QRA Technical Guidance

[Revision No: 3]
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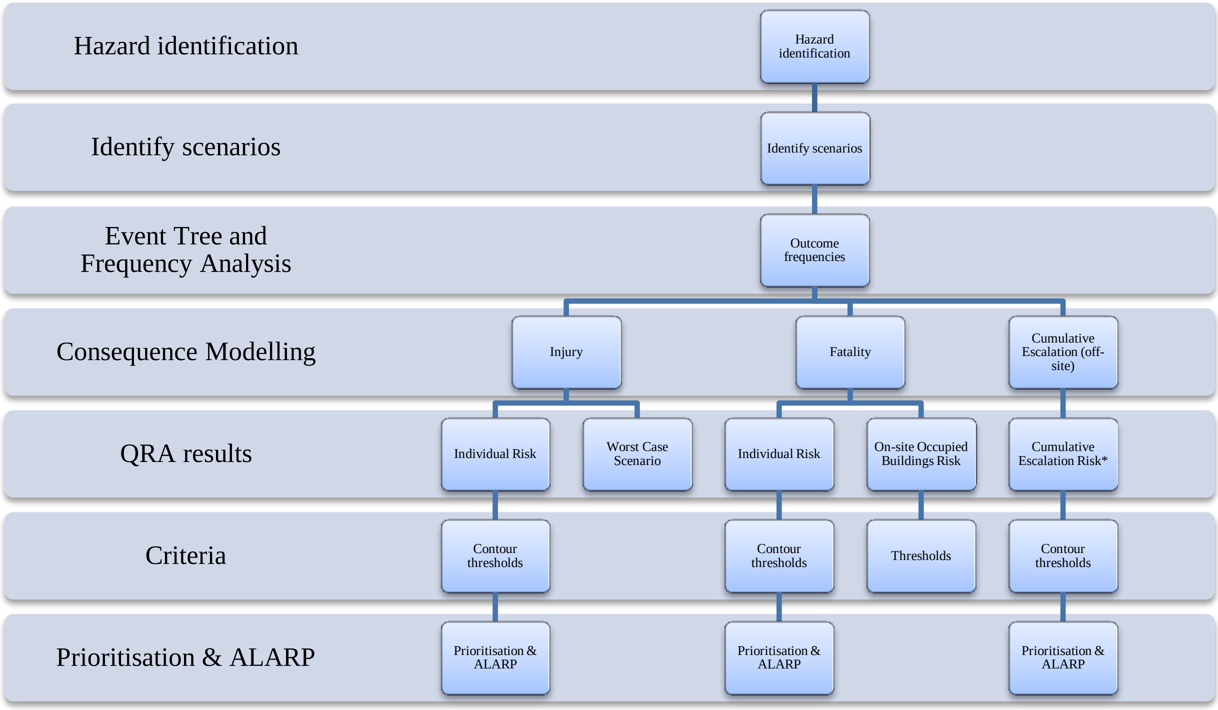
Contents

1 QRA Study

A QRA study is made up of a number of steps (Figure 1).



*Cumulative Escalation Risk is modelled the same way as Individual Risk. The term 'Cumulative Escalation Risk' refers to the IR equivalent for structures, and is used to differentiate between risk to structures and risk to humans (IR)

Figure 1 QRA Study Process

The process starts with hazard identification, from which the scenarios to take forward in the QRA study are derived.

Outcome frequencies for these scenarios are then calculated using failure rates, event trees and modifiers.

Consequences are calculated to determine distances and footprints to specified harm levels grouped into specific categories:

- injury to people;
- fatality to people (both on-site and off-site);
- escalation off-site.

The required results are then presented. These are either in terms of consequence or risk:

- For consequence-based results, distances to specific harm levels and outcome frequencies should be provided and specified harm zones produced.
- For risk-based results the groups of footprints to specified harm levels along with outcome frequencies and weather data for the different categories noted above are used to calculate individual risk. Individual risk is the summation of risks from all the scenarios within the defined Boundary and is usually calculated on a grid and presented graphically in the form of iso-contours for specific risk levels. In addition, an occupied buildings assessment should be carried out.

These results are then compared to specified criteria. The criteria relate to different types of sensitive receptors, boundaries and land types.

The results of the risk evaluation are then prioritised to identify a set of scenarios for consideration for risk reduction to reduce the risk to ALARP. They also form a key input to emergency response planning.

2 Hazard Identification

Suitable hazard identification should be carried out in order to identify all possible accident scenarios for the QRA.

A basic top down hazard identification using keywords such as fire, explosion and toxic release is usually adequate to identify major accident scenarios.

3 Identify Scenarios

From the hazards identified, the scenarios list should be generated (Section 3.1). Any scenarios identified but excluded from either hazard range calculation or risk calculation should be justified.

Process related scenarios, such as runaway reaction (if not already considered in frequency databases used) and overfilling should also be identified. Where insufficient information is available for the quantification of these scenarios, this justification should be provided.

For each of the scenarios, the different outcomes should be identified (see Section 4.2) depending on the hazardous material.

3.1 Scenarios

Scenarios considered within the QRA should be identified by means of a systematic procedure. This should use available project documentation (e.g. process and instrumentation diagrams, process flowsheets, layout diagrams) to identify all significant inventories of hazardous materials. The list of scenarios to include in the QRA should comprise loss of containment of each inventory via:

- Catastrophic failure (cold failure and hot failure/BLEVE)
- A suitable range of hole sizes (see Section 4.1.1.1).

Appropriate scenario screening methods may be used in considering scenarios to be included within the QRA, such methods include:

- Installation screening procedure in RIVM Reference Manual Bevi Risk Assessments – this method shall be supplemented with other approaches and/or justifications to demonstrate that a representative risk profile of the site is reflected.

Any other methods proposed shall be justified accordingly. In assessing allowable scenario screening methods, Agencies will consider the effect of excluded scenario(s) on QRA results, and in providing a representative risk profile of the site.

3.1.1 Fixed Installations

Each inventory will have specific location details within the QRA. It may be possible to group scenarios into a smaller representative set for consequence modelling purposes. If so, the resulting harm footprints should be applied to each location with the appropriate frequency.

It is expected that most scenarios will be modelled assuming catastrophic failure and a range of hole sizes. However there could be additional scenarios which give rise to different scenarios as a result of process operations. Many of these will be included within generic failure rates relating to catastrophic failure and a range of hole sizes.

Consideration should be given as to whether process operations could cause scenarios which have not otherwise been considered, in terms of both frequency and consequences. Examples would include:

- Mischarging into reactors and storage tanks causing runaway reaction (particularly if causing release of toxic gas due to the reaction);
    - The main event to be modelled for a chemical reactor is catastrophic failure due to overpressure caused by runaway reaction. Frequency is available in the HSE FRED database (http://www.hse.gov.uk/landuseplanning/failure-rates.pdf) under FR1.1.4. Appropriate flammable (fireball/ jet fire/pool fire etc.) and toxic outcomes should be considered based on the material. A worst case substance released, between normal reactor contents and products should also be considered.
    - If the site has storage tanks containing chemicals that would react to give a toxic gas then the runaway reaction due to filling into the wrong tank should be considered. Frequency should be based on the HSE FRED database. Consequences based on dispersion of toxic gas should be based on filling rate reacting until detection and shut down.
- Overfilling of gasoline (or similar storage tanks giving rise to explosion such as at Buncefield UK in 2005 (potential, unless eliminated by design, for VCE under conditions not previously expected to cause VCE)):
    - A 'Buncefield-like' explosion should be considered in the QRA where relevant, using the following simplified methodology. Atmospheric storage tanks for which this simplified methodology applies ("in-scope tanks") are as follows: Vertical, cylindrical, non-refrigerated, above-ground storage tanks with greater than 100 m^3/hour and with overflow above 5m. All tanks are in scope i.e. all liquid outflow geometries and tanks with and without wind girders. The only exception is tanks with fully enclosed overflow pipes bringing any release to ground level.
        - ✓ Containing any of the following substances: gasoline, acetone, benzene, crude oils (with Reid Vapour Pressure≥2.5 psi), methyl ethyl ketone (MEK), naphthas, reformate (worst case-light), natural gas liquids (condensate), methyl tert butyl ether, iso pentane, toluene.
        - ✓ For single component liquids not listed above, those with a Reid vapour pressure ≥2.5psi are in scope.
        - ✓ For multi-component mixtures not listed above and with a Reid vapour pressure ≥2.5psi, the filling rate for which tanks are in scope is determined from: Filling rate (m^3/hr) x liquid density (kg/m^3)/tank perimeter (m) >3600. (Note: a default density of 750 kg/m^3 could be used.)
        - ✓ (Note: for a new installation it is possible to design liquid overflows that are piped to ground level, thereby preventing formation of a major mist cloud).
    - For in-scope tanks, the harm footprints to be used for modelling of VCE from tank overfill are as follows.

Weightings are to be applied to the harm footprints indicated below, as described under Section 6.2.4 of this Technical Guidance:

IR (Fatality):

- ✓ 3% fatality harm footprint – use a circle of radius 400 metres from the tank wall
- ✓ 10% fatality harm footprint – use a circle of radius 300 metres from the tank wall
- ✓ 50% fatality harm footprint – use a circle of radius 250 metres from the tank wall

IR (Injury):

- ✓ 3% fatality harm footprint – use a circle of radius 400 metres from the tank wall

Cumulative Escalation:

- ✓ 2 psi harm footprint: use a circle of radius 400 metres from the tank wall

On-site Occupied Buildings:

- ✓ 3% fatality harm footprint – use a circle of radius 400 metres from the tank wall
- ✓ 10% fatality harm footprint – use a circle of radius 300 metres from the tank wall
- ✓ 50% fatality harm footprint – use a circle of radius 250 metres from the tank wall

ALTERNATIVE METHOD

For alternative method in determining the harm footprints of overfilling scenarios, a more accurate calculation method is provided in HSE Research Report RR 908 or FABIG (Fire and Blast Information Group) Technical Note 12. This method can be used to make a calculation of the cloud size. For the cloud size calculated by this method, it is reasonable to assume 100% fatality; 100% injury and 100% escalation within the cloud and no effects outside the cloud (similar to a flash fire but including escalation). The RR908 / FABIG method predicts the cloud size but not the overpressure. It should then be assumed that a high order VCE occurs within the cloud, with overpressure sufficient to cause 100% fatality. There is very low overpressure outside the cloud based on evidence from Buncefield.

