, outside of which the stage will impact on a person less than once in $1\text{x}10^{-6}$ opportunities. The 1×10^{-6} probability of impact isopleth on a large facility for that same spent stage would be further away from the nominal impact point than the 1×10^{-6} probability of impact isopleth on a person because of the facility's larger size.

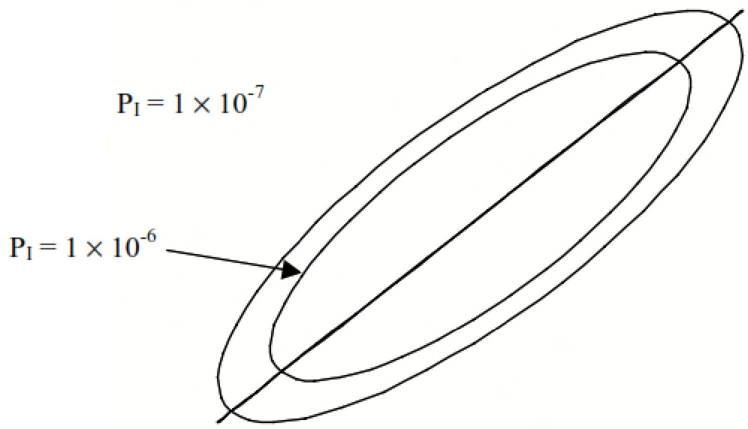

Figure 13. Sample probability of impact isopleths

4.12.2 Impact probability isopleths can be computed by establishing a grid with an impact area at each intersection of the grid. An impact area size is then chosen. For example, if the probability of impacting on a person is the objective then use an area of one square metre. If impact probability is needed for a larger area (e.g., a large building of 100 m x 100 m) then use an area of 10,000 square metres. After the impact area is chosen, the impact probability can be computed for each of the grid points, then contours (isopleths) can be drawn that represent constant levels of impact probability.

4.12.3 Individual risk isopleths are contour lines on a map connecting places of equal risk and can be calculated using the same method as described in 4.12.2. Individual risk isopleths are used for calculating the probability of impact on a person, with the isopleth measure being the casualty expectation for a particular scenario ($E_{c,ijk}$) as defined in section 4.11. The individual risk isopleths can be determined by calculating, for each intersection point of the grid, the multiplication of the probability of impact, number of fragments, casualty area, and population density at the intersection of the grid. These individual risk isopleths are the key output of the risk hazard analysis and a key element of demonstrating that the launch safety standards are met.

4.13 Demonstrating conformity with the launch safety standards

4.13.1 The results of the risk hazard analysis form the basis for demonstrating conformity with the launch safety standards which must be met before a specific launch or return can be approved. This section provides a guide to the type of documentation that can be used to demonstrate conformity.

4.13.2 The casualty expectation standards set out in section 3 acknowledge public expectations that the risk of death or serious injury from commercial space activities should not exceed that from comparable industries. It is also recognised that it is more difficult to accurately measure actual risk than to determine that the risk is below a certain acceptable threshold.

4.13.3 Collective risk is the total risk to the public from a launch. The E_c used as a measure of risk to the public should be based on the total risk over all phases of flight where the public is exposed; that is, ascent to orbit, and return from orbit. Risks in orbit are generally to physical assets and not to people and therefore can be excluded. The total risk as defined above is the ‘collective’ risk.

4.13.4 Individual risk is the highest risk to any single person exposed to the launch. This must also be controlled, but limits on individual risk are not sufficient to control the collective risk. Individual risk does not take into account the number of people exposed to the hazard. Collective risk is necessarily the primary measure of mission risk. Individual risk should be included as a secondary measure that must also be satisfied at some level of acceptability, but never as a sole criterion.

4.13.5 From a mission-planning standpoint, risks from impacting inert and exploding debris should be the primary considerations. Risks from toxic gases must be considered if the vehicle has fuels that can produce these gases either in a normal launch or an aborted launch.

4.13.6 Distant focusing overpressure (DFO) from a ground explosion from an abort in the launch area may cause window breakage to occur up to 30 km from the launch site. Both the toxic gas risk and the DFO risks are dependent upon the weather conditions at the time of launch. They are generally looked upon as constraints on the day of launch due to weather. As a constraint they can lead to a launch hold if the launch risk including toxic and DFO risk exceeds the acceptable risk standard. These hazards are generally not considered in overflight risks. Toxic and DFO risks are described in detail in International Association for the Advancement of Space Safety book, the *Safety Design for Space Operations*. [4].

4.13.7 The three major casualty expectation criteria specified in the launch safety standards are:

- Collective risk to the public on a per-launch basis (casualty expectation standard);
- The highest risk to an individual of the public on a per-launch basis; and
- The highest risk to an individual of the public on a per-year basis.

4.13.8 The populations of foreign countries must be considered under the same criteria as Australia's population. Individuals supporting the launch or return are not considered under the public risk criteria in the launch safety standards and risk hazard analysis because they are not considered part of the general public.

4.13.9 The following are the standards to be met and include ascent, descent and landing operations:

- Casualty expectation standard 1×10^{-4} casualties per launch (collective risk);
- Maximum individual risk (casualty) 1×10^{-6} per launch; and
- Maximum individual risk (casualty) 1×10^{-5} per year.

4.13.10 Additionally, the asset safety standard is used to address the potential of debris creating a catastrophic chain of events on particular property known as assets with catastrophic potential. The asset safety standard for 'trigger debris' impact on an asset with catastrophic potential is 1×10^{-6} where 'trigger debris', is debris for which impact could initiate a chain of events that could produce many casualties.

4.13.11 During the flight of the launch vehicle, it is common for one and sometimes two stages to be dropped as fuel is consumed. Also early in flight, once the atmosphere has thinned enough, fairings that enclose and protect the satellite in its early passage through the lower atmosphere are jettisoned. Each of these pieces has a planned drop zone defined as a three standard deviation footprint that contains 0.997 of all impacts. Within each zone, calculations are performed to determine risks to people or property. Drop zones are usually selected to be free of people. The casualty safety standards also apply in drop zones, so the launch must not proceed if any individual is within the 1×10^{-6} individual risk isopleth. If the asset risk from "trigger debris" exceeds 1×10^{-6}, then the drop zone would be inappropriate and would need to be relocated. This method applies to drop zones on land or sea.

4.13.12 As a guide, applicants should provide the following documentation:

1. Risk hazard analysis report capturing all inputs, outputs, and assumptions used while conducting the risk hazard analysis to show consistency with the *Flight Safety Code* methodology.

2. Casualty Expectation (E_c) (total casualty expectation for the mission) and maximum third-party collective risk;

3. Individual risk isopleths and controlled areas: map showing each drop zone and landing site and the 1×10^{-6} individual risk isopleth. The individual risk isopleth is to be calculated on the basis of a person in the open.

4. Probability of impact isopleths on assets with catastrophic potential and controlled areas: map showing each drop zone and landing site and the 1×10^{-6} probability of impact isopleth for 'trigger debris' on a hypothetical object of the same physical dimensions as an asset with catastrophic potential. (Assets with catastrophic potential inside or in the vicinity of the 1×10^{-6} probability of impact isopleth for particular trigger debris should be identified, with separate maps for each type of trigger debris. In this context 'in the vicinity' means within 50km.).

Appendix 1 – Methodology for calculating casualty area A_c

Casualty area calculation A_c

Overview

When debris impacts the ground, there is a region in which a person who is present will become a casualty; this is called the casualty area. The definition of casualty is severe injury (requiring hospitalisation) or death. A person can become a casualty both outside and inside a shelter because of:

- Direct impact from debris;
- Being struck inside the structure from debris created by the fragment (e.g. roof failure);
- Direct overpressure and impulse from an explosion of vehicle or propellant; and
- Debris effects internal to a structure on occupants due to a nearby explosion of a vehicle or propellant.

The effects of these are elaborated further respectively in the following subsections within this Appendix:

- Inert debris effects on people in the open;
- Inert debris effects on people in structures;
- Explosive debris effects on people in the open; and
- Explosive debris effects on people in structures.

Calculation methodology

The equation for calculating Casualty Area $A_c$is expressed as follows:

$$A_c = A_{c\,(inert)} + A_{c\,(explosive)}$$

Where:

$A_{c\,(inert)}$ comprises a basic component $A_{c\,(basic)}$ which is made up of debris falling vertically and diagonally, and a ricocheting or skid component F_{skid}; and

$A_{c\,(explosive)}$ is the area where a casualty can occur due to explosive debris This contribution to Casualty Area is calculated from converting propellant weights into equivalent TNT weights and using an explosive overpressure threshold of 25 kPa (overpressures of up to 65 kPa will be considered on a case-by-case basis).

Calculation of $A_{c\,(inert)}$ and $A_{c\,(explosive)}$ are explained in the subsequent subsections.

Inert debris effects $A_{c\ (inert)}$

Inert debris effects on people in the open

Several factors should be considered in the computation of casualty areas for inert debris. These include the size of the fragment, the size of a person, the velocity vector at impact, and whether the fragment remains intact after impact or disintegrates (splatters). If it stays intact, it may ricochet or slide, depending on the velocity vector (magnitude and angle), the effective coefficient of restitution and the effective coefficient of friction between the fragment and the ground. Included in ricochet are the effects of tumble, as well as rebound or bounce.

