CHEMICAL ENGINEERING TRANSACTIONS
VOL. 77, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216
DOI: 10.3303/CET1977158

Safety Distances Due to Domino Effects

Gerald M.H. Laheij[a,*], Margreet B. Spoelstra[b], Soedesh Mahesh[a]

[a]National Institute for Public Health and the Environment, P.O.Box 1, 3720 BA Bilthoven, the Netherlands
[b]Institute for Safety, P.O.Box 7010, 6801 HA Arnhem, the Netherlands
gerald.laheij@rivm.nl

Domino effects can be defined as the escalation of an initial failure of a system, resulting in the failure of a second nearby situated system with more severe consequences. Domino effects are not a part of the prescribed risk methodologies in the Netherlands, used for spatial planning purposes. However, in some risk methodologies domino effects are specifically addressed. Examples are domino effects due to nearby airports, wind turbines and flooding's; they have to be considered when they contribute for more than 10 percent to the initial failure frequency of equipment. Domino effects have to be considered as well in determining internal safety distances within establishments and in the design of pipeline corridors. In determining safety distances for LPG storage sites, the most important type of domino accident is the BLEVE of a pressure vessel. The initiating events that are identified are pool fire, jet fire and fire from buildings. Safety distances are defined that should reduce the likelihood of a BLEVE. With respect to pipeline corridors domino effects are a threat due to the high density of pipelines in the corridor and failure of one pipeline may result in the failure of an adjacent pipeline. Pipeline corridors are planned all over the Netherlands and in view of these developments an investigation was started into the design of domino free pipeline corridors. Initiating events that are identified are among other overpressure caused by physical explosions, heat radiation resulting from a pool fire or a jet fire, a large temperature drop caused by the release of liquefied gases or supercritical fluids and earth removal causing free span problems. This paper gives an overview of the different approaches in the Netherlands used to control the probability of domino effects, with a focus on LPG storage sites and pipeline corridors.

1. Introduction

A domino event can be defined as an accident that involves a loss of containment and that is the result of an escalation of another accident that occurred nearby. The effect of the domino event is often more disastrous than that of the initiating event itself (Cozanni et al., 2005). There are many variations of this definition as the circumstances leading to domino effects can differ considerably (Reniers, 2010). For instance, the initiating effect and the domino event may or may not occur within the same chemical plant. Furthermore, both events may or may not involve the release of hazardous substances. When the initiating event involves a release of a hazardous substance, the effect leading to the domino event can either be heat radiation (pool fire, jet fire), overpressure (explosion) or fragment impact (explosion, BLEVE). For transmission pipelines also free span or cooling effects can be of importance. The failure of equipment due to the release of a corrosive medium from a vessel or an adjacent pipeline is not considered to be a domino effect, because the target equipment will not fail immediately as it is expected that there will be enough time to take measures to prevent its failure.
The way in which prevention of domino events is considered in the Netherlands, depends on the circumstances that may lead to a domino event. From the perspective of a plant or pipeline corridor with hazardous substances, the prevention of domino effects is considered by:

A. SEVESO Directives 96/82/EC and 2012/18/EU state that domino effects between two adjacent SEVESO plants have to be identified (EU, 2012). In the Netherlands, the Instrument for Domino Identification (IDE) was developed for this purpose (RIVM, 2003). IDE offers tabulations of calculated domino distances for various combinations of installations.

Paper Received: 17 November 2018; Revised: 24 April 2019; Accepted: 28 June 2019

Please cite this article as: Laheij G., Spoelstra M., Mahesh S., 2019, Safety distances due to domino effects, Chemical Engineering Transactions, 77, 943-948 DOI:10.3303/CET1977158

B. National technical standards, such as the Hazardous Substances Publication Series (PGS, 2018) and NEN standards for transmission pipelines are in place to reduce the likelihood of domino effects (NEN, 2018). These standards and provide guidance for companies, pipeline operators and competent authorities. The guidelines define which safety distances or technical design measures have to be implemented. If a company complies with the appropriate guideline, domino effects between two installations within the same plant do not have to be accounted for in quantitative risk analyses (QRA).
C. Natural disasters, wind turbine failures and airplane crashes may lead to failure of an installation within a chemical plant or to the failure of pipelines in a pipeline corridor. Domino effects caused by natural disasters are not taken into account in Dutch quantitative risk analyses. Domino effects caused by wind turbine failures or airplane crashes, on the other hand, should be taken into account if the failure frequency of the relevant installation increases by more than 10% of the intrinsic failure frequency of the type of equipment concerned (RIVM, 2009).
D. In the Netherlands, the AASTP-1 guideline of the NATO is used to prevent the likelihood of domino effects caused by overpressure effects and fragmentation of explosives and ammunitions (NATO, 2010). Domino effects caused by fragment projection and overpressure effects of fireworks are prevented by the Dutch Fireworks Act (Vuurwerkbesluit, 2002).

