Criteria for separation distances between major hazard installations to limit the risk of escalating domino failures

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In an effort to protect the general public, Major Hazard Installations (MHI) are often clustered together into heavy industrial areas where enforcement of regulatory controls and emergency response efforts can be focused. However, this can create a problem of unintended domino effects between independent facilities.

Although there is much guidance on land-use planning to protect the general public from individual MHIs (e.g. UK HSE PADHI), there is limited guidance on protecting independent MHIs from each other and thereby protecting the public from possible escalating domino effects. The rationale is often that the types of events that could lead to domino failures are so unlikely that their contribution to risk is suitably low. Therefore, compliance with process plant equipment separation distances, often specified in local standards, is considered sufficient. These distances are typically in the range of 5 – 25 meters. In effect, a type of low likelihood possibility of mutual destruction is tolerated.

A study was conducted on one such a Major Hazard Complex in South Africa using the results of quantitative risk assessments for each of three independent MHIs. The study distinguished between domino effects that could be diminishing, neutral or escalating in terms of consequences. When it comes to protecting their assets, independent MHI facilities are concerned with all three of these types of domino impacts. In terms of protecting the pubic it is the possibly of escalating domino effects that is of particular concern.

The study has suggested some possible risk based criteria that might be considered for ensuring suitable separation distances between neighbouring independent MHIs with mutual domino effects. The criteria require a comparison of the risks of key initiating events at each facility and setting a limit on the contribution from each MHI. The criteria to limit escalating domino effects should be more stringent than where the effects are neutral or diminishing.

Although the application of these criteria currently requires considerable effort in terms of QRA etc, the criteria do represent a starting point for an overall philosophy. The focus going forward would be to simplify the process.

1. SETTING THE SCENE

In South Africa there are numerous highly hazardous industries, both existing and new proposed developments. These are sometimes located in proximity to residential areas and are often adjacent to other existing hazardous industrial facilities. In 1999, Regulations were promulgated under the Occupational Health and Safety Act of 1993 no. 85, revised in July 2001 [Ref 1] which, similar to the COMAH and SEVESO regulations, required assessment and regulation of the risks posed by facilities in order to protect the public from Bhopal type events. The regulations were called the Major Hazard Installation Regulations (MHI). These Regulations require:

1. *Regulation 9 (1) (b) - No local government shall permit the erection of a new major hazard installation at a **separation distance** less than that which poses a risk to neighbouring independent major hazard installations.*

However, no guidance is provided on what constitutes a suitable separation distance.

The following is an example of a scenario that has arisen to test this issue of domino effects. This example will be referred to throughout this paper.

In 2010 Company A (liquified flammable gas) wished to established an LPG bulk storage and bottling facility at their existing site. A Major Hazard Installation (MHI) risk assessment (i.e. a QRA) was conducted and it was duly concluded that the site was not suitable as it presented unacceptably high risks to neighbouring residents.

Company A subsequently decided to establish the facility on a new site within a zoned Hazardous Industrial Complex. An MHI QRA was conducted, the development was approved and the facility built in 2013. The MHI QRA indicated a maximum impact zone of 370m. During the MHI notification process, Company A were limited in the size their LPG bulk tank due to their proximity (100m) to the neighbouring Company C. Company C was an existing MHI with large bulk toxic liquefied gas tanks and the potential to impact on thousands of persons for many kilometres from the site. The restriction was to prevent domino failures from LPG onto toxic gas tanks. In addition, Company A was obliged to lease additional land to ensure that the $1* 10^{-4}$ individual risk contour remained within their site boundaries.

In 2015 Company B (flammable gas) proposed to build a natural gas compression facility immediately adjacent the Company A (liquified flammable gas) site. The MHI risk assessment for the Company B (flammable gas) site concluded that the facility presented tolerably low risks although domino effects could occur, i.e. the Company B (flammable gas) installation had the potential to damage Company A (liquified flammable gas) facilities leading to a release of LPG and secondary fires and explosions. The MHI RA indicated a maximum significant impact zone of about 100m. Company A (liquified flammable gas) raised an objection based on the potential domino effects through the National Energy Regulator of South Africa. As part of addressing the objection by Company A (liquified flammable gas), a second independent QRA of the Company B (flammable gas) facility was commissioned. This study indicated higher risks than the original MHI but the maximum impact zone of about 100m and the potential domino effects were confirmed. Never the less, the objection was not upheld and the Company B (flammable gas) MHI was approved and construction begun. Figure 1.1 below shows the layout of the installations.

