Australian Government | Australian Space Agency

MAXIMUM PROBABLE LOSS METHODOLOGY

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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 Maximum Probable Loss Methodology to align with the *Space (Launches and Returns) Act 2018* and the associated *Space (Launches and Returns) (Insurance) Rules 2019*.

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1 Introduction

1.1 Overview

1.1.1 This document sets out the methodology to be used to calculate the maximum probable loss that might occur due to certain launch and return activities.

1.1.2 The *Maximum Probable Loss Methodology* may be used to determine the insured amount (insured amount is defined in the *Space (Launches and Returns) Act 2018*).

1.1.3 The Act specifies that the minimum amount of insurance is at least equal to the lesser of:

- An amount specified in the rules;
- An amount determined using a method specified in the rules.

1.1.4 The *Maximum Probable Loss Methodology* is the method specified in *Space (Launches and Returns) (Insurance) Rules 2019*.

1.1.5 Maximum probable loss (MPL) is a risk-based analysis that is designed to capture the greatest potential loss for bodily injuries and property damages that can reasonably be expected to occur as a result of launch or re-entry activities. MPL measures probabilities, not possibilities, to identify events that are sufficiently probable as to warrant financial responsibility to cover their consequences. Insurance requirements based on MPL calculations are established at a level that provide financial protection against the consequences of events that are deemed sufficiently probable under the methodology.

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 *Maximum Probable Loss Methodology* uses a number of terms that are unique to the space launch industry and which have meanings of particular relevance in this document. Terminology is therefore defined as set out below and should be read in context of this document. For further definitions, see the *Space (Launches and Returns) Act 2018*.

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

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

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.

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.

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

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

flight path: the path in air or space followed by the launch vehicle.

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 key: the entry point of a space object for landing operations, usually high above the landing site, or nearly so, at which parachute deployment or other landing manoeuvres are initiated.

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

high-value asset: A high-value asset is one for which the maximum probable loss values for property damage, loss of use and environmental damage and clean-up calculated using the gross bounding approach would be inappropriate.

impact limit lines: the limits within which all debris created by activation of the flight safety system should be contained.

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

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.

insured amount: for an Australian launch permit, Australian high power rocket permit, overseas payload permit or return authorisation, means the amount for which the holder of the permit or authorisation is required to be insured under Division 7 of Part 3 of the Act in respect of the launch or launches, and any return, covered by the permit or authorisation. In determining this amount, disregard paragraph 47 (2) (b) of the Act (which deals with direct financial responsibility).

launch: defined in the *Space (Launches and Returns) Act 2018* 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 area: the place where the launch of a space object or high power rocket occurs.

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.

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.

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

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.

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

space object: defined in the *Space (Launches and Returns) Act 2018* 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.

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

2.2 Acronyms and abbreviations

2.2.1 This *Maximum Probable Loss Methodology* uses a number of acronyms which are unique to the space launch industry and which have meanings of particular relevance in this document.

ELV: expendable launch vehicle

EFFBD: enhanced functional flow block diagram

FSS: flight safety system

GDP: gross domestic product

IA: impact area

IIP: instantaneous impact point

ILL: impact limit line

MPL: maximum probable loss

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

3 Standard for probability of impact threshold to calculate MPL

3.1 Overview

3.1.1 The maximum probable loss (MPL) value must be sufficient to cover financial liabilities arising from injuries to third-party persons and damages to properties from all launch or return mishaps that are reasonably likely to occur.

3.1.2 A probability of impact threshold is used as a quantitative measure to distinguish unlikely events from those that are sufficiently likely to warrant inclusion in the MPL.

3.2 Standard

3.2.1 The threshold for this maximum probable loss methodology is set at a probability of impact of:

1×10^{-7} (1 in 10 million).

3.2.2 With the threshold approach, insurance requirements can be expected to cover the full costs of all accidents within the selected threshold.

4 Methodology overview

4.1 Overview

4.1.1 The steps comprised in the generalised MPL process are described in this section and presented graphically in Figure 1, Figure 2, and Figure 3. These figures are enhanced functional flow block diagrams (EFFBD) with the following characteristics:

- White rectangles are activities that are required to be performed to calculate the maximum probable loss and are comprised of an activity reference ID (top), activity description (middle), and the section reference in the MPL;
- The grey ovals are inputs and outputs from the activity; and
- Circles with 'IT' are iteration loops, whereby the activities are performed repeatedly for the number of iterations required by the line connecting the 'IT' circles.

4.1.2 The complete MPL process can be thought of as a two-phase process. During the first phase the applicant needs to gather all the relevant information to develop the MPL evaluation, while during the second phase the applicant combines all the information and then develops the MPL valuations.

4.1.3 Intermediate MPL valuations are made separately for third-party losses for each phase of flight (uprange, downrange, and return). Even when the determination is made that the risk to the public, during any given phase, is beyond the specified probability of impact threshold, the applicant should state this to avoid the appearance of having skipped or overlooked an aspect of the analysis.

4.1.4 The final MPL valuation will be the highest values obtained for all the phases of flight considered.

4.1.5 More broadly, the applicant is required to estimate third-party losses for the phases of flight (uprange, downrange and return) in the following manner;

- For each flight phase, develop the probability of impact isopleths based on the failure modes and break-up model for the vehicle, which is available from the risk hazard analysis calculations from the *Flight Safety Code*;
- Develop the casualty areas corresponding to the vehicle failure response modes which is also available from the risk hazard analysis calculations from the *Flight Safety Code*;
- Calculate the area defined by the 10^{-7} probability of impact isopleths;
- Overlay the casualty area over population centres within the 10^{-7} probability of impact isopleth and calculate the casualties;
- Use this casualty calculation to calculate the MPL contribution property loss;
- Calculate the MPL contributions due to loss of use;
- Calculate the MPL contributions due to environmental damage;

- Calculate specific MPL assessments for accident scenarios involving specific high-value assets within the 10^{-7} probability of impact isopleth for:

    - Property damage,

    - Loss of use, and

    - Environmental damages.

- Identify the highest MPL value across all mishap scenarios based on the total MPL derived from the contributions from casualties, from property loss, and any from environmental damage and clean-up as well as loss of use; and

- Finally, complete the MPL assessment and fill out the example form in section 8.