For a direct impact from debris falling vertically, the casualty area takes into account both the projected area of the debris and the projected area of the human body from above. Usually, the radius of the human body is assumed to be 0.3 m. If the velocity and weight of the fragment exceeds the boundary criteria presented in Figure 14, the person becomes a casualty. The criterion in Figure 14 is for ‘average general public’. The associated casualty area is:

$$A_{c\ (basic)(vertical)} = \pi \left(r_p + \sqrt{\frac{A_p}{\pi}} \right)^2$$

Where:

r_p is the radius of the “standard person” (0.3 m); and

A_p is the projected area of the fragment.

The projected area of the fragment, A_p is defined as:

$$A_p = \pi\, r_f^2$$

Where:

r_f is the equivalent radius of the fragment.

Conversely, the equivalent radius of the fragment r_f is:

$$r_f = \sqrt{\frac{A_p}{\pi}}$$

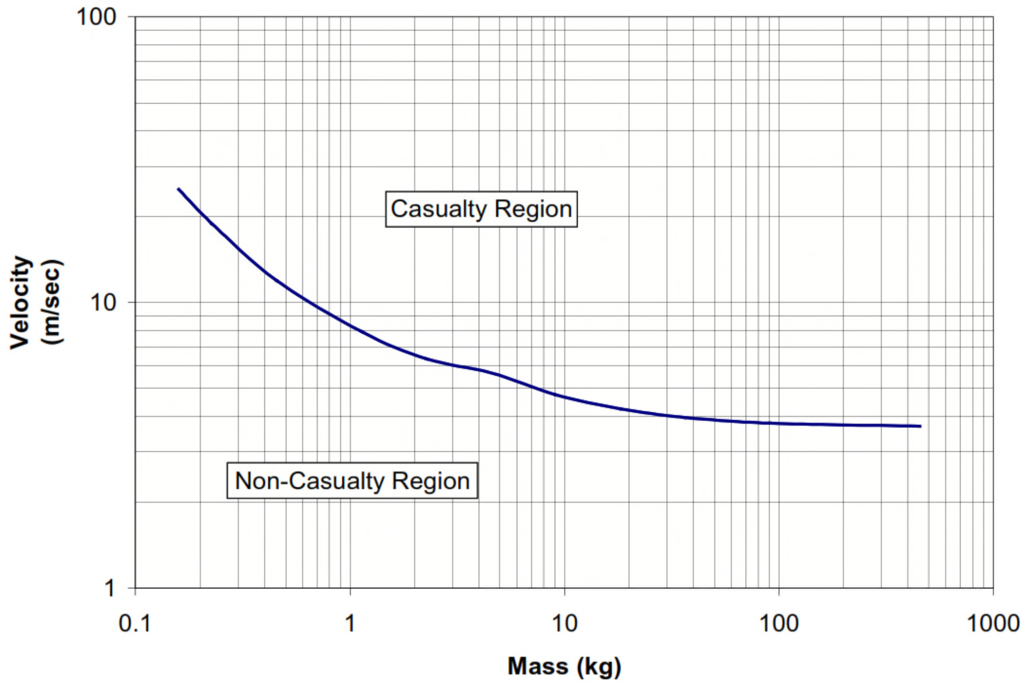

Figure 14. Impact velocity regions for casualties and non-casualties

The casualty area grows when considering angular strike and the dynamic effects of impact on the ground and subsequent motion. The casualty area for impact at an angle relative to vertical is:

$$A_{c\,(basic)} = \pi\left(r_p + \sqrt{\frac{A_p}{\pi}}\right)^2 + 2\left(r_p + \sqrt{\frac{A_p}{\pi}}\right) h \tan\alpha$$

Where:

r_p is the radius of the 'standard person',

r_f is the radius of a circular fragment,

h is height of the "standard person" (2 m), and

α is the impact angle as defined in Figure 12.

Figure 15 is provided as a guideline for 'reasonableness' for total basic casualty area. The plot contains the total casualty area for several common expendable launch vehicles (ELV) (without identification) as a function of vehicle inert debris weight; that is, no solid or liquid propellant and no solid rocket motor casing. These numbers make use of the debris lists developed by the vehicle launch organisation. There is a very distinct trend and estimates of basic casualty area should generally fall within 20 per cent of the trend line of the data.

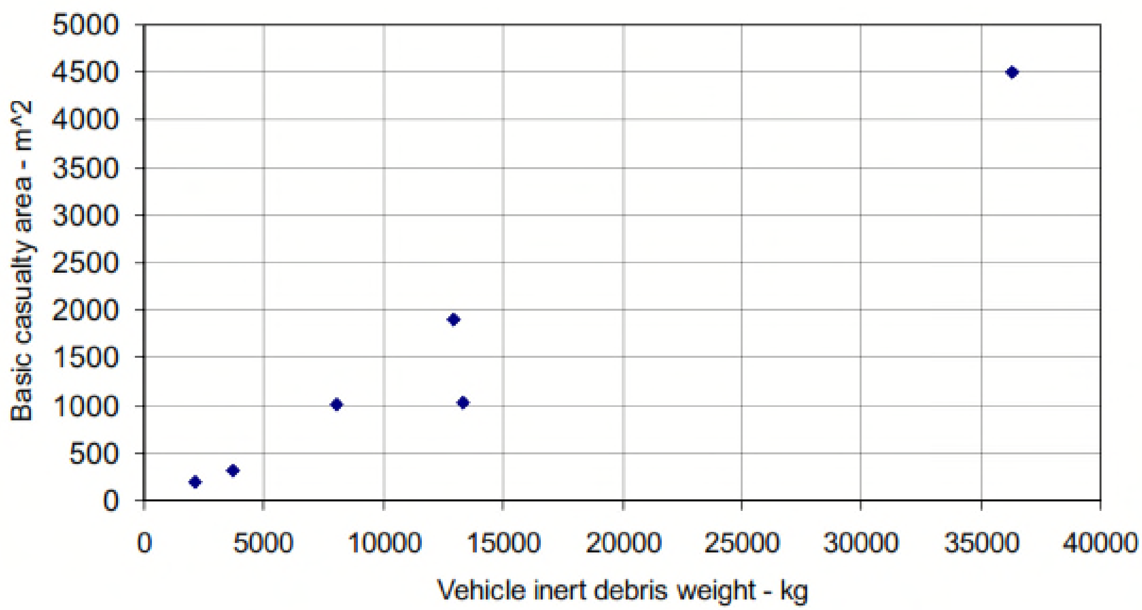

Figure 15. Basic casualty area versus total weight of inert debris for several different expendable launch vehicles

To handle the aspects of bounce, skid, roll, and break-up and splatter upon impact involves speculation with shapes, coefficients of restitution, friction coefficients, and the vulnerability of people to the fragment after bounce, skid, roll, etc.

This process is complex and requires assumptions. A reasonable model covering the post impact behaviour is to multiply A_p by a factor of F_{skid}, thereby modifying the projected area of the debris fragment to account for secondary effects as discussed in the *FAA Flight Safety Analysis Handbook* [5]. The equation to calculate $A_{c\,(inert)}$ including F_{skid} is follows:

$$A_{c\,(inert)} = \pi\left(r_p + \sqrt{\frac{F_{skid}A_p}{\pi}}\right)^2 + 2\left(r_p + \sqrt{\frac{F_{skid}A_p}{\pi}}\right)h\tan\alpha$$

Where:

F_{skid} is nominally a defined as a factor of 4.36 as defined in the *FAA Flight Safety Analysis Handbook* [5]. Note that F_{skid} is significantly impacted by factors such as altitude of the failure or type of terrain (pavement, soft ground), which have a marked effect on the $A_{c\,(inert)}$ computation. These details are discussed in detail in section 6.5 of the *FAA Flight Safety Analysis Handbook* [5].

Figure 16 was also developed from some common ELV data. It provides the number of debris fragments as a function of inert vehicle weight.

An estimate of the total basic casualty area from Figure 15 divided by an estimate of the number of fragments from Figure 16 will produce an average basic casualty area.