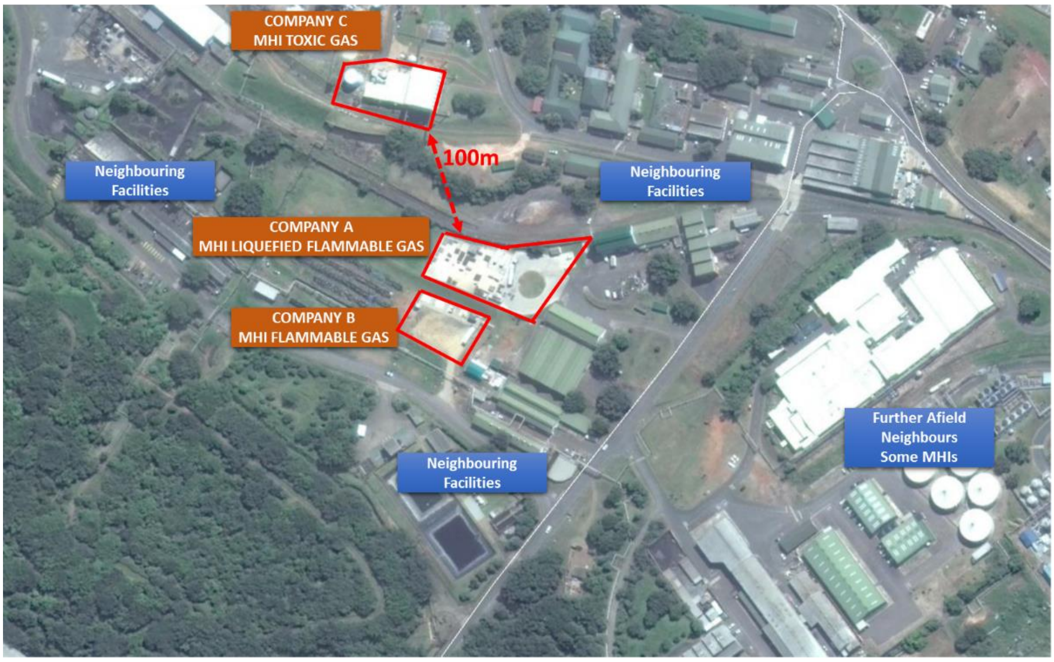


FIGURE 1.1 – Relative location of the various facilities

In 2017, subsequent to the initial MHI approval, and even before construction was complete, Company B (flammable gas) proposed to upgrade their facility. An MHI RA was conducted and it was concluded that the impact range was now 315m, but that the risks were still tolerably low. Again, the issue of potential domino effects on Company A (liquified flammable gas) was raised, but the expansion was approved.

During this entire process is became clear that there were no agreed procedures for the authorities to follow in responding to an objection based on domino effects and there were no criteria to use to decide whether domino effects are tolerable or not.

The methods and criteria presented below form the basis of a proposed way forward in assessing the domino effect aspects as required by the MHI regulations in South Africa.

2. LEGISLATION REGARDING DOMINO EFFECTS

In developing a proposed domino effect method for South Africa, the first step was to investigate the legislative framework regarding domino effects in other countries around the world.

2.1 SOUTH AFRICAN MHI REGULATIONS

The Major Hazard Installation Regulations under the Occupational Health and Safety Act of 1993 no. 85, revised in July 2001, require:

2. *Regulation 5 (5) (b) (vii) - The* ***potential effects*** *of an incident on an adjacent major hazard installation or part thereof, to be included in the MHI Risk Assessment.*

3. *Regulation 9 (1) (b) - No local government shall permit the erection of a new major hazard installation at a* ***separation distance*** *less than that which poses a risk to neighbouring independent major hazard installations.*

Item 1 above is not specific and the risk assessment could include any aspect of domino effects from detailed graphics to a mere statement that domino effects are possible.

As per item 2 above, the regulations could be interpreted to say that there should be "no risk", i.e. no potential consequence, at the neighbouring MHI. However, this would sterilize large tracts of land as even small fuel tanks can have a potential impact range of a hundred meters or more. With the vague term "No risk", the MHI Regulations provide no guidance as to what constitutes a suitable separation distance between MHIs. The authorities who approve the MHI applications do not have technical risk assessment expertise readily available to them and are dependent on the QRAs produced by the MHI companies.

In South Africa, MHI Companies are required to make use of Accredited Risk Assessors (called Approved Inspection Authorities - AIAs) to compile their QRAs. In future, this accreditation process could provide a means to standardize some aspects of the determination of domino effects, the establishment of guiding criteria and the assessment process.