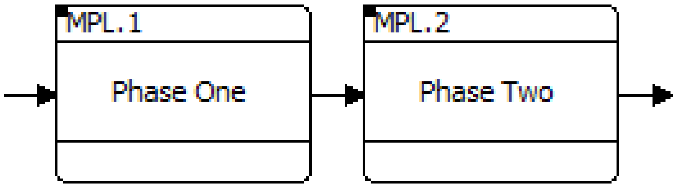

Figure 1. MPL methodology phases

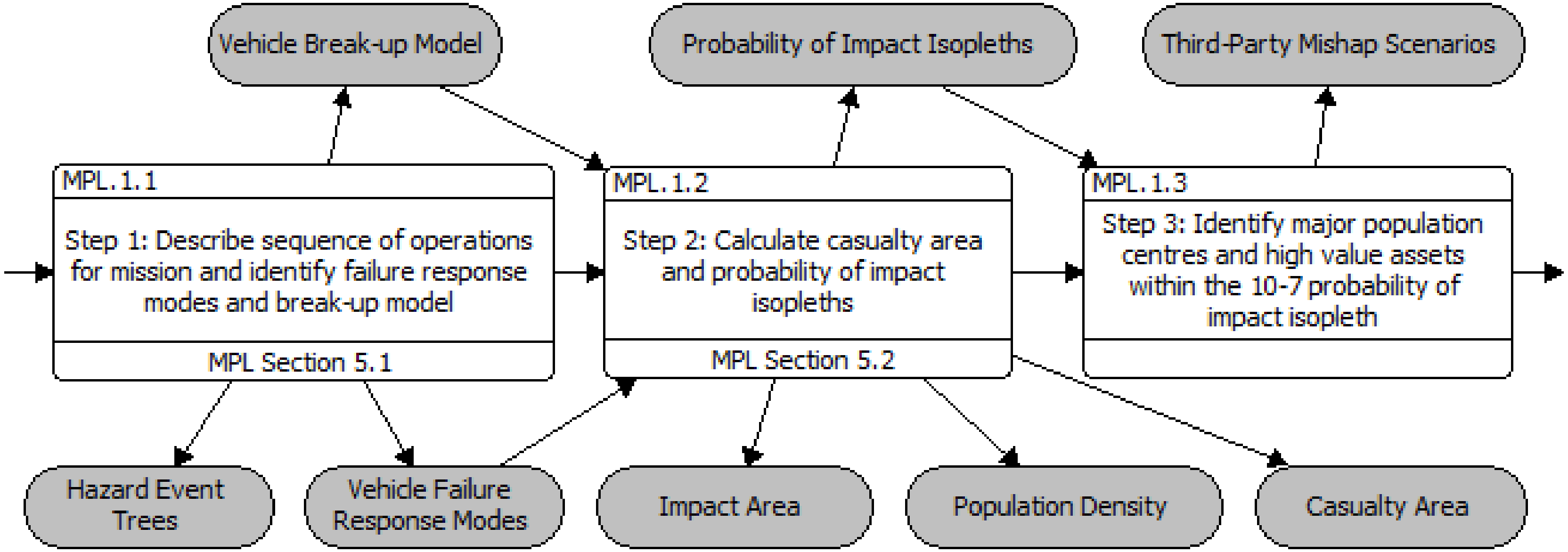

Figure 2. MPL methodology phase one

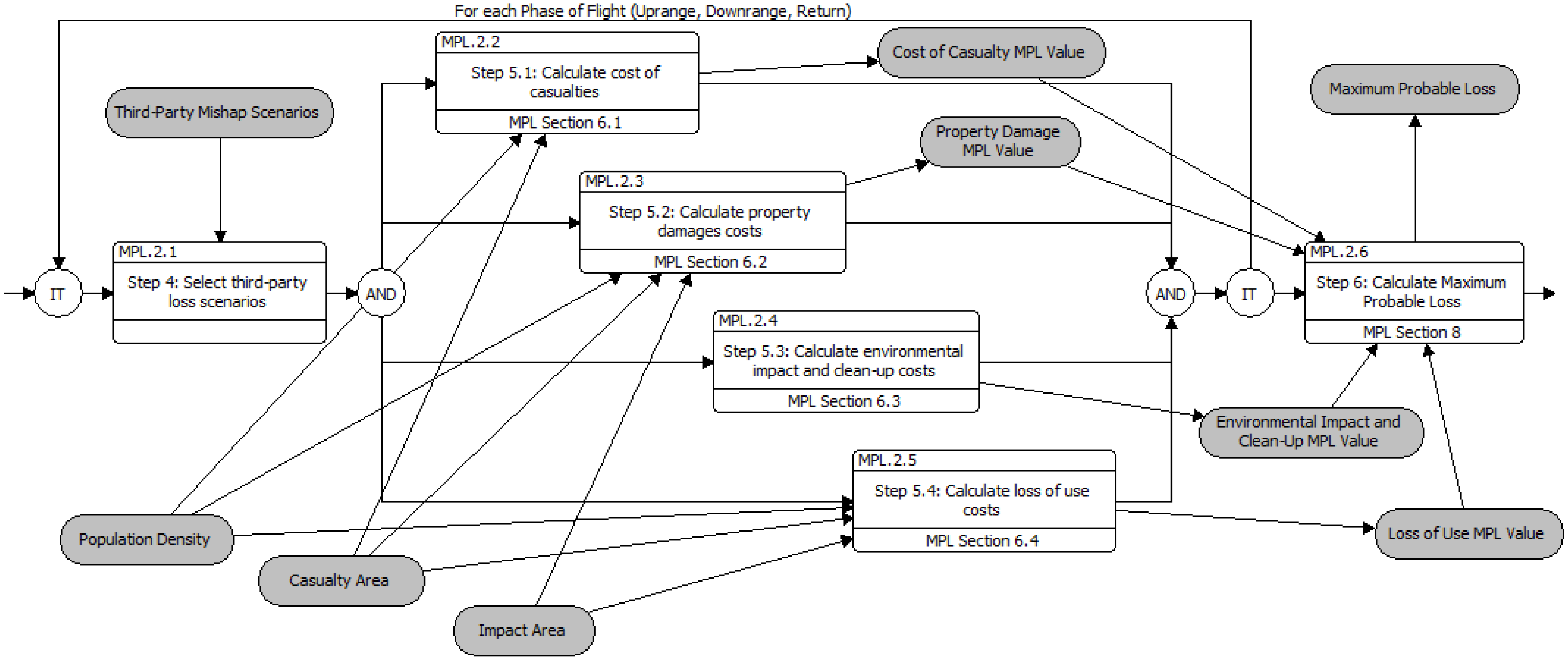

Figure 3. MPL methodology phase two

4.2 Phase one: risk hazard analysis and mishap identification

4.2.1 **Step 1:** Understand and describe the sequence of operations for the entire mission, including identification and evaluation of the vehicle failure response modes, and the vehicle break-up model. Section 5.1 of the MPL Methodology provides example hazard event trees that can be used to describe the sequence of operations for the mission and identify failure response modes, and section 4.7 of the *Flight Safety Code* describes how to determine failure response modes for the flight vehicle in more detail. This process needs to be covered in detail while doing the risk hazard analysis in the *Flight Safety Code*; therefore, if the risk hazard analysis has been conducted, use vehicle failure response modes and the vehicle break-up model from that process for this step.

4.2.2 **Step 2:** Develop the casualty areas corresponding to the vehicle failure response modes, and the 10^{-7} probability of impact isopleths for uprange, downrange, and return phases of flight as appropriate. If the risk hazard analysis from the *Flight Safety Code* has been conducted for the launch or return, the casualty areas and the probability of impact isopleths will already have been developed and should be used in the MPL methodology. Probability of impact isopleths define areas that that will contain all the impacts from debris resulting from any possible mishap, to within the 10^{-7} probability of impact threshold. In other words, the probability of any debris falling outside the identified area is smaller, or more remote, than 1 in 10,000,000.

4.2.3 **Step 3:** Determine the third-party persons, population centres, and property at risk for all phases of flight (uprange, downrange, and returns), and identify all the major population centres, and high-value assets within the 10^{-7} probability of impact isopleth that are likely to result in significant financial damages by a debris impact scenario. For the analysis, the MPL will be based on an assumption that a mishap *will* occur and *will* place people and property at risk.

4.3 Phase two: calculating MPL in each loss category

4.3.1 **Step 4:** Screen out mishap scenarios with low losses relative to other scenarios that create higher losses within each phase of flight (uprange, downrange, and return). In other words, find the highest risk drivers for each phase of flight (i.e., the highest population centres and the highest value assets) and do not spend time assessing losses from mishaps that cause comparatively minor damage or occur in less densely populated areas. Low-loss scenarios are screened out – they are superseded by the highest loss scenario for each failure mode unless there is a chance that the low loss and higher loss events are not mutually exclusive. Loss events that are not mutually exclusive (i.e., they can occur due to the same failure event) must be aggregated together to account for all potential losses from the same failure event.

4.3.2 **Step 5:** For each mishap scenario identified in step 4, calculate MPL in each loss category, including:

- Cost of casualties,
- Property damage,
- Loss of use, and
- Environmental damage and clean-up.