- It is noted that all other relevant outcomes (i.e. other than VCE caused by tank overfill for in-scope tanks which may adopt the simplified methodology described above) should still be considered and modelled as defined in the QRA Guidelines (note: harm footprints as indicated in Section 5.4 of this Technical Guidance). The harm footprints for all other relevant events (e.g. catastrophic failure, hole sizes etc.) should be modelled, and this includes other VCEs whereby the simplified methodology does not apply (i.e. not in-scope tanks).
- For the frequency calculation of overfilling, the following can be used:

  EITHER

  - ➢ In cases where the QRA is developed in advance of detailed design for a new installation or major modification, it is acceptable to base the frequency on company targets for the frequency of an event giving the estimated number of casualties within the footprint. If the QRA indicated that risk criteria would not be achieved then the target frequency would need to be reduced so as to meet criteria. The detailed design would then need to achieve the target frequency. Potential consequences are to assume 100% fatality of all people inside the 50% fatality footprint in revised QRA guidelines or 100% fatality in the more accurate footprint calculated using the HSE Research Report RR 908 or the FABIG methodology. The following example scenario risk targets could be used:

Potential number of fatalities	Target frequency
1-10	1E-06 – 1E-07/yr
11-50	1E-07 – 1E-08/yr
50-100	1E-08 – 1E-09/yr
100+	< 1E-09/yr

OR

- Carry out frequency estimation using methods such as Fault Tree Analysis (FTA) or layer of protection analysis (LOPA). For inclusion in the LOPA estimation, all barriers must be independent (no double-counting, no common cause failures) and maximum risk reduction per barrier is 0.1 (with justification) unless there is strong justification for a lower value, e.g. ESD with SIL suitable for a lower PFD.
  - Possible initiating events:
    - ✓ Frequency of filling x Probability of failure of basic control system to prevent overfill, or Probability of Human error e.g. miscalculation of volume available in tank, sending fluid to the wrong tank.
  - Conditional modifiers:
    - ✓ Wind/weather probability as for F1 in Singapore (because not possible to form large enough cloud in higher wind). A weather probability of 0.1 can be used for Singapore based on zero wind speed conditions. Also, low enough wind speed will not exist within refinery/ process units where the processes use enough heat to produce convection driven wind flows. (This will only be relevant for storage tanks that are situated within process units.)
    - ✓ Release lasts long enough to produce a large cloud. A default assumption would be duration > 10 minutes.
    - ✓ Fuel reactivity
    - ✓ Ignition probability. Usually = 1 if large cloud produced as it will extend beyond classified zones and will last for significant time. This is the overall ignition probability. The relevant ignition probability is that for ignition if the cloud has not already ignited early (before the cloud radius reached 100 metres). There are different approaches to estimating the early ignition probability:
      1. Use to OGP early ignition probability
      2. Use an area based ignition probability (refer to paper by Lisbona, Briggs and Wardman). The relevant area is for a 100 m radius. Table 2 gives an ignition density parameter. It can be

used in equation (1) to give the ignition probability within a 100 metre radius.

3. Use a more sophisticated ignition model than OGP. The UK Energy Institute Guidelines on ignition probability provides one such model. It also discusses area based approaches for progressive modelling of flash fires in a similar way to option 2 above.

    - ✓ Account may be taken of existing on-site strong ignition sources such as furnaces (accounting for the probability of them being in operation). Hot surfaces would need to be hot enough (auto-ignition temperatures are measured with a large area of hot surface for a small sample of flammable gas so it cannot be assumed that ignition will always occur above the auto-ignition temperature). Insulated steam piping is unlikely to be hot enough at the insulation surface.
  - ▪ Possible barriers (include only if present), e.g.:
    - ✓ Basic control overfill shutdown system (not allowable if failure of basic control system is initiating event)
    - ✓ Independent overfill alarm and operator action to stop filling
    - ✓ Independent overfill emergency shutdown system (SIL rated)
    - ✓ Gas detection system or CCTV plus automatic or operator action to prevent cloud getting large enough. Means of isolation (operator or automatic) needs to be independent of other barriers. Gas detection and isolation would need to take place within about 10 minutes. Detection is important in low wind situations and it is relatively easy to achieve good detection via a minimal number of gas detectors because there is no wind to blow the cloud away from detectors. Therefore one detector in a bund is sufficient. Companies may use 2 detectors in a bund as a means of screening spurious alarms. For isolation of overfill, the isolation would need to be either automatic or remotely actuated using a push button, because isolation is needed within 10 minutes.
    - ✓ Diverse level measurement e.g. as input to calculations of volume remaining in tank
    - ✓ Procedure for checking calculations of volume remaining in tank
    - ✓ Procedure or interlocks to prevent filling wrong tank
- Processing conditions that could lead to release at elevated temperature (e.g. above flash point), or pressure, such that consequences would be significantly worse;
- Confined explosion within process equipment or building, which could give rise to larger hazard ranges than external VCE;
- Fires in chemical warehousing (toxic combustion products);
- Fires involving storage compounds containing drums and IBCs.

Relevant scenarios due to process operations should be identified so far as is possible from the information and HAZID studies available at the time that the QRA is developed. If any significant scenarios are subsequently identified, e.g. as the result of HAZOP, these should be included in any future revision of the QRA.

The range of potential outcomes considered should include (depending on the physical properties of the hazardous materials concerned):

- Pool fire;
- Jet fire;
- BLEVE Fireball;
- Flash fire;
- Vapour cloud explosion (VCE);
- Pressure vessel burst e.g. due to runaway reaction or internal explosion;
- Toxic release.

3.1.2 Pipelines

In addition a range of potential operational failures should be considered with a view to including any additional scenarios which could be significant and have higher failure rates than generic historical data and/or give rise to different potential consequences. For example:

- Accelerated corrosion, e.g. need to increase frequency as a result of releases of corrosive products from other pipelines in the rack.

Relevant scenarios due to process operations should be identified so far as is possible from the information and HAZID studies available at the time that the QRA is developed. If any significant scenarios are subsequently identified, e.g. as the result of HAZOP, these should be included in any future revision of the QRA.

The range of potential outcomes considered should include:

- Pool fire;
- Jet fire;
- BLEVE Fireball;
- Flash fire;
- Vapour cloud explosion (VCE);
- Toxic release.

3.1.3 Bulk transport

In addition a range of potential operational failures should be considered with a view to including any additional scenarios which could be significant and have higher failure rates than generic historical data and/or give rise to different potential consequences. These scenarios' frequencies should be distributed over the entire route length. Examples of such scenarios are shown below. These scenarios may be excluded from QRA if justifications are provided on how such scenarios are prevented:

- Overfilling during loading and subsequent warm-up and pressure rise/venting due to liquid thermal expansion during transport:
    - Release frequency is the probability of overfilling (e.g. based on taking account of the SIL of overfill protection instrumented shut-down system and the probability of failure on demand of any additional barriers to overfilling) x deliveries per year. This may be modified by the fraction of overfilling cases expected to lead to the isotanker becoming liquid full due to thermal expansion and should be justified. Scenarios will depend on tanker design and properties of load, e.g. release through PRV, failure of isotanker container if no PRV or PRV fails, BLEVE due to released flammable material causing fire around isotanker.
- Runaway reaction (e.g. due to warm-up during transport) should be considered where relevant.

- Reaction of incompatible substances (e.g. as a result of vehicle crash or inadequately secured load) should be considered where relevant.

The range of potential outcomes considered should include:

- Pool fire;
- Jet fire;
- BLEVE Fireball;
- Flash fire;
- Vapour cloud explosion (VCE) (any route segments which are clearly vulnerable due to congestion);
- Toxic release;
- Pressure burst due to runaway reaction.

4 Frequency Analysis

The likelihood of each outcome should be calculated. Frequency data for the event should be obtained from an appropriate data source. Outcome frequencies should be calculated for risk calculations, taking into account appropriate modifiers. The results should be tabulated.

4.1 Frequency Data

4.1.1 Data sources

Statistics and frequency estimates used shall be representative of the conditions in Singapore and specific to the accident scenario(s) to which they are applied. References shall be provided for the failure data used. Justification shall be provided for the choice of failure rate data and its relevance to the industry sector and conditions for which it is being applied.
If loss of containment failure rates are derived from fault tree analysis, because there are no suitable historical failure rates and the scenario is very specific, for example some runaway reaction scenarios, then all assumptions shall be clear and justified. Any necessary assumptions about human error probabilities shall also be justified.

The following data sources should be used, as applicable to situation.

4.1.1.1 Fixed Installation

To promote consistency between QRAs, the following historical failure rate data should be used.

- UK failure rates: (http://www.hse.gov.uk/landuseplanning/failure-rates.pdf);
  - For Large Vessels, Small and Medium Atmospheric Tanks, Refrigerated Ambient Pressure Vessels, LNG Refrigerated Vessels, Liquid Oxygen Refrigerated Vessels, the hole sizes to be modelled shall be as specified in HSE FRED.
  - For all other equipment (e.g. Pressure Vessels, Chemical Reactors, Valves, Pumps, Hoses and Couplings, Flanges, Gaskets, Pipework), the following representative hole sizes are to be modelled, where relevant. The failure rates obtained from HSE FRED shall be used in determining the failure rates for the representative hole sizes as shown below.

Representative Hole Size	**10mm**	**25mm**	**75mm**	**Catastrophic failure / Guillotine (for piping/pipeline)**

Failure Rates for this range of hole sizes to be used	0 to 15mm	16mm to 49mm	50mm onwards	Instantaneous release for catastrophic failure of pressure vessel/equipment Full bore release for piping/pipeline

Any other suitable sources of historical failure rates may be used if the specified source above does not contain the required information.

For multiple equipment items within the same isolatable section:

a. If hole sizes are common between equipment items, the frequencies for each equipment item shall be considered. The whole isolatable inventory shall be modelled for each hole size.
b. If hole sizes are different between equipment items, then each equipment item should be modelled separately based on each equipment item's failure rate and representative hole sizes. The whole isolatable inventory shall be modelled for each hole size. For piping connected to major equipment item (e.g. vessel) within an isolatable section, if the piping is less than 10 metres (absolute length), a simplification may be made by considering only the major equipment item (e.g. vessel)'s failure rates and hole sizes.
c. Equipment items are not to be double-counted. For example, an isolation valve should be considered only once in the modelling for one isolatable section rather than for both isolatable sections on each side of the valve.

- For road tankers and transport containers within the Boundary of the Installation (i.e. within the Boundary of a Fixed Installation if included in the scope of a Fixed Installation QRA), where suitable measures (including speed limits) have been applied to minimise the risk of road traffic accidents, the failure rates from the Netherlands Purple Book (Guidelines for Quantitative Risk Assessment RIVM BEVI Manual Module C) may be used.

4.1.1.2 Pipeline

Relevant historical failure rates should be used for pipelines and ancillary equipment. To promote consistency between QRAs, the following sources of data should be used.

Suitable sources of data include:

1. UK failure rates: (http://www.hse.gov.uk/landuseplanning/failure-rates.pdf) for above ground pipelines;
2. Suitably selected data sources for buried pipelines, such as:
    - EGIG (European gas pipelines) – more for gas
    - CONCAWE (International including hazardous liquid pipelines)
    - UKOPA (UK pipelines) – more for flammable gas
    - CCPS (Guidelines for Chemical Transportation Risk Analysis, CCPS/AIChE, ISBN 0-8169-0626-2, 1995)

Note: If a pipeline has some sections which are buried and some which are above ground, then failure rates should be chosen for each section based on whether they are above ground or buried.

4.1.1.3 Bulk Transport

Local accident rate of 2.20E-07 accidents/km/year shall be used.

In addition, the following historical failure rate data should be used:

- CCPS (Guidelines for Chemical Transportation Risk Analysis, CCPS/AIChE, ISBN 0-8169-0626-2, 1995)

In most cases for a transport QRA, the frequency for an event involving a leak of a certain size will be derived from the combination of:

- Probability that crash leads to a release. A probability of approximately 0.05 is suggested by sources such as CCPS.
- Probability that release is of specific size. This can, for example, be obtained from the UK failure rate data (see above) for an appropriate pressure vessel by using the failure rates for each hole size.

For road tankers and transport containers within the boundary of the Installation (i.e. within the Boundary of a Fixed Installation if included in the scope of a Fixed Installation QRA), where suitable measures (including speed limits) have been applied to minimise the risk of road traffic accidents, the failure rates from the Netherlands Purple Book (Guidelines for Quantitative Risk Assessment RIVM BEVI Manual Module C) may be used.