2.2 INTERNATIONAL LEGISLATION AND GUIDELINES

2.2.1 UK COMAH REGULATIONS

In the United Kingdom (UK), the QRAs for COMAH (MHI) sites are submitted to authorities with well-resourced departments of experts to assess the validity of the submissions. The UK Health and Safety Executive (HSE) use the As Low As Reasonably Practicable (ALARP) triangle approach to assess the acceptability of risks posed by new COMAH sites [Ref 2]. New COMAH sites should aim to have individual risk levels in public areas beyond their site boundaries which are below 1×10^{-6} d/p/y. Off-site risk levels above 1×10^{-4} d/p/y are intolerable. In between these two levels the risks can only be tolerated if the MHI facility has done everything reasonably practicable to reduce the risks, i.e. risks are ALARP.

The recent 2015 review of the COMAH regulations [Ref 3] has increased focus on interplant impacts and has specifically defined so called "Domino Groups". However, there is only a requirement to cooperate with Authorities and to set up joint emergency plans etc. There is no separation distance requirement or guidance.

2.2.2 UK HSE LAND USE PLANNING

Land-use planning is done separately from the COMAH regulations but is still mediated by the UK HSE. A system call "Planning advice for development near hazardous installations" (PADHI) [Ref 4] is in place at the HSE and applies within any pre-determined consultation zone around an existing MHI (COMAH site).

This planning advice deals mostly with restrictions on non-industrial developments. The only restriction on industrial developments adjacent each other is for facilities with more than 100 occupants per building or with three occupied storeys. PADHI has no advice on restrictions of MHIs adjacent each other (all Level 1 developments) and no guidance on suitable separation distances either in terms of consequence or risks.

In an HSE Land Use Planning (LUP) supporting document [Ref 5] there is reference to consequence thresholds for the consultation distances. In this document, the only reference to domino effects indicates that there are no firm criteria but that the consequences should be considered. The document refers to a table showing the potential damage upon difference structures for various blast over pressures. This table shows that at over pressure above 21 kPa plant equipment can start to be damaged, at pressures above 35kPa extensive damage would be expected and ther could be direct pressure vessel damaged at 70 kPa.

2.2.3 UK INDUSTRIAL PLANNING

There is other UK planning advice regarding incompatible industrial developments [Ref 6]. The Advice suggests that even when the proposed new MHI has reasonably low risks, but the potential nature of the impacts may jeopardise the continued existence of existing neighbours, then this may be refused planning approval. No specific criteria are provided.

2.2.4 OTHER COUNTRIES

An internet search revealed no other land use planning guidance on industrial separation. Canadian Ontario advice for residential – industrial separation was found but no industrial – industrial separation.

2.2.5 STANDARDS AND GUIDELINES

There are numerous standards for the separation of flammable gases and liquids. Most of these indicate relatively small separation distances that do not take into account the potential impacts of explosions, jet fires etc. For example, a South Africa Standard on LPG, SANS 10087 Part 3 [Ref 7], indicates that a 25-ton LPG tank need only be located 9.5m from the neighbouring site.

The South Africa legislated public separation distances for explosives correlate approximately with distance to the 7 – 14 kPa blast over pressure level. However, if this were extended to flammable gases, separation distances based on 7 – 14 kPa over pressures may be impractical as flammable vapours clouds can drift a substantial distance from the source before they ignite and explode.

The Fire Protection Research Foundation advice on separation distances for National Fire Protection Association (NFPA – USA) technical committees, particularly in light of the NFPA – 400 Hazardous Material Code standard, (Separation Distance in NFPA Codes and Standards, 2014) [Ref 8] suggests that a risk based approach to MHI separation is a bare minimum. They do however note that focussing solely on risk without taking consequence into account is short sighted. They suggest that for scenarios with the possibility of vapour could explosions, a risk based approach ignores the possibility that it could occur while a consequence based approach may be burdensome. They suggest a hybrid approach where risks must firstly be suitably low and then consequence analysis should yield an understanding of worst case scenarios, how they could occur, how to prevent them and how to mitigate against them by methods other than pure physical separation.

2.3 SUMMARY OF LEGISLATED SEPARATION CRITERIA

In summary therefore, apart from the requirement to aim for a location specific individual risk level of 1×10^{-6} d/p/y at neighbouring facilities and certainly to not exceed 1×10^{-4} d/p/y beyond the site boundary, and compliance with separation distances specified in legislated standards, there are no specific and clear legislative guidelines on the separation of MHI facilities from each other.