For the case where multiple, mutually exclusive losses might occur, investigate each scenario to determine the one that results in the greatest loss within the 10^{-7} probability of impact isopleth.

4.3.2.1 **Step 5.1: Calculate the cost of casualties**: Identify the highest potential third-party casualty losses by overlaying the casualty area over the highest population density identified in the mishap scenario within the 10^{-7} probability of impact isopleth.

4.3.2.2 **Step 5.2: Calculate property damage costs**: To estimate third-party property loss, use whichever of the following two methods provides the higher MPL value:

1. 50 per cent of the cost of casualties defined in Step 5.1; or
2. If there is a particular high-value asset within the 10^{-7} probability of impact isopleth, make an accurate engineering evaluation of the property damage costs due to potential impacts.

4.3.2.3 **Step 5.3: Calculate loss of use**: For loss of use, the applicant will use whichever value is higher from the following two methods:

1. The value obtained by multiplying the per capita gross domestic product (GDP) of the country where the casualties may occur, by the number of casualties estimated; or
2. If there is a particular high-value asset within the 10^{-7} probability of impact isopleth, make an accurate engineering evaluation of the costs associated with loss of use due to potential impacts.

4.3.2.4 Note that the costs associated with loss of use include the cost of consequential damages that might result from the mishap, such as the costs associated with loss of supply to customers, other business losses due to inability to operate the facility, etc.

4.3.2.5 **Step 5.4: Estimate environmental impact costs**: To estimate the costs associated with environmental damage and clean-up, use whichever of the following two methods provides the higher MPL value:

1. $170,000; or
2. If there is a particular high-value asset within the 10^{-7} probability of impact isopleth facing an impact that would result in environmental damage, make an accurate engineering evaluation of the costs associated with restoring the environment to the condition which would have existed if that damage had not occurred.

4.3.2.6 Note that the environmental and clean-up costs include the cost of consequential damages that might result from the mishap such as an oil spill. The consequential damages include the direct effects of the debris impact on the facility and the consequences of those impacts on the facility, such as those that may result in the release from the facility of toxic, hazardous or polluting materials.

4.3.3 **Step 6:** Determine the total MPL value for third-party losses by adding the highest values obtained for cost of casualties in Step 5.1, property damage in Step 5.2, loss of use in Step 5.3, and environmental impacts and clean-up costs in Step 5.4.

4.3.4 This completes the MPL calculations for a single mishap scenario. These steps need to be repeated for each mishap scenario within each phase of flight. The highest value MPL out of each scenario represents the total MPL for the launch or return.

4.3.5 Finally, it cannot be overemphasised that the MPL process, because of the remoteness of the threshold, all but assumes the occurrence of a mishap that places at risk the highest population density within the area defined by the probability of impact threshold. Extensive or rigorous modelling at the tail of any normally distributed function becomes highly subjective and dependent on the mathematical models used, but the results of such scrutiny do not yield results more logical or understandable than a simplified analysis that uses a gross bounding criterion, as does this generic MPL methodology.

5 Phase one: risk hazard analysis and mishap identification

5.1 Understand and describe sequence of operations for the mission and evaluate vehicle failure response modes and break-up model

5.1.1 The first step required for the MPL methodology is for the applicant to understand and describe the sequence of operations for the entire mission, and identify and evaluate the vehicle failure response modes and vehicle break-up models.

5.1.2 Understand and describe the sequence of operations:

5.1.2.1 A hazard event trees is one method widely used for describing the sequence of operations for a mission and identifying failure response modes.

5.1.2.2 An illustrations of a simple hazard event tree for a generic launch mission is described in Figure 4 and Table 1, where:

- Figure 4 is the illustration of a generic launch hazard event tree,
- Table 1 describes the event tree nodes in further detail; and
- Section 5.1.3 describes the detail of the outcomes identified in Figure 4

5.1.2.3 The applicant may develop similar hazard event trees for their particular vehicle to describe the sequence of operations for the mission. Figure 5 and Figure 6 are provided as useful examples of the simple event trees the applicant may want to use where applicable. These event trees can be helpful in understanding the risk profile of the launch or return.