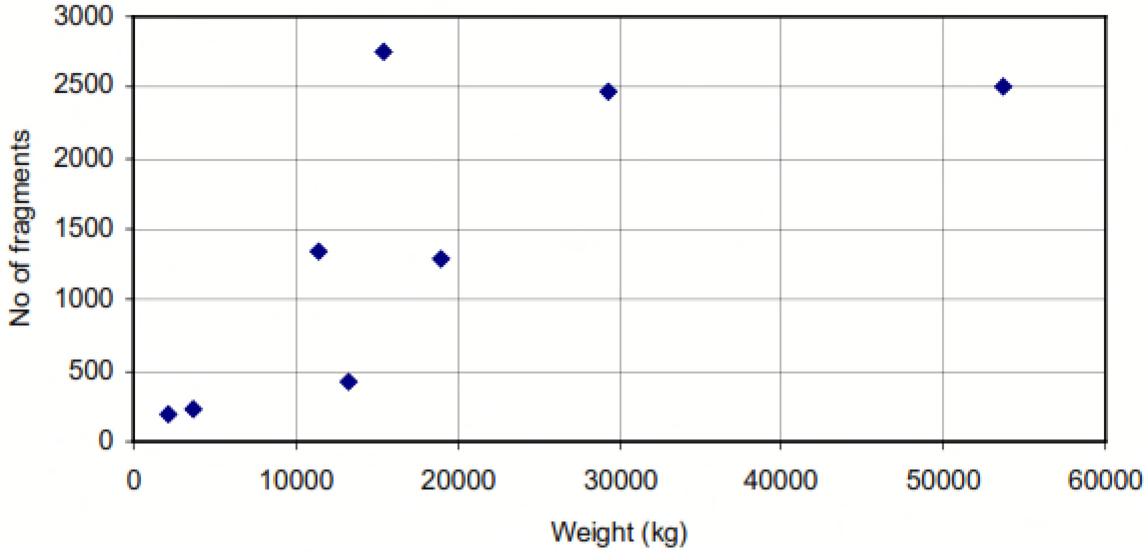

Figure 16. Number of debris fragments versus total weight of inert debris for several different expendable launch vehicles

<u>Inert debris effects on people in structures</u>

If a fragment is heavy enough and the velocity is high enough, it can penetrate the roof of a structure and either impact directly on an occupant or cause structural debris to impact on an occupant. Since each different location of impact on the roof will have a different effect, work to develop relationships was performed on impacts over thousands of locations on the roofs and over many roof types that were finally apportioned into several categories.

After fragment penetration into the structure and the secondary debris was determined, the same rules were applied to the vulnerability of the occupants as to people standing in the open.

The result is the set of curves shown in Figure 17, Figure 18 and Figure 19 for fragments falling at terminal velocity with drag coefficients (C_D) of 0.75 for high and medium, and 0.87 for low density fragments (based on the general shapes and masses expected in each fragment group; light fragments can represent skin panels while heavy fragments can represent heavy engine equipment, and medium, the fragments in between).

The vertical scale gives the average casualty area due to roof penetration for three different general roof classes. Each figure represents a different class of fragment densities. Note that, as fragments weigh less and have lower impact velocities they are less likely to penetrate. In these cases the average casualty area converges to the minimum casualty area for a person.

A subset of the numerical results is listed in Table 9, Table 10, and Table 11. The following trends can be noted:

(1) The smallest casualty area is approximately 0.3 m^2, which corresponds to the projected area of an average person with a radius of 0.3 m.

(2) No casualties internal to a structure are expected from fragments less than 0.4 kg.

Below a certain fragment weight, heavier structures tend to offer more protection as they do not fail. However, as fragments become heavy enough to penetrate the heavier structures, more casualties may be expected due to heavier secondary debris. Some of the irregularities of the curves may be attributed to the fact that as the fragment size increases, the fragment may no longer fit between the joists of a roof structure, and therefore the probability of penetrating through a relatively weak roof plate drops to zero.

Meanwhile the kinetic energy may become large enough to fail the joists, resulting in steep increments of casualty area. It is similar when the fragment becomes too large to fit between the girders. These irregularities are consistent with the discontinuities observed in the individual HACK/CF [13] runs. Averaging over different building designs within a structure category and principal component analysis tends to smooth the discontinuities.

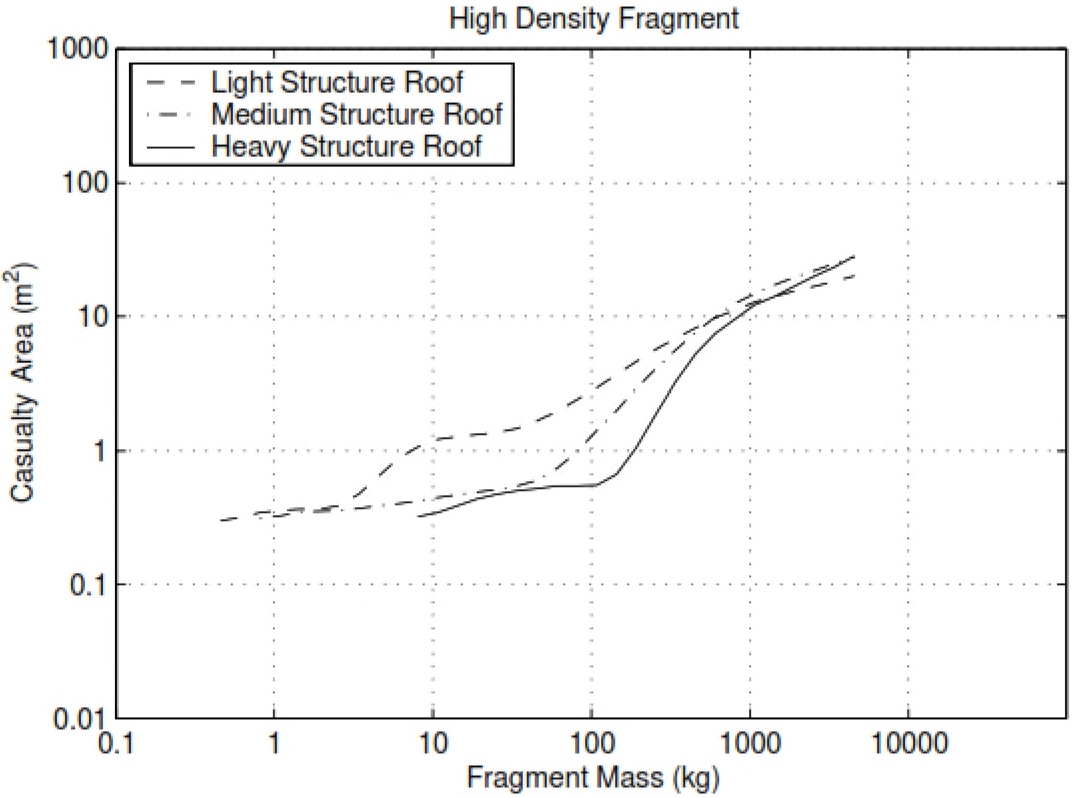

Figure 17. Casualty Areas for high density fragments (2408 kg/m3, C_D = 0.75)

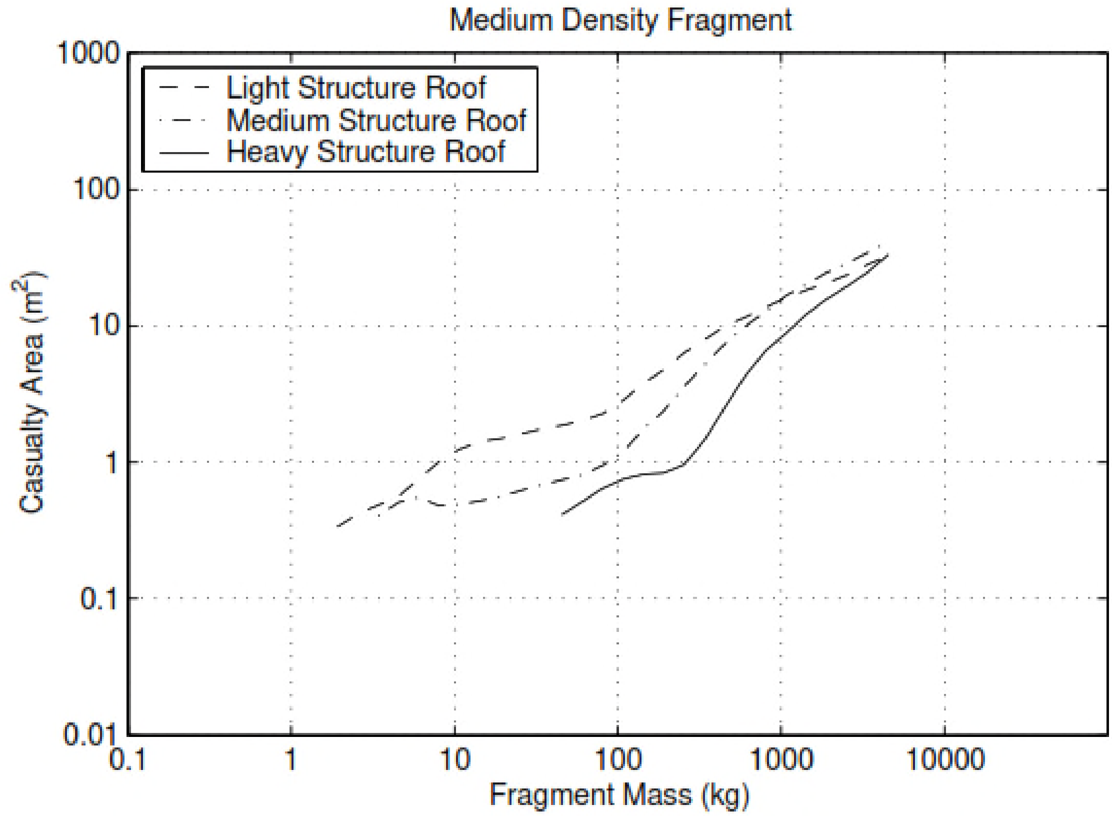

Figure 18. Casualty Areas for medium density fragments (554 kg/m3, C_D = 0.75)

