COMMONWEALTH OF AUSTRALIA

SPACE LICENSING AND SAFETY OFFICE

MAXIMUM PROBABLE LOSS METHODOLOGY

Second Edition

Department of Industry, Tourism and Resources

1 July, 2002

ISBN 0 642 72144 0

ITR 2002/063

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I. INTRODUCTION

This document presents a methodology for determining risks and potential consequences due to mishaps that may occur during phases of flight of space vehicles beginning at ignition and ending either on orbit, impact or recovery. Insurance requirements remain in place for the entire flight's liability period and are not phase specific. The methodology here presented is termed the maximum probable loss (MPL) methodology.

Maximum probable loss (MPL) is a risk-based analysis that yields the greatest potential loss, for bodily injuries and property damages, that can reasonably be expected to occur as a result of licensed 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 are established at a level that provides financial protection against the consequences of events that are deemed sufficiently probable under the regulations. A probability threshold is used as a quantitative measure to distinguish unlikely events from those which are sufficiently probable to warrant inclusion in the MPL. Loss or damage that has a likelihood of occurring that is equal to or greater than the probability threshold is considered probable. The probability that losses would exceed the MPL is no higher than the probability threshold, which in this study is set at 10^{-7} (1 in 10 million).

While the MPL methodology may be used for any type of loss category, for our purposes, the methodology is focused on risks to third parties, to their persons and their property, and deals with the potential casualties, property damage, loss of use and environmental damage that may result from each phase of flight.

The MPL methodology developed for the Commonwealth of Australia includes indirect, consequential damages, such as the ones that could result from loss-of-supply claims by customers, or ones that could result from a consequential oil spill, or other consequential losses, if the probability that such an accident may happen is within the 10^{-7} probability threshold. This is done because 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 as well as the amount of damages in any legal claim. Most courts will give recognition to such consequential damages.

The MPL methodology requires the applicant to develop or estimate the debris catalogue and resulting casualty areas for its vehicle at different flight phases and requires the applicant to calculate impact probabilities during different phases of flight. The applicant will develop the debris casualty areas, calculations for probability of impact and casualty expectation in accordance with the "Risk Hazard Analysis" in the current version of the SLASO Flight Safety Code.

One aspect of the MPL methodology is based on a bounding approach, which removes most of the need for substantial mathematical analyses and computations. Experience shows that operating at remote probabilities with minimal empirical data is problematic and often results in conclusions too speculative to justify a rigorous mathematical risk assessment. Similarly, breaking the flight into many discrete phases does not aid the MPL process; in fact, it would needlessly encumber that process. Instead, the MPL methodology looks at gross phases, such as uprange in the launch area and downrange during overflight for expendable launch vehicles.

The bounding approach identifies an area around the planned flight trajectory that will contain all the impacts from debris resulting from any possible mishap, to within the 10^{-7} probability threshold. In other words, the probability of any debris falling outside the identified area is smaller, or more remote, than the 10^{-7} threshold. Within the identified area the MPL methodology determines a monetary value to the estimated casualties, the loss of property, the loss of use, and the environmental damages and clean up costs that are expected. In particular, casualties are assigned a monetary value, which for the current study has been set at 5,000,000 A$ per person. The property damages that may result from the impact of the vehicle or its debris are characterized as a percentage of the value of the estimated casualties. For the current study, the percentage has been set at 50 percent. Loss of use is estimated using the gross domestic product per capita and the estimated number of casualties. Finally, in the bounding approach, environmental damages and clean-up costs are estimated as 100,000 A$.

In addition to the bounding approach, if there is a particular high-valued third-party asset individually facing an impact probability at or within the 10^{-7} threshold, the MPL methodology calls for an accurate engineering evaluation of the likely property losses due to impact, plus the resulting loss of use, environmental damage and cleanup costs associated with the high-valued facility, including consequential losses. A high-value asset is one for which the MPL values for property damage, loss of use and environmental damage and clean-up calculated using the gross bounding approach described above would be inappropriate.

The property loss, loss of use and environmental damage and clean up MPL values will be the higher of the values obtained using the gross bounding approach and the high-value facility assessment.

The MPL methodology here presented is not dependent on the specific characteristics of the launch or re-entry site or approach corridors. It is dependent only on the risks posed to people and property within the probability threshold area. Thus, whether launching from Woomera, Christmas Island, Gladstone or elsewhere, this methodology may be used. The risk to the public, which is based on the development of probability threshold areas for launch, re-entry and recovery vehicles, includes the fact that SLASO will impose a phased reliability assessment approach for permit applicants, assigning only low vehicle reliability values initially, followed by higher reliability values as flight data support over the course of time.

The MPL methodology requires the permit applicant to develop the break-up model, the debris catalogue and resulting Casualty Areas (CA) for its vehicle at different flight phases and requires the applicant to develop probability of impact contours during different phases of flight.

II. METHODOLOGY

The steps comprised in the generalized MPL process are described in this section and presented graphically in Figure 1. The complete MPL process can be thought of as being 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 integrates all the information and then develops the MPL recommendations.

Intermediate MPL recommendations are made separately for third-party losses for each phase of flight. Even when the determination is made that the risk to the public, during any given phase, is beyond the accepted probability threshold, the applicant will want to so state to avoid the appearance of having skipped or overlooked an aspect of the analysis.

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

(a) Phase One: Gather information

(b) Phase Two: MPL recommendations

Figure 1: MPL process flow chart

PHASE ONE

Step 1: Complete preparatory risk analysis by developing the vehicle break-up model, the lethal debris area, the Casualty Area, and the impact probability threshold contours for uprange, downrange, re-entry and recovery as appropriate. Impact probability threshold contours define areas that that will contain all the impacts from debris resulting from any possible mishap, to within the 10^{-7} probability threshold. In other words, the probability of any debris falling outside the identified area is smaller, or more remote, than the 10^{-7} threshold. The area defined by a probability threshold contour is called a probability threshold area.

In addition to gathering all the relevant information the applicant must be aware of and follow the recommendations contained in the "Risk Hazard Analysis" in the SLASO Flight Safety Code.

Step 2: Understand and describe the sequence of operations for the entire mission and the presence of hazardous materials, including any of the payload.

Step 3: Determine the third-party persons and property at risk. For uprange and downrange activities, including ELV launches, re-entry vehicle and RLV recovery, the area within the probability threshold contour is at risk.

Step 4: Describe typical accident scenarios. Reviewing the accident scenarios is a way for the applicant to understand the different failures and the likely consequences. Because no engineered system can reasonably guarantee a probability of failure lower than the 10^{-7} threshold, it is safe to conclude that the MPL will be based on an assumption that a mishap *will* occur and *will* place people and property at risk.