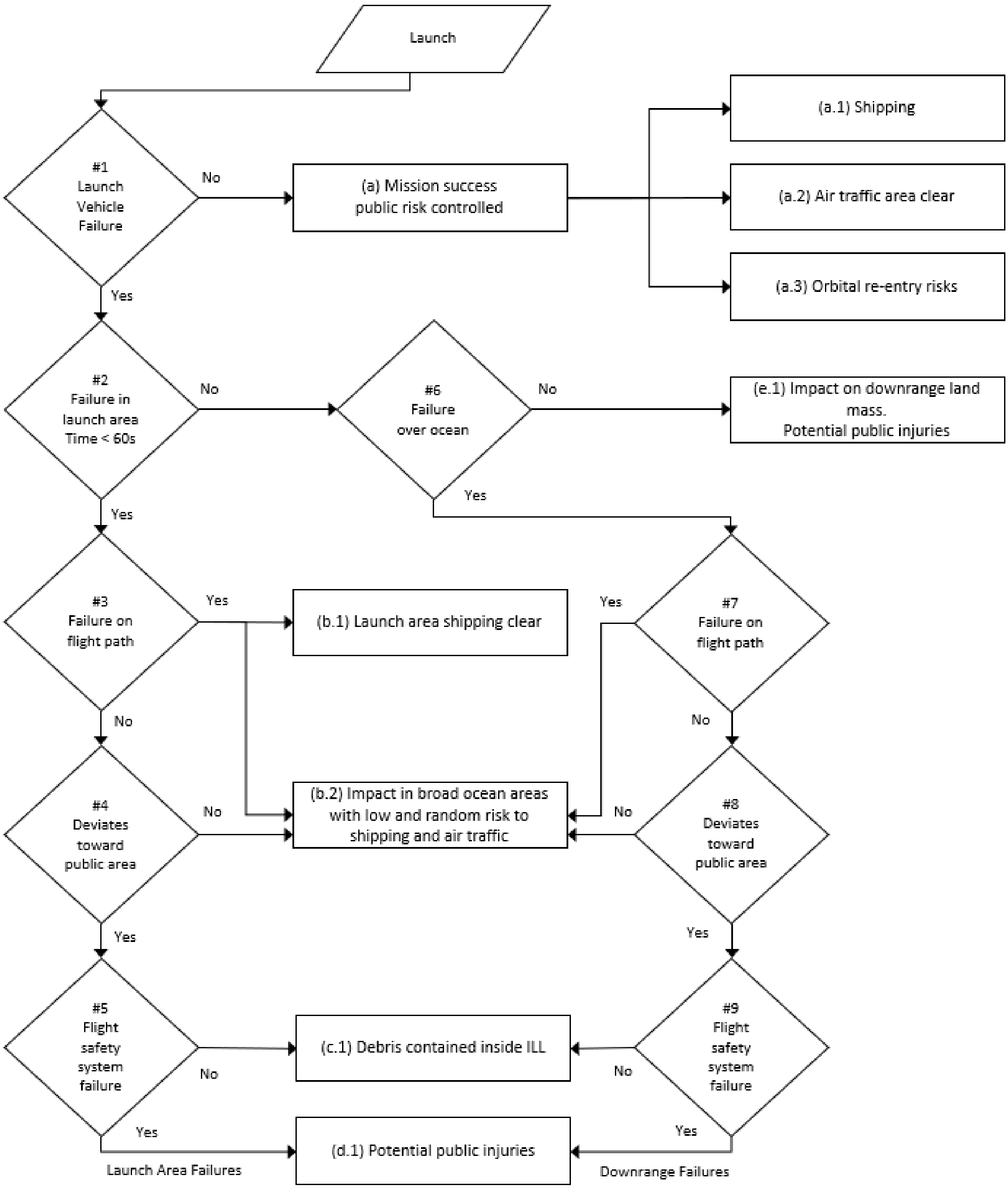

Figure 4. Generic launch hazard event tree

Table 1. Generic launch hazard event tree nodes

Event tree node	Description
1. Launch vehicle failure	Probability that launch vehicle will fail; that is, that the flight will not be successful. YES path= P (launch vehicle failure) NO path = 1-P (launch vehicle failure)
2. Failure in launch area	Probability of a failure in the launch area during the early flight phase, typically within 60 seconds after launch. $0 < T < 60$. YES path = P (failure in launch area) NO path = 1-P (failure in launch area)
3. Failure on flight path	Probability of failure occurring on the nominal flight path. YES path = P (failure on original flight path) NO path = 1-P (failure on original flight path)
4. Deviates off nominal flight path toward public areas	Probability of deviation from nominal flight path toward populated areas protected by impact limit lines (ILLs) set in the flight safety system. YES path = P (deviates towards public areas) NO path = 1-P (deviates towards public areas)
5. Flight safety system fails	Probability that the flight safety system (FSS) will fail; that is, 1-(reliability of the specific FSS being used). YES path = P (FSS failure) NO path = 1- P (FSS failure)
6. Failure over ocean areas	Probability that flight failure will occur over ocean areas; that is, 1-(probability that failure will occur during overflight of populated downrange land masses). YES path = P (failure over open ocean) NO path = 1- P (failure over open ocean)
7. Failure on flight path	Probability of failure occurring on the nominal flight path and will not deviate toward public areas. YES path = P (failure on original flight path) NO path = 1- P (failure on original flight path)
8. Deviates toward public areas	Probability of deviation toward populated areas. YES path = P (deviates towards public areas) NO path = 1-P (deviates towards public areas)
9. Flight safety system fails	Probability that the flight safety system (FSS) will fail. YES path = P (FSS failure) NO path = 1-P (FSS failure)

5.1.3 Generic launch hazard event tree outcomes are as follows:

(a) **Mission success, public risks controlled**. *May directly follow event node 1.*

- (a.1) **Shipping.** Risks to shipping from booster or other discarded debris impacting within planned areas is controlled
- (a.2) **Air traffic, area clear.** Planned air traffic exposures.
- (a.3) **Orbital re-entry risks.** Risks to third parties on-orbit or from eventual decay from orbit controlled.

(b) *May directly follow event nodes 3, 4, 7 and 9.*

- (b.1) **Launch area shipping clear.** Risks to shipping in the ocean area near the launch site are low.
- (b.2) **Impact in broad ocean area — low and random risk to shipping and air traffic.** Random risk to shipping and air traffic in the broad ocean areas.

(c) *May directly follow event nodes 5 and 9.*

- (c.1) **Debris contained inside impact limit lines (ILL).** Risks associated with debris that is contained within the ILLs.

(d) *May directly follow event nodes 5, 6 and 9.*

- (d.1) **Potential public casualties.** Risks to the public in areas outside the ILLs.

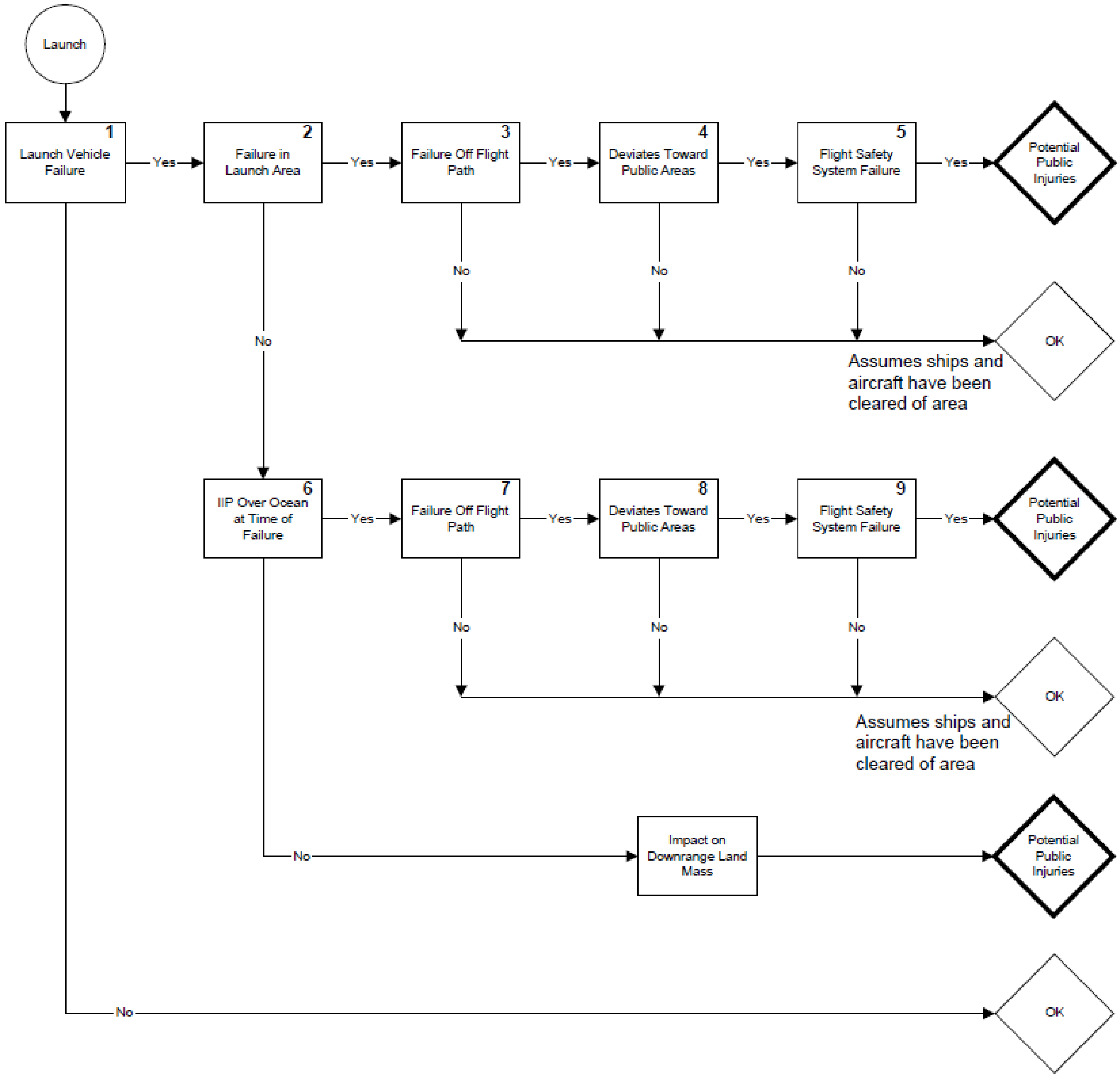

Figure 5. Generic ELV launch event hazard tree (proposed sample)