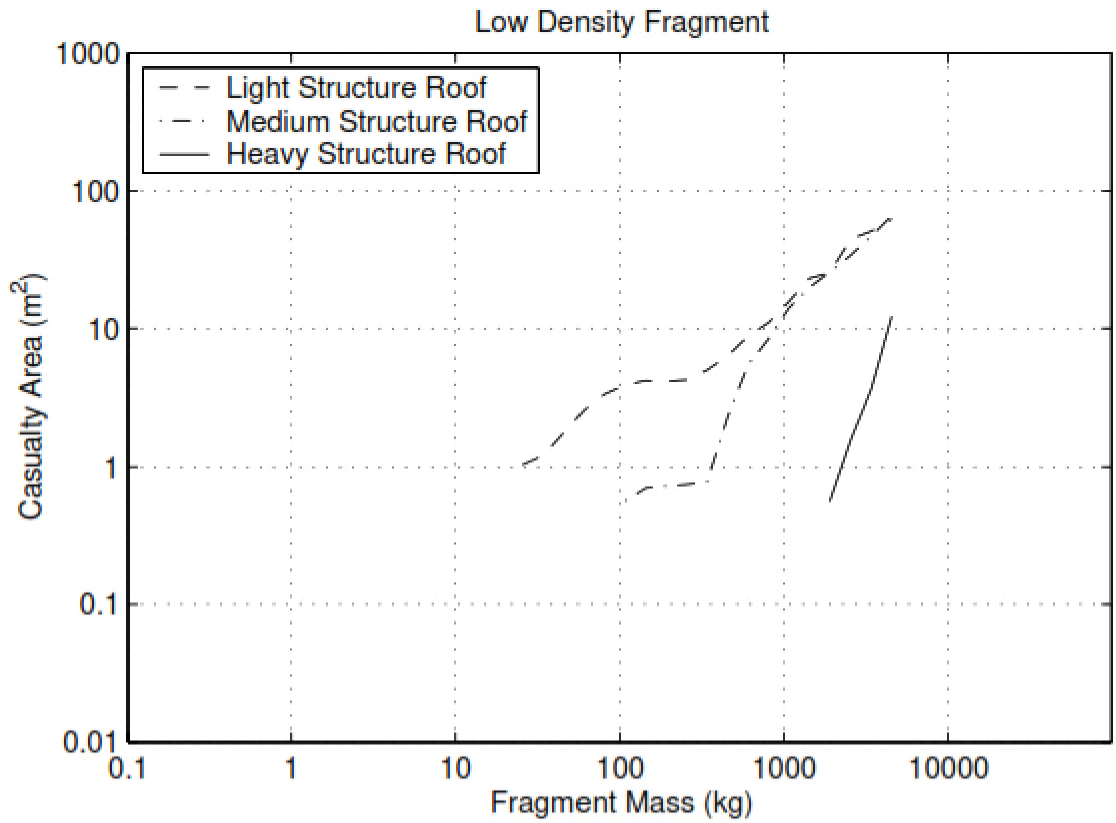

Figure 19. Casualty Areas for low density fragments (27.7 kg/m3, C_D = 0.87)

Table 9. Building casualty area for high density fragments

			Casualty Area (m2)		
Fragment Mass (kg)	**Mean Fragment Area (m2)**	**Impact Velocity (m/s)**	**Light Structure Roof**	**Medium Structure Roof**	**Heavy Structure Roof**
0.045	0.000708	36.9	0	0	0
0.143	0.00152	44.5	0	0	0
0.454	0.00329	54	0.301	0	0
1.43	0.00708	65.5	0.367	0.351	0
4.54	0.0152	79.2	0.646	0.387	0
14.3	0.0329	96	1.27	0.468	0.391
45.4	0.0708	116	1.66	0.604	0.522
143	0.152	141	3.7	2.01	0.665
454	0.329	171	8.17	7.67	5.26
1430	0.708	207	14.1	17.3	14.1
4540	1.52	251	20.1	27.7	28.3

Table 10. Building casualty area for medium density fragments

			Casualty Area (m2)		
Fragment Mass (kg)	**Mean Fragment Area (m2)**	**Impact Velocity (m/s)**	**Light Structure Roof**	**Medium Structure Roof**	**Heavy Structure Roof**
0.045	0.00189	22.6	0	0	0
0.143	0.00406	27.3	0	0	0
0.454	0.00876	33.2	0	0	0
1.43	0.0189	40.2	0	0	0
4.54	0.0406	48.5	0.563	0.509	0
14.3	0.0876	58.8	1.41	0.519	0
45.4	0.189	71.3	1.87	0.742	0.411
143	0.406	86.3	3.75	1.75	0.821
454	0.876	105	9.94	7.36	2.53
1430	1.89	127	18.2	20.1	12.1
4540	4.06	154	32.6	41.2	33.4

Table 11. Building casualty area for low density fragments

			Casualty Area (m2)		
Fragment Mass (kg)	Mean Fragment Area (m2)	Impact Velocity (m/s)	Light Structure Roof	Medium Structure Roof	Heavy Structure Roof
0.045	0.0139	7.71	0	0	0
0.143	0.0299	9.36	0	0	0
0.454	0.0645	11.3	0	0	0
1.43	0.139	13.7	0	0	0
4.54	0.299	16.6	0	0	0
14.3	0.645	20.1	0	0	0
45.4	1.39	24.4	1.76	0	0
143	2.99	29.5	4.17	0.698	0
454	6.45	35.7	6.32	2.31	0
1430	13.9	43.3	23.1	19.8	0
4540	29.9	52.4	62.0	66.2	12.3

Explosive debris effects $\boldsymbol{A_{c\ (explosive)}}$

Explosive casualty area calculation methodology

$A_{c\ (explosive)}$ is the explosive debris contribution to casualty area calculated from converting propellant weights into equivalent TNT weights and using an explosive overpressure threshold to determine the effective casualty area.

$A_{c\ (explosive)}$ can be calculated from the equation:

$$A_{c\ (explosive)} = \pi R_e^2$$

Where:

R_e is the radius for the explosive casualty area (m).

1. <u>Determination of yield (NEW) from impacts of explosive debris – liquid propellants</u>

The curves in Figure 20 were obtained from Project Pyro [14] [15], which was a test program, performed in the 1960s.

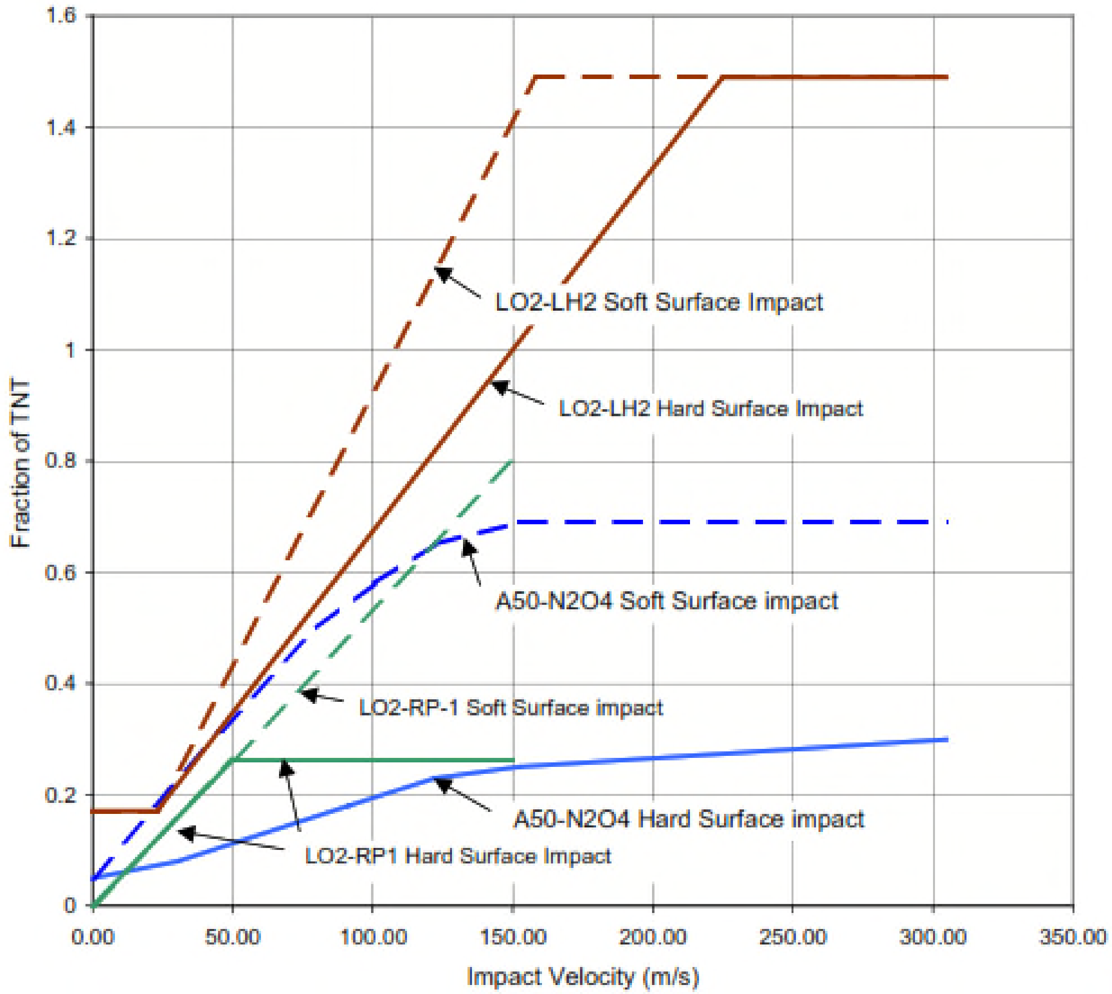

Figure 20. Equivalent TNT yield of rocket liquid propellant explosions as a function of impact velocity

Research has been performed on the yields at impacts below 50 m/s [16]. However, impacts at these low velocities are not expected, except very near the launch pad and therefore are not included in this discussion.