4.1.2 Frequency Modifiers

With suitable justification, it is acceptable to take credit for suitably designed hardware measures which reduce the frequency of the loss of containment event, for example the design of a pipeline with higher wall thickness and reduced design stress (reduced ratio of operating pressure to design pressure) since these factors can reduce the frequency of failure as a result of third party activity (e.g. inadvertent impact of a buried pipeline with a mechanical excavator).

It may also be allowable to take credit for scenario-specific measures that incorporate operator action, e.g. to cool down a reactor or to stop filling for an overfilled vessel. Probability of failure needs to consider the availability of an operator (including, if action provides mitigation, that the operator might become a casualty) and the probability of human error.

‘Management factors’, unless strongly justified shall not be applied to historical failure frequencies of containment systems. Such measures may not be taken into account in modifying historical failure rates because some of the inventory of equipment items used to derive the historical failure rates will have had the risk reduction measure. Double-counting of the effects of a risk reduction measure is not allowed. For novel hardware risk reduction measures, credit might be allowable with suitable justification. Also, any credit given for an operator’s current excellent record of safety management, would need to be maintained over the life-time of the installation and cannot therefore be justified for QRA at the pre-construction stage (e.g. due to possible future changed ownership).

It is also acceptable to take credit for risk reduction measures which are part of the event tree following loss of containment (see Section 4.2 below). Credit may also be taken for hardware risk reduction measures, such as suitably designed passive fire protection, in preventing escalation events.

4.2 Event Trees

Event trees relevant to the scenarios being modelled should be developed. Probabilities for each branch in the event trees should be determined and justified.

The event trees determine the outcome frequencies that feed into the risk summation process.

The following event trees are generic non-exhaustive event trees for flammable and toxic outcomes. They do not cover specific process operations.

In the following figures, the event (frequency) indicates the source frequency data (for example Section 4.1.1.1 for fixed installations) and the outcome (frequency) indicates the resultant frequency that feeds into the risk calculation (Section 6).

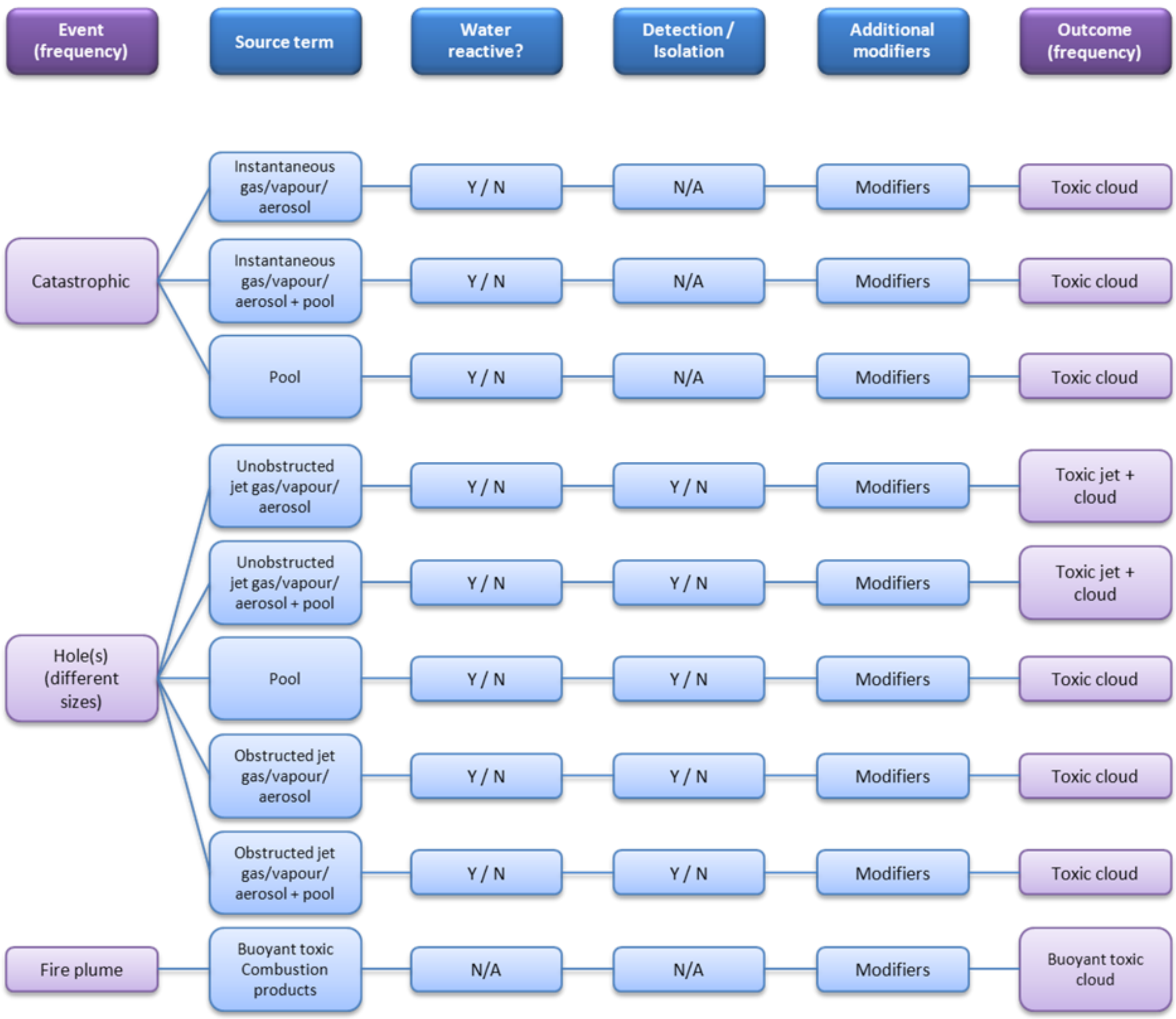


Figure 2 Toxic release

Table 1 Explanatory notes for Figure 2

Heading	Terms from event box	Comments
Event (frequency)	Catastrophic	Catastrophic failure of the containment should be considered
	Holes	Several hole sizes should be considered
	Fire plume	An event involving toxic smoke may need to be considered depending on whether it is possible. The smoke may involve combustion products, the parent material or both
Source term	Gas/vapour/aerosol	Whether from a hole or a catastrophic release, some part of the release may be in the gas/vapour phase possibly including liquid aerosol. Some of that aerosol may evaporate within the vapour cloud to produce more vapour and so needs to be modelled as part of the vapour cloud
	Unobstructed	An unobstructed jet will retain its momentum (velocity) and give enhanced dispersion as air is entrained into the cloud
	Obstructed	A percentage of jets may be obstructed e.g. impact with the ground or other objects within a few metres of the release. Impact will reduce the momentum and so tend to increase dispersion distances, but may also cause aerosol droplets to coalesce and form a pool
	Pool	A pool of liquid on the ground, which may or may not be contained by a bund or dyke
	Buoyant combustion products	The smoke from a fire, which due to the high temperature will be buoyant
Water reactive	Y/N	If the toxic fluid reacts with water (e.g. HF, $TiCl_4$, PCl_3, $POCl_3$) then this should be taken into account in the source term and dispersion modelling. Y/N = yes/no
Weather	F1+B2+C3	These three weather categories should be modelled for each toxic release
Detection/isolation		For releases through holes (e.g. in piping) an automatic shut-down system may be successful at isolating the release
Additional modifiers		There may be one or more additional modifiers
Outcome (frequency)		All the events give rise to a toxic cloud which will disperse with distance. In some cases the dispersion will be enhanced by jet entrainment which is included within many dispersion models