This paper focusses on how domino effects for LPG storage vessels and natural gas pipelines in pipeline corridors are considered in National Technical standards. For both an impression is given of the initiating events of domino effects. A more comprehensive overview is given in Spoelstra et al. (2015) and Werkgroep Domino Buisleidingen (2016).

2. LPG and propane vessels

LPG or propane can be stored on a small scale or on a large scale. Guideline PGS 18 describes the storage of LPG at depots, while guideline PGS 19 covers the storage of propane and butane on small scale (private use) (PGS, 2018). The main domino event to be considered is the instantaneous release of the content of a vessel due to a Boiling Liquid Expanding Vapour Explosion (BLEVE). The initiating event is a pool fire of a tank containing flammable liquids. Also a jet fire or thermal load due to a nearby burning object can initiate a BLEVE. Safety distance for preventing a BLEVE due to a pool fire or jet fire will be discussed in this paper.

A BLEVE is described as the “sudden loss of containment of a pressurized liquefied gas, which results in rapidly expanding vapor and flashing liquid” (CCPS, 2010). The definition implies that a BLEVE is purely a physical explosion. The accompanying escalation effects of overpressure and fragment projection are however often ignored in risk calculations for flammable products such as LPG. The reason for this is that upon explosion of the vessel the released content can ignite causing a fireball. The effect distances of a fireball are much larger compared to the effect of the explosion itself (Hemmatian et al., 2015).

2.1 Thermal load due to a pool fire

When an LPG or propane pressure vessel is placed in the vicinity of tanks that contain atmospheric flammable liquids, a pool fire may develop whenever such an atmospheric tank fails. The pool fire can irradiate the LPG or propane vessel. The key parameters for the radiation intensity to which the LPG or propane vessel is exposed, are the diameter of the pool fire and the distance between the pool and the LPG vessel. An important criterion for developing internal safety distances is the maximum allowable heat radiation intensity to which the pressure vessel can be exposed. A thermal load of 10 kW/m^2 is used as the maximum allowable heat radiation intensity for deriving safety distances. This a conservative criterion that may be applied to all types of tanks, including atmospheric tanks and pressurized vessels that may or may not be equipped with fire protection facilities. A thermal load of 35 kW/m^2 can be applied to LPG or propane vessels that can withstand higher radiation intensities. Owners of vessels that want to apply distances from this set have to justify that the relevant vessel can withstand this heat radiation intensity of 35 kW/m^2 for a long period of time. Using different threshold values for different types of vessels is in line with Cozzani et al. (2013). Figure 1 presents the distances to the contours representing a heat load of 10 kW/m^2 or 35 kW/m^2 at an observer height of 1 m starting from the edge of the pool. Pool fire calculations, using n-hexane as the model compound, were done using the SAFETI-NL software program (DNVGL, 2007). The markers represent the results of the calculations and are denoted as ‘calculated’. The maximum distance from the edge of a pool fire, is 26 meters and is obtained for a pool fire with a burning pool surface of 200 m^2. Smaller distances were calculated for pool fires surfaces larger than 200 m^2. The outcomes of the calculations, showing first an increase and subsequently a decrease in consequence distance, can be explained by two phenomena with opposing impact. During the combustion a fraction of the produced energy is emitted as radiation. For small fires this energy is directly transmitted to the environment. When the pool fire surface area is increased, more heat is radiated to the environment, resulting in larger distances. Large fires on the other hand, burn inefficiently and produce a substantial amount of soot. The heat radiated by the fire is partly absorbed by the soot particles and converted to convective heat. This is referred to as ‘flame obscuration’. This flame obscuration explains why distances can decrease beyond a certain pool fire surface diameter. The lines represent the results that are actually used in guidelines PGS 18 and PGS 19 as internal safety distances. The difference with the calculated distances is that the distance to be used does not decrease at the right side of the graph. The reasons is that it is difficult to communicate that the safety distance for a large pool (e.g. 500 m^2) is smaller than the safety distance for a smaller pool (e.g. 200 m^2). Using the maximum distance for larger pools is easier to communicate and a conservative approach.

