MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

19th Annual International Symposium
October 25-27, 2016 • College Station, Texas

High Pressure Relief Systems in LNG Receiving Terminals – A Safety Case for HP Flare

Sunny Choi, Venkatesh Sourirajan, Gary Li
IRESC
* Email: sunny.choi@irescglobal.com

Abstract

Worldwide demand for liquefied natural gas (LNG) has been steadily increasing, leading to the design and construction of larger receiving terminals in recent years. While the safety record of the LNG industry has been good, it may be beneficial to review some of the standard design safety features, with regard to their adequacy given the increased scale of the new facilities. In particular, unlike other industries where hydrocarbon vents are connected to flare system, it is common practice to route pressure safety valve (PSV) discharges on vaporizers to the atmosphere directly. The relief loads from one single vaporizer PSV has increased from 50t/hr in the past to the latest 300t/hr. As a result, it has become challenging to dispose of such a large quantity of flammable gas through atmospheric vents in a safe manner. Furthermore, during events such as blockage of the send-out pipeline, simultaneous relief of PSVs from multiple vaporizers may increase the total combined discharge rate to more than 1,000t/hr. High thermal radiation arising from the ignition of such a release may lead to damage of nearby equipment, piping and structures as well as personnel injury or fatality. To account for such effects, some designers have transformed the PSV discharge from simple tailpipes to multiple vent stacks with elevations of more than 20m.

The objective of this paper is to assess the hazards (possible consequences and likelihood) due to a flammable gas release from LNG vaporizer PSVs to the atmosphere with respect to personnel safety, asset damage and plant unavailability. The result can be used to evaluate the potential costs and benefits of introducing a high pressure flare system taking into account the associated capital and operating costs (e.g. extra land, pipework, structure). Apart from additional flare system, several other alternate mitigation measures are also proposed for consideration.

Introduction

In a LNG regasification terminal, the key process comprises pumping and vaporizing LNG from storage tanks to deliver natural gas to consumers. The vaporization process is carried out in the LNG vaporizer which is a specialized type of heat exchanger with LNG entering at about -155C° and natural gas exiting at about 10C°. The vaporization occurs by heat exchange with a hot medium such as sea water. Pressure Safety Valves (PSVs) are provided for the blocked outlet case at the vaporizer outlet and are typically vented to atmosphere. Atmospheric venting of a large quantity of flammable natural gas can pose hazards to the facility and its personnel if ignited. This paper examines the risk to safety, asset and plant availability due to such venting and evaluates the benefits of routing the PSV discharge to flare as an alternative design option.

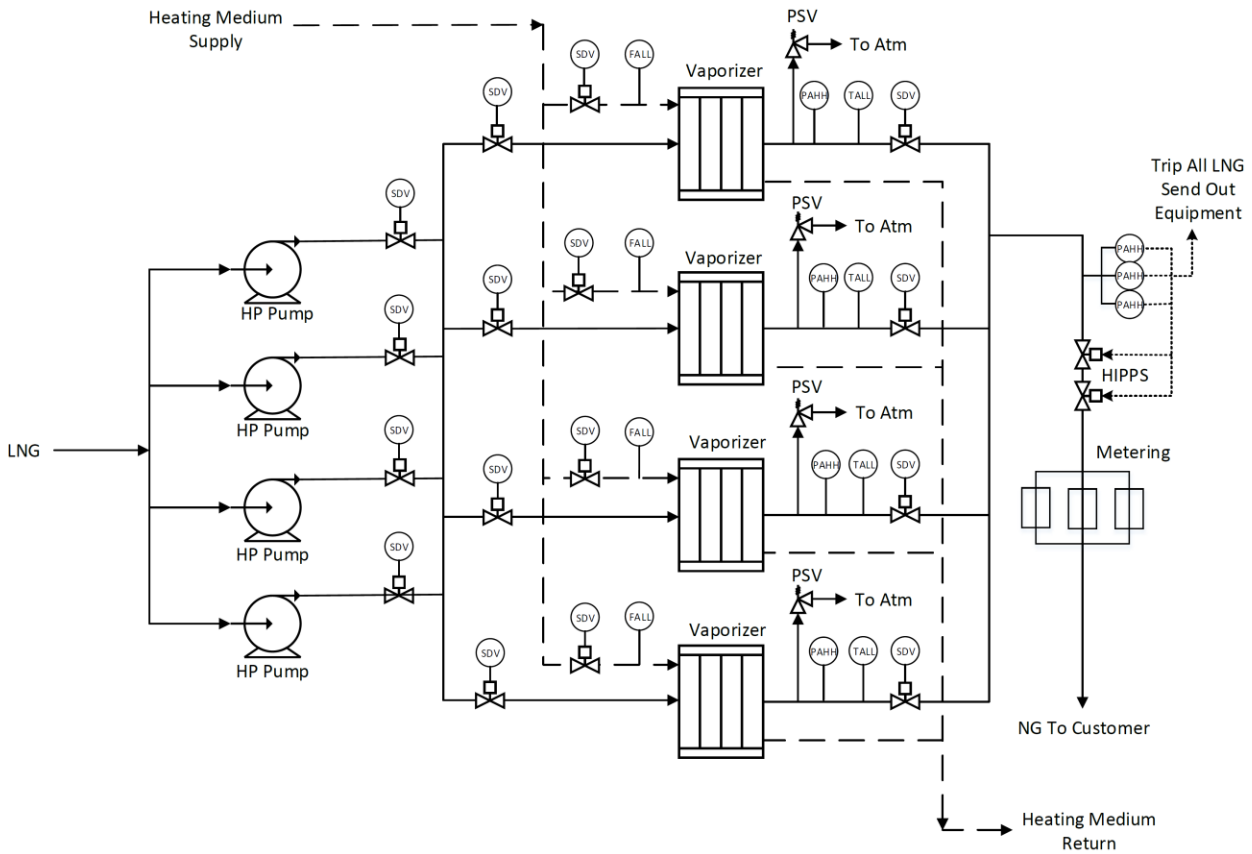
Atmospheric Venting in Other Process Industries