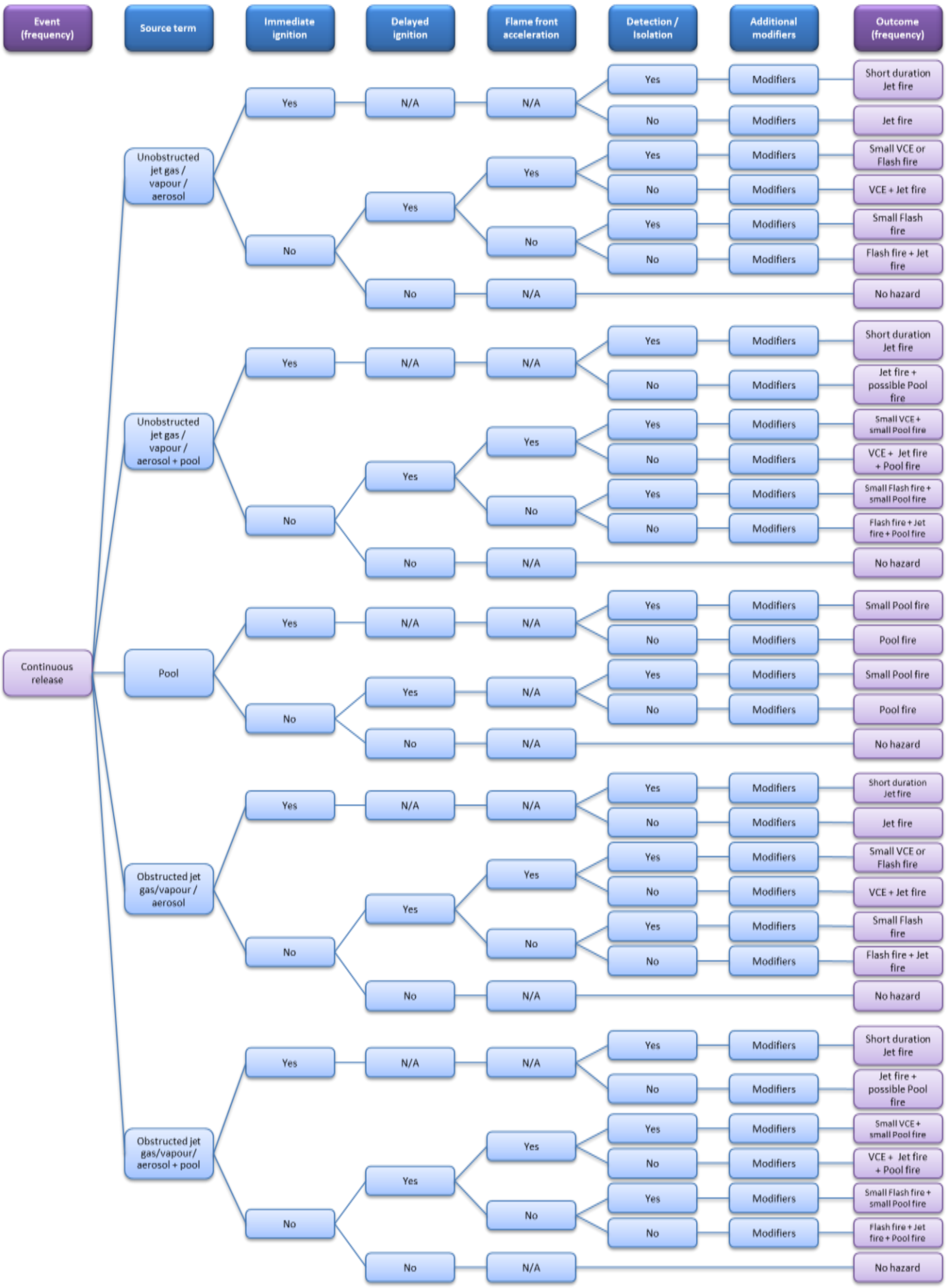


Figure 3 Continuous flammable release

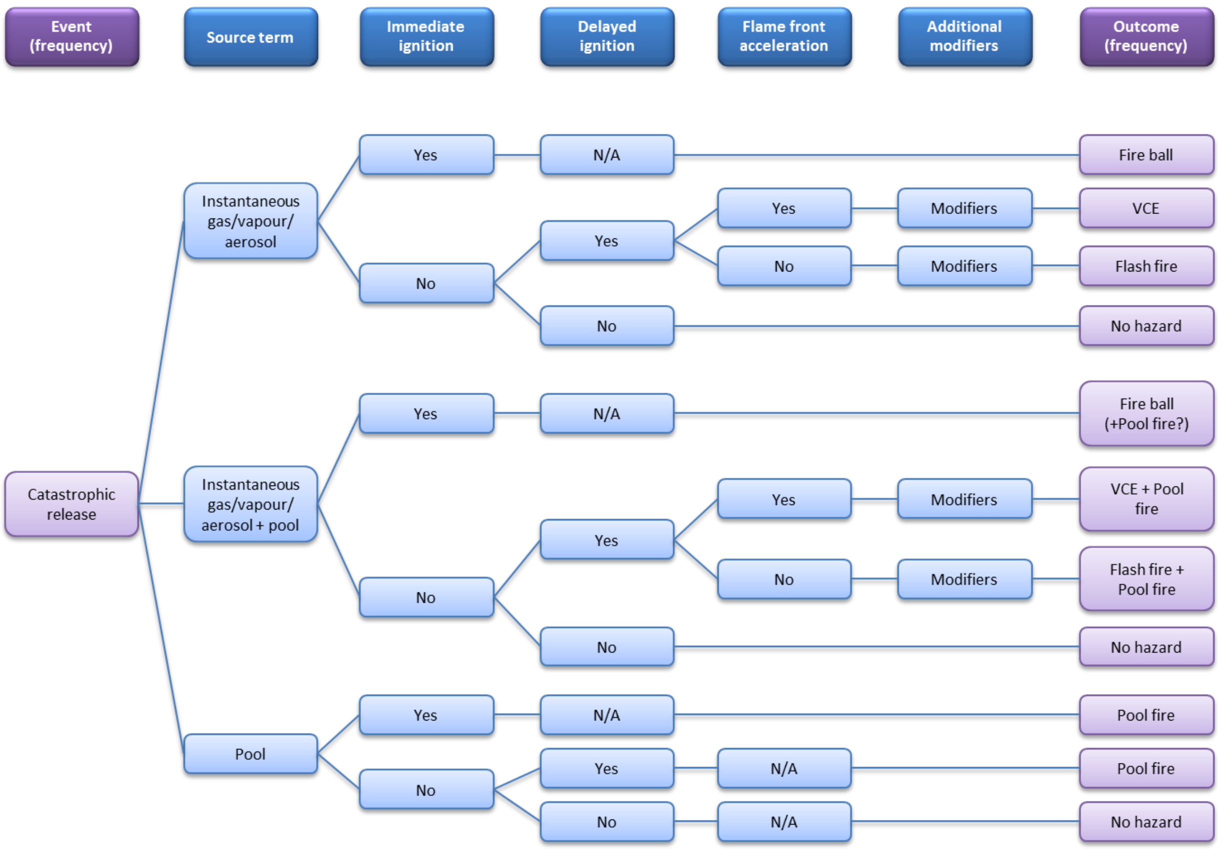


Figure 4 Catastrophic flammable release

Table 2 Explanatory Notes for Figure 3 and Figure 4

Heading	Terms from event box	Comments
Event	Catastrophic	Catastrophic failure of the containment should be considered
	Continuous	Continuous release of the containment should be considered
Source term	Gas/vapour/aerosol	Whether from a hole or a catastrophic release, some part of the release may be in the gas/vapour phase possibly including liquid aerosol. Some of that aerosol may evaporate within the vapour cloud to produce more vapour and so needs to be modelled as part of the vapour cloud
	Pool	A pool of liquid on the ground, which may or may not be contained by a bund or dyke. VCE and flash fire hazards should be considered due to formation of flammable vapour cloud arising from pool evaporation.
	Unobstructed	An unobstructed jet will retain its momentum (velocity) and give enhanced dispersion as air is entrained into the cloud
	Obstructed	A percentage of jets may be obstructed e.g. impact with the ground or other objects within a few metres of the release. Impact will reduce the momentum and so tend to increase dispersion distances, but may also cause aerosol droplets to coalesce and form a pool
Immediate ignition	Yes/ No	Ignition early enough that a flammable vapour cloud large enough to cause a significant VCE or flash fire hazard has not had time to form

Delayed ignition	Yes/ No	Ignition late in the development of the event such that a significant flammable vapour cloud and/or large pool exists prior to ignition. For some outcomes such as flash fire, ignition probability may be taken into account in the risk calculation and not in the event tree
Flame front acceleration	Yes/ No	Congestion and/ or semi confinement of a flammable vapour cloud such that a VCE rather than a flash fire would occur
Detection/isolation		For releases through holes (e.g. in piping) an automatic shut-down system may be successful at isolating the release
Additional modifiers		There may be one or more additional modifiers
Outcome		These are the outcome consequence(s). In some cases there is more than one outcome consequence. For example, a release which will form a flammable cloud with delayed ignition will give rise to a VCE or flash fire. After this has happened, a jet fire will remain, and (if a flammable pool had formed) a pool fire also. Outcome consequences due to escalation to other inventories have not been shown on these event trees but should be considered, e.g. pool fire or jet fires escalating to BLEVE fireball
Short duration jet fire	Specific outcome	If an un-isolated jet fire has a different harm footprint from an isolated jet fire (e.g. where isolation occurs prior to escape), a short duration jet fire may be considered. However, it is noted that there may be instances whereby un-isolated jet fire produces same harm footprint as isolated jet fire, for e.g. when exposure duration is greater than 30s (see Section 5.2.4.1, where 30s considers escape)

4.3 Event Tree Modifiers

Table 3 below provides a list of modifiers which may be included in a QRA as described in the table, and sets limits for the range of values of the probability of failure on demand. Any other modifiers proposed to be used shall be justified.

Table 3 Event tree modifiers which may be included within QRA

Modifier	Description	Comments
Ignition probability	Probability that flammable release ignites. Ignition models usually correlate with flow rate of release. The probability of ignition tends towards 1 as the duration of the release increases (especially if the cloud reaches beyond hazardous area classification zone 2) or if the cloud reaches strong ignition sources such as furnaces.	Value used to be based on OGP data on assigning ignition probabilities. Value used to be fully justified if different. Note that ignition probabilities in Cox, Lees and Ang, Classification of Hazardous Locations, shall not be used.
Ignition probability: Ratio of immediate: delayed ignition	Probability that flammable release ignites once a significant flammable cloud has been formed. Ignition models may correlate with flow rate of release, area of flammable cloud etc.	Value used to be based on OGP data on assigning ignition probabilities. Value used to be fully justified if different

Modifier	Description	Comments
Probability FF or VCE	Probability that an ignited flammable cloud will give rise to a flash fire rather than a vapour cloud explosion.	(Probability of flash fire) + (Probability of VCE) = 1 Should preferably be determined and justified from a consideration of whether turbulence generating structures (congestion/ semi-confinement) exist, release rate, dispersion and size of the flammable vapour cloud.
Probability of gas or liquid release for two-phase vessels	Hazard ranges tend to be larger for liquid or two-phase releases than for gas releases. Probability split required for different release events.	Probability split between gas and liquid release to be justified taking account of height of normal liquid level and number of connections (which could potentially fail) above and below liquid level. Note that rapid depressuring can sometimes cause liquid release from the top of a vessel due to level swell.
Operating time	Percentage of time that the operation which could lead to release occurs.	Should be justified. May be relevant for road tanker loading/ offloading unless frequency based on number of deliveries per year.

Modifier	Description	Comments
Detection and shut-down system	Probability of failure on demand of system which detects a loss of containment (e.g. pressure loss, gas detection etc) and operates shutdown valve(s) which will isolate the release or much reduce the quantity released.	Should be justified with reference to intention to provide system with suitable IEC61508/ 61511 safety integrity level (SIL) for entire system including detection, logic, field wiring or equivalent, actuators and valves. Extensive evidence and SIL2 rating required for lower end of range. Lower probabilities may be possible for SIL3 but better solution is often multiple diverse systems at SIL2 or SIL1. It should be noted that SIL 3 is very onerous to design in practice and will require suitable maintenance and inspection frequencies to maintain the level of risk reduction. Suitable SIL report will be required when available to justify SIL assumed. Shut down system should not normally rely on manual isolation. Manual isolation may be acceptable with justification if there is sufficient time available in the development of the scenario, the human failure probability is assessed (including the probability that an operator is not present, not available or has become a casualty), and that operators should not be expected to enter an ignited or unignited flammable release to achieve isolation, nor to enter a toxic cloud without suitable PPE. Remote isolation (e.g. push button activation of shut-down system) may be included but human failure probability shall be included. Claims for systems utilising the plant basic control system (rather than a separate safety system) to be limited to a minimum of 0.1 and even this requires justification. A probability of 1 should be used if failure of the basic process control system (BPS) could initiate the loss of containment and there are common components between the BPS and the detection and shut-down system. Where mitigation systems include safety-related control systems, for example gas detection followed by automatic shut-down valves and/or active fire protection (deluge/ sprinkler systems), the system should be designed to a safety integrity level (SIL) compatible with the probability of failure on demand (PFD) claimed. The following Table adapted from IEC 61508/ IEC 61511 provides the PFD range for each SIL (SIL greater than SIL2 would not normally be expected as part of a shut-down system, although it may be possible to achieve greater risk reduction using more than one diverse SIL-rated system).

Table 4 Safety integrity level and probability of failure on demand

Safety integrity level (SIL)	PFD range
SIL 3	$10^{-4} – 10^{-3}$
SIL 2	$10^{-3} – 10^{-2}$
SIL 1	$10^{-2} – 10^{-1}$
Not designed to achieve SIL	$< 10^{-1}$

Modifier	Description	Comments
Active Fire Protection (AFP)	Probability of failure on demand of deluge, sprinkler or remote automated fire monitor system.	Probability to be justified including correct specification of the system, and probabilities of detection, activation and blockage of nozzles. Availability of water, foam etc. should also be considered. Account should only be taken of multiple AFP systems if they provide duplicate coverage of the same area.
Passive Fire Protection (PFP) (installation of properly designed specialist fire protection material/ coating to surface of vessel or structure. Specialist fire-proofing materials include cementitious, intumescent, ablating or subliming)	Probability of failure to prevent escalation to protected vessel or structure	PFP which is present and properly designed for fire may be assumed to prevent escalation (PFD of 0). Probability to be justified including correct specification for the type and duration of fire, quality control of application, protection from damage including any explosion which could be part of the event, any need for periodic removal to allow inspection of the vessel/structure, maintenance and repair regime. Credit should not be claimed for normal thermal insulation unless it can be shown to be capable of preventing escalation from the fire and that it will not become dislodged by the action of fire-fighting water.
Fire wall	Probability of failure to prevent escalation, injury or fatality	Probability to be justified including correct specification for the type and duration of fire (pool fire or jet fire), installation to withstand any explosion which could be part of the event, absence of penetrations which would undermine its function. A properly specified and designed fire wall that can be expected to withstand its design fire outcomes for the specified duration may prevent harm or escalation (PFD = 0).
Blast wall	Probability of failure to prevent escalation, injury or fatality	Probability to be justified including correct specification for expected overpressure and duration, absence of penetrations which would undermine its function, ability to stop missiles. If the blast wall has been designed to withstand the blast then the PFD = 0. If the blast wall design is inadequate for the blast, then the PFD = 1. If blast wall has been designed using an 'exceedance curve' approach, this will provide a probability of blast wall failure, on average, for a range of events and modelling assumptions.