3 METHODOLOGY

3.1 SCENARIO IDENTIFICATION

Only fires and explosions are expected to lead to direct domino failures. Toxic gas events may indirectly lead to failures through causing the death of operators and the loss of control of plant. However, this cannot be easily quantified, so only direct domino effects are considered here.

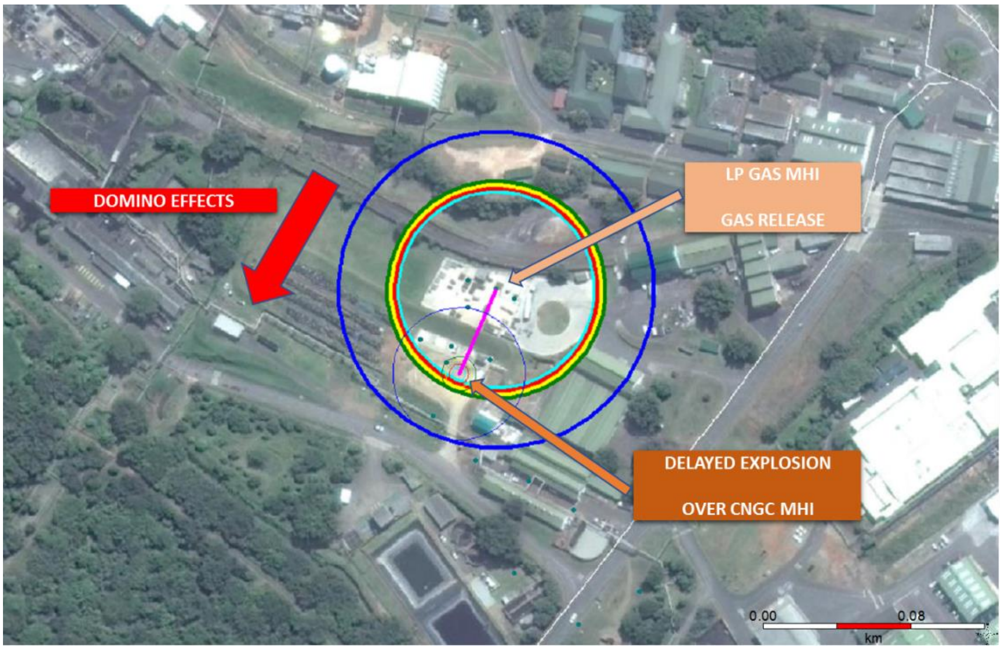
For short duration events, high levels of explosion over-pressure (21 - 70kPa) and fire radiation levels (37kW/m^2) can be expected to adversely affect process equipment integrity. For example, 21kPa may shift pipes leading to failure, 35kPa may overturn a road tanker and 70 kPa may directly compromise a pressure vessel [Ref 5]. For long duration events, (e.g. more than a few minutes) the radiation level at which damage occurs could be lower as the heat is continuously absorbed, possibly leading to gradual deformation/melting of equipment over time.

These high levels of impact extending beyond the site boundary into a neighbouring MHI could lead to failure of hazardous installations on the neighbouring sites and therefore to domino MHI failures. The consequence threshold levels to be used in the analysis will depend on the type of facility that could be impacted on. Clearly 70 kPa over pressure will impact on all facilities, but in some cases a lower threshold of 21kPa may also be relevant, e.g. where external scrubbers are connected to protective enclosures and failure of connecting pipework could lead to catastrophic releases.

The first step is therefore an analysis of the type of equipment at the impacted facility and the major failure scenarios to be prevented. Although it is acknowledged that small domino failures can eventually lead to larger events, in order to keep the analysis simple, the focus should be kept on preventing a few major events. For example, such events at the Company A (liquified flammable gas) would be a large liquid puncture, catastrophic rupture or BLEVE of either the LPG road tanker or the bulk tank.