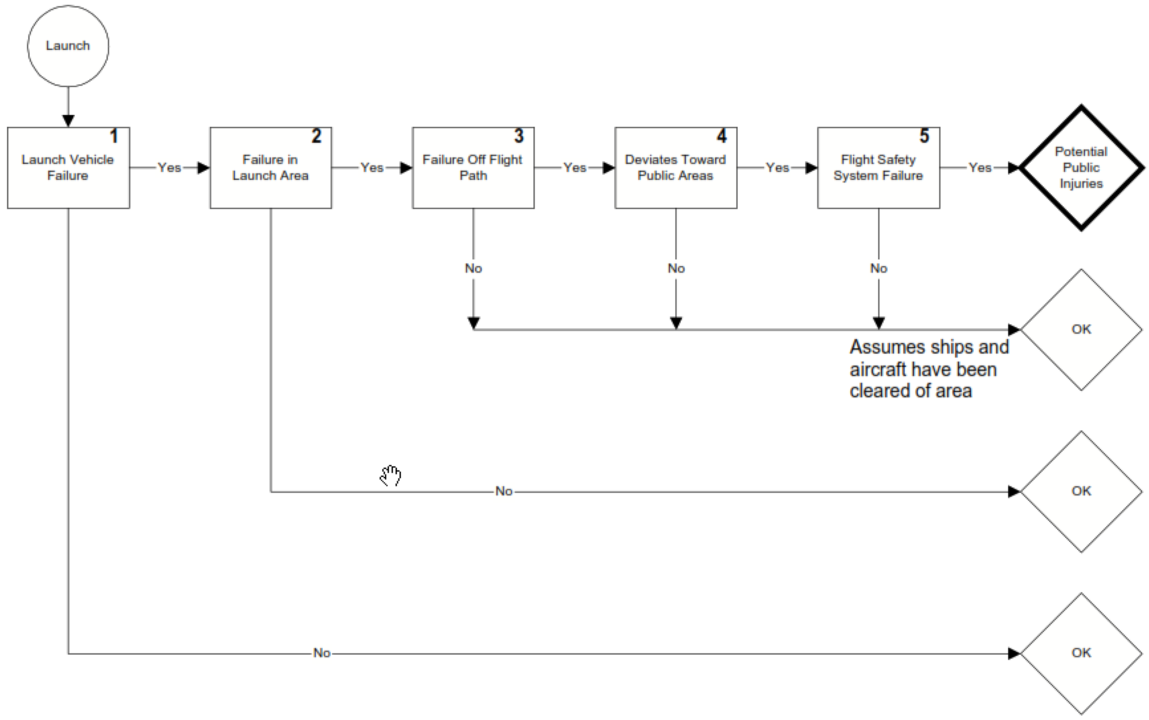

Figure 6. Generic high power rocket launch event hazard tree (proposed sample)

5.1.4 Evaluate vehicle failure response modes and mishap scenarios:

5.1.5 By leveraging the hazard event trees analysis, failure response modes and mishap scenarios can be identified for the mission. The following example mishap scenarios are those that may, either individually or in combination, result in a vehicle potentially posing a hazard to third-party persons and resulting in property damage.

5.1.6 Many of these scenarios most likely will result in activation of the vehicle's flight safety system (FSS). This section is included to prompt the applicant during their analyses of vehicle failure modes.

- Solid motor burn through
- Liquid propellant ignition
- Anomalous trajectory
- Flight safety system failure
- In-flight break up
- Release of toxic gases
- Failure to pitch over
- Improper roll manoeuvre
- Shift or loss of inertial reference
- Ascending stage or payload impacting airborne aircraft
- Descending stage, payload or re-entry vehicle impacting airborne aircraft

- Stage or re-entry vehicle impacting person or property after parachute descent
- Stage, payload or re-entry vehicle impacting person or property after ballistic or autonomous approach
- Stage, payload or re-entry vehicle igniting a fire on the ground
- Re-entry vehicle fails to separate from the upper stage or on-orbit platform
- Re-entry vehicle re-enters but fails to re-enter at the planned-for position and time
- Re-entry vehicle has an undetected critical system failure
- Re-entry vehicle scattering debris during re-entry
- Re-entry vehicle releasing hazardous materials

5.1.7 The list above should be read in conjunction with the failure response modes analysis conducted as part of the *Flight Safety Code*'s risk hazard analysis. Section 4.6 of the *Flight Safety Code* describes how to determine failure response modes for the flight vehicle in more detail. This section states that, to accurately assess the impact on public safety throughout all phases of the flight, the failure probability for a risk analysis must be assessed for 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.

5.1.8 This failure response mode analysis needs to be covered in detail while performing the risk hazard analysis in the *Flight Safety Code*. If the risk hazard analysis has already been conducted, the vehicle failure response modes from that process may be used for this step.

5.1.9 <u>Determine vehicle break-up models:</u>

5.1.9.1 The applicant is required to develop a break-up model and a debris catalogue for their vehicle through either of the methods described in the risk hazard analysis methodology in section 4.7 of the *Flight Safety Code*.

5.1.10 The two sources for developing a debris catalogue identified in the *Flight Safety Code* are:

1. Obtain the debris catalogue developed by the manufacturer of the launch vehicle or return vehicle; or
2. Develop the debris catalogue in conjunction with the manufacturer, based on the various parts and components of the vehicle.

5.1.10.1 The vehicle break-up data should 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.

5.1.10.2 The data should include the various parameters required for the risk hazard analysis such as:

- Fragment ballistic coefficient,
- Aerodynamic characteristics,
- Weight,

- Projected area, and
- Imparted velocity at break-up.

5.1.11 The vehicle break-up model is then used as the basis for calculating casualty area in the following step.

5.1.12 This analysis needs to be covered in detail while performing the risk hazard analysis from the *Flight Safety Code.* If the risk hazard analysis has already been conducted, the vehicle break-up model from that process may be used for this step.

5.2 Calculate casualty area and probability of impact isopleths

5.2.1 Following the identification of the vehicle failure response modes and the development of the vehicle break-up model, the applicant must develop the casualty areas, and the probability of impact isopleths for uprange, downrange, and returns through the use of the risk hazard analysis methodology from the *Flight Safety Code*. If the applicant has completed the risk hazard analysis for the proposed launch or return, the casualty area and probability of impact isopleths will already be available to calculate the MPL.

5.2.2 Casualty Area

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

5.2.2.2 The applicant must identify casualty areas resulting from vehicle failures leading to debris impacts for each of the uprange, downrange and return phases of flight. The issues to be considered 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', and angle of impact.

5.2.2.3 The methodology for developing the casualty area is contained in Appendix 1 of the *Flight Safety Code*. The applicant must create a debris catalogue by converting the total non-volatile mass of the launch vehicle (including payloads) into fragment groups. Following that, the applicant is to assume that: all resultant fragments, either striking a person directly or glancing a person, will result in a casualty. The equation to be used for calculating the casualty area is expressed as:

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

Where:

$A_{c(inert)}$ comprises a basic casualty area component $A_{c(basic)}$ which is made up of debris falling vertically and diagonally, and components for debris skidding F_{skid}.

$A_{c(explosive)}$ is the explosive debris contribution to A_c calculated from converting propellant weights into equivalent TNT weights and using an explosive overpressure threshold of 25 kPa.

5.2.2.4 The applicant must develop the casualty areas for their vehicle for the various phases of flight based on the risk hazard analysis in the current version of the *Flight Safety Code*, and then use those casualty areas in the next stages of this MPL methodology.

5.2.3 Probability of impact isopleths

5.2.3.1 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 probability of impact isopleth positions change with the size of the debris fragments and the number of debris fragments. The 10^{-7} 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 1 in 10,000,000 opportunities.

5.2.3.2 Probability of impact isopleths can be developed by simulating the flight and subsequent ground impact of the launch vehicle debris many times for both the nominal flight parameters and failure response modes of the vehicle. Based on the probability of the failure response mode occurring, a distribution of debris impact points can be established, over which probability of impact isopleths can be identified, including the 10^{-7} probability of impact isopleth. Section 4.13 of the *Flight Safety Code* describes in detail how the probability of impact isopleths are calculated.

5.2.3.3 These probability of impact isopleths need to be derived while performing the risk hazard analysis in the *Flight Safety Code*. If this risk hazard analysis has already been conducted, the probability of impact isopleths from that process may be used for this step.

5.2.3.4 Once the 10^{-7} probability of impact isopleth is obtained, the MPL bounding approach is made more conservative by assuming that there is an equally likely chance for an accident to occur anywhere inside this 10^{-7} probability of impact isopleth.