Step 5: Use the "Risk Hazard Analysis" in the SLASO Flight Safety Code to compute the probability of expected casualties and damages resulting from off-range launch vehicles.

PHASE TWO

Step 6: Screen out scenarios with low losses relative to other scenarios within each phase of flight. In other words, find the risk drivers for each phase of flight and don't spend time assessing losses from minor mishaps or in less densely populated areas. Low-loss scenarios are screened out, provided that there is no significant chance of aggregated losses from more than one scenario, in situations where scenarios are not mutually exclusive.

Step 7: Determine MPL for third-party loss scenarios. 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 probability threshold.

To develop third-party casualty losses during flight, overlay the CA over the highest homogeneous population density in the area of concern.

To estimate third-party property loss, use whichever of the following two methods provides the higher MPL value:

1. 50 percent of the third-party casualty MPL recommendation; or
2. If there is a particular high-valued third-party asset individually facing an impact probability of 10^{-7} or greater, make an accurate engineering evaluation of the property losses due to those impacts.

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

1. 100,000 A$; or
2. If there is a particular high-valued third-party asset individually facing an impact probability of 10^{-7} or greater, make an accurate engineering evaluation of the cost associated with restoring the environment to the condition which would have existed if that damage had not occurred.

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, if there is a probability 10^{-7} or higher that such an accident may happen. The consequential damages include direct effects of the debris impact on the facility and the consequences of those impacts on the facility, such as may result from the release from the facility of toxic, hazardous, or polluting materials.

For loss of use, the applicant will use whichever value is higher:

1. That obtained by multiplying the per capita Gross Domestic Product (GDP) of the country where casualties may result by the number of casualties estimated; or

2. If there is a particular high-valued third-party asset individually facing an impact probability of 10^{-7} or greater, make an accurate evaluation of the loss-of-use value.

Note that the loss-of-use costs include the cost of consequential damages that might result from the mishap such as loss of supply to customers, if there is a probability of 10^{-7} or higher that such an accident may happen.

Step 8: Select the MPL recommendation for third-party losses. The loss estimates made in Step 7 associated with the various accidents within the probability threshold area constitute the listing of losses from which the applicant must choose.

III. MPL PROBABILITY THRESHOLD

The insurance requirements that the permit applicant has to satisfy must protect third-party persons and properties from all events that are reasonably likely to occur.

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

Once the threshold probability is selected, the largest accident that could occur within that threshold is determined. The threshold chosen is such that the probability of all larger and more costly accidents is less than (more remote than) that threshold. With the threshold approach, insurance requirements can be expected to cover the full costs of all accidents within the selected threshold. The threshold for this study is set at a probability of 10^{-7} (1 in 10 million).

In order to establish the people and the properties exposed to risk from the launch vehicle, the bounding approach identifies an area around the planned flight trajectory that will contain all the impacts from debris resulting from any possible mishap, to within the 10^{-7} probability threshold. This is called the probability threshold area. In other words, the probability of any debris falling outside the probability threshold area is smaller (more remote) than the 10^{-7} threshold. The probability threshold contour is a line on a map that is the boundary of the probability threshold area.

Once the probability threshold area 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 the probability threshold contour. However, accident scenarios involving particular high-value facilities within the probability threshold area are only considered if there is a probability of 10^{-7} or higher of such specific accidents occurring.

IV. ESTIMATE OF COSTS FOR LOSSES

CASUALTIES

A monetary value of 5,000,000 A$ is attributed to each casualty. The MPL approach is conservative in not differentiating between fatalities and serious injuries, treating both as casualties.

PROPERTY

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

The loss of property value given by the MPL for uprange or launch area third-party property is half of 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 so as to be included in whatever MPL value results from possible casualties. The downrange approach may be used from the time during the launch when the Risk Hazard Analysis supports the assumption that the property losses are sufficiently small so as to be included in whatever MPL value results from possible casualties, taking account of rounding. This typically occurs during upper stage flight.

If high-valued third-party assets are found to be within the probability threshold area during any phase of the mission, and if they are individually at risk at or within the 10^{-7} probability threshold, 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.

To use the approximate method to calculate the loss of property to a high-valued asset, start by locating the assets with the highest value that lie within the probability threshold area and identify those individually at risk at within the 10^{-7} probability threshold. Calculate the portion of the assets that would be damaged by the impact of the vehicle or its debris, if the probability of such an impact is within the 10^{-7} probability threshold. The damaged portion of the asset is found by multiplying the asset area, or footprint, by the ratio given by the CA and the impact area (IA). The meaning of CA and IA is explained in more detail in a following section. The CA value for a specific vehicle has to be provided by the permit applicant while the numerical value of IA, when it is not given by the applicant, can be assumed to be 3,450,000 m^2 or one nautical mile squared in the uprange area. As explained later, the IA expands during flight, reaching exceedingly large dimensions later in flight. 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.

LOSS OF USE

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

First, base the loss-of-use estimate of the expected impact of a mishap on the Gross Domestic Product (GDP) for the region at risk by multiplying the expected casualties by the per capita GDP of the region at risk. The MPL analyst should determine the average per capita GDP for the risk area in question.

If high-valued third-party assets are found to be within the probability threshold area and individually at risk within the 10^{-7} probability threshold, 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.

Note that, unlike the U.S. practice, the loss-of-use costs in the MPL methodology developed for the Commonwealth of Australia include indirect damages, such as the ones that could result from loss-of-supply claims by customers or other indirect consequential losses, if there is a probability higher than 10^{-7} that such an accident may happen. This is done because 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 as well as the amount of damages in any legal claim. Most courts will give recognition to such consequential damages.

Second, even though a rigorous evaluation should always be conducted for high-valued assets, the MPL methodology offers a way of obtaining an approximate loss-of-use value for such facilities, following the same line of thought 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 which would have existed if the damaged had not occurred is different from one year, the total amount of the loss of use has to be adjusted accordingly.

ENVIRONMENTAL DAMAGE AND CLEAN-UP COSTS

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

1. 100,000 A$; or
2. If there is a particular high-valued third-party asset individually facing an impact probability of 10^{-7} or greater, make an accurate evaluation of the cost associated with restoring the environment to the condition which would have existed if that damage had not occurred.