Once the fraction of TNT yield is calculated, the TNT net equivalent weight (TNT yield in kg) of the propellant can be calculated as follows:

$$NEW = W \times (Fraction\ of\ TNT)$$

2. Determination of yield (NEW) from impacts of explosive debris – solid propellants

A general formula for the fraction of TNT yield of solid propellant in an explosion resulting from impact is[13] [17]:

$$Fraction\ of\ TNT = 1.28 \times \left(1 + e^{a} \times (2.2046 \times W)^{b} \times \left(3.2808 \times \frac{V}{S}\right)^{c}\right)^{-1}$$

Where:

W is a the total propellant weight (kg),

V is the impact velocity (m/s),

S is the surface hardness factor:

S = 2.92 for water

S = 1.81 for soft soil

S = 1.41 for concrete

S = 1 for steel

a = 12.16

b = -0.156

c = -1.55

Once the fraction of TNT yield is calculated, the TNT net equivalent weight (TNT yield in kg) of the propellant can be calculated as follows:

$$NEW = W \times (Fraction\ of\ TNT)$$

[13] The above formulation was developed by Wilde and Anderson and is based on a fit to a combination of theoretical results (PIRAT program) and test data. [15]

Explosive debris effects on people in the open

1. Methods for calculating radius for the explosive casualty area (R_e) for people in the open

The following subsections propose two methods for calculating the radius for explosive casualty area for people in the open R_e, namely through:

- Empirical equation method, or
- Graphical representation method.

Empirical equation method

The radius for the explosive casualty area for people in the open can be calculated empirically through the following equation:

$$R_e = K \times (NEW)^{1/3}$$

Where:

K is a distance scaling factor (m/kg$^{1/3}$); and

NEW is the TNT equivalent weight of the propellant, or yield (kg).

The factor K is addressed in a number of publications. Two references provided by the US FAA are US DOD 6055.9-STD, *DOD Ammunition and Explosive Safety Standards* (August 1997) [11] and Chemical Propulsion Information Agency Publication 394, *Hazards of Chemical Rockets and Propellants* 30 June 1985) [12].

Different K-factor values can be used to find the radius for other peak incident overpressure levels, for example US DOD 6055.9-STD [11] states a K-factor of 20 corresponds to a 6.2 kPa overpressure threshold, a K-factor of 7.2 corresponds to a 24 kPa overpressure threshold, and a K-factor of 3.6 corresponds to a 82.7 kPa overpressure threshold.

As defined in section 4.10, $A_{c\ (explosive)}$ must be calculated to an explosive overpressure threshold of 25 kPa (overpressures of up to 65 kPa will be considered on a case-by-case basis).

NEW is the TNT equivalent weight of the propellant, or yield. It must be calculated differently for liquid and solid propellants, as defined in the previous subsections.

Graphical representation method

For estimating the probability of slight and severe casualties from a blast wave, the following effects were considered:

- Soft tissue effects – damage to lungs, GI tract, larynx, and eardrum (rupture for serious and temporary hearing loss for slight); and
- Whole Body Translation – general body impact only.

Lovelace data [18] for each of the soft tissue damages were used to define the combined pressure and impulse (P-I) associated with the 1 per cent (threshold) and 50 per cent probability of serious injury. These levels were then used to define probit functions for each effect. P-I diagrams for serious injury due to whole body translation were constructed using two different methods:

1. The Netherlands Organization of Applied Scientific Research (TNO) fatality probit function for whole body translation was scaled based on the ratio between the impact velocity for fatality and serious injury at the 50 per cent probability level. [19] The fatality-to-serious injury ratio was based on comparing the impact velocity at the 50 per cent probability level based on the Biodynamics/Engineering, Inc (BEI) skull fracture model for large masses. [20]

2. TNO fatality probabilities for a given P and I were directly translated to serious injury probabilities by using the ratio between casualty and fatality probability based on the BEI skull fracture model for large masses.

P-I diagrams for soft tissue and whole body translation effects and for slight injury, serious injury and fatality have been developed based on the methods described above. These P-I diagrams were then used to determine the effective casualty and fatality distance as a function of yield (NEW). Figure 21 and Figure 23 show the effective distance and a comparison against constant overpressure lines.

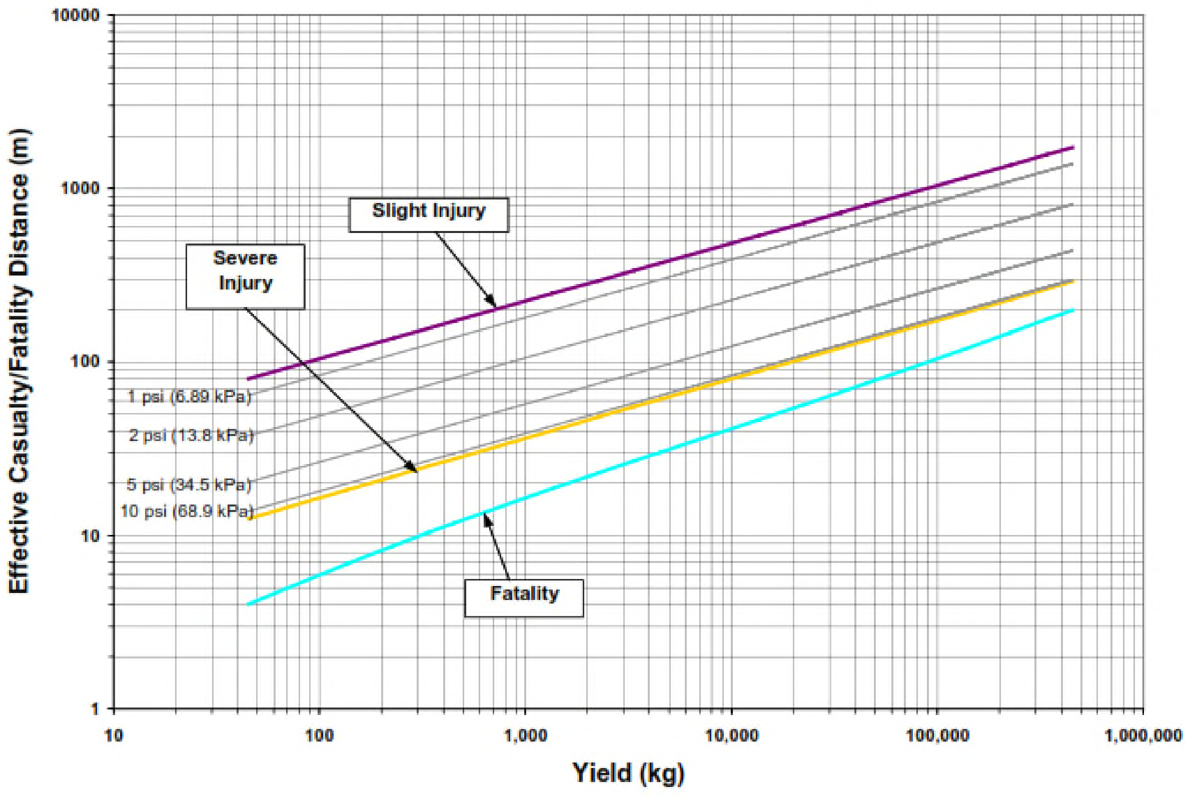

Figure 21. Casualty distance (radius for the explosive casualty area (R_e)) for people in the open exposed to a blast wave from an explosion

2. Explosive Debris Effects on People in Structures

Structures are usually thought of as providing protection to people from debris and blast waves. However, a blast wave can produce considerable harm to people inside the structure, either due to flying glass shards or elements (panels, etc.) of the structure itself.

Figure 22 shows the general approach adopted for systematically estimating casualty probabilities for explosive events. This approach [21] is very similar to one used in a WS Atkins study to determine fatality probability functions for structures subjected to vapour cloud explosions [22].

The steps shown in Figure 22 capture the basic phenomena that define the effects of air blast loading on a structure and its occupants:

- The blast loading on the structure is defined and the window glazing is checked for breakage.
- If breakage occurs, the flying shards are tracked and their impact on a building occupant is used to estimate their contribution to the probability of casualty given an explosive event occurs, [P(c|e)].
- After glass breakage occurs, the loads acting on the structure are revised to account for venting and the external cladding checked for failure. If wall or roof segments fail, the cladding debris is tracked and its impact on building occupants used to estimate their contribution to the probability of casualty.
- If the building is susceptible to collapse, the blast loads are revised again to reflect the potential for additional venting and the structure checked for collapse. If the building construction is susceptible to collapse, the impact of large building components striking occupants is used to estimate their contribution to the probability of casualty.
- The contributions due to glass breakage, debris throw and collapse are then combined.