3.2 CONSEQUENCE ANALYSIS

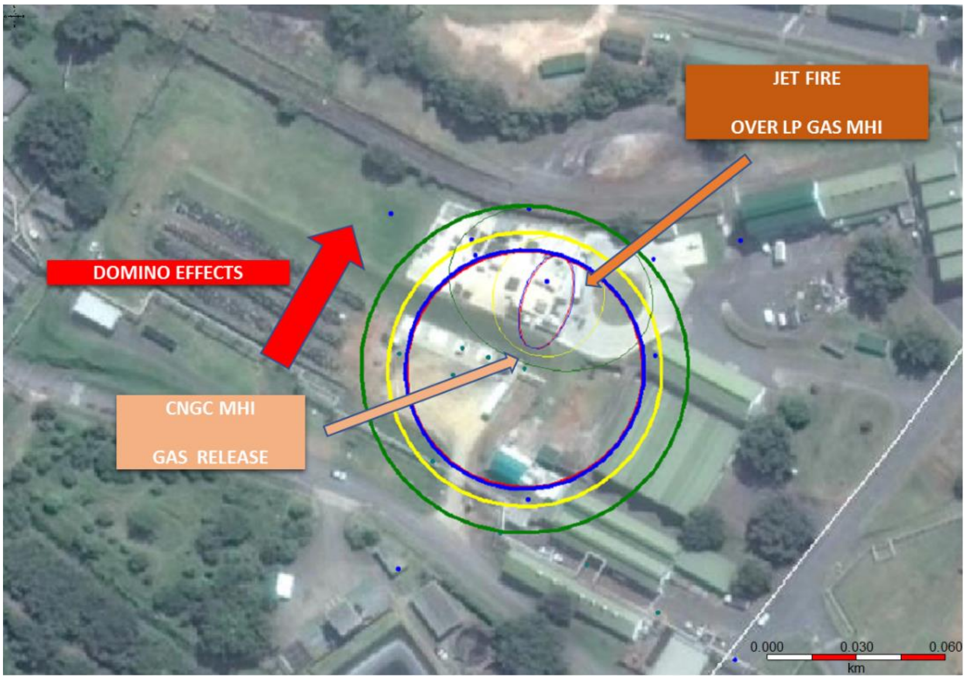
The second step in analysing domino effects is to determine possible fire and explosion scenario that could originate offsite. This is done with the typical hazard analysis and consequence analysis modelling. For example, in the context of the Company A and Company B, the delayed explosion over pressures from an LPG pipeline rupture scenario are plotted below. There are clearly over pressures high enough to cause domino failures over the adjacent plants and this scenario must be included in the analysis.



- **Turquoise = 70 kPa – Pressure vessel damage – 53m**
- **Red = 35 kPa - Severe plant damage**
- **Yellow = 21 kPa – Start of equipment damage**
- Green = 14kPa 1% lethality
- Blue = 2 kPa - Maximum extent of missiles

FIGURE 3.1 – Delayed explosion over pressures showing domino impact zone

In the reverse direction, a failure of a high pressure natural gas line could produce a jet fire with impacts over the LPG site possibly leading to a BLEVE of the LPG tanks.



- **Red = 37.5 kW/m^2 – Significant chance of domino failures – 38m**
- Blue = 35 kW/m^2 – Severe damage
- Yellow = 12.5 kW/m^2 - 1% lethality
- Green = 4 kW/m^2 - Maximum extent of minor injuries

FIGURE 3.2 – Jet fire radiation zones showing domino impact zone

The compilation of a full quantitative risk assessment (QRA) model for the neighbouring major hazard installation is a good starting point. Once the model is compiled it can be used to produce the analysis specific to domino effects. However, a standard QRA model produces risks in units of human deaths, which are of no use in domino failure analysis. There may software that allows the risk calculations to be changed from producing human fatalities to producing the proposed domino failure criteria instead. However, without such software, only the consequence and likelihood modelling aspects of the QRA are used and the remaining domino analysis can be done using a spreadsheet.

3.3 LIKELIHOOD ANALYSIS

The major scenarios to be prevented at the various facilities (as identified in the section above) need to be quantified in terms of likelihood. For example, at Company A (liquified flammable gas) the chance of large liquid punctures, catastrophic ruptures or BLEVEs of the road tanker or bulk tanks occurring due to failure events originating at Company A itself, was estimated at 5.5×10^{-6} events per year. This number was based on a standard failure data and short fault tree analysis typically used as input for the QRA.

In terms of the new Company B (flammable gas) neighbour impacting on the LP Gas facility, key domino failure scenarios to prevent are natural gas explosions generating over pressures that can lead to overturning of the LPG road tanker (35 kPa) or rupture of the bulk LPG pressure vessels (70kPa) as well as radiation levels in excess of 37.5kW/m^2 that could compromise the bulk LPG tanks.