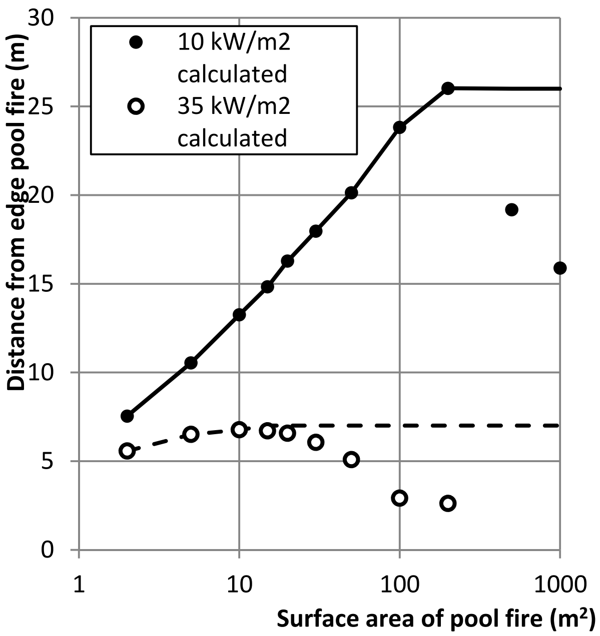

Figure 1: Safety distances for LPG or propane pressure vessels to prevent domino events due to heat radiation from a pool fire.

2.2 Thermal load due to a jet fire

Another domino effect considered is the possibility of a jet fire when an LPG or propane pressure vessel is placed near vessels containing LPG or other flammable liquefied gasses. The key parameters for the radiation intensity to which the vessel is exposed, are the orifice diameter of the leak and the release phase of the flammable material. The orifice diameter is assumed to be equal to 10% of the diameter of the largest pipe connection to the vessel from which the flammable material is released (initiating event). Jet fire calculations were performed assuming the receiving LPG vessel is not covered with ground or equipped with other fire protection facilities. The results of the calculations are given in Figure 2. Note that when the sizes of two adjacent propane vessels differ, the size of the largest connection is used to determine the appropriate safety distance.

3. Pipeline corridors

In the Netherlands, about 20,000 kilometers of transmission pipelines transporting natural gas, oil products and chemicals have been constructed in the last five decades. As it has become increasingly difficult to plan and construct new pipelines efficiently in a country as densely populated as the Netherlands. New transmission pipelines are now going to be constructed, as much as feasible, in specially designated pipeline corridors (Ministry of Infrastructure and the Environment, 2012). The width of these corridors, which are normally 70 meters wide, is such that new pipelines can be constructed and maintained without disturbing adjacent pipelines or cables. Because of the presence of dwellings or of pre-approved plans to build them, the width of some of the designated pipeline corridors is limited to several tens of meters. As the number of pipelines in a corridor could be as high as ten, the distance between pipelines in smaller pipeline corridors is reduced to one to three meters. This distance may be insufficient to rule out domino effects occurring between

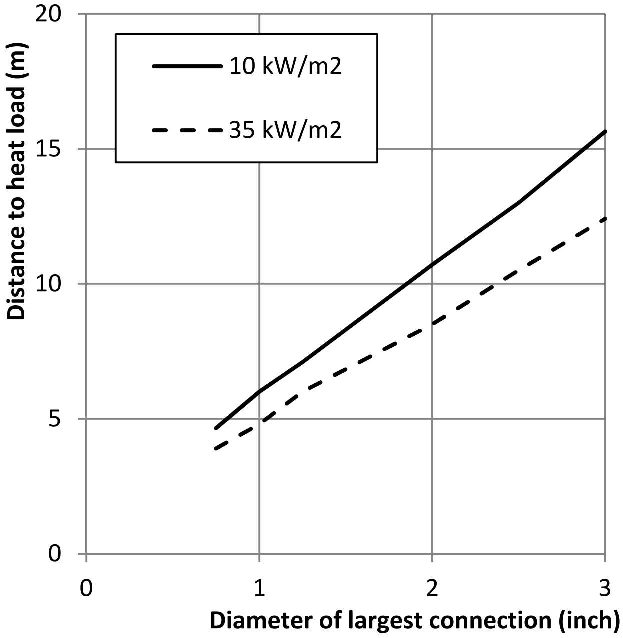

Figure 2: Calculated safety distances for LPG or propane pressure vessels to prevent domino events due to radiation from a jet fire.

parallel running pipelines. In total, this applies to approximately 100 to 200 kilometers of the designated corridors, some 5-10% of the total length of the pipeline corridors (Ministry of Infrastructure and the Environment, 2012).
In cooperation with Dutch pipeline operators and the Dutch government, an investigation started to devise a domino-free design of pipeline corridors and manage the risk in situations where it was thought that domino effects could occur. The results of this investigation are included in Dutch Technical Agreement 8036:2018 (NEN, 2018).
Depending on the physical state and flammability of the substance transported by the initial failing pipeline, the following initiating events can create a domino effect: thermal load, overpressure, earth removal and temperature drop. In case a natural gas pipeline initiates the domino event and another natural gas pipeline is target of the event, thermal load, overpressure and earth removal apply.