In the past, the process industry has made use of atmospheric vents for pressure relief. For example, PSVs on tall columns such as Demethanizers were often routed to the atmosphere as it was considered safe to relieve at such elevations. Atmospheric venting also helped minimize the flare requirements, for example by reducing the peak relief flow rate and by removing the need for a dedicated cold flare for systems operating at very low temperature. In recent years, the process industries, including LNG Liquefaction plants have largely moved towards routing all discharge of flammable materials to flare. In LNG regasification terminals, however, an atmospheric venting arrangement for vaporizer PSVs continues to be the norm. It is observed that the capacity of LNG vaporizers has significantly increased in recent years. While terminals constructed in the past used to have vaporizers with capacities of 50t/hr to 100t/hr and occasionally 150t/hr, improvements in vaporizer design and efficiency have led to new terminals typically with 200t/hr or even 300t/hr vaporizers. As such, the volume of natural gas released to the atmosphere during a pressure relief event, and the potential consequences should the released material ignite, has increased significantly.

Typical LNG Regasification System Design

In a LNG regasification terminal, LNG is sent to the vaporizers through the LP pump (in-tank) and HP pump operating in series to deliver the required pressure. The vaporization is performed by means of changing heat with the heating medium, which is typically sea water. A schematic flow diagram is presented in Figure 1.

Figure 1 – Flow Diagram of a Typical LNG Regasification Train



Emergency isolation valves are provided both at the inlet and outlet of each vaporizer. The vaporizer and the immediate outlet piping are designed for the HP pump shut off pressure as well as LNG temperature. However, piping specification downstream of vaporizer typically transitions from stainless steel to carbon steel and from high pressure (HP pump shutoff pressure) to low pressure (downstream pipeline design pressure). The transition point is typically 5m to 15m downstream of the vaporizer. The PSV at the immediate outlet of the vaporizer is designed for the blocked outlet case (continued vaporization under blocked vapor outlet condition) and typically vented to atmosphere. Depending on the system design pressure, which is dictated by the gas delivery pressure to downstream consumers, the PSVs may be set between 50barg to 135barg. The height of the PSV vent is usually about 10m to 20m from ground level. The vaporizer system is provided with a Low Low Temperature (TALL) trip and a High High Pressure (PAHH) trip at the individual vaporizer outlet. A Low Low Flow (FALL) trip is also provided on the heating medium side, to shut down the LNG flow on the loss of heating medium. The downstream system may be safeguarded by a High Integrity Pressure Protection System (HIPPS) trip on the common header (shutting off all vaporizer inlet valves and all HP pumps) or by another set of PSVs (set at pipeline design pressure) also routed to the atmosphere. In large terminals, the number of vaporizers may be 10 or more.

Scenarios that can lead to the opening of the vaporizer PSVs are mainly associated with a blocked outlet, which can occur due to the closure of any valves downstream of the vaporizer. Upon closure of any such outlet valves, if any of the HP pumps fails to trip or the vaporizer inlet LNG valve fails to close, the pressure in the system would build up due to continued vaporization of LNG leading to the lifting of PSVs. System pressure may also build up due to a sudden loss of demand from any of the pipeline gas consumers. The author is aware of two incidents in a LNG regasification terminal when PSVs on multiple vaporizers lifted due to inadvertent valve closure at the gas pipeline station resulting in blocked outlet, although no ignition occurred. The PSVs lifted before the PAHH could react due to the slow response time. Another scenario is the premature lifting or inadvertent opening of PSV during normal operation which can lead to discharge of gas to the atmosphere. Such instances of premature lifting of PSV are widely reported in the industry and also experienced in LNG industry [1].

There are typically two main criteria which govern the design of any atmospheric vent, namely dispersion and thermal radiation criteria. In terms of dispersion, most standards require