Using the consequence modelling, a list can be made of all the scenarios that can impact on the neighbouring site in a manner that could lead to domino failures. The likelihood of these equipment failures can be determined and added together, e.g. all failures possibly leading to explosion events with an over pressure greater than 35kPa at a distance of 30m. For example:

SCENARIO NUMBERS	COMPANY B FAILURE SCENARIO DESCRIPTION (Events that could lead to domino failures offsite)	COMBINED FAILURE FREQUENCY
41	Catastrophic rupture and early explosion or fireball of a CNG cylinder on a trailer	6.00×10^{-6}
1,8,9,24	Jet fire or delayed explosion from a rupture of the high-pressure gas supply line or the 250-bar compressor discharge line	1.24×10^{-5}
41,42,10,45	Delayed explosion from a rupture or puncture of a cylinder, the high-pressure gas supply line or opening/failure of the cylinder valve	1.81×10^{-5}

TABLE – 3.3 – List of events originating at Company B that can lead to major domino failures at Company A

However, the equipment failure frequencies listed above are higher than the likelihoods of explosions or fires. There is a probability that an explosion will not occur and that the wind is not blowing in the right direction, or for jet fires the fire may not be pointing the right direction etc. One could take each scenario and analyse it in detail, however to simplify the process all similar incidents were grouped together and a combined probability of explosive ignition was used as well as a combined average wind and weather factor.

An ignition probability factor of 0.01 is suggested if delayed explosions are the only possible domino causes (e.g. from catastrophic rupture) and 0.1 if there are delayed explosion as well as jet fire or fireball/BLEVE issues also associated with the failure incident (e.g. from pipeline rupture). The wind direction factor would depend on the proximity of the neighbours and the dominant wind directions. In this case, Company A and Company B (flammable gas) sites are in the dominant wind directions from each other, i.e. 25% of the time from the north east and 25% from the south west and factor of 0.25 was applied. Company C (liquefied toxic gas) is not in a dominant wind direction with respect to Company A (liquified flammable gas) and therefore a wind lower factor of 0.1 was applied.

SCENARIO TYPES	IGNITION FACTOR	WIND DIRECTION FACTOR
Early explosion and fireball	Fireball only lasts 7 seconds 0.1	1
Jet fire and delayed explosion	0.1	0.25
Delayed explosion only	0.01 (includes weather stability factor)	0.25

TABLE – 3.4 – ignition and wind direction factors to be applied to Companies A and B

The following Company B (flammable gas) events are considered to have the potential to impact on Company A (liquified flammable gas):

SCENARIO NUMBERS AND DESCRIPTIONS	FAILURE FREQUENCY	IGNITION FACTOR	WIND DIRECTION FACTOR	DOMINO EFFECT FREQUENCY
41 – Catastrophic rupture and early explosion or fireball of a cylinder on a trailer	6.00×10^{-6}	0.1	1	6.00×10^{-7}
1,8,9,24 Jet fire or delayed explosion from a rupture of the high-pressure gas supply line or the 250-bar compressor discharge line	1.24×10^{-5}	0.1	0.25	3.11×10^{-7}
41,42,10,45 Delayed explosion from a rupture or puncture of a cylinder, the high-pressure gas supply line or opening/failure of the cylinder valve	1.81×10^{-5}	0.01	0.25	4.52×10^{-8}
TOTAL				**9.56×10^{-7}**

TABLE – 3.5 – combined frequencies of event originating at Company B that can impact on Company A

To extend the example to show the reverse direction of domino effects, the key scenario to prevent at Company B (flammable gas) is an explosion with over pressures that can lead to overturning of the road trailer (35 kPa) or rupture of the cascade pressure vessel (70kPa) as well as radiation levels in excess of 37.5kW/m2 at the cascade or trailers.

The likelihood of large punctures and catastrophic ruptures of the trailer cylinders and the cascade tanks due to events originating at Company B (flammable gas) itself is 8.3 x 10^{-5} events per year.

The following Company A (liquified flammable gas) events are considered to have the potential to impact on Company B (flammable gas):

SCENARIO NUMBERS AND DESCRIPTIONS	FAILURE FREQUENCY	IGNITION FACTOR	WIND DIRECTION FACTOR	DOMINO EFFECT FREQUENCY
1&9 – Catastrophic rupture and early explosion or BLEVE of road tanker or bulk stock tank	3.01 x 10^{-6}	BLEVE not sufficient 0.1	1	3.01 x 10^{-7}
10&5b&7B Jet fire or delayed explosion from large puncture on bulk tanks or road tanker hose/pipework rupture	6.37 x 10^{-4}	0.1	0.25	1.59 x 10^{-5}
1,9,2,5ab,7ab,13b,11,14 Delayed explosion from large puncture on bulk tanks or road tanker, or hose/pipework rupture	8.31 x 10^{-4}	0.01	0.25	2.08 x 10^{-6}
TOTAL				**1.83 x 10^{-5}**

TABLE – 3.6 – combined frequencies of event originating at Company A that can impact on Company B

The key scenario to prevent at the Company C (liquefied toxic gas) is an explosion with over pressures that can lead to overturning of the transport tankers (35 kPa) as well as damage to the bulk storage tank enclosures and pipework (21kPa) or rupture of the bulk pressure vessels (70kPa). Radiation levels in excess of 37.5kW/m2 are not expected at the chemical facilities.