Note that, unlike the U.S. practice, the environmental damages and clean-up costs in the MPL methodology developed for the Commonwealth of Australia include indirect damages, such as the ones that could be originated by an oil spill caused by an impacting vehicle, if there is a probability higher than 10^{-7} that such an accident may happen. This is done because, it can reasonably be anticipated that parties suffering consequential losses (loss of business and profits, environmental cleanup 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. Most courts will give recognition to such consequential damages.

EXAMPLE OF PROPERTY LOSS, LOSS-OF-USE AND CLEAN-UP COST

MPL evaluations using the two methods presented to calculate the loss of property, loss-of-use and clean-up costs follow. The calculations for both the uprange phase and the downrange phase are presented.

Uprange phase

Method 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 5,000,000 A$ and the Australian per capita GDP is assumed to be 40,000 A$. Note that the dollar values used were accurate for the year 1998.

Example Calculation of Method 1

Casualties:	calculated by MPL process	= 3
Loss of life value:	3 x 5,000,000 A$	= 15,000,000 A$
Loss of property:	50% loss of life	= 7,500,000 A$
Per capita GDP per year		= 40,000 A$
Time out of use		= 1 year
Loss of use	3 x 40,000 A$	= 120,000 A$
Clean-up costs		= 100,000 A$
Property, loss of use and clean-up MPL value		= 7,760,000 A$
Total MPL value		**= 22,700,000 A$**

Method 2

Locate the assets with the highest value that lie within the probability threshold area and consider accident scenarios that have probabilities within the 10^{-7} probability threshold. 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 CA divided by IA. 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 added.

Example Calculation of Method 2

For this second example it is assumed that there are two high-valued properties within the 10^{-7} probability threshold area: a farm and a factory. The parameters of a hypothetical impacting vehicle are given in Table 1 while the parameters for the farm and the factory are given in Table 2.

Table 1: Hypothetical vehicle parameters

Casualty Area CA	3,250 m^2
Impact Area IA	3,450,000 m^2
Ratio $\frac{ECA}{IA}$	$\frac{1}{1{,}062}$

Table 2: Hypothetical farm and factory values

	Farm	Factory
Property size	47,000 m^2	20,000 m^2
Property value	15,000,000 A$	2,200,000,000 A$
Property value per m^2	319 A$	110,000 A$
Annual revenues	5,000,000 A$	750,000,000 A$
Revenue per m^2	106 A$	37,500 A$
Time out of use	8 months	15 months

From the values given in Table 1 and Table 2 it is possible to calculate the total loss for the high-valued asset farm and factory

Farm

Loss of property farm	$\frac{1}{1{,}062}$ x 47,000 m^2 x 319 A$/$m^2$	= 14,118 A$
Loss of use farm	$\frac{1}{1{,}062}$ x 47,000 m^2 x 106 A$/$m^2$ x $\frac{8}{12}$	= 3,127 A$
Clean-up costs		= 100,000 A$
Property, use and cleanup loss: farm		**= 117,245 A$**

Factory

Loss of property factory	$\frac{1}{1{,}062}$ x 20,000 m^2 x 110,000 A$/$m^2$	= 2,071,563 A$
Loss of use factory	$\frac{1}{1{,}062}$ x 20,000 m^2 x 37,500 A$/$m^2$ x $\frac{15}{12}$	= 882,768 A$
Clean-up costs	(assumed)	= 600,000 A$
Property, use and cleanup loss: factory		**= 3,554,331 A$**

These two approaches will give only a rough approximation, however they are both relatively easy to determine from available data. In addition, 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% of the loss of life; the 7,500,000 A$ of the bounding approach.

Note that the estimates used in the example calculation for method 2 above should not be read as obviating the need for specific damage analysis of accident scenarios involving high-value assets that have a probability within the 10^{-7} threshold.

Downrange and re-entry phases

Downrange property losses and re-entry property losses are believed to be sufficiently small so as to be included in whatever MPL value results from possible casualties. However, if there is a particular high-valued third-party asset individually facing an impact probability of 10^{-7} or greater, for damage that could occur with a probability within the10^{-7} probability threshold, a specific assessment is made of the property loss, loss-of-use and environmental damage and clean-up values.

V. MPL ANALYSIS BY PHASE OF FLIGHT

ROADMAP FOR THE APPLICANT

Estimate third-party losses for the phases of flight uprange, downrange and re-entry. For each phase, develop the contours given by the probability of impacts and, for those areas within the probability threshold area, calculate the MPL value. Calculate specific assessments for accident scenarios involving specific high-value assets within the threshold area, if those accident scenarios have a probability within the 10^{-7} probability threshold. That value will show the contributions from casualties, from property loss, and any from environmental damage and cleanup as well as loss of use. The applicant will complete the estimation and fill out the form in section six.

It cannot be overemphasized 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 of concern. 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. Figures 2 and 3 are provided as illustrations of the simple logic behind the MPL estimation of public risk. The applicant may develop similar Event Trees for his own particular vehicle concept. Figures 4 and 5 are provided as useful examples of the simple event trees the applicant may want to use where applicable.