Depending on the level of blast loading and the type of construction, the overall casualty probability may be dominated by glazing breakage alone, or from combinations of glass breakage, cladding failure and/or collapse.

Figure 23 includes the blast effect on occupants of a single structure type, a pre-engineered metal building with a particular glass area-to-floor area ratio. The curve shows that for large blast yields at a distance, it is more risky to be inside than outside. If the launch vehicle has the potential for a large explosion on impact, consideration should be given therefore to the risk to building occupants. The 2-psi (13.8 kPa) curve in Figure 23 offers a reasonable upper bound.

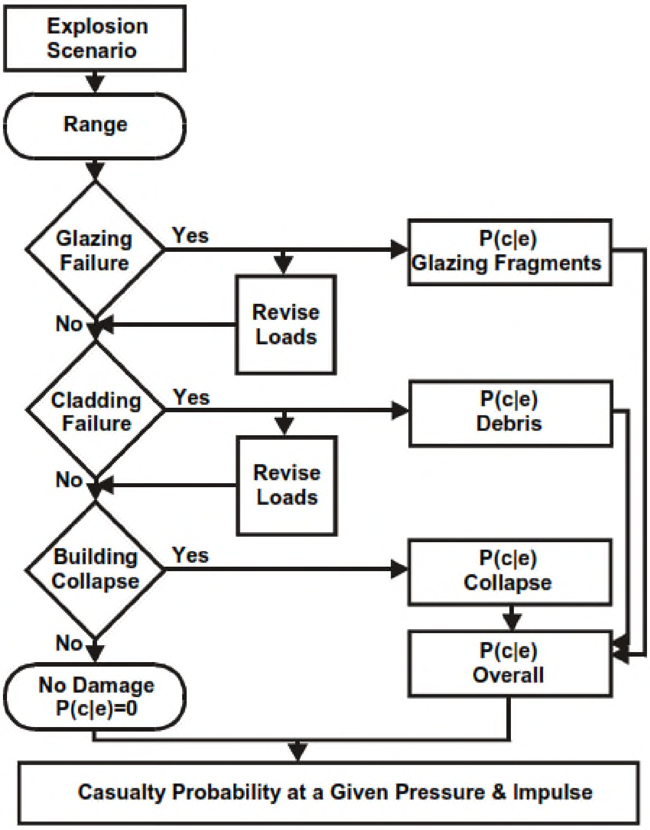

Figure 22. Steps for estimating casualty probability given an explosive event

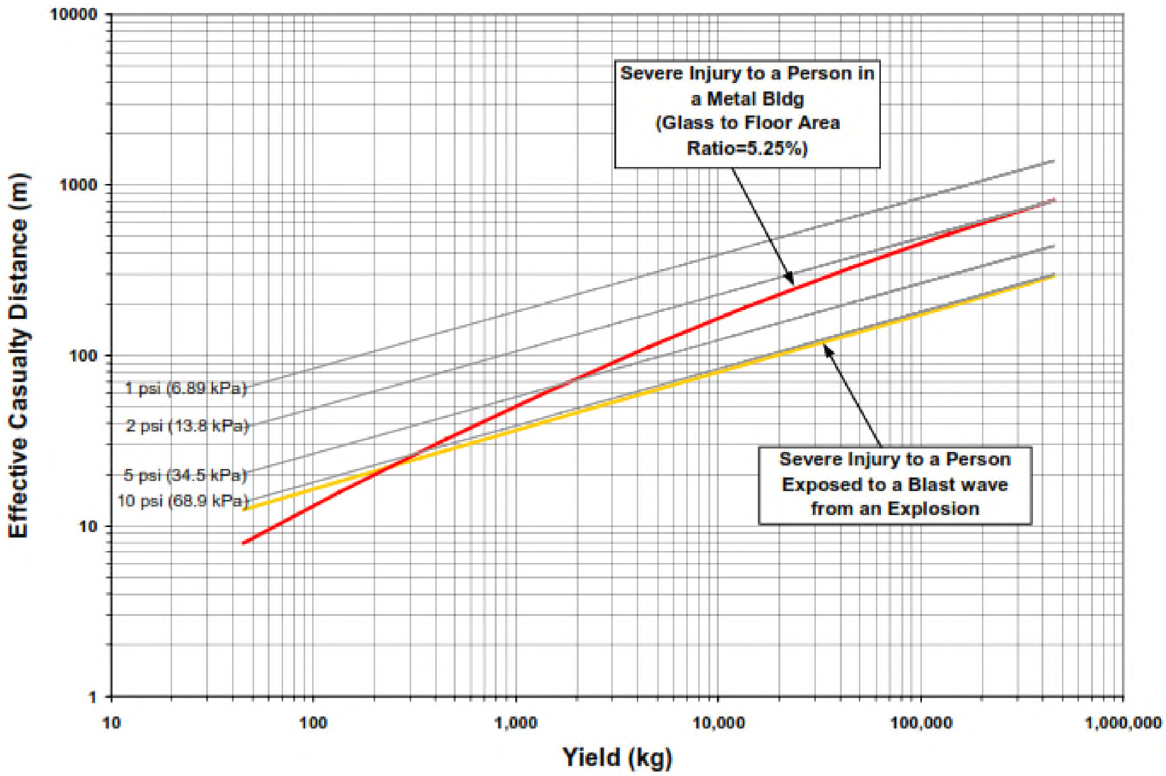

Figure 23. Casualty distance (<u>radius for the explosive casualty area (R_e)</u>) for people in the open or in a light structure exposed to a blast wave from an explosion

Appendix 2 – risk analysis examples

1. Vehicle Description

Consider a two-stage expendable launch vehicle with the following characteristics:

- First launch
  - Using the formula for P_f, probability of failure during the first launch is 0.25.
  - Assume that the total failure probability of each stage is equal, i.e. 0.125 (note that if other vehicle specific data are available that can improve the failure probability estimate, it should be used).
  - Assume that the failure probability during each stage is apportioned as follows:
    - Failure of the rocket motor to ignite – 10%
    - Failure of the guidance and control – leading to a malfunction turn away from the direction of the nominal velocity vector – 25%
    - Failure in the propulsion system leading to an explosion and break-up of the vehicle (on-course) – 50%.
- Liquid propelled (LOX and kerosene)
- First stage – 20 m x 3 m, inert weight = 6000 kg[14]
- Second stage and payload – 10m x 3 m, inert weight 5000 kg
- Impact range of first stage = 150 km
- Vacuum IIP rate at the time of jettison of the first stage – 2 km/sec
- Impact dispersions of the jettisoned first stage
  - Down-range standard deviation = 10 km
  - Crossrange standard deviation = 5 km
- Basic casualty area (no bounce, slide, skip, splatter, or angular impact)
  - Stage I - 900 m^2 (estimated from Appendix 1, Figure 15)
  - Stage II and payload - 600 m^2 (estimated from Appendix 1, Figure 15)
- Estimated number of fragments
  - Stage I –800 (estimated from Appendix 1, Figure 16)
  - Stage II and payload – 700 (estimated from Appendix 1, Figure 16)

[14] These numbers are purely for demonstration and may not be realistic

2. Determination of risk to an asset with catastrophic potential from the jettisoned first stage

Assume that the asset has the dimension of 100 m x 100 m. To compute the impact probability of the stage on the asset, find the nominal drag-corrected impact point for the stage and locate the position of the impact point relative to the asset location. For this example, assume that the mean impact point of the stage falls 10 km short and 4 km to the left of the asset.

The impact area for the computation is defined as the area of the asset increased by 1/2 booster length in each direction with a radius of 1/2 booster length filling in the corners. Using the equation in Section 4.9.4, the value of P_I for jettisoned stage impact on the asset is $P_I = 2.01 \times 10^{-5}$ (shown in the table from a spreadsheet that follows).

If the P_I is to be less than 1×10^{-6} (or any other criterion), the equation in section 4.9.5 can be rearranged as follows to place a minimum value on the allowable offsets (mean impact point of the stage), x and y.

The condition is satisfied if:

$$2\left(\ln\left(\frac{2\pi\sigma_x\sigma_y}{A}\right) + \ln(P_I)\right) \leq \left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2$$

Where P_I is an input parameter in the equation.

The values that satisfy this inequality for P_I = 1×10^{-5}, 1×10^{-6}, 1×10^{-7} and 1×10^{-8} for these particular values of A, x and y are shown in Table 12.

Table 12. Minimum value allowable to satisfy specified P_I

Required P_I	Minimum value of $\left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2$
1×10^{-5}	17.4
1×10^{-6}	27.6
1×10^{-7}	35
1×10^{-8}	41

Note, in the table that follows on the next page, that when computing P_I for a single person in the open, P_I is never larger than 8.77×10^{-7}. This would not be true if the impact uncertainties for the stage were reduced.