6 Phase two: calculating MPL in each loss category

6.1 Cost of casualties

6.1.1 This MPL methodology is based on using the methods for determining casualty expectations in the risk hazard analysis from the *Flight Safety Code*, and adapting these methods to find the highest number of casualties or the highest property damage that may occur within the 10^{-7} probability of impact isopleth. To convert number of casualties into a financial figure for the purposes of determining the required insurance amount, a monetary value of $4,500,000 is attributed to each casualty. The MPL approach is conservative in that it does not differentiate between fatalities and serious injuries, treating both as casualties.

6.1.2 Calculating Casualties - primary effects of debris:

6.1.2.1 The number of casualties is determined by overlaying the casualty area over the area containing the highest population density that can be found anywhere within the 10^{-7} probability of impact isopleth.

6.1.2.2 For the uprange phase, the applicant should use an area of 3.45 km^2 centred on the launch pad or the 10^{-7} probability of impact isopleth, whichever is larger, to calculate the casualties based on the highest population concentration in that area.

6.1.2.3 For downrange and returns, the applicant should use the casualty area defined by the casualty area calculations based on the vehicle failure modes, then overlay this area onto the highest population density within the 10^{-7} probability of impact isopleth.

6.1.2.4 The calculation to use for overlaying is:

$$CAS = A_c \times D_{pop}$$

Where:

A_c = casualty area in m^2

D_{pop} = population density in persons/km^2, converted to persons/m^2

$$CAS = \frac{persons/km^2}{1 \times 10^6\ m^2/km^2} \times A_c\ m^2$$

6.1.2.5 Small vehicles operating in areas of considerable population density yield only very small fractions of a casualty. For example, from the above relationship, a vehicle with a casualty area of 93 m^2 that is potentially impacting an area with a population density of 580 persons/km^2 will cause 5.39×10^{-2} casualties, or 0.0539 casualties. A vehicle with a casualty area of 3,700 m^2 posing a hazard to that same population density will cause 2.15 casualties.

6.1.2.6 Casualties are rounded to the nearest whole number. Casualties equal to or above 0.5 (i.e. a half of a casualty), will be assigned as 1 casualty. Casualties below that number will be set at 0. Casualties equal to or above 2.5 up through 3.49 will be assigned as 3 casualties, and so on. In the above example that yielded 2.15 casualties, 2 casualties would be assigned.

6.1.3 Calculating Casualties - secondary effects of debris

6.1.3.1 Potential secondary effects such as fires, explosions, building collapses and the like, will cause casualties. Because crash dynamics are so varied, use a factor or boundary of 1.5 times as many casualties as were estimated for the primary or initial debris. The value of 1.5 is considered conservative in that it may serve to overestimate casualties. However, this is based in part on crash dynamics observed during aircraft and launch vehicle crashes, which often result in affected on-ground property suffering secondary damage beyond the initial impact and further placing any occupants at risk. Secondary effects of debris do not apply for downrange or return mishaps because the vehicles or stages will be almost or totally devoid of propellants, and atmospheric re-entry of the debris will consume some portion of the debris, which does not happen during an uprange mishap.

6.1.3.2 To determine the number of casualties from secondary causes, such as post-impact structure collapses and fires, multiply the number of rounded up primary casualties by a factor of 1.5 to obtain the number of casualties from secondary causes. The total number of casualties for the phase is the total of the two values.

6.1.3.3 Table 2 shows the results of sample calculations and the resulting casualty MPL value based on $4,500,000 per casualty. Because initial rounding takes place before entering Table 3, rounding to the nearest whole casualty number will suffice. Therefore, in the first row, (1 casualty from debris) x (1.5) = 1.5 casualties from secondary effects. That 1.5 casualty value is rounded up to 2.0, resulting in 3 total estimated casualties, as shown.

Table 2. Casualty loss estimations from primary debris plus secondary effects

Casualties from Debris	Casualties from Secondary Effects	Total Estimated Casualties	Third-party persons MPL value at $4,500,000 per casualty
1	2	3	$13,500,000
2	3	5	$22,500,000
3	5	8	$36,000,000
4	6	10	$45,000,000
5	8	13	$58,500,000
6	9	15	$67,500,000
7	11	18	$81,000,000
8	12	20	$90,000,000
9	14	23	$103,500,000
10	15	25	$112,500,000
11	17	28	$126,000,000
12	18	30	$135,000,000
13	20	33	$148,500,000

6.2 Property damage

6.2.1 The applicant will estimate loss of property value by whichever of the following two methods provides the higher MPL value.

6.2.2 Bounding approach (loss of property as a function of the casualty loss estimate)

6.2.2.1 The loss of property value given by the bounding approach is half the value of the estimated casualties. For downrange property losses or losses due to re-entry mishaps, property losses are believed to be sufficiently small to be included in whatever MPL value results from possible casualties.

6.2.2.2 Third-party property losses are estimated at 50 per cent of the value of the casualty losses to third-party persons, including from the primary and secondary effects of debris. The applicant will determine the third-party property loss as shown in the equation below. Because of the conservative nature of the casualty loss estimations and the rounding that has already been done, further rounding is not needed.

6.2.2.3 The bounding approach calculation to use for property loss is:

$$MPL = CAS \times 0.5 \times \$4{,}500{,}000$$

Where:

MPL = MPL value for third-party property loss in $

CAS = number of casualties

and $4,500,000 is the cost per casualty; for example, if a total of 3 casualties for an MPL value of $13,500,000 were estimated to occur, then the third-party property loss would be $6,750,000.

6.2.3 Property damage as a function of the specific high-value asset:

6.2.3.1 If high-value assets are found to be within the 10^{-7} probability of impact isopleth during any phase of the mission, loss estimates to such high-value assets must be made by sound engineering and financial estimates that specifically address the facility’s construction, and the explosive or impact effects of the vehicle or its debris. Even though a rigorous evaluation should always be conducted for high-valued assets, the MPL methodology offers a way of obtaining an approximate value for such facilities.

6.2.3.2 To use the approximate method to calculate the loss of property to a high-value asset, start by locating the assets with the highest value that lie within the 10^{-7} probability of impact isopleth. Calculate the portion of the assets that would be damaged by the impact of the vehicle or its debris. The damaged portion of the asset is found by multiplying the asset area, or footprint, by the ratio given by the casualty area and the impact area. The casualty area value for a specific vehicle has to be provided by the applicant, while the numerical value of impact area, when it is not provided by the applicant, can be assumed to be 3,450,000 m^2 or one nautical mile squared for the uprange phases of flight.

6.2.3.3 The trajectory and pattern on the ground, or footprint, of the debris is a function of induced velocity, ballistic coefficient, altitude at the time of the occurrence, and any wind drift effects. With most vehicles, the ground (or ocean) impact area of the debris is in the order of 3.45 km^2 when the vehicle's destruction occurs early in the flight. This impact area may grow to

85-175 km^2 as the vehicle continues to accelerate and ascend, and may reach to thousands of km^2 as the instantaneous impact point (IIP) for the upper stages crosses downrange land masses. For returns, the impact area will be the size of most countries at the completion of the de-orbit burn, and in the order of 3.45km^2 at parachute deployment or high key. For winged return vehicles or vehicles with powered descent, the ground impact area is defined by the IIP trace on return with a minimum size of 3.45km^2 as it approaches the ground.

6.2.3.4 The loss of property is then given by multiplying the damaged surface of the facility by the property value per metre squared of the asset.