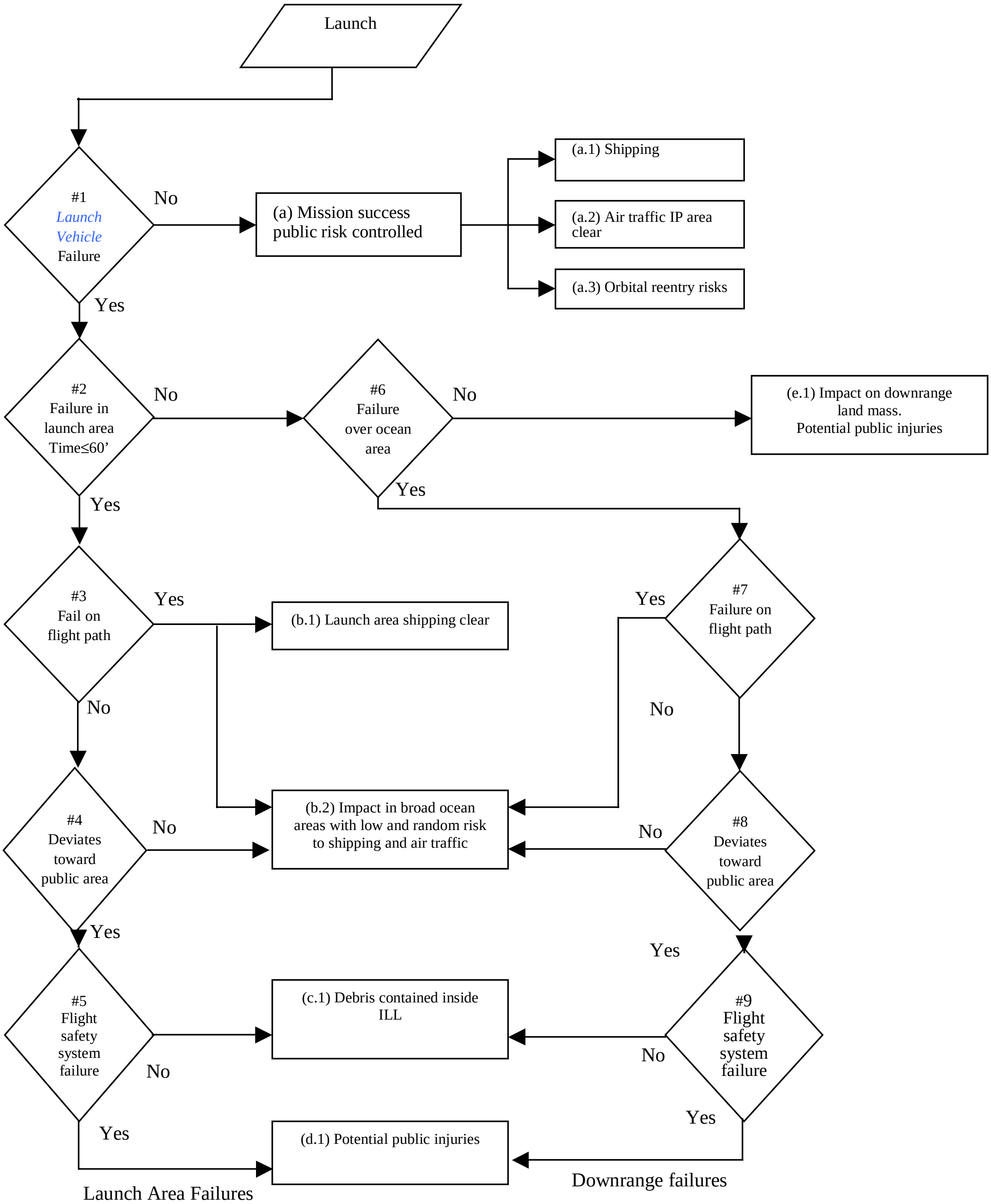

Figure 2. Public Launch Hazard Event Tree (FAA)

EVENT NODES

1 Launch vehicle failure:	Probability that launch vehicle will fail, i.e., that the flight will not be successful. YES = 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 Fail on flight path:	Probability of failure occurring on the original flight path. YES path = P (failure on original flight path) NO path = 1-P (failure on original flight path)
4 Deviates toward public areas	Probability of deviation toward populated areas protected by impact limit lines (ILLs). 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, i.e., 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, i.e., 1- (probability that failure will occur during overflight of Micronesia, Australia, Asia or other populated downrange land masses). YES path = P (failure over open ocean) NO path = 1- P (failure over open ocean)
7 Fail on flight path	Probability of failure occurring on the original 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 FSS will fail. YES path = P (FSS failure) NO path = 1- P (FSS failure)

Figure 3: Public Launch Hazard Event Tree Nodes – Definitions (continued)

OUTCOMES

(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.

(a.2) **Air traffic, IP area clear** Planned air traffic exposures.

(a.3) **Orbital re-entry risks** Risks to third parties from eventual decay from orbit of on-orbit hardware.

(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.

(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 3: Public Launch Hazard Event Tree Nodes - Definitions (continued)

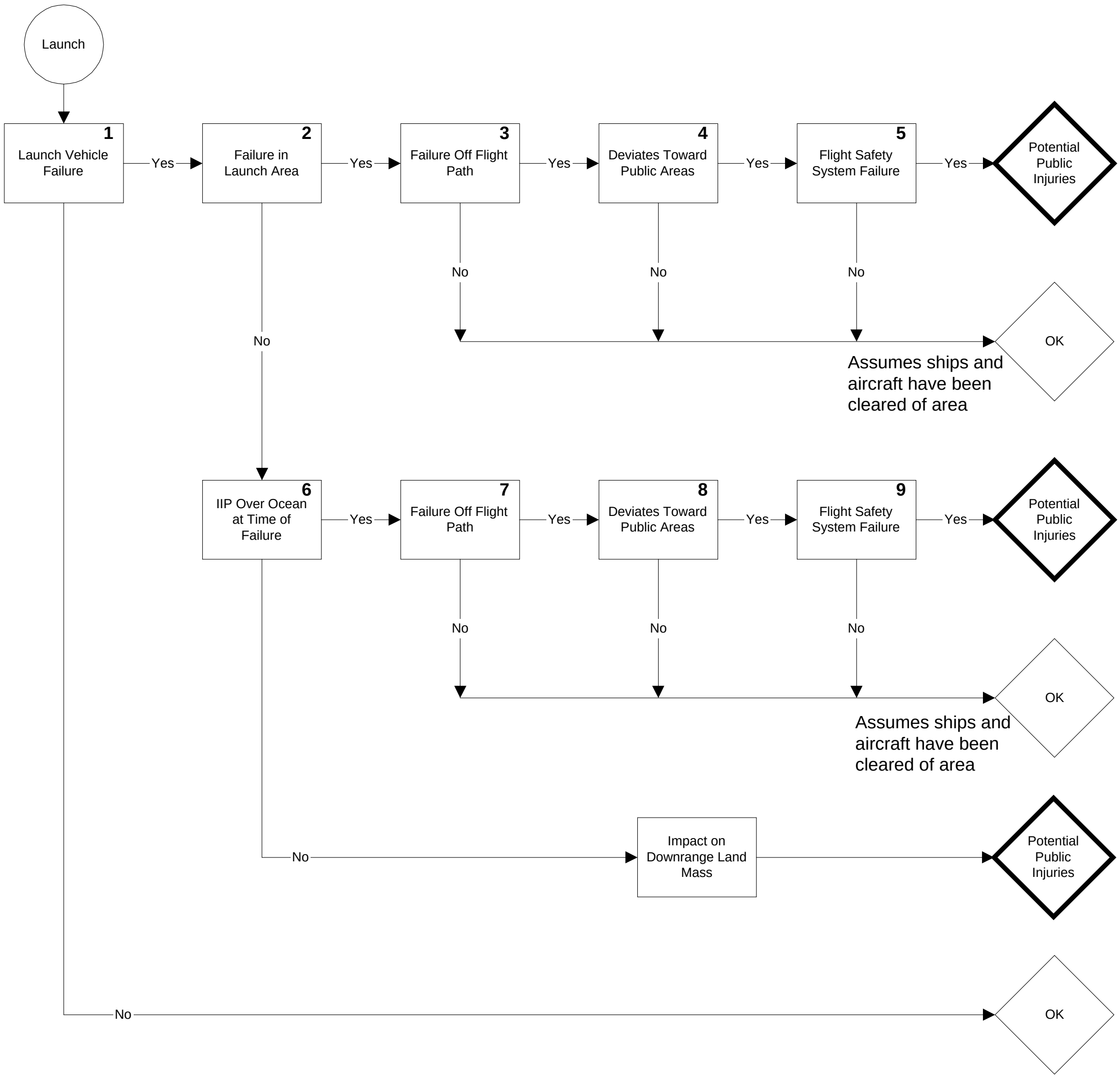

Figure 4. ELV Public Launch Hazard Event Tree (proposed sample)