If the impact probability from the empty stage on a person standing in the open is needed, then the basic casualty area (not considering break-up, slide, roll, skid, splatter or angular impact) is the plan form of the stage plus 0.3 m all around.

This is approximated by the basic casualty area formulation in Appendix 1, that is:

$$A_{c\,(basic)(vertical)} = \pi \left(r_p + \sqrt{\frac{A_p}{\pi}} \right)^2$$

Where:

r_p is the radius of the "standard person" = 0.3 m; and

A_p is the projected area of the fragment = $(x + 2r_p) \times (y + 2r_p) = 74.16\ m^2$

Thus, for this case, $A_{c\,(basic)(vertical)} = 83.6\ m^2$.

If a multiplier of 4.36 is introduced for post impact behaviour, and if the stage falls at 5 degrees off the vertical, the equation expands to:

$$A_{c\,(inert)} = \pi \left(r_p + \sqrt{\frac{F_{skid} A_p}{\pi}} \right)^2 + 2 \left(r_p + \sqrt{\frac{F_{skid} A_p}{\pi}} \right) h \tan \alpha$$

Where:

r_p is the radius of the "standard person" = 0.3 m;

A_p is the projected area of the fragment = 74.16 m^2;

h is the height of the "standard person" = 2 m; and

α is the angle of the fragment = 5 degrees.

Therefore, the casualty area becomes $A_{c\,(inert)} = 346.4\ m^2$

Table 13, Table 14, and Table 15 provide example computations.

Table 13. Asset dimensions and stage impact dispersions

Asset length (m)	100
Asset width (m)	100
Downrange standard deviation (sigma x) (km)	10
Crossrange standard deviation (sigma y) (km)	5

Table 14. Casualty area computation for impacting a person

Impacting stage dimensions (m)	$x = 20\ m,$ $y = 3\ m$
Number of objects	$n = 1$
Radius of a standard person (m)	$r_p = 0.3\ m$
Height of a standard person (m)	$h = 2.0\ m$
Factor to account for bounce, skid, slide, etc.	$F_{skid} = 4.36$
Angle of impact (degrees off vertical)	$\alpha = 5\ deg$
Equivalent radius (including F_{skid}) (m)	$r_f = \sqrt{\frac{F_{skid} A_p}{\pi}} = 10.15\ m$
Projected area of fragment (m^2)	$A_p = (x + 2r_p) \times (y + 2r_p) = 74.16\ m^2$
Casualty area (m^2) (Using equation above)	$A_c = 346.4\ m^2$

Table 15. Sample computation of risks due to impacts of spent stages on assets with catastrophic potential

Area at risk	Asset Area (m^2)	Effective Impact Area (m^2)	DR Location in Drop Zone (x) (km)	CR Location in Drop Zone (y) (km)	(x+sqrt (A)) / Sigma x	(x-sqrt (A)) / Sigma x	P(x)	(y+sqrt (A)) / Sigma y	(y-sqrt (A)) / Sigma y	P(y)	Pi = P(x)*P(y)	Ec per Person on Significant Asset
Asset with catastrophic potential	10000	14314	0	0	5.98E-03	-5.98E-03	4.77E-03	1.20E-02	-1.20E-02	9.55E-03	4.56E-05	1.26E-06
	10000	14314	5	0	5.06E-01	4.94E-01	4.21E-03	1.20E-02	-1.20E-02	9.55E-03	4.02E-05	1.11E-06
	10000	14314	10	0	1.01E+00	9.94E-01	2.89E-03	1.20E-02	-1.20E-02	9.55E-03	2.76E-05	7.61E-07
	10000	14314	-10	4	-9.94E-01	-1.01E+00	2.89E-03	8.12E-01	7.88E-01	6.93E-03	2.01E-05	5.53E-07
	10000	14314	15	0	1.51E+00	1.49E+00	1.55E-03	1.20E-02	-1.20E-02	9.55E-03	1.48E-05	4.08E-07
	10000	14314	20	0	2.01E+00	1.99E+00	6.46E-04	1.20E-02	-1.20E-02	9.55E-03	6.17E-06	1.70E-07
	10000	14314	25	0	2.51E+00	2.49E+00	2.10E-04	1.20E-02	-1.20E-02	9.55E-03	2.00E-06	5.52E-08
	10000	14314	30	0	3.01E+00	2.99E+00	5.30E-05	1.20E-02	-1.20E-02	9.55E-03	5.06E-07	1.39E-08
	10000	14314	35	0	3.51E+00	3.49E+00	1.04E-05	1.20E-02	-1.20E-02	9.55E-03	9.97E-08	2.75E-09
Person		276	0	0	8.30E-04	-8.30E-04	6.62E-04	1.66E-03	-1.66E-03	1.32E-03	8.77E-07	
		6	5	0	5.01E-01	4.99E-01	5.84E-04	1.66E-03	-1.66E-03	1.32E-03	7.74E-07	
		6	10	0	1.00E+00	9.99E-01	4.02E-04	1.66E-03	-1.66E-03	1.32E-03	5.32E-07	
		6	15	0	1.50E+00	1.50E+00	2.15E-04	1.66E-03	-1.66E-03	1.32E-03	2.85E-07	
		6	20	0	2.00E+00	2.00E+00	8.96E-05	1.66E-03	-1.66E-03	1.32E-03	1.19E-07	
		6	25	0	2.50E+00	2.50E+00	2.91E-05	1.66E-03	-1.66E-03	1.32E-03	3.85E-08	
		6	30	0	3.00E+00	3.00E+00	7.36E-06	1.66E-03	-1.66E-03	1.32E-03	9.74E-09	
		6	35	0	3.50E+00	3.50E+00	1.45E-06	1.66E-03	-1.66E-03	1.32E-03	1.92E-09	

Notes:

(1) If more than one identical objects are impacting, the total P_I for N objects is:

$$P_I = 1 - (1 - P_I)^N$$

(2) When the area to be impacted is much larger than the jettisoned stage, the impact area is defined as the area of the structure (e.g., an oil platform) increased by 1/2 stage length in each direction with a radius of 1/2 stage length filling in the corners.

(3) The impact area for a person is the same as the casualty area since impact by an object of this size can be assumed to always produce a casualty.

Table 16. Offset requirements to keep P_I below specified level

Computation of offset required to maintain P_I less than specified value for an area that is large relative to the jettisoned stage					
P_I value =	1.00E-05	1.00E-06	1.00E-07	1.E-08	1.00E-09
σ_x (km) =	10	10	10	10	10
σ_y (km) =	5	5	5	5	5
impact area (km^2))=	1.43E-02	1.43E-02	1.43E-02	1.43E-02	1.43E-02
$\left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2 >$	3.03	7.64	12.24	16.85	21.45
If $y = 0$ then $x >$	17.4	27.6	35.0	41.0	46.3
x/σ_x =	1.7	2.8	3.5	4.1	4.6
Computation of offset required to maintain PI less than specified value for a single person standing in the open with the jettisoned stage breaking up upon impact					
P_I value =	1.00E-05	1.00E-06	1.00E-07	1.E-08	1.00E-09
σ_x (km) =	10	10	10	10	10
σ_y (km) =	5	5	5	5	5
impact area (km^2))=	2.76E-04	2.76E-04	2.76E-04	2.76E-04	2.76E-04
$\left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2 >$	Not poss.	Not poss.	4.34	8.95	13.55
If $y = 0$ then $x >$	Not poss.	Not poss.	20.8	29.9	36.8
x/σ_x =	Not poss.	Not poss.	2.1	3.0	3.7

Adjustment for Failure Probability

Technically, any vehicle that fails prior to staging will not present a risk from a jettisoned stage. In this case, it was assumed that the vehicle would fail during first stage flight with a probability of 0.125. Therefore, the probability of jettisoning an empty stage should be 0.875 not 1.0. Presumably then, all of the impact probability figures associated with an empty stage presented in this section should be lowered by multiplying the P_I by 0.875.

Failure of the Next Stage to Start

At staging, the first stage is jettisoned and the second stage rocket engines are ignited. If these engine(s) fail to ignite, the second stage will fall in the general region of the jettisoned first stage. The difference will be that the second stage will be full of propellant, have a higher ballistic coefficient and may break up depending upon either the action of the abort system or aerodynamic loads. The probability of this event will be the probability of having succeeded during the first stage of flight, but failing at the beginning of the second. Therefore:

$$P_f = 0.875 \times 0.125 \times 0.10 = 0.0109$$

Next, looking at each case:

1. If the vehicle is aborted and the propellants are jettisoned, then the risks are similar to those of an empty stage. Note that the dimensions of the stage will be different than that of the jettisoned first stage and the nominal impact point and impact dispersions may be different because of differences in the ballistic coefficient, wind effects, etc. Since the fuel jettison takes time, the ballistic coefficient will be changing as the propellant mass in the vehicle is being reduced.

2. If there is no abort, and no vehicle break-up, the stage can impact intact and explode. The rules for computing yield from an explosion upon impact are described in Appendix 1. The extent of damage from an explosion is based upon overpressure and impulse from the explosion. If there is no capability to evaluate damages to the asset more precisely, use 25 kPa as the overpressure which if exceeded will produce unacceptable damage or casualties.