The likelihood of large punctures and catastrophic rupture of the bulk toxic gas tanks or transport tankers with failure of the building and/or scrubber system due to event originating at the Company C (liquefied toxic gas) itself is 3.73 x 10^{-4} events per year.

The following Company A (liquified flammable gas) events are considered to have the potential to impact on Company C:

SCENARIO NUMBERS AND DESCRIPTIONS	FAILURE FREQUENCY	IGNITION FACTOR	WIND DIRECTION FACTOR	DOMINO EFFECT FREQUENCY
1&9 – Catastrophic rupture and early explosion or BLEVE of road tanker or bulk stock tank	3.01 x 10^{-6}	BLEVE not sufficient 0.1	1	3.01 x 10^{-7}
2, 5a&b, 7a&b Delayed explosion from large puncture on bulk tanks or road tanker hose/pipework rupture	6.43 x 10^{-4}	0.01	0.25	1.61 x 10^{-6}
TOTAL				**1.91 x 10^{-6}**

TABLE – 3.7 – combined frequencies of event originating at Company A that can impact on Company C

3.6 CATEGORIES OF DOMINO EFFECTS

When considering domino effects between independent MHIs, there are three broad categories of domino failures:

1. CONSTANT - Domino events where the magnitude of subsequent events is relatively constant and the impact zone is not extended significantly, e.g. where one CNG trailer system or LPG tank fails leading to another similar system/tank failure after the first. In this case, the impact zone of the second event will be largely the same as the

first. Within the overall impact zone, the effects will be more severe if persons who escaped the first event are affected by the second or third event. Equipment slightly damaged in the first event may be damaged further in the second event.

2. DIMINISHING - Domino events where the magnitude of subsequent events is smaller, e.g. where an LPG tank fails and after that the smaller CNG cylinder trailer system ruptures. Within the overall impact zone, the effects may be slightly more severe if persons who escaped the first event are affected by the second or third event. Equipment damaged in the first event is unlikely to be damaged further by subsequent events.
3. ESCALATING – The worst case. Domino events where the magnitude of subsequent events is increasing, e.g. where one CNG trailer system fails (impact zone 100m) leading to LPG tank failure (impact zone 370m) leading to the failure of a bulk toxic gas storage tank (impact zone +1000m). The toxic gas storage tank impact zone is a few kilometres while the initial CNG impact zone is only a hundred meters or so. In this case, persons who were unaffected by the primary event now become involved in the secondary event. Equipment unaffected by the first event may be directly damaged by the second or third event.

3.7 ASSESSMENT CRITERIA

Any domino criteria that are applied should ensure that the chance of public persons, or employees at independent MHIs, being fatally affected from domino events is always be less than the chance of failures due to the original installation itself.

Therefore, as a first basic principle criterion, the likelihood of major events due to domino failure causes originating at a new MHI next to an existing independent MHI must be less than the likelihood posed by the installation itself.

In addition, it is proposed that the prevention of the three categories of domino effects should be assessed and treated differently.

1. The DIMINISHING domino effects should be addressed using the normal design codes of practice that specify separation distances e.g. SANS 10087 and / or NFPA separation distances. Ideally, the likelihood of domino failures due to a new MHI next to an existing independent MHI should be less than the likelihood posed by the installation itself,
2. The CONSTANT domino effects should be addressed using the above-mentioned design codes as well as a risk based approach. The likelihood of domino failures due to a new MHI next to an existing independent MHI should be much less than the likelihood posed by the installation itself, e.g. at least one order of magnitude lower likelihood of occurrence.
3. The ESCALATING domino effects should be addressed using the design codes, a risk based approach as well as due consideration for possible extreme consequences. A likelihood of domino failures due to a new MHI next to an existing independent MHI should be very much less than the likelihood posed by the installation itself, e.g. at least two orders of magnitude lower. This extra order of magnitude allows for the possibility of deterioration in the integrity of process safety management at the new facility over the entire life time of the plant, e.g. due to management restructuring, take-overs, harsh economic conditions. In certain cases, the consequences of domino failures may be so severe that the risk may not be justified.