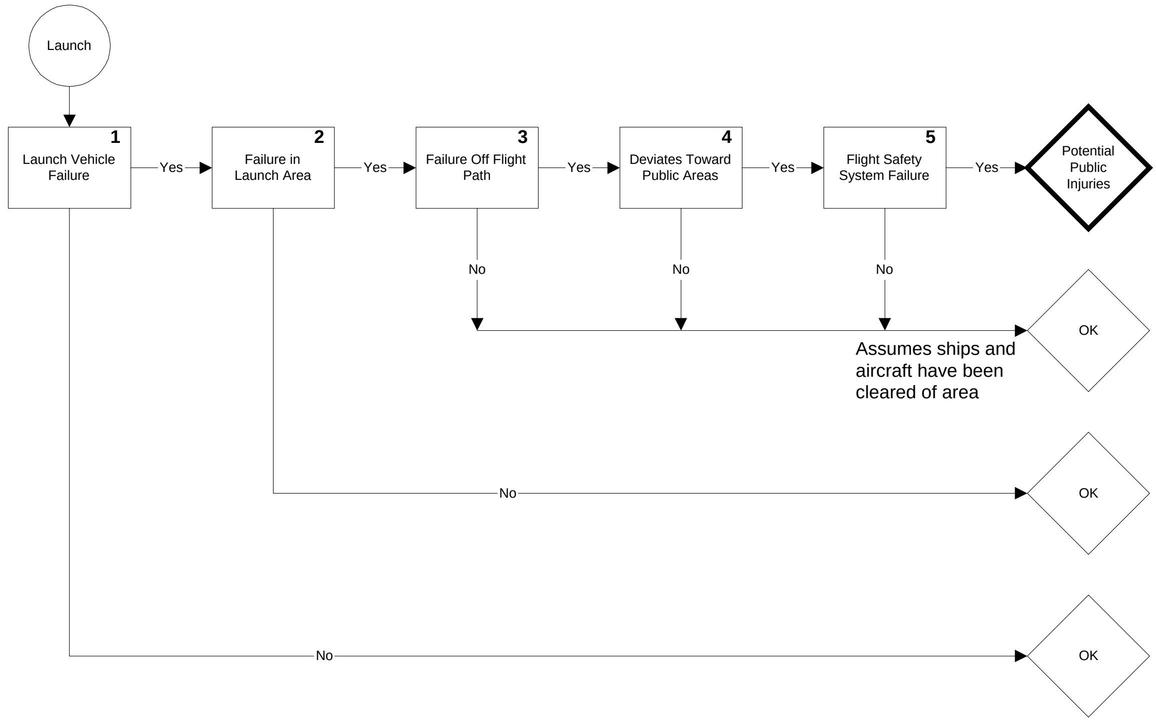

Figure 5. Suborbital Public Launch Event Hazard Tree (proposed sample)

Primary effects of debris

The debris hazards vary as a function of the destruct action, vehicle failure mode and time in flight of the occurrence. Debris is normally classified by ballistic coefficient, cross sectional area, total fragment weight and the number of fragments. The debris likely to cause the most serious damage is that with the higher ballistic coefficient. Other debris is considered less significant but may also cause damage and casualties. The permit applicant will be required to develop a debris catalogue and corresponding impact footprint along the instantaneous impact point (IIP) for his vehicle for any portion of the flight during which third parties are exposed.

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 (IA) of the debris is on the order of 3.45 km^2 when the vehicle's destruction occurs early in the flight, 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 IIP for the upper stages crosses downrange land masses. For re-entry and recovery, the IA will be the size of most countries at the completion of the de-orbit burn and on the order of 3.45km^2 at parachute deployment or high key[1]. Casualties and property loss result from the primary effects of impact by debris.

Secondary effects of debris

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, but 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 mishaps or re-entry 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.

Effects of toxic materials

At the present time and the foreseeable future, 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.

MISHAP SCENARIOS TO CONSIDER

The following accident 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. As is evident, 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 his analyses.

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[1] High key refers to the entry point of the space object for landing operations, usually high above the landing site, or nearly so, at which parachute deployment or other landing manoeuvres are initiated.

i. Solid motor burn through
ii. Liquid propellant ignition
iii. Anomalous trajectory
iv. Flight Safety System failure
v. In-flight breakup
vi. Release of toxic gases
vii. Failure to pitch over
viii. Improper roll manoeuvre
ix. Shift or loss of inertial reference
x. Ascending stage or payload impacting airborne aircraft
xi. Descending stage, payload or re-entry vehicle impacting airborne aircraft
xii. Stage or re-entry vehicle impacting person or property after parachute descent
xiii. Stage, payload or re-entry vehicle impacting person or property after ballistic or autonomous approach
xiv. Stage, payload or re-entry vehicle igniting a fire on the ground
xv. Re-entry vehicle fails to separate from the upper stage or on-orbit platform
xvi. Re-entry vehicle re-enters but fails to re-enter at the planned-for position and time
xvii. Re-entry vehicle has an undetected critical system failure
xviii. Re-entry vehicle scattering debris during re-entry
xix. Re-entry vehicle releasing hazardous materials

CASUALTY AREA

Casualty Area

The permit applicant is to develop a break-up model, a debris catalog on his vehicle and refine that further into an Casualty Area for uprange and downrange 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,” angle of impact, and calculation of the composite or Casualty Area. The methodology for developing the CA is contained in the “Risk Hazard Analysis” of the SLASO Flight Safety Code. The applicant is to create his debris catalogue by converting the total non-volatile mass of the launch vehicle (including payloads) into ballistically lethal fragments. Following that, he is to assume that: all resultant fragments, either striking a person directly or glancing a person, will result in death or serious injury; that no individual debris casualty areas overlap; and that the dimensions of a "standard person" are 0.3m in radius and 2.0m in height. The standard person radius of 0.3 m is added to the dimension of each piece of lethal debris in the vehicle's debris catalogue. The equation to be used for calculating the CA is expressed as:

$$CA = CA_{(inert)} + CA_{(explosive)}$$

Where:

$CA_{(inert)}$ comprises a basic casualty area component $CA_{(basic)}$ which is made up of debris falling vertically and diagonally, and components for debris skidding $CA_{(skid)}$. For each debris group, the lethal debris area is the basic area plus the area found for debris skidding. $CA_{(explosive)}$ is the explosive debris contribution to CA calculated from converting propellant weights into equivalent TNT weights and using an explosive overpressure threshold of 25 kPa.