3. If the stage is destroyed or breaks up aerodynamically, the propellants will be dispersed, but the casualty area will now have to take into consideration many inert pieces. The casualty area, based on weight of inert debris should fall within the range shown in Appendix 1. Appendix 1 also has a range of number of pieces as a function of total inert debris weight. When a stage or vehicle breaks up, the impact probability computation must consider the fact that the pieces spread and impact over a wider area. A simple model for computing impact probability is to divide the total casualty area by the number of pieces; this will give a single reference casualty area. Then compute the impact probability of that single piece assuming that the impact dispersions are the same for all pieces. This is not a particularly robust assumption because each fragment or fragment group could have a different mean impact point and different values for their impact dispersions. If this could have a serious effect on the conclusions of a risk analysis, then a more complete study involving debris details, trajectories and dispersions must be performed.

   However, to demonstrate the effect of multiple debris pieces, this example will be continued. Assume a total inert debris mass of 6000 kg that represents approximately 800 pieces with an average fragment weight of 7.5 kg. Based on Figure 15 in Appendix 1, it appears that a debris mass of 6000 kg will have a total basic casualty area of 900 m^2 based on the chart of the results of past practice. Divided by 800, the average basic casualty area is 1.1 m^2. For the case of assessing whether any fragment strikes an asset with catastrophic potential, then the dimension of a human in the basic casualty area equation must be removed.

Since: $A_{c\,(basic)(vertical)} = \pi \left(r_p + \sqrt{\frac{A_p}{\pi}} \right)^2$, the adjusted casualty area is:

$$A' = A_p = \pi \left(\sqrt{\frac{A_c}{\pi}} - r_p \right)^2 = \pi \left(\sqrt{\frac{1.1}{\pi}} - 0.3 \right)^2 = 0.267\, m^2$$

Adding the radius associated with this dimension around the 100m x 100 m asset with catastrophic potential gives the effective impact area associated with a small fragment hitting the asset. Using the same procedure as that for a spent stage, compute the impact probability of the smaller fragment on the asset. Then assume that all fragments are statistically independent of each other.

The probability of at least one fragment impacting on the asset with catastrophic potential is $P_{IN} = 1 - (1 - P_I)^N$ where P_I is the impact probability on the asset with catastrophic potential for a single fragment and N is the number of fragments. This P_{IN} is conditional upon the probability of the second stage motor failing to ignite and the probability that the stage will break up either due to abort action or aerodynamic loads.

The lesson from the above exercise is that breaking up into many pieces increases the impact probability. On the other hand, however, the consequence of impact from any of many pieces is much less than the consequence of impact of a single intact stage and payload, with a potential ensuing explosion.

3. Determination of risk to an asset with catastrophic potential and/or people from the failure of vehicle during powered flight (downrange beyond the launch area)

Downrange risks can be computed with the corridor model suggested in section 4.9.8. This model operates, like the jettisoned stage model, with separate impact probability computations in the downrange and crossrange directions. Like the former, the crossrange uncertainty is represented by a normal distribution. However, in the downrange direction, the distribution is represented by selecting an interval of distance along the locus of the IIP[15] and computing the probability that the vehicle will fail during the time that the IIP is within the interval. In this model, the interval distance is the square root of the area of a particular population centre. The crossrange impact probability is calculated using the distances from the mean path of the IIP to the inner and outer edges of the population centre. The population centre is usually assumed to be square for convenience of computation.

Table 17 shows that the failure rate during flight is 0.0005625. If this is during second stage flight, and the first stage had a failure probability of 0.125, and the start-up failure probability for the second stage is 0.125 x 0.057 = 0.007125, then the failure rate below is reduced accordingly.

[15] The IIP is assumed to be based on drag corrected impacts of the intact stage and payload.

Table 17. Failure rate computations

Vehicle failure probability $P_f = (ax + r)/(x + n)$	$P_f = 0.25$ $a = 0.25$
Parameters used in vehicle failure probability computation	$x = 4$ $r = 0$ $n = 0$
Powered flight time – ½ each stage (s)	$t_p = 400$
Total start-up failure probability (both stages)	$P_{su} = 0.01425$
Average failure rate (failures/s)	$fr = 0.0005894$

Table 18 provides parametrically:

1. The impact probability of an intact empty second stage and payload (flight aborted, but the vehicle not broken up and not containing propellant at impact); and
2. The risk to a single person on the asset.

If we assume that:

- The crossrange uncertainty of the IIP of the second stage and payload is 2 km;
- The IIP rate is 1 km/sec; and
- The offset of the IIP from the asset is 4 km;

then the impact probability of the stage and payload on the asset (from the tables) is 2.0×10^{-7}.

If we want to find the crossrange position of the locus of IIP that produces a $P_I = 1 \times 10^{-6}$, interpolate the values in the table, giving a result of approximately 1.54 km cross range as follows.

$$y_c = y_1 + \frac{P_I - P_{I_1}}{P_{I_2} - P_{I_1}} \times (y_2 - y_1) = 4 + \frac{1 \times 10^{-6} - 2.0 \times 10^{-7}}{1.5 \times 10^{-6} - 2.0 \times 10^{-7}} \times (0 - 4) = 1.54\ km$$

The comments about explosive or aerodynamic break-up of the stage discussed in the previous section apply here. Having many pieces instead of one will raise the impact probability. However, the individual effect of a single fragment will be much less than the effect of the entire stage and payload.

This entire process can be applied to many population centres, not just one. The best approach is to first determine the total population of an area of concern. Then subtract the total population of all of the identified communities from the total population of the area at risk to determine the population in the countryside. The countryside can then be divided into large areas with very low populations, with each area being treated as a population centre. The casualty area for these population centres does not need to take into account fragment dimensions to compute impact probability, the contribution is too small.

Table 18. P_I and E_c using corridor model for various IIP rates, crossrange standard deviations and offsets of an asset with catastrophic potential from the nominal locus of the IIP.

Crossrange standard deviation of locus of IIP = 2 km		IIP Rate (IIPR) (km/s)					
		1		2		3	
		PI	Ec/pers	PI	Ec/pers	PI	Ec/pers
Offset of Asset from Nominal IIP (yc) (km)	0	1.5E-06	2.4E-08	7.4E-07	1.2E-08	3.0E-07	4.7E-09
	4	2.0E-07	3.2E-09	1.0E-07	1.6E-09	4.0E-08	6.4E-10
	8	5.0E-10	8.0E-12	2.5E-10	4.0E-12	9.9E-11	1.6E-12
	12	2.3E-14	3.6E-16	1.1E-14	1.8E-16	4.5E-15	7.3E-17
	16	2.2E-20	3.4E-22	1.1E-20	1.7E-22	4.3E-21	6.9E-23
	20	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Crossrange standard deviation of locus of IIP = 4 km		IIP Rate (IIPR) (km/s)					
		1		2		3	
		PI	Ec/pers	PI	Ec/pers	PI	Ec/pers
Offset of Asset from Nominal IIP (yc) (km)	0	7.4E-07	1.2E-08	3.7E-07	5.9E-09	1.5E-07	2.4E-09
	4	4.5E-07	7.2E-09	2.2E-07	3.6E-09	9.0E-08	1.4E-09
	8	1.0E-07	1.6E-09	5.0E-08	8.0E-10	2.0E-08	3.2E-10
	12	8.2E-09	1.3E-10	4.1E-09	6.6E-11	1.6E-09	2.6E-11
	16	2.5E-10	4.0E-12	1.2E-10	2.0E-12	5.0E-11	7.9E-13
	20	2.8E-12	4.4E-14	1.4E-12	2.2E-14	5.5E-13	8.8E-15

Crossrange standard deviation of locus of IIP = 8 km		IIP Rate (IIPR) (km/s)					
		1		2		3	
		PI	Ec/pers	PI	Ec/pers	PI	Ec/pers
Offset of Asset from Nominal IIP (yc) (km)	0	3.7E-07	5.9E-09	1.8E-07	3.0E-09	7.4E-08	1.2E-09
	4	3.3E-07	5.2E-09	1.6E-07	2.6E-09	6.5E-08	1.0E-09
	8	2.2E-07	3.6E-09	1.1E-07	1.8E-09	4.5E-08	7.2E-10
	12	1.2E-07	1.9E-09	6.0E-08	9.6E-10	2.4E-08	3.8E-10
	16	5.0E-08	8.0E-10	2.5E-08	4.0E-10	1.0E-08	1.6E-10
	20	1.6E-08	2.6E-10	8.1E-09	1.3E-10	3.2E-09	5.2E-11

Other Considerations

If the vehicle impacts intact, the crossrange dispersions are primarily due to normal guidance and performance variations, wind dispersions, and possibly dispersion due to a malfunction turn. The problem gets much more complicated if the vehicle breaks up. The many pieces of debris will vary in size and ballistic coefficient, they will have different velocity impulses due to any explosion, and they will all be affected by any vehicle malfunction turn. The more effective way of doing this analysis is to divide up the debris into categories that have commonality in ballistic coefficient and velocity impulse for each category. Then compute a drag-corrected IIP for each of the different categories. These drag-corrected IIPs will have different arrival times, and may be offset from one another because of wind and earth rotation effects. The risk analysis is then performed for each debris category, for all population centres, and then summed.

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