	DOMINO EFFECT TYPE	**SUGGESTED CRITERIA**
1	Diminishing	Normal Design Separation Standards **And** Totalized sum of likelihood of neighbour impact < sum of existing plant likelihood
2	Constant	Normal Design Separation Standards **And** Totalized sum of likelihood of neighbour impact << sum of existing plant likelihood – 1 order of magnitude
3	Escalating	Normal Design Separation Standards **And** Totalized sum of likelihood of neighbour impact <<<< sum of existing plant likelihood – 2 orders of magnitude

TABLE – 3.8 – proposed domino criteria

In summary, the domino assessment criteria not be absolute once off numbers for all facilities. The criteria are relative to the type of facility, the existing onsite risks, as well as whether the domino effects are escalating or not, i.e. the criteria become situation specific numbers.

4 RESULTS AND DISCUSSION – THE CRITERIA IN ACTION

These assessment criteria will be illustrated below with reference to the example of the three companies A, B and C.

The domino effects from Company B to Company A could be escalating. Using the above criteria, the likelihood should two orders of magnitude lower than 5.5 x 10 $^{-6}$ events per year, i.e. less than 5.5 x 10 $^{-8}$ events per year. The combined likelihood of Company B (flammable gas) failures leading to potential domino failures at Company A (liquified flammable gas) is 9.56 x 10 $^{-7}$ events per year. This is not low enough and therefore these domino effects could be judged unacceptable. In this case, further separation by distance would probably reduce the domino likelihood. The analysis could be repeated with a greater separation distance and suitable recommendations made.

The table below summarizes the results for all three companies:

DOMINO EFFECT DIRECTION	TYPE OF DOMINO EFFECT	LIKE-LIHOOD CRITERION	FACILITY RISK	EXTERNAL DOMINO RISK	LIKELIHOOD DIFFERENCE	ASSESSMENT
Company B (flammable gas) towards Company A (liquified flammable gas)	Escalating	> 2 Orders of Magnitude (OOM)	5.5 x 10 $^{-6}$	9.56 x 10 $^{-7}$	< 1 Order of Magnitude (OOM)	Not acceptable
Company A (liquified flammable gas) towards Company B (flammable gas)	Diminishing	Less	8.3 x 10 $^{-5}$	1.83 x 10 $^{-5}$	< 1 OOM	Tolerable
Company A (liquified flammable gas) towards Company C (liquefied toxic gas)	Escalating	> 2 OOM	3.7 x 10 $^{-4}$	1.96 x 10 $^{-6}$	> 2 OOM	Acceptable

TABLE – 4.1 – illustration of the evaluation of domino effects in three directions between three MHIs

The above results illustrate another pertinent issue when judging domino effects. The likelihood of domino effects of Company A on Company B (1.83 x 10 $^{-5)}$ is a higher number, in absolute terms, than the domino effects in the reverse direction (9.56 x 10 $^{-7}$). However, because the judgement criteria are based on comparison to likelihoods of onsite failures as well as whether the effects are escalating or not, the higher absolute number turns out to be an acceptably low domino result while the lower number reverse domino effect is not tolerable.

5 CONCLUSIONS

The following conclusions have been made:

1. There is very little clear guidance in the literature or legislation on suitable separation distances between MHI facilities in order to minimize potential domino effects.
2. Domino effects between MHI can be escalating, constant or diminishing in consequence.
3. It is proposed that likelihood of a new neighbouring MHI site causing major domino failures on an existing MHI site should be significantly lower than the likelihood of that failure happening on the site if it were alone. A relative likelihood criterion is proposed.
4. A practical method for approximating these combined major incident likelihoods for both the plant on its own and the adjacent plants domino failures is suggested. Simplified factors for wind and weather impacts as well as probability of ignition need to be taken into account in addition to pure equipment failure data.
5. Where the potential consequences of domino failures are diminishing, the likelihood should be lower than for the site on its own.
6. Where the potential consequences of domino failures are constant, the likelihood should be at least one order of magnitude lower.

7. Where the potential consequences of domino failures are escalating, the likelihood of domino effects should be even lower, e.g. at least two orders of magnitude lower than the site incident likelihood. This extra order of magnitude allows for variation in the quality of process safety management at the new site and should ensure that the domino risks remain less than the normal risks under most circumstances over the lifetime of both plants.

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