The licence or permit applicant is to develop the CA for his vehicle based on the "Risk Hazard Analysis" in the current version of the SLASO Flight Safety Code apply that dimension in this MPL methodology.

<u>Scaling factor to account for debris skidding</u>. If a permit applicant is not able to develop the complete Casualty Area for its vehicle as detailed in the its "Risk Hazard Analysis" of the SLASO Flight Safety Code, SLASO requires that the applicant increase the basic casualty area developed in its debris catalog by a factor of 4.7, and furthermore instructs the applicant to use this scaled up casualty area, in conjunction with the $CA_{(explosive)}$, to obtain the CA for use in estimating MPL losses.

Casualty Area for small rockets. Because it is problematic to develop debris catalogues for very small rockets, typically due to resource limitations and the absence of data, the below Figure 6, which results from an interpolation of data contained in Research Triangle Institute's (RTI) "Small Rocket Risk Analysis", May 16, 1991, may be used to estimate the Casualty Area for unstable (tumbling) small rockets with a total impulse up to 200,000 pound-seconds. To be properly conservative, the applicant will use the amplified CA in estimating casualties. The small rocket permit applicant is to develop the Casualty Area as described above for larger vehicles, but, if SLASO authorizes it, the applicant may use the values found from Figure 6.

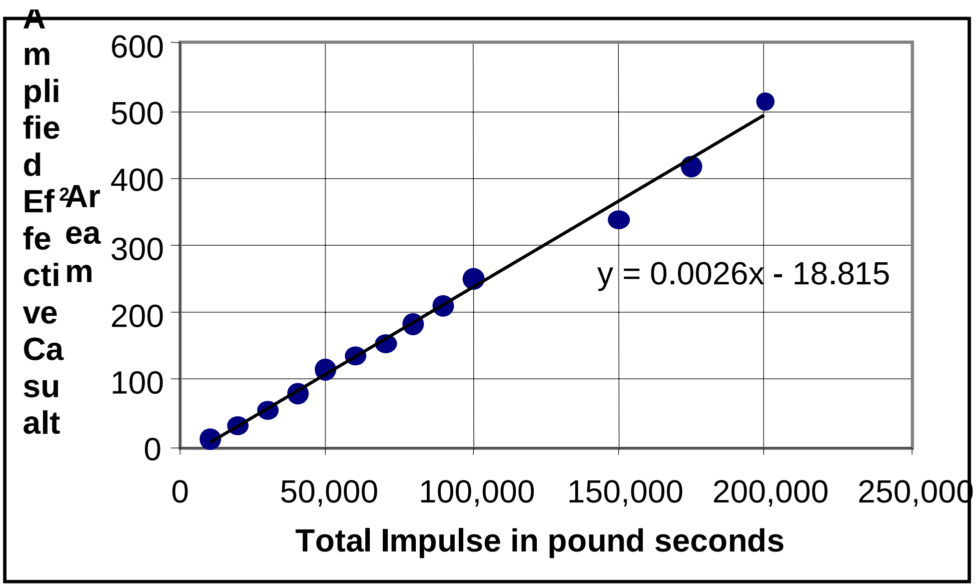

Figure 6: Interpolation of data obtained from the Research Triangle Institute for amplified effective casualty as a function of the total impulse per pound per second for small rockets

FOR AREA LOSSES

People - primary effects of debris

Losses to people within the probability threshold area are determined by layering the CA over an area containing the highest population density that can be found anywhere within the contours. For launches from Woomera, for example, that population density is likely to be based on Roxby Downs. For launches from Hummock Hill Island off Gladstone Queensland, Gladstone will likely have the population density to consider. For launches from the proposed Asia-Pacific

Space Centre on Australia's Christmas Island External Territory, the population density to consider may reside on a launch area island.

For re-entry, people and properties within the probability threshold area are considered at risk. For re-entry and landing at Woomera for example, if the contour includes Port Lincoln, and if that is the most densely populated area at risk with an area equivalent to the debris footprint, the population at risk may be based on the population density that results from that city’s 14,000 residents.

For RLV activities, the area at risk lies along and within the probability threshold area contours as the stage makes its descent, approach and landing. The population density at risk is the highest within the probability threshold area.

The number of casualties is estimated by the layering approach, where the CA is layered on the highest population density cluster within the probability threshold area. For the uprange or launch area phase, and for recovery, the permit applicant is to find an area that is close to 3.45 km^2 in size (which corresponds to the impact area IA), that has the highest population density of all areas within the probability threshold area.

The calculation to use for layering is:

$$\text{Casualties} = (CA) \times (D_{Pop})$$

CA = Casualty Area in m^2

D_{Pop} = Population density in persons/km^2, converted to persons/m^2

$$\text{Casualties} = \frac{persons / km^2}{1 \, x \, 10^6 \, m^2 / km^2} \times CA \; m^2$$

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 an Casualty

Area of 93 m^2 that is hazarding an area with a population density of 580 persons/km^2 (but populated to an area of about 3.45 km^2) will cause 5.39×10^{-2} casualties, or 0.0539 casualties. A vehicle with an Casualty Area of 3,700 m^2 posing a hazard to that same population density will cause 2.15 casualties.

Casualties are rounded to the nearest whole number. Casualties equal to or above 0.5, a half of a casualty, will be assigned as one casualty. Casualties below that number will be set at zero. Casualties in excess of 1.5 up through 2.49 will be assigned as two casualties. Casualties equal to or above 2.5 up through 3.49 will be assigned as three casualties, and so forth. In the above example that yielded 2.15 casualties, two casualties would be assigned.

People - secondary effects of debris

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. Table 3 shows the results of sample calculations and the resulting casualty MPL value based on 5,000,000 A$ million per casualty. Because initial rounding takes place before entering Table 3, rounding to the nearest whole casualty number will suffice. Thus, in the first row, (one 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 three total estimated casualties, as shown.