Modifier	**Description**	**Comments**
Explosion panels	Probability of failure to prevent escalation, injury or fatality	Properly designed explosion panels can reduce the overpressure from an internal explosion and so may prevent escalation including building collapse which could cause fatality. The PFD of an explosion panel is likely to be low so the main issue is whether it is designed for the outcome. Explosion panels will not prevent injury or fatality to personnel in the building caused by the thermal effects of the explosion. Probability used to be fully justified.
Toxic refuge	Probability of failure to prevent injury or fatality	Probability to be justified including probability of successful escape into toxic refuge, prevention of contaminated air from entering (e.g. positive pressure operation, air locks, door and window seals etc.), adequacy of air supply and cooling system for the duration of the incident. If the toxic refuge is suitably specified for the outcome including the expected duration, then the PFD will be dominated by human factors of ensuring that personnel are able to reach the refuge and leave the refuge into fresh air once the toxic cloud has passed.
Specially designed control room	Probability of failure to prevent injury or fatality	Probability to be justified including correct specification of control room to withstand worst case external VCE, fires, toxic gas for the necessary duration.
Occupied building	Probability of failure to protect occupants	Probability to be justified including air change rate, procedure to close doors and windows during toxic release and to evacuate personnel into fresh air afterwards, construction to prevent damage/ collapse from VCE and multiple fires which would prevent evacuation. For flash fires, probability to be justified for consideration of protection by the building, for e.g. building construction (non-combustible materials). Probability should not be double-counted with harm levels (section 5.4) that take account of the protection provided by the building.
Secondary containment system with scrubber	Probability of failure on demand	This is for toxic releases. Probability to be justified. It should be clear which events the system is designed for. For example, such systems may be used to reduce the risk during loading/offloading of chlorine road tankers. However catastrophic and large releases will overpressure and demolish the containment system. For smaller releases, the availability/reliability of the scrubber, including starting pumps on detection of a release, will determine the probability of failure.

Modifier	Description	Comments
Water deluge - effect on release of soluble toxic gas	Probability of reduced quantity of soluble toxic gas in dispersing cloud.	API 751, 2013 Safe Operation of Hydrofluoric Acid Alkylation Units - Fourth Edition refers to a publication that gives reductions in the amount of HF releases as a function of the ratio of deluge water to HF. Credit could be taken for the resulting smaller harm footprint in the case that the operation of the deluge system is successful. The full harm footprint should be included for (1 – probability of success). Probability to be justified based on SIL of detection of HF/actuation of deluge system and also on the geometry of the design and probability for the plume to escape the deluge system. Justification required for extrapolation to gases other than HF.

5 Consequence Modelling

The required consequence modelling is detailed in this Section. This defines the harm distances and harm footprints required for the QRA.

5.1 Models

The models and software used and the basis for their selection for each specific outcome, considering applicability, should be stated clearly including version number. Where it is industry standard software with validated models, stating the inputs used and the models selected is sufficient. Otherwise, details of the calculations should be provided and justified accordingly.

5.1.1 Industry standard software and models

Industry standard software includes DNV PHAST; TNO Effects; CERC ADMS (particularly buoyant dispersion); Shell Global Solutions FRED; BP CIRRUS; SAFER TRACE. Note that standard software has had some validation and verification but this does not mean that uncertainty can be ignored. Also all software and models have limits of applicability which the consultants shall take into account.

5.2 Assumptions

5.2.1 Source terms

- Time for isolation. Where credit is claimed for isolation of releases, either by an automatic shut-down system or manually, isolation times should be no lower than the following:
  - 1 minute for automatically operated shut down valves
  - 5 minutes for remotely operated shut-down valves (operated using a push button from a safe area)
  - 20 minutes for manual isolation
- Two-phase vessels. Storage tanks should be assumed to be full. The assumption of what percentage of releases is of liquid should be based on a relative height of the liquid when full and/or the distribution of connections above or below the liquid level.
- Overturned road tankers. The possibility of road tankers overturning following a vehicle crash should be considered so that liquid release is possible even if there are no connections into the normal liquid space.
- Site specific source terms should be considered, e.g. releases that would be into confined areas, tank details that would lead to generation of liquid aerosol following overfilling.

- Hole sizes. A range of possible hole sizes and catastrophic failure should be considered. Refer to Section 4.1.1.
- Pressurised releases.
  - If a two-phase jet impacts close to point of release and loses momentum then assume a pool is formed and consider vapour produced from initial flashing plus pool evaporation
  - If jet does not impact and flash fraction is greater than 15%, assume that 100% vaporisation occurs within the jet.
  - If flash fraction < 15% then assume 2 x flash fraction becomes vapour
  - Consequence models, such as PHAST, that model evaporation of droplets can be used as an alternative to these assumptions.
- Water reactives. If the hazardous material reacts with water and this would increase the hazard range, then reaction with water should be modelled. In the simplest terms, dispersion of the toxic product should be modelled, making a justified assumption about the percentage conversion and resulting source temperature.
- Combustion products. Toxic combustion products from major fires should be modelled.
- Warehouses. Toxic combustion products from chemical warehouse fires should be modelled. In addition, the possibility of entrainment of unburnt toxic material, especially finely divided solids, into the fire plume should be considered.
- The diameter of any evaporating pool should be considered and justified. For catastrophic failure of liquid storage tanks, bund overtopping and possible bund demolition by the liquid wave should be considered.

5.2.2 Dispersion modelling

- No credit should be taken for people being indoors when calculating individual risk. An exception is that credit may be taken for a suitably designed toxic refuge preventing harm to on-site personnel in occupied buildings.
- Suitable dispersion models should be used depending on whether the release is of heavy, passive or buoyant gas/vapour.
- A suitable value should be chosen for the ground roughness which should consider the range of the dispersion and err on the side of low roughness. Ground roughness should be no more than 0.3m.

5.2.3 Flammables modelling

- Vapour cloud explosions should be modelled using a method which takes account of turbulence generators such as congestion and semi-confinement. An example would be the TNO multi-energy model, where source strength of 5 to 7 is typically used for congested volumes, subject to justifications for the specific value used. Any assumptions about the percentage of a flammable cloud within a congested volume should be justified. Suitable CFD modelling would also be appropriate as an alternative.
- Flash fires should be modelled to the lower flammable limit (LFL).
- Jet fires. Horizontal jet fires should usually be assumed as the worst case unless justification can be provided otherwise.

5.2.4 Harm criteria

5.2.4.1 Probits

Probits are not expected to be necessary to produce harm criteria in most cases since the harm criteria required have been defined in these guidelines. In any cases where probits are required:

- Suitable and justified probit equations shall be used, e.g. those in the TNO Green Book
- For the use of toxic probit equation in the TNO Green Book, the exposure duration used is typically a maximum of 30 minutes. However, exposure durations greater than 30 minutes shall be considered unless justifications provided.
- For thermal radiation the harm level for injury and 3% fatality is 4kW/m^2 for any exposure duration.
- The following probit shall be used to obtain the radiation intensity equivalent to 10% and 50% fatality:

$$\mathrm{Pr} = -41.61 + 2.79\, ln\left(I^{4/3} \times t\right)$$

where I is in W/m^2 and t is in s

The fire exposure duration used (minimum of 30 seconds) shall be justified. Any other durations if used shall be justified. For example:

- Duration of a fireball (time to burn out);
- Time for jet fire release to be isolated (if isolation is possible and for branches of event tree where isolation is successful);
- Time for pool fire to burn out (which may take into account isolation of release for branches of event tree where isolation is successful);
- Time for emergency response (firefighting) to extinguish the fire, if this is realistic (for branches of event tree where firefighting is successful).

Relevant probit values are:

- Pr = 3.72, for 10% fatality
- Pr = 5.00, for 50% fatality

5.2.4.2 On-site occupied buildings

Harm criteria should be based on the following as appropriate:

- UK Chemical Industries Association 'Guidance for the location and design of occupied buildings on chemical manufacturing sites' 3rd edition, http://www.cia.org.uk/AboutUs/OrderPublications/Publicationdetails/tabid/146/pubctl/DetailPublication/ID/12/Default.aspx, or
- API RP 752: Management of Hazards Associated With Location of Process Plant Buildings, 2009.
- API RP 753 - Management of Hazards Associated With Location of Process Plant Portable Buildings, 2007
- HSE Research report 084, Effects of flashfires on building occupants, http://www.hse.gov.uk/research/rrpdf/rr084.pdf

If different harm levels are used for specific buildings then this should be justified. The risk assessment methodology described in this QRA Technical Guidance shall be used for occupied buildings risk assessment. If any other methodologies or harm levels are used, they should be justified.

5.3 Weather

Weather categories F1, B2 and C3 should be modelled for each outcome. Category F1 represents typical night time weather and categories B2 and C3 represent typical day time weather.

- Humidity should be set to 85%.
- Ambient temperature should be assumed to be 30°C
- Solar Radiation should be set as follows:
  - Day time: 1000 W/m^2
  - Night time: 0 W/m^2

5.4 Harm Footprints

Harm footprints are required to calculate IR (Fatality), IR (injury) and Cumulative Escalation, for checking if QRA criteria thresholds are met.

For this purpose, the footprint dimensions should be modelled for each outcome (Tables 6 to 9). The results should be tabulated along with outcome frequency. Dispersion results should be for receptors outside of buildings and not take any account of any protection offered by buildings, except for assessment of risk to occupied buildings. For example the harm criteria for overpressure from VCEs take account of most fatalities being due to building damage or collapse.

Table 6 Harm Footprints required for IR (Fatality)

Hazard	Harm level
Toxic	3% fatality
	10% fatality
	50% fatality
Thermal radiation from fire (e.g. Fireball, Jet Fire, Pool Fire)	$4kW/m^2$
	$15.3kW/m^2$ (for exposure duration at 30 seconds)*
	$21.6kW/m^2$ (for exposure duration at 30 seconds)*
	$37.5kW/m^2$
Flash Fire	LFL
Overpressure from explosion (e.g. BLEVE, VCE)	5psi
	7psi
	10psi

**For durations longer than 30 seconds, thermal probit to be used to determine radiation intensity (refer to Section 5.2.4.1).*

Table 7 Harm Footprints required for IR (Injury)

Hazard	Harm level
Toxic*	AEGL-3
Thermal radiation from fire (e.g. jet fire, pool fire, fire ball)	$4kW/m^2$
Flash Fire	LFL
Overpressure from explosion (e.g. BLEVE, VCE)	1 psi

**For exposure durations ≤10 minutes, 10 minute AEGL-3 shall be used. For exposure durations >10 minutes and ≤30 minutes, a weighted average between 10 minute AEGL-3 and 30 minute AEGL-3 shall be used. For* *exposure durations >30 minutes and ≤60 minutes, a weighted average between 30 minute AEGL-3 and 60 minute AEGL-3 shall be used. For exposure durations >60 minutes, 60 minute AEGL-3 shall be used. For substances without an AEGL-3 value, 3% fatality shall be used. Weighted average refers to linearly interpolated value.*

In addition to the harm footprints indicated in Table 7, the harm footprints for ERPG-2 and Fireball zone shall be presented for information.