3.1 Crater formation

The crater width is an important factor as domino effects between parallel pipelines usually only occur when the domino effect initiating pipeline and the target pipeline are inside the same crater (Silva et al, 2016). For pipelines transporting natural gas, crater dimensions depend on the diameter and pressure of the initiating pipeline, the depth of cover and the type of soil covering the pipelines.

Table 1: Crater width (m) of natural gas pipelines as function of pipeline diameter and depth of cover. Soil type: mixed soil.

Diameter (mm)	Depth of cover (m)				
	0.8	1.0	1.2	1.5	1.75
457	7.4	8.0	8.6	9.2	9.8
610	8.8	9.6	10.2	11.2	11.8
914	10.6	12.6	13.4	14.4	15.2
1219	14.4	15.2	16.2	17.4	18.4

Several models are available to calculate the dimensions of the crater width as a result of a rupture of a natural gas pipeline (TNO, 1973; Leis et al., 2002; Acton et al., 2010; Silva et al., 2016). Crater widths for several diameter/depth of cover combinations are determined using the model of Leis (Leis et al., 2002; Acton et al., 2010). The results, given in Table 1, imply that a separation distance of 10 meters, equal to half of the maximum calculated crater width, is enough for constructing a domino-free pipeline corridor.

3.2 Overpressure

The rupture of a high-pressure transmission pipeline results in overpressure effects caused by the physical explosion. Whether an adjacent pipeline fails as a result of the physical explosion depends on the substance transported and on a number of the pipeline parameters of the adjacent target pipeline. If a natural gas pipeline ruptures and the target pipeline is also transporting natural gas, the overpressure effects can be calculated by using the TNO model (TNO, 1973). Enhancements of this model have been made in Prophet (Acton et al., 2010). Using Prophet, some minimum separation distances are calculated and outlined in Table 2. The target pipeline has a diameter of 1219 mm and operates at a pressure of 8 MPa (design factor 0.65). The overpressure that the target pipeline can withstand is about 7 MPa.

Table 2 : Examples of the minimum distances required between natural gas pipelines in order to avoid failure of the target pipeline (1219 mm, 8 MPa) caused by overpressure effects.

Diameter (mm)	Pressure (MPa)	Minimum distance (m)
457	8	0.2
610	8	0.3
914	8	0.3
1219	8	0.5

3.3 Thermal load

When a failing pipeline transporting a flammable gas or a flammable liquid ignites, a jet fire or a pool fire results. Target pipelines in the same crater as the domino effect initiating pipeline can consequently fail because of the thermal load of the jet fire or pool fire. Whether the target pipeline fails depends on the diameter and pressure of the domino effect initiating pipeline and the cooling potential of the target pipeline. The cooling potential depends on the caloric value of the flammable gas or liquid transported, its specific heat and thermal conductivity and the flow velocity in the target pipeline (Acton et al., 2010). Table 3 gives some critical flow velocities for natural gas pipelines exposed to the thermal load of an adjacent natural gas pipeline. The design factor of the target pipeline equals 0.65. From Table 3 at can be concluded that under normal operating conditions the gas velocities are high enough to avoid domino effects caused by the thermal load as long as the flow in the target pipeline is maintained.

Table 3: Critical flow velocities (m/s) required to prevent failure of the target pipeline (natural gas/natural gas), pressure initiating pipeline is 8 MPa.

Diameter (mm)	Pressure (MPa)		
	4	6.6	8
457	0.45	0.42	0.39
610	0.61	0.56	0.51
914	1.05	0.93	0.81
1219	1.63	1.42	1.22

3.4 Additional measures

Additional measures are required if failure of the target pipeline caused by overpressure effects, thermal load or free span cannot be excluded. As external interference is the most important failure cause for most types of pipelines, additional measures, which reduce the probability of failure caused by external interference can be applied. Examples of these measures are an increased wall thickness of the pipelines and the presence of a fence at the borders of the pipeline corridor. These measures will not prevent a domino effect but will increase the overall safety level of the pipeline corridor. The design of the corridor is another measure that can be applied. For example, the type of soil used in the pipeline corridor is of importance as it has a significant influence on the width of the crater. Choosing a soil type that minimizes the width of the crater reduces the probability of the occurrence of a domino effect. Clay type soils are therefore preferable to more sandy types of soils, as the differences in crater widths can be up to a factor two (Silva et al., 2016). In corridors which currently contain no pipelines or only a few pipeline the probability of escalation can be reduced as much as possible by careful consideration of the sequence of the pipelines. For example, pipelines which would produce the most severe effects could be situated at greater depths. This reduces the probability of these pipelines being situated in the same crater as the domino effect initiating pipeline. Also, new pipelines in the pipeline corridor could have a heat resistant coating.