6.2.3.5 An approximate value of the loss of property can be described in general terms as follows:

$$MPL_{LOP} = V \times \frac{A_c}{IA} \times S_f$$

Where:

MPL_{LOP} = MPL value for loss of property, in \$

V = property value of the facility per meter squared, in \$

A_c = casualty area for that flight phase, in m^2

IA = impact area of the vehicle debris, in m^2

S_f = facility size / footprint area occupied by the facility, in m^2

6.3 Loss of use

6.3.1 Damage to high-value assets from debris impact may put the entire asset or a portion of the asset out of action for a period of time. During this time, the high-value asset is operating at less than full capacity or not at all; therefore, its economic output is diminished. The reduction of income due to this inactivity is called loss of use. To determine the damages resulting from loss of use of the high-value asset, the applicant will calculate loss of use by whichever of the following two methods provides the higher MPL value.

6.3.2 <u>Bounding approach (loss of use as a function of per capita gross domestic product)</u>

6.3.2.1 This loss of use estimate is calculated utilising the gross domestic product (GDP) for the country at risk. It is calculated by multiplying the number of expected casualties by the per capita GDP as follows:

$$MPL_{LOU} = CAS \times GDP$$

Where

MPL_{LOU} = MPL value for loss of use, in \$

CAS = number of casualties

GDP = per capita gross domestic product, in \$

6.3.3 Loss of use as a function of the specific high-value asset

6.3.3.1 If high-value assets are found to be within the 10^{-7} probability of impact isopleth during any phase of the mission, loss-of-use estimates to such high-value assets must be based on engineering and financial estimates that specifically address the facility's construction and the explosive or impact effects of the vehicle or its debris, and the loss-of-use consequences which could reasonably be expected to ensue from such damage.

6.3.3.2 Although a rigorous evaluation should always be conducted for high-value assets, the MPL methodology offers a way of obtaining an approximate loss-of-use value for such facilities, following the same approach as for the determination of loss of property. The damaged property area already found in the calculation of the loss of property should be multiplied by the annual revenue per-metre squared generated by the facility. If it can be determined that the time needed to restore the facility to the condition that would have existed if the damage had not occurred is different from one year, the total amount of the loss of use has to be adjusted accordingly.

6.3.3.3 The high-value asset approach for MPL_{LOU} may be calculated as follows:

$$MPL_{LOU} = R \times \frac{A_c}{IA} \times S_f \times T$$

Where:

MPL_{LOU}	= MPL value for loss of use, in $
R	= annual revenue of the facility per meter squared, in $
A_c	= casualty area for that flight phase in m^2
IA	= impact area of the vehicle debris in m^2
S_f	= facility size/footprint area occupied by the facility in m^2
T	= time out, in years, needed to reinstate the facility to the same operational state it had before the accident,

6.3.4 The loss-of-use costs in the MPL methodology includes indirect damages, such as damages that could result from loss-of-supply claims by customers or other indirect consequential losses. This is done as it can reasonably be anticipated that parties suffering consequential losses (loss of business and profits etc.) will include the estimated value of these consequential losses in calculating the amount of the insurance claim and the amount of damages in any legal claim.

6.4 Environmental damage and clean-up costs

6.4.1 The applicant must estimate the cost associated with environmental damage and clean up by whichever of the following two methods provides the highest MPL value:

1. Bounding approach:
    a. $170,000; or
2. Environmental damage and clean-up costs as a function of a specific high-value asset:
    a. If there is a particular high-value asset with the 10^{-7} probability of impact isopleth, and this impact would have environmental damage (such as the release of oil or toxic

gases) the applicant must make an accurate evaluation of the cost associated with restoring the environment to the condition that would have existed if that damage had not occurred.

6.4.2 The environmental damages and clean-up costs in the MPL methodology developed include indirect damages, such as the ones that could be originated by an oil spill caused by an impacting vehicle. This is done because, it can reasonably be anticipated that parties suffering consequential losses (loss of business and profits, environmental clean-up etc.) will include the estimated value of these consequential losses in calculating the amount of the insurance claim as well as the amount of damages in any legal claim.

6.5 Example MPL calculation

6.5.1 An example of an MPL calculation illustrating the use of both the bounding approach method and the specific high-value asset method is presented below. These methods illustrate the MPL calculation of the cost of casualties, the loss of property, loss-of-use and environmental clean-up costs. The calculations are similar for all phases of flight; however, this example uses the impact area for the uprange or the final approach in the return phase of flight.

6.5.2 Bounding approach method

6.5.2.1 The calculations in the example assume that the MPL evaluation has determined that a mishap will cause 3 casualties. Each casualty is assigned a monetary value of $4,500,000 and the Australian per capita GDP is assumed to be $74,000 (note, for this example monetary values are for the year 2019).

Table 3. Example bounding approach calculation method

Category	Parameter	Calculation	Value
Cost of casualties	Number of casualties	$CAS = A_c \times D_{pop} = 3$	
	Cost of casualties total	$MPL_{CAS} = CAS \times \$4{,}500{,}000$	**$13,500,000**
Property damage	**Property damage total**	$MPL_{PD} = MPL_{CAS} \times 0.5$	**$6,750,000**
Loss of use	Per capita GDP	$GDP = \$74{,}000$	
	Loss-of-use total	$MPL_{LOU} = CAS \times GDP$	**$222,000**
Environmental impact	**Environmental impact total**	$MPL_{ENV} = \$170{,}000$	**$170,000**
Total MPL	$\boldsymbol{MPL = MPL_{CAS} + MPL_{PD} + MPL_{LOU} + MPL_{ENV}}$		**$20,494,000**

6.5.3 Specific high-value asset method

6.5.3.1 Locate the assets with the highest value that lie within the 10^{-7} probability of impact isopleth. Calculate the portion of the assets that would be damaged by the impact of the vehicle or its debris. The portion of damaged asset is given by multiplying the total surface of the high-valued facility by the ratio given by casualty area divided by impact area. The damaged property area is then multiplied by the property value per-metre squared to obtain the loss of property, and by the annual revenues per-metre squared to obtain the loss-of-use cost. Finally, the environmental and clean-up costs are estimated by analysis of the potential environmental damage and added to the total.

6.5.3.2 For this calculation, it is assumed that there are two high-value assets within the 10^{-7} probability of impact isopleth: a farm and a factory. The parameters of a hypothetical impacting vehicle are given in Table 4, while the parameters for the farm and the factory are given in Table 5.

Table 4. Hypothetical vehicle parameters

Parameter	Value
Casualty area	3,250 m^2
Impact area IA	3,450,000 m^2
Ratio CA/IA	1/1,062

Table 5. Hypothetical farm and factory values

	Farm	Factory
Property size	47,000 m^2	20,000 m^2
Property value	$25,500,000	$3,750,000,000
Property value per m^2	$543	$187,500
Annual revenues	$8,500,000	$1,275,000,000
Revenue per m^2	$181	$63,750
Time out of use (loss of use)	8 months	15 months

6.5.4 From the values given in Table 4 and Table 5, it is possible to calculate the total loss for the high-value asset farm and factory in Table 6 and Table 7.

Table 6. Specific high-value asset method for a hypothetical farm

Category	Calculation	Value
Loss of property	$\frac{1}{1{,}062} \times 47{,}000\ m^2 \times \$543\ /\ m^2$	= $24,022
Loss of use	$\frac{1}{1{,}062} \times 47{,}000\ m^2 \times \$181\ /\ m^2 \times \frac{8}{12}$	= $5,338
Clean-up costs	Based on specified clean-up costs	= $170,000
Property, use and clean-up loss: farm		**= $199,360**

Table 7. Specific high-value asset method for a hypothetical factory

Category	Calculation	Value
Loss of property	$\frac{1}{1{,}062} \times 20{,}000\ m^2 \times \$187{,}500\ /\ m^2$	= $3,532,609
Loss of use	$\frac{1}{1{,}062} \times 20{,}000\ m^2 \times \$63{,}750\ /\ m^2 \times \frac{15}{12}$	= $1,501,359
Clean-up costs	Calculated by analysis of the environmental damage	= $1,020,000
Property, use and clean-up loss: factory		**= $6,053,967**

6.5.5 <u>Calculating MPL from the maximum of the bounding approach method and the specific high-value asset method</u>

6.5.5.1 Using the results obtained from the previous two methods, the total MPL for the phase of flight is calculated by taking the maximum dollar value in each category from either method, and summing these values to estimate the total MPL. This process is shown in Table 8.