Worst Case Scenarios (for both WCS-offsite and WCS) causing the largest injury harm distances for toxic release, fire and explosion outcomes shall also be identified.

Table 8:Harm Footprints required for Cumulative Escalation

Hazard	Harm level
Thermal radiation from fire (e.g. Fireball, Jet Fire, Pool Fire)	$20kW/m^2$
Overpressure from explosion (e.g. BLEVE, VCE)	2 psi

Cumulative Escalation scenarios (for both CE-offsite and CE) causing the largest harm distances for fire at $20kW/m^2$ and explosion at 2psi shall also be identified.

Table 9: Harm footprints required for IR to on-site occupied buildings

Hazard	Harm level
Toxic	3% fatality
	10% fatality
	50% fatality
Thermal radiation from fire (e.g. Fireball, Jet Fire, Pool Fire)	3% fatality
	10% fatality
	50% fatality
	100% fatality
Flash Fire	LFL
Overpressure from explosion (e.g. BLEVE, VCE)	3% fatality
	10% fatality
	50% fatality

The risk assessment methodology described in the QRA Guidelines shall be used for occupied buildings risk assessment. If any other methodologies, harm levels and occupancy modifiers are used, they should be justified. Relevant harm criteria may be used depending on the construction of the on-site buildings. For example, some buildings may offer protection to occupants from some types of fires. The overpressure causing 3%, 10% and 50% fatality to building occupants will also depend on the construction of the building. See Section 5.2.4.2.

6 Individual Risk (or Cumulative Escalation Risk) calculation

Individual risk (or Cumulative Escalation risk) is the summation of risks from all the outcomes affecting any location and is usually calculated on a grid. Iso-contours for specific risk levels can then be generated from this underlying data.

6.1 Harm Footprints

The footprint dimensions should be modelled for each outcome and weather condition. This will typically define maximum hazard distance (d), maximum width (mw), distance to maximum width (dmw) and minimum distance (-d) that would represent an idealised footprint (Figure 5). Circular footprints could be considered for VCE and fireball but not for others.

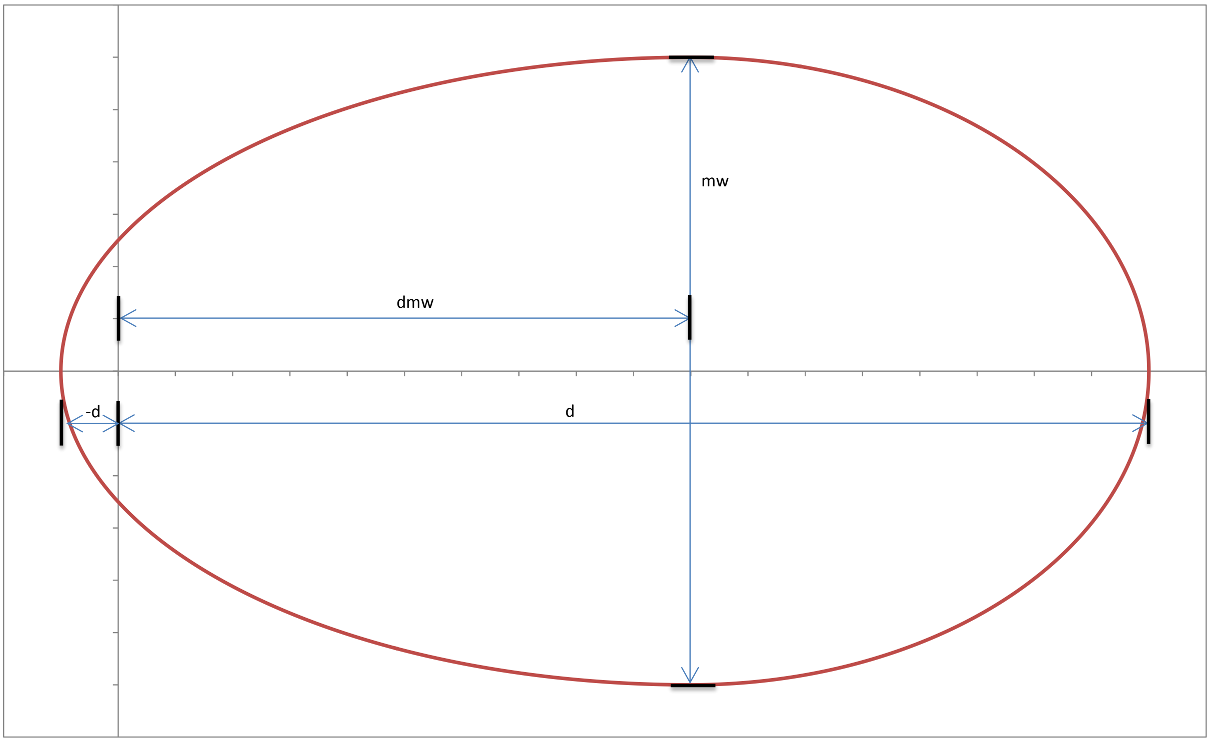


Figure 5 Idealised footprint

Footprints should be calculated for each outcome, to all relevant harm criteria (Section 5.4) and for the following weather conditions (Table 10).

Table 10: Weather conditions

Weather	F1+B2+C3	These three weather categories should be modelled for each event outcome where weather is relevant.

6.2 Modifiers for Individual Risk

The risk calculation process needs to take into account the following modifiers which are further described below. The modifiers used should be justified and tabulated.

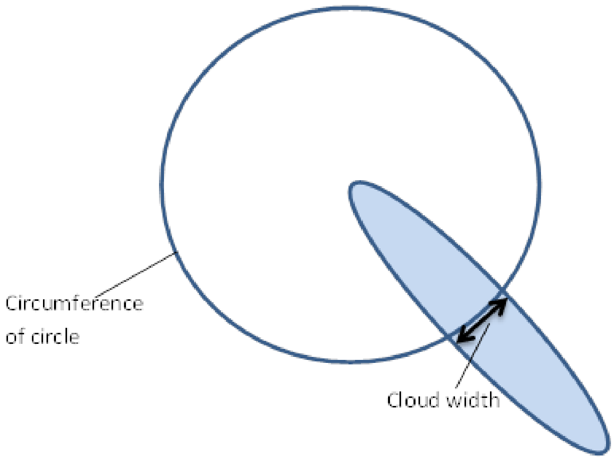
- Positional or fractional coverage of footprint at location;
- Weather category split;
- Wind bias at location;
- Weightings of harm effect;
- Delayed ignition probability if not factored in event tree;
- Occupancy.

See Section 4.3 for relevant modifiers for Event Trees.

6.2.1 Positional or fractional coverage of footprint at location

Table 11: IR modifiers for footprints

IR modifier	Definition	Comments
Footprint shape	Probability in an IR calculation that a release will	For narrow toxic clouds = (cloud width)/ (circumference of circle) at given distance.

	reach a particular grid point at a particular distance from the release point. NB. Do not double count with any calculation made within IR software as most IR software is already programmed to account for directional events like jet fire and toxic vapour cloud.	 For circular footprints = 1 provided that hazard range reaches grid point.

6.2.2 Weather

Table 12: IR modifiers for weather

IR modifier	Definition	Comments
Weather category	% of time that weather is category (stability/ wind speed combination) which gives rise to hazard range	To be supported by weather data
Wind direction	% of time that wind is in each direction, represented as the bias used in IR calculations	To be supported by weather data

The splits used between weather categories F1, B2 and C3 should be specified and justified. Weather splits used should be tabulated. Direction bias data used should be specified and justified. Table 13 provides a set of weather data for F1, B2 and C3 derived from data provided by Singapore Met office.

Table 13: Weather category splits and direction bias

Direction	Weather Category			Total
	F1	B2	C3	
N	3.76	6.26	1.33	11.34
NNE	3.72	5.46	3.37	12.54
NE	1.92	2.76	1.07	5.74
ENE	1.26	1.76	0.23	3.24
E	1.59	2.29	0.37	4.24
ESE	1.79	2.49	0.67	4.94
SE	2.29	3.29	0.97	6.54
SSE	2.46	3.62	0.97	7.04
S	3.46	5.42	1.37	10.24
SSW	2.16	3.26	0.63	6.04
SW	1.42	2.06	0.27	3.74
WSW	1.22	1.72	0.10	3.04
W	1.82	2.86	0.17	4.84
WNW	1.82	2.92	0.10	4.84
NW	1.92	3.16	0.07	5.14

NNW	2.36	3.99	0.10	6.44
	34.95	53.28	11.77	100

6.2.3 Indoor/Outdoor

The footprints calculated do not distinguish between indoor and outdoor and so no reduction for indoor/outdoor splits should be taken into account (probability of being outdoor is 1.0)

6.2.4 Weightings

Weightings should apply to footprints, to take into account for the probability of the harm effect within the footprint.

6.2.4.1 Injury

For injury risk, the weightings applied to each footprint will be 1.0.

6.2.4.2 Fatality

In order to calculate individual risk of fatality to people, some of the outcomes should use a set of footprints with weightings applied to account for likelihood of fatality for each footprint within the set. The following weightings shall be applied to outcome frequencies for the respective footprints.

Table 14: Weightings for fatality footprints

Hazard	**Harm footprint/set**	**Weightings for IR (Fatality)**
Thermal radiation from fire (e.g. Fireball, Jet Fire, Pool Fire)	4kW/m^2 or 3% fatality (for occupied buildings)	0.065
	15.3kW/m^2 or 10% fatality (for occupied buildings)	0.235
	21.6kW/m^2 or 50% fatality (for occupied buildings)	0.45
	37.5kW/m^2 or 100% fatality (for occupied buildings)	0.25
Toxic	3% fatality	0.065
	10% fatality	0.235
	50% fatality	0.45
Flash Fire	LFL	1.0
VCE	5psi or 3% fatality (for occupied buildings)	0.065
	7psi or 10% fatality (for occupied buildings)	0.235
	10psi or 50% fatality (for occupied buildings)	0.45

6.2.4.3 Escalation

For escalation risk, the weightings applied to each footprint will be 1.0.

6.2.5 Occupancy

For all IR and cumulative escalation calculations except those for on-site occupied buildings, the occupancy shall be 1.0.

For on-site occupied buildings only, the IR is modified by the percentage of time that the most exposed individual will be present in the building. The percentage of time should be justified for each building.

6.3 Risk Calculation and Summation

The software package used for the risk summation should be stated and a simple description of the basic approach the software uses for the calculation should be provided. The resolution of the calculation grid should be sufficient to avoid calculation based errors and align with the Singapore SVY21 coordinate system. This should be no greater than 10m spacing.

If incremental positions of footprints around the windrose are used in the summation process, the step size should be small of the order of 1 degree steps or smaller.

6.3.1 Fixed Installations
Risk summation should be conducted for scenarios identified within the Boundary.

6.3.2 Pipeline
Risk summation should be conducted at point locations along the pipeline route using an appropriate frequency per unit length (e.g. frequency per km per year). Spacing should be chosen so as to avoid calculation based errors.

6.3.3 Bulk Transport
Risk summation should be at point locations along the route.

6.3.4 On-site Occupied Buildings
Risk summation should be for the location of each on-site occupied building.

7 QRA Results
The QRA results are then, separately, compared to specified QRA criteria. The criteria may be in the form of toxicity, thermal loading (fire) or blast overpressure (explosion). This is explained further below.

7.1 Consequence Results
The following harm zones (with harm distances indicated where relevant) should be presented:

- WCS-offsite;
- WCS;
- CE-offsite;
- CE;
- ERPG-2 zone (for emergency response planning);
- Fireball Zone in relation to high-rise buildings.