Table 3. Launch area/uprange 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 5,000,000 A$ per casualty
1	2	3	15,000,000 A$
2	3	5	25,000,000 A$
3	5	8	40,000,000 A$
4	6	10	50,000,000 A$
5	8	13	65,000,000 A$
6	9	15	75,000,000 A$
7	11	18	90,000,000 A$
8	12	20	100,000,000 A$
9	14	23	115,000,000 A$
10	15	25	125,000,000 A$
11	17	28	140,000,000 A$
12	18	30	150,000,000 A$
13	20	33	165,000,000 A$
14	21	35	175,000,000 A$

Loss of property as a function of the casualty loss estimate

Third-party property losses are estimated at 50% of the value of the losses to third-party persons 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.

The calculation to use for launch area property loss is:

$$MPL_{(LAP)} = CAS_{(LA)} \times (0.5) \times (5{,}000{,}000 \text{ A\$})$$

where

CA = Casualty Area in m^2

$MPL_{(LAP)}$	=	MPL value for launch area third-party property in A$
$CAS_{(LA)}$	=	Casualties in the launch area
5,000,000 A$	=	Cost per casualty

For example, if a total of 3 casualties for an MPL value of 15,000,000 A$ were estimated to result then the third-party property loss would be 7,500,000 A$.

Loss of property as a function of the specific facility

If the risk analysis conducted in accordance with the current version of the "Risk Hazard Analysis" in the SLASO Flight Safety Code shows a single high-value facility within the probability threshold area, such as an oil platform or mine, the applicant is required to conduct a special assessment to determine the damage that would be caused by impact on that facility by the vehicle, its stages or expected debris, if the probability of such damage occurring is higher than the 10^{-7} threshold. The assessment will be specific to the size and strength of the facility versus the impact and explosive effects of the mishap vehicle. The damage estimate thus calculated will be compared to any generated by the layering approach and its property bounding method, with the higher of the two values being assigned as the property MPL value for that phase of flight.

An approximate value of the loss of property can be obtained as presented in the previous section "estimating costs for losses" and here reported in general terms

$$MPL_{(LOP)} = (\text{Property Value } m^2) \times \left(\frac{ECA}{IA}\right) \times (\text{Facility size})$$

where

$MPL_{(LOP)}$	=	MPL value for loss of property in A$
Property Value m^2	=	Property value of the facility per metre squared, in A$
CA	=	Casualty Area for that flight phase
IA	=	Impact area of the vehicle debris
Facility size	=	Footprint area occupied by the facility expressed in m^2

Loss of use

For loss of use, the applicant will use whichever value is higher, the value obtained by overlaying the debris area over a facility of known size and annual revenue, if that facility itself is at risk within the 10^{-7} threshold, or that obtained by multiplying the per capita Gross Domestic Product (GDP) of the country where casualties may result times the number of casualties estimated.

$$MPL_{(LOU)} = CAS_{(LA)} \times (GDP)$$

where

MPL $_{(LOU)}$ = MPL value for loss of use in A$

CAS = Casualties estimated

GDP = Per capita Gross Domestic Product, in A$, for Australia

Or

$$MPL_{(LOU)} = (\text{Revenues p.a./m}^2) \times \left(\frac{ECA}{IA}\right) \times (\text{Facility size m}^2) \times (\text{Time out in months/12})$$

where

MPL $_{(LOU)}$ = MPL value for loss of use in A$

Revenues = Annual revenue of the facility per metre squared, in A$

CA = Casualty Area for that flight phase

IA = Impact area of the vehicle debris

Facility size = Footprint area occupied by the facility expressed in m^2

Time out = Time, in months, needed to reinstate the facility state to the same one it had before the accident, based on an estimated proportion to a year.

Environmental damage and cleanup

The applicant will estimate the cost associated with environmental damage and clean-up by whichever of the following two methods provides the higher MPL value: 100,000 A$; or, if there is a particular high-valued third-party asset individually facing an impact probability of 10^{-7} or greater, an accurate evaluation of the cost associated with restoring the environment to the condition which would have existed if that damage had not occurred.

Note that, unlike the U.S. practice, the environmental damages and clean-up costs in the MPL methodology developed for the Commonwealth of Australia include indirect damages, such as the ones that could be caused by an oil spill caused by an impacting vehicle, if there is a probability higher than 10^{-7} that such an accident may happen. The rationale for including indirect damages is that it can reasonably be anticipated that parties suffering consequential losses (loss of business and profits, environmental cleanup 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. Most courts will give recognition to such consequential damages.

Launch area MPL value estimated	____________
Casualties x A$5 million	____________
Property (0.50 of casualty MPL value) ***or*** ***Facility damage estimate***	____________
Loss of use (Casualties x GDP/capita) ***or*** ***Facility damage estimate (Loss of use)***	____________
Environmental (100,000 A$) ***or*** ***Facility damage estimate (Environment)***	____________

FOR DOWNRANGE OVERFLIGHT

For downrange, the people and property at risk are those within the probability threshold area. This is estimated to be a swath along the IIP extending hundreds of kilometres laterally. Property and people inhabiting the downrange area overflown by the IIP for an ELV’s stages will likely be at a level of risk within the 10^{-7} probability threshold. If the hazard analysis supports that assumption, the number of casualties will be determined by overlaying the CA on the area with the highest known population density in the area being overflown (nominal trajectory ± lateral dimension). A key difference between the launch area or uprange methodology and this downrange one is that in the uprange, the debris and the highest population density at risk were about the size of 3.45 km^2, but here, the very large debris IA will likely cover major sections of countries. Thus, the population density chosen for the MPL estimation is the highest of the coastal regions of Australia or countries (e.g., Japan) or even geographic areas (e.g. North America) overflown. As with the launch area casualty estimations, the layering method is used.

The calculation to use for layering is:

Casualties = (CA) x (D_{Pop})

CA = Casualty Area in m^2 for this phase of flight

D_{Pop} = Population density in persons/km^2, converted to persons/m^2

$$\text{Casualties} = \left(\frac{persons / km^2}{1\,x\,10^6\,m^2 / km^2}\right) \text{ x (CA)}$$

The third-party MPL value for downrange overflight is based only on the predicted number of casualties multiplied by the 5,000,000 A$ cost of a casualty. Losses due to toxic effects, explosive effects, property damage, loss of use, and environmental damage and cleanup are expected to be contained within the cost assigned to casualties. 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 cleanup are expected to be contained within the cost assigned to casualties. This is typically during upper stage flight.