4. Conclusions

Appropriate safety distances reduce the likelihood of domino effects. For LPG pressure vessels, a maximum heat load on the pressure vessel of 10 kW/m^2 or 35 kW/m^2 was used to derive standard safety distances. These distances are incorporated in two Dutch guidelines, PGS 18 and PGS 19. Distances for a heat load of 35 kW/m^2 can be used only if it is convincingly demonstrated that the considered vessel can withstand such a heat load for a prolonged period.

For natural gas pipelines in pipeline corridors crater models and domino consequence models are available To ensure a domino-free design, it is necessary to exclude the possibility of another pipeline being situated in the same crater as the domino effect initiating pipeline. For natural gas pipelines, a separation distance in the order of 10 meters is sufficient. However, the soil type used in the pipeline corridor is also of importance. If a domino-free design of the pipeline corridor is not possible, separation distances between pipelines should be such that domino effect caused by overpressure effects, thermal load can be avoided as much as possible.

References

Acton M., Jackson N., Jager E., 2010, Development of guidelines for parallel pipelines, 8th International Pipeline Conference, Volume 4, Calgary, Canada, 485-495.

CCPS, 2010, Guidelines for vapor cloud explosion, pressure vessel burst, BLEVE and flash fire hazards, 2nd ed., Wiley, New York, USA.

Cozanni V., Antonioni G., Spadoni G., Zanelli S., 2005, The assessment of risk caused by domino effect in quantitative area risk analysis, Journal of Hazardous Materials, 217, 14 – 30.

Cozanni V., Tugnoli A., Bonvicine S., Salzano E., 2013, Threshold-based approach in domino effects, Domino Effects in the Process Industry, edited by Reniers G. and Cozzanni V., 1st Edition, Elsevier, Amsterdam, the Netherlands.

DNVGL, 2007, Software for the assessment of flammable and toxic impact, version 6.54.

EU, 2012, Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC.

Hemmatian B., Planas E., Casal J., 2015, Fire as a primary event of accident domino sequences: the case of BLEVE, Reliability Engineering and System Safety, 139, 141 – 148.

Leis B.N., Pimputkar S.M., Ghadiali N.D., 2002, Line Rupture and the Spacing of Parallel Pipelines, Project PR 3-9604, Pipeline Research Council International, Houston.

Ministry of Infrastructure and the Environment, 2012, Structuurvisie Buisleidingen 2012 – 2035 (in Dutch).

NATO, 2010, Manual of NATO safety principles for the storage of military ammunition and explosives, AASTP-01, <nso.nato.int> accessed 18.09.2018.

Nederlands Normalisatie-instituut, 2018, Nederlandse Technische Afspraak 8036:2018. Requirements for the joint location of pipeline systems in a pipeline corridor (in Dutch).

PGS, 2018, <www.publicatiereeksgevaarlijkestoffen.nl> accessed 18.09.2018.

Reniers G., 2010, An external domino effects investment approach to improve cross-plant safety within chemical clusters, Journal of Hazardous Materials, 177, 167 – 174.

RIVM, 2003, Instrument Domino-Effecten (in Dutch), <www.rivm.nl> accessed 18.09.2018.

RIVM, 2009, Reference Manual Bevi Risk Assessments version 3.2, <www.rivm.nl> accessed 18.09.2018.

Silva E.P., Nele M., Frutuoso e Melo P.F., Könözsy L., 2016, Underground parallel pipelines domino effect: an analysis based on pipeline crater models and historical accidents, Journal of Loss Prevention in the Process Industries, 43, 315 – 331.

Spoelstra M.B., Mahesh S., Kooi E., Heezen P., 2015, Domino effects at LPG and propane storage sites in the Netherlands, Reliability Engineering and System Safety, 143, 85 – 90.

TNO, 1973, Safe design of pipeline corridors, onderzoek model Maasvlakte, RVO-TNO 9124-1.

Vuurwerkbesluit, 2002, <wetten.overheid.nl> accessed 18.09.2018 (in Dutch).

Werkgroep Domino Buisleidingen, 2016, Domino aspecten van buisleidingen (Bevb) (in Dutch).