7.2 Risk Results
Once the outcome frequencies and harm footprints have been calculated, the individual risk (or cumulative escalation risk) calculation can be made by determining the sum of risks at each location. Individual risk (or cumulative escalation risk) (Section 6) shall be calculated for:

- injury to people;
- fatality to people (both on-site and off-site);
- escalation off-site.

7.2.1 IR (Fatality)
In order to calculate individual risk of fatality to people, appropriate weightings shall be applied to outcome frequencies (see Section 6.2.4.2).

The cumulative (for all outcomes indicated in Table 6) iso-contours for the relevant criteria (refer to Criteria Guidelines) are to be determined, based on footprints generated:

- $5x10^{-5}$ /year (example for Fixed Installation);

- $5x10^{-6}$ /year (example for Fixed Installation).

The top risk contributors at the Boundary point where the IR (Fatality) contour at $5x10^{-6}$ /year (example for Fixed Installation) has the largest off-site distance shall be presented. The top risk contributors refer to outcomes contributing to 1% or more of the IR (Fatality) risk at that point.

7.2.2 IR (Injury)

The cumulative (for all outcomes indicated in Table 7) iso-contours for the relevant criteria are to be determined, based on injury harm footprints generated:

- $3x10^{-7}$ /year (example for Fixed Installation).

The top risk contributors at the Boundary point where the IR (Injury) contour at $3x10^{-7}$ /year (example for Fixed Installation) has the largest off-site distance shall be presented. The top risk contributors refer to outcomes contributing to 1% or more of the IR (Injury) risk at that point.

7.2.3 Cumulative Escalation

The cumulative (for all outcomes indicated in Table 8) iso-contours for the relevant criteria are to be determined, based on footprints generated:

- $1x10^{-4}$ /year (example for Fixed Installation).

7.2.4 On-site Occupied Buildings

The individual risk (fatality) at on-site occupied buildings (e.g. control rooms/ administrative buildings) should be calculated and presented. This can be readily accomplished by the QRA if individual risk grids have been calculated to sufficient resolution. For occupied buildings, individual risk is to the person at most risk within the building and the IR takes account of their 'occupancy', the fraction of time for which they are present in the building. IR footprints should be generated for:

- $1x10^{-3}$/ year.

The Potential Loss of Life (PLL) values (= IR value x highest estimated population number in building) for top risk contributors at the on-site occupied building shall be presented. The top risk contributors refer to outcomes contributing to 1% or more of the IR (Fatality) risk at the occupied building.

8 Prioritisation for risk reduction

The QRA results should be considered in prioritisation for risk reduction. Top risk contributors (see Section 7) should be considered.

Prioritisation for risk reduction may take into account the potential consequences in terms of:

- Harm to humans;
- Significant damage including escalation;
- Impact on sensitive receptors.

A risk matrix, such as the example below, may be used as a guide to the ranking of scenarios.

Table 15: Example risk prioritisation matrix

	1-10 injuries	**10-100 injuries**	**100-1000 injuries**	**> 1000 injuries**

Frequency (per year)	Limited on-site damage < $2M	Significant on-site/ limited off-site damage $2-100M	Catastrophic on-site/ significant off-site damage $100-$2000 M	Catastrophic off-site damage > $2000M
1E-6 – 1E-5	1	1	1	1
1E-7 – 1E-6	3	2	2	1
1E-8 – 1E-7	4	3	2	1
< 1E-8	5	4	3	1

Note:

1. priorities range from 1 (highest) to 5 (lowest);
2. injuries should be estimated based on the number of people within the harm footprints for injury, defined in Section 5.4.

A table shall be provided which identifies and ranks the scenarios prioritised for the consideration of further risk reduction and should include:

- Identification of the scenario (e.g. cross-reference to description);
- Location;
- Hazard range;
- Which (if any) risk criteria are not met;
- Contribution of scenario to consequence-based and/or cumulative risk criteria;
- Potential consequences;
- Identification of sensitive receptors which could be impacted;
- Comments (reasons for the ranking, which will be a judgment made on the basis of all the above considerations).

9 Continuous Risk Reduction /ALARP demonstration

Authorities may require appropriate preventive/mitigating measures to be incorporated into the design and operation keep the risks to ALARP. For MHIs, ALARP shall be demonstrated according to requirements of the Safety Case Regime. For non-MHIs, ALARP (if required) may consider the guidance on ALARP demonstration as indicated in this QRA Technical Guidance.

The adequacy of proposed risk reduction measures will be evaluated based on their effectiveness in mitigating the identified hazards. Mitigating measures are differentiated into three broad types, namely preventive, protective and emergency response measures. The Responsible Party is required to consider all practical measures to reduce both accident frequency and consequence impacts. It is also required to demonstrate that the proposed mitigating measures do not introduce additional risks to the facility itself or surroundings.

9.1 Identification of potential further risk reduction

A study could be carried out for each of the identified priority scenarios to identify specific risk reduction measures. This should be focussed by the type of risk reduction required (prevention of injury/ fatality; and/or prevention of escalation), and keywords (such as the following) which cover the types of risk reduction measures which may be possible:

Reduce consequences (preventive), e.g. use safer substance(s), reduce pressure, detection and shut-down or blowdown systems, remove personnel from vicinity , relocate (equipment/ pipeline/ transport route) to increase separation distances, reduce congestion to minimise

VCE consequences, segregation of incompatible substances (e.g. flammables from toxics), pipelines crack arrestors, etc.

Reduce frequency (preventive), e.g. detection and shut-down systems, improved specification of pressure systems (lower design factor, better corrosion resistance); for pipelines: use of slabbing and/or increased depth of cover, strict controls on hot-work; choice of transport route to avoid any road junctions etc. that have a history of high accident frequencies, etc.

Mitigate (protective), e.g passive fire protection, active fire protection, blast walls, explosion venting of buildings and equipment, toxic refuges, water sprays to prevent BLEVE, etc

Emergency response/ emergency services, e.g. evacuation procedures, awareness/training of the public, firefighting, prevention of evaporation from pools (e.g. foam blankets), water curtains (e.g. to safeguard escape routes), etc.

9.2 Qualitative ALARP demonstration

The principle of ALARP is that further risk reduction should be provided unless the cost would significantly outweigh the benefits.

Usually, when relevant international good practice has been applied in the design and operation, further risk reduction is unnecessary. Therefore the good practice that has been followed in the design, as relevant to the scenario considered, should be identified. However, further risk reduction may sometimes be required if the risk is very high, e.g. involving potential impact on large numbers of people or major escalation potential.

The identified potential risk reduction measures should be further assessed to make decisions as to whether they should be implemented. Each potential risk reduction measure should be assessed and the decision about whether to implement and reasons/justifications should be recorded. Reasons for not implementing a further risk reduction measure might include:

- That it is not practicable, e.g. it would not work in practice to reduce the risk, or it would not allow the normal production/transport operation to take place.
- That it transfers risk to another area such that there would be either no benefit or an increase in overall risk.
- That the reduction in risk would not be worthwhile in comparison with the costs that would be incurred.

The higher the potential hazard that is being reduced, the more the cost should outweigh the benefit if it is not to be implemented. Uncertainties should be addressed by overestimating the risk reduction and underestimating the costs.

Often the decision on potential risk reduction can be made qualitatively using engineering judgment. In more borderline cases, approximate quantification can be helpful (see Section 10). Any low cost and technically viable risk reduction options should normally be implemented.

10 Quantitative ALARP demonstration illustration

An approximate estimate of the available spend to achieve ALARP can be obtained from the following:

Cost = GDF x [(benefit of injuries prevented) + (benefit of avoided damage/escalation)]

Where:
GDF (gross disproportion factor) is a multiplier to ensure that the cost outweighs the benefits. It ranges from 1 if the risk is very low (priorities 4 or 5 in the prioritisation matrix in section 10); through 5 for priority 3; to 10 if the risk is unacceptable or the priority is 1 or 2 in the prioritisation matrix.

10.1 Benefit of injuries prevented

The benefit per injury estimate should take account of the range of levels of injury which might be expected for the scenario(s) considered.

One example of estimating benefit per injury prevented is shown below. Other methods may be considered where justified accordingly.

Benefit = ($ per injury) x Δ(number x frequency) x (remaining lifetime)

($ per injury) is the estimated average compensation value for an injury.
Δ(number x frequency) is the change in the product of number affected (consequence) and frequency, due to the risk reduction measure(s) under consideration.
Number =number of injuries.

All scenarios whose risk will be reduced by the proposed risk reduction should be included.

The remaining lifetime of the plant, pipeline or transport system will be the design life for new systems. For existing systems, robust justification is required for short assumed remaining lifetimes.

For estimation of population data, the population data from Department of Statistics Singapore can be considered to estimate the population density.

10.2 Benefit of avoided damage and escalation

One example of estimating benefit of avoided damage and escalation is shown below. Other methods may be considered where justified accordingly.

Benefit of avoided damage
= (change in frequency due to risk reduction) x (cost of avoided damage)

Avoided damage should be the full estimated cost of an accident. This could include the cost of clean-up after the accident, including that of all escalation from the original scenario (on-site and off-site), compensation to third parties, and any costs imposed by the emergency services for attending the accident, the cost of re-instating the damaged equipment/ pipeline/ transport/ other buildings or infrastructure (including demolition, redesign, rebuild), cost of lost business during the process of rebuild, compensation to third parties, etc. Companies may also wish to consider including the cost of a major incident to their reputation and hence to wider sales potential and profitability.

The insured costs are generally only a fraction of the total costs of a major accident.
Note that the frequency of escalation events will be the same as that of the initiating scenario unless there are justified risk reduction measures and other factors in place to prevent escalation.

11 Emergency Response Plan

The QRA should support the development of the Emergency Response Plan (ERP), for example:

- All identified outcomes should be covered by the ERP;
- Understanding of the possible means of controlling and mitigating the outcomes and the potential for escalation. Such possible means of control include: the isolation of hazardous inventories and the removal of inventories (where appropriate); the use of fire fighting/mitigation measures; and the prevention of domino effects (such as cooling of vessels to prevent BLEVE);
- Determination of hazard ranges in terms of location of the emergency control centres; first aid centres; emergency refuges; muster points; pre-defined forward control points; location and availability of access, rescue and escape routes; fire pumps and firewater lagoons; switches to remotely actuate shut-down valves, deluge systems, etc.;
- Determination of the stocks of resources which will need to be mobilised to control each incident, including fire-fighting water, foam compound, monitors which can be deployed to allow cooling of vessels to prevent BLEVE whilst the firefighters can be remote from the potential consequences, PPE, breathing apparatus and escape respirators, first aid equipment;
- Understanding the potential for escalation to adjacent installations and the implications for any mutual aid agreements which include those installations;
- Provision and location of infrastructure such as walls or screening to protect firefighters and equipment, protected escape routes, toxic refuges, provision to prevent contamination of watercourses with contaminated firewater run-off;
- Understanding the potential outcomes so as to develop and provide training and exercising of the ERP;
- Estimation of the numbers and locations of potential injuries and fatalities so as to plan for evacuation to hospital, the provision of temporary mortuary facilities, and the capacity required of arrangements to provide information to relatives;
- Determination of the area over which advice needs to be provided to the adjacent population about what to do during any potential major accident;
- Estimation of the duration of the incident and planning for welfare provision and shift changes for responders.