Table 8. MPL value for phase of flight

Phase of flight MPL value (sum of max values)		**$22,771,359**
Category	**Value**	**Maximum Value**
Cost of casualties	$13,500,000	$13,500,000
Property (50% of casualty MPL value)	$6,750,000	$6,750,000
Property damage estimate (factory)	$3,532,609	
Property damage estimate (farm)	$24,022	
Loss of use (Casualties x GDP/capita)	$222,000	$1,501,359
Loss of use (Loss of use) (factory)	$1,501,359	
Loss of use (Loss of use) (farm)	$5,338	
Environmental bounding approach ($170,000)	$170,000	$1,020,000
Environmental (factory)	$1,020,000	
Environmental (farm)	$170,000	

6.5.5.2 Notice how, even though the factory had very high property and use values, the property MPL value in this example is driven by the third-party loss of property, calculated as 50 per cent of the cost of casualties: based on 3 casualties the property loss from the bounding approach is \$6,750,000, which is much larger than the property damage to the factory of \$3,532,609 calculated using the specific high-value asset approach.

6.5.5.3 Note that the estimates used in the example calculation for the specific high-value asset approach above are hypothetical numbers used to illustrate the methodology are not to be used by an applicant in their case to the Agency for the determination of the insured amount. All applicants must conduct specific damage analysis of high-value assets that fall within the 10^{-7} impact probability of impact threshold.

7 MPL analysis by phase of flight

7.1 Uprange MPL

7.1.1 The MPL for the uprange phase of flight is analysed assuming the vehicle breaks up in a manner that produces the largest casualty area in the launch area. Within the 10^{-7} probability of impact isopleth, the debris catalogue resulting from planned and unplanned destruct actions will drive the calculation for number of casualties.

7.1.2 Casualties will be estimated by overlaying the casualty area over the highest population density within the 10^{-7} probability of impact isopleth. The MPL estimate for uprange will be based on the computation that yields the greatest number of casualties.

7.1.3 Secondary effects of debris do apply for uprange mishaps because the vehicles or stages will likely contain propellants with explosive potential.

7.1.4 Casualties and property damage due to the toxic effects of on-board propellants are discounted for mishaps occurring outside the boundary of the launch site, both in the uprange and downrange areas. The effects of toxic materials can be discounted because any such material would be unlikely to survive the initial fireball.

7.1.5 Estimate casualties by using the same overlay technique as described in section 6.1. The values associated with property loss, loss of use and environmental damage are calculated as described in section 6.

7.2 Downrange MPL

7.2.1 The downrange approach may be used from the time during the launch when the hazard analysis supports the assumption that the property damage, loss of use, and environmental damage and clean-up are expected to be contained within the cost assigned to casualties. This is typically during upper stage flight.

7.2.2 Downrange property losses are believed to be sufficiently small to be included in whatever MPL value results from possible casualties. However, if there is a particular high-value asset within the 10^{-7} probability of impact isopleth, a specific assessment is made of the property loss, loss of use, and environmental damage and clean-up values.

7.2.3 For downrange, the people and property at risk are those within the 10^{-7} probability of impact isopleth. This is estimated to be a swath along the instantaneous impact point (IIP) extending hundreds of kilometres laterally. Property and people inhabiting the downrange area may be at a level of risk within the 10^{-7} probability of impact isopleth, which will be determined as part of the risk hazard analysis (conducted as part of the *Flight Safety Code*). The number of casualties will be determined by overlaying the casualty area on the area with the highest known population density within the 10^{-7} probability of impact isopleth.

7.2.4 A key difference between the uprange (launch area) and the downrange is that in the uprange, the debris impact area, and therefore the highest population density at risk is about the size of 3.45 km^2. However, for the downrange, the potential impact area can be very large (likely covering major sections of countries). Therefore, the population density chosen for the MPL estimation is the highest within the 10^{-7} probability of impact isopleth of the regions overflown. As with the launch area casualty estimations, the overlay method is used as defined in section 6.1.

7.2.5 Secondary effects of debris do not apply for downrange mishaps because the vehicles or stages will be almost or totally devoid of propellants, and atmospheric re-entry of the debris will consume some portion of the debris. This does not happen during an uprange mishap.

7.2.6 Casualties and property damage due to the toxic effects of on-board propellants are discounted for mishaps occurring outside the boundary of the launch site, both in the uprange and downrange areas. The effects of toxic materials can be discounted because any such material would be unlikely to survive the initial fireball.

7.2.7 Small vehicles, or small upper stages and payloads, operating in areas of considerable population density yield only very small fractions of a casualty. For example, if an upper stage and payload have a casualty area of about 186 m^2 during overflight over a population density of about 460 persons/km^2, the overflight will result in 8.56×10^{-2} casualties, or 0.0856 casualties. Because this casualty estimation is not even one tenth of a casualty, the MPL recommendation for downrange overflight will be zero for this example.

7.3 Return MPL

7.3.1 The MPL for the return phase of flight is analysed assuming the vehicle breaks up in a manner that produces the largest casualty area. Within the 10^{-7} probability of impact isopleth, the debris catalogue resulting from planned and unplanned destruct actions will drive the calculation for number of casualties.

7.3.2 Casualties will be estimated by overlaying the casualty area over the highest population density of an area within the 10^{-7} probability of impact isopleth. The MPL estimate for return will be based on the computation that yields the greatest number of casualties.

7.3.3 Secondary effects of debris do not apply for return mishaps because the vehicles or stages will be almost or totally devoid of propellants, and atmospheric re-entry of the debris will consume some portion of the debris. This does not happen during an uprange mishap.

7.3.4 Estimate casualties by using the same overlay technique as described in section 6.1. The values associated with property loss, loss of use and environmental damage are calculated as described in section 6. For return vehicles or vehicles with powered descent, the ground impact area is defined by the instantaneous impact point trace on return with a minimum size of 3.45km^2 as it approaches the ground.

8 Tables for recording MPL summary

The permit applicant should fill out the following table with the results of the MPL estimations and provide a copy to the Australian Space Agency. The value of the top line in any loss area is the summation of the individual loss categories.

Table 9. Estimations of uprange MPL values

Uprange MPL value (sum of max values)		
Category	**Value**	**Maximum Value**
Cost of casualties		
Property (50% of casualty MPL value)		
Facility damage estimate		
Loss of use (Casualties x GDP/capita)		
Facility damage estimate (Loss of use)		
Environmental ($170,000)		
Facility damage estimate (Environment)		

Table 10. Estimations of downrange MPL values

Downrange MPL value (sum of max values)		
Category	**Value**	**Maximum Value**
Cost of casualties		
Property (included in cost of casualties)		
Facility damage estimate		
Loss of use (included in cost of casualties)		
Facility damage estimate (Loss of use)		
Environmental (included in cost of casualties)		
Facility damage estimate (Environment)		

Table 11. Estimations of return MPL values

Return MPL value (sum of max values)		
Category	**Value**	**Maximum Value**
Cost of casualties		
Property (50% of casualty MPL value)		
Facility damage estimate		
Loss of use (Casualties x GDP/capita)		
Facility damage estimate (Loss of use)		
Environmental ($170,000)		
Facility damage estimate (Environment)		