However, if there is a particular high-valued third-party asset individually facing an impact probability of 10^{-7} or greater, an accurate evaluation of the cost associated with property damage, loss of use and environmental damage and cleanup needs to be conducted.

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 an Casualty Area of about 186 m^2 during overflight near Japan, which has a population density of about 460 persons/km^2, the overflight will result in 8.56 x 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.

Downrange MPL value estimated	____________
Casualties x A$5 million	____________
Property (Included in casualty value) ***or*** ***Facility damage estimate (Property)***	____________
Loss of use (Included in casualty value) ***or*** ***Facility damage estimate (Loss of use)***	____________
Environment (Included in casualty value) ***or*** ***Facility damage estimate (Environment)***	____________

FOR RE-ENTRY

Unplanned re-entry

The risk from *unplanned* re-entry of space components and payloads is sufficiently small to be considered negligible. Further MPL analysis in this area is not necessary.

Unplanned re-entry MPL value estimated ***<u>Zero</u>***

Planned re-entry

The MPL for a re-entry vehicle is analyzed assuming the vehicle remains intact, as it is designed to do. Within the probability threshold area for planned re-entry, CA is prescribed as two times the footprint. This is sufficient to include the additional area formed by increasing the object's dimensions by 0.3 m in all directions to account for the standard radius of a person.

The probability threshold area contour will be plotted at: the completion of the de-orbit burn; when the IIP first touches Australia; then at discrete intervals until the final contour, which is at parachute deployment or high key, depending on the vehicle type. Casualties will be estimated by overlaying the CA over the highest population density of an area equivalent to the IA of the debris that will result from a failure at each of the discrete points. Thus, there will be five or six casualty estimations for the re-entry, one for each of the probability threshold area contours and each based on the vehicle's CA acting on the highest population density equivalent to the changing debris footprint. The MPL estimate for re-entry will be based on the computation that yields the greatest number of casualties.

Estimate casualties by using the same layering technique as before. The value associated with property loss will be 0.5 of the value of casualties, with loss of use and environmental damage and cleanup estimated as previously. If less than one-tenth of a casualty is estimated, the MPL is set at zero. If a specific high-value facility is individually at risk, property loss, loss of use and environmental damage are set as previously, if the probability of such damage is higher than the 10^{-7} threshold.

The calculation to use for layering is:

Casualties	=	(CA) x (D_{Pop})
CA	=	Casualty Area in m^2 for this phase of flight
D_{Pop}	=	Population density in persons/km^2, converted to persons/m^2

$$\text{Casualties} = \left(\frac{persons / km^2}{1\,x\,10^6\,m^2 / km^2}\right) \text{ x (CA)}$$

Planned re-entry MPL value estimated ____________

Casualties x A$5 million ____________

Property (0.50 of casualty MPL value)
or
Facility damage estimate } ____________

Loss of use (Casualties x GDP/capita)
or
Facility damage estimate (Loss of use) } ____________

Environmental (100,000 A$)
or
Facility damage estimate (Environment) } ____________

FOR RECOVERY

The MPL for the recovery or landing of an RLV is analyzed assuming the vehicle breaks up in a manner that produces the largest CA. Within the probability threshold area, the debris catalogue resulting from planned and unplanned destruct actions, adjusted for the 0.3 m radius of a person, will be scaled up by the 4.7 factor that addresses the effects of the debris sliding, bouncing or splattering. A blast component to the CA is not required because it is assumed the stage or vehicle has expended all or most of its propellant and the resulting debris will have little or no blast component.

As with planned re-entry, the probability threshold area contour will be plotted at: the completion of the de-orbit burn; when the IIP first touches Australia; then at discrete intervals until the final contour, which is at parachute deployment or high key, depending on the vehicle type. Casualties will be estimated by overlaying the CA over the highest population density of an area equivalent to the IA of the debris that will result from a failure at each of the discrete points. Thus, there will be five or six casualty estimations for the re-entry, one for each of the probability threshold area contours and each based on the vehicle's CA acting on the highest population density equivalent to the changing debris IA. The MPL estimate for re-entry will be based on the computation that yields the greatest number of casualties.

Estimate casualties by using the same layering technique as before. The value associated with property loss will be 0.5 of the value of casualties, with loss of use and environmental damage and cleanup estimated as previously. If less than one-tenth of a casualty is estimated, the MPL is set at zero. If a specific high-value facility is at risk, property loss, loss of use and environmental damage are set as previously, if the probability of such damage is higher than the 10^{-7} threshold.

RLV recovery MPL value estimated	____________
Casualties x A$5 million	____________
Property (0.50 of casualty MPL value) ***or*** ***Facility damage estimate***	____________
Loss of use (Casualties x GDP/capita) ***or*** ***Facility damage estimate (Loss of use)***	____________
Environmental (100,000 A$) ***or*** ***Facility damage estimate (Environment)***	____________

VI. MPL SUMMARY

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

Launch area MPL value estimated	____________
Casualties x A$5 million	____________
Property (0.50 of casualty MPL value) ***or*** ***Facility damage estimate***	____________
Loss of use (Casualties x GDP/capita) ***or*** ***Facility damage estimate (Loss of use)***	____________
Environmental (100,000 A$) ***or*** ***Facility damage estimate (Environment)***	____________

Downrange MPL value estimated	____________
Casualties x A$5 million	____________
Property (Included in casualty value) ***or*** ***Facility damage estimate***	____________
Loss of use (Included in casualty value) ***or*** ***Facility damage estimate (Loss of use)***	____________
Environment (Included in casualty value) ***or*** ***Facility damage estimate (Environment)***	____________

Planned re-entry MPL value estimated ____________

Casualties x A$5 million ____________

Property (0.50 of casualty MPL value)
or
Facility damage estimate } ____________

Loss of use (Casualties x GDP/capita)
or
Facility damage estimate (Loss of use) } ____________

Environmental (100,000 A$)
or
Facility damage estimate (Environment) } ____________

RLV recovery MPL value estimated ____________

Casualties x A$5 million ____________

Property (0.50 of casualty MPL value)
or
Facility damage estimate } ____________

Loss of use (Casualties x GDP/capita)
or
Facility damage estimate (Loss of use) } ____________

Environmental (100,000 A$)
or
Facility damage estimate (Environment) } ____________

Upon completion of the MPL and this section, forward same to SLASO.

VII. CONTACT DETAILS

For further information about the licensing regime set out under the *Space Activities Act 1998*, including matters set out in this Maximum Probable Loss Methodology, interested parties should contact:

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CANBERRA ACT 2601

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