12 For Existing Installations/Pipelines Undergoing Change/Expansion – involving transition into 2016 QRA Guidelines

Definitions:

"**Existing Installation/Pipeline**" – Existing Installation/Pipeline at brownfield sites

"**New/Modified Unit(s)**" – Changes to Existing Installation/Pipeline made after the 2016 QRA Guidelines were implemented. Such changes may be due to expansion, modifications and/or Addition & Alteration (A&A) works.

Note: (1) For existing Installations/Pipelines, a Responsible Party's's Installation/Pipeline may comprise of **New/Modified Unit(s)** added on to **Existing Installation/Pipeline**. (2) For brand new Installations/Pipelines at greenfield sites established after the 2016 QRA Guidelines are implemented, QRA criteria and requirements as indicated in the 2016 QRA Guidelines shall apply.

A Fixed Installation/Pipeline QRA considers risks within the Boundary of the Installation/Pipeline, where Boundary is defined in Section 13. This QRA will produce risk results representing the Installation/Pipeline's risk profile (i.e. a sum of risks from **Existing Installation/Pipeline** and **New/Modified Unit(s)** (if any)).

Site-specific Considerations:

For **Existing Installations/Pipelines** undergoing changes that require a QRA to be done (refer to Section 3 of QRA Criteria Guidelines), Agencies may have the following additional considerations:

1. The **New/Modified Unit(s)** shall adopt the QRA methodology as indicated in the 2016 QRA Guidelines. As for **Existing Installations/Pipelines**, simplified QRA approaches may be considered, including:
    - Representative major accident scenarios selected for the QRA may be defined and justified. Reference may be made to Process Hazard Analysis (PHA) and/or top risk contributors identified from past QRAs. For Fixed Installations, the representative scenarios should cover the geographical coverage of the Installation.

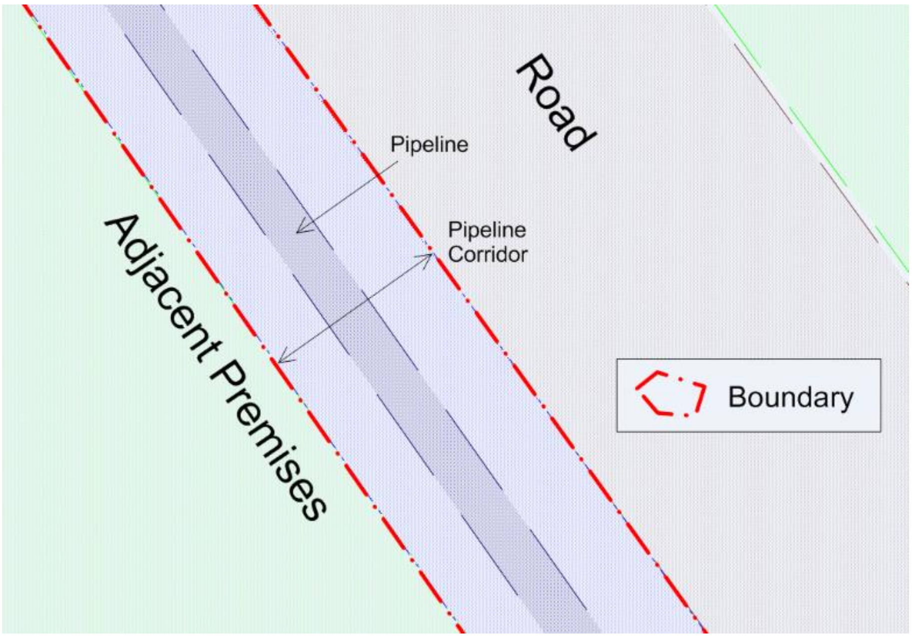
    Any other QRA approaches and/or scenario selection methods if used, shall be justified accordingly.

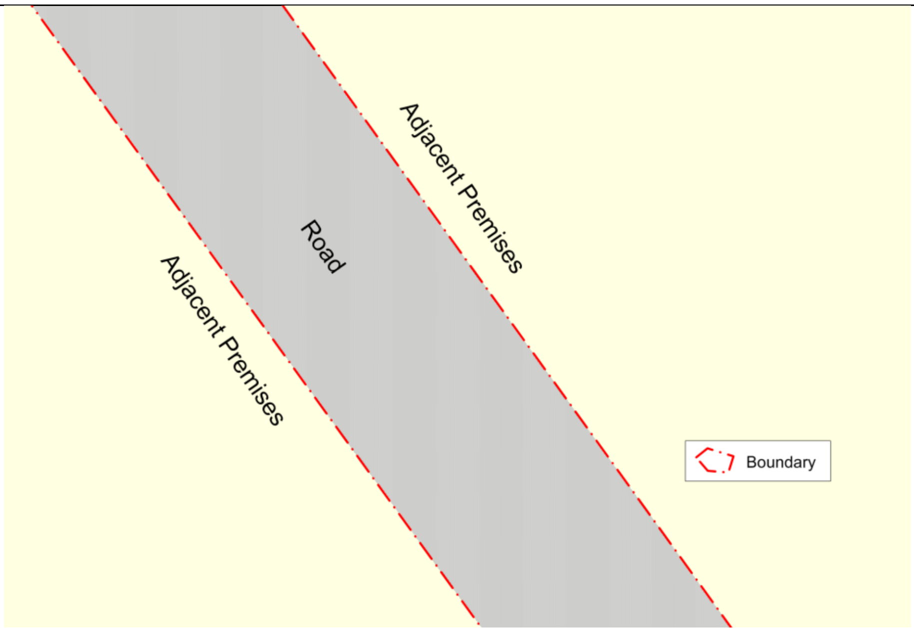
2. Risk Contours generated shall consider risks within the Installation/Pipeline Boundary and shall be assessed for compliance with QRA criteria as stipulated in the 2016 QRA Guidelines.

3. In view of case-specific circumstances that may be encountered in the compliance of QRA criteria for Existing Installations/Pipelines undergoing change, the following may be considered subject to pre-consultation with MHD:

- Failure to comply with QRA criteria – Agencies shall consider the demonstration of ALARP if criteria cannot be met due to risk contributors from **Existing Installation/Pipeline**. If criteria cannot be met due to risk contributors from **New/Modified Unit(s)**, then risks are to be reduced until criteria are met.

13 Definitions and Abbreviations

Fixed Installation	A Fixed Installation may comprise one or more process units or plants (individual operating units which are part of the Installation), all of which belong to the Responsible Party, and which are located within a contiguous land plot demarcated by the Fixed Installation Boundary.
Boundary	**Fixed Installation**: For fixed installations, the boundary is the perimeter of a contiguous land plot on which the installation is operated by the Responsible Party. In event of proposed third party operations within the boundary of fixed installation, company should consult MHD on the need for risk integration. **Pipeline**: The boundary shall be taken from the edge of road to the nearest adjacent premises boundary along the pipeline route (or pipeline service corridor where applicable).  **Bulk Transport**: The boundary shall be taken to be the nearest adjacent premises boundary along the transport route.

	
AEGL	Acute Exposure Guideline Level
ALARP	As Low As Reasonably Practicable
CBPD	Central Building Plan Department
CE-offsite	Cumulative Escalation (off-site) refers to the outcomes which give the largest hazard distances for fire at $20kW/m^2$ and explosion at 2psi, relative to the Boundary.
CE	Cumulative Escalation refers to the outcomes which give the largest hazard distances for fire at $20kW/m^2$ and explosion at 2psi, irrespective of Boundary.
CED	Central Enforcement Department
ERPG	Emergency Response Plan Guidelines
FSSD	Fire Safety and Shelter Department
Harm Zone	Consequence distance to a specified harm level in any direction from a source. Would describe a circle for a single point or an outline around a route.
Harm Footprint	Consequence results to a specified harm level from a release in a single direction with distance and width.
IR	Individual Risks summed from all sources of risk within the defined Boundary
IR (injury)	Individual risk of injury to people
IR (fatality)	Individual risk of fatality to people
Cumulative Escalation	Cumulative risk of escalation off-site

<table>
<tr><td>HTVTS</td><td>Hazmat Transport Vehicle Tracking System</td></tr>
<tr><td>MHI</td><td>Major Hazard Installation</td></tr>
<tr><td>NEA</td><td>National Environment Agency</td></tr>
<tr><td>OSHD</td><td>Occupational Safety and Health Department</td></tr>
<tr><td>PCD</td><td>Pollution Control Department</td></tr>
<tr><td>QRA</td><td>Quantitative Risk Assessment</td></tr>
<tr><td>Registered Consultant</td><td>A consultancy company which is registered in Singapore for the conduct of QRAs</td></tr>
<tr><td>Responsible Party</td><td> Fixed Installation: Commercial Entity who operates or controls the installation, or to whom the decisive economic or decision-making power over the technical functioning of the installation has been delegated. Pipeline: Commercial Entity who operates or controls the pipeline within the defined Boundary, or to whom the decisive economic or decision-making power over the technical functioning of the pipelines within the defined Boundary has been delegated. Bulk Transport: Commercial Entity who operates or controls the bulk transport, or to whom the decisive economic or decision-making power has been delegated. </td></tr>
<tr><td>SCDF</td><td>Singapore Civil Defence Force</td></tr>
<tr><td>Development Types and Sensitive Receptors</td><td> Information on land types (e.g. commercial / industrial) and locations of sensitive receptors may be determined from the latest URA Master Plan available in the link: http://www.ura.gov.sg/uol/master-plan.aspx?p1=view-master-plan, and the SLA OneMap available in the link: http://www.onemap.sg/index.html. Table indicates the types of developments and sensitive receptors which should be considered. Table 16: List of Development Types and Sensitive Receptors <table>
<tr><th></th><th>List of Development Types and Sensitive Receptors</th></tr>
<tr><td>Industrial Development</td><td>The following development types as indicated in the URA Master Plan:
Business 1
Business 1 – White
Business 2
Business 2 – White
Business Park
Business Park - White</td></tr>
<tr><td>Commercial Development</td><td>The following development types as indicated in the URA Master Plan:
Commercial</td></tr>
<tr><td>Sensitive Receptors</td><td>The following development types as indicated in the URA Master Plan:
Residential</td></tr>
</table></td></tr>
</table>

	▪ Residential with Commercial at 1st Storey ▪ Commercial and Residential ▪ Hotel ▪ White ▪ Residential / Institution ▪ Health & Medical Care ▪ Educational Institution ▪ Place of Worship ▪ Civic & Community Institution ▪ Park ▪ Beach Area ▪ Sports & Recreation ▪ Transport Facilities ▪ Railway ▪ Mass Rapid Transit ▪ Light Rapid Transit ▪ Port / Airport ▪ Reserve Site ▪ Special Use The following sensitive receptors as indicated in the SLA OneMap and/or advised by Agencies: ▪ Child Care Centres ▪ Workers' Dormitories Some of the sensitive receptors located on Jurong Island, may be excluded from the above list on a case-by-case basis, for e.g. bus terminal/fire station. The need to consider additional sensitive receptors may be specifically indicated by the Agencies.
MHD	Major Hazards Department
TPA	Third Party Activity (e.g. excavation activities adjacent to buried pipelines)
URA	Urban Redevelopment Authority
WCS-offsite	Worst Case Scenario (off-site). The outcomes which give the largest injury hazard distances for toxic release, fire and explosion, relative to the Boundary.
WCS	Worst Case Scenario. The outcomes which give the largest injury hazard distances for toxic release, fire and explosion, irrespective of Boundary.
Occupied building	An on-site building which is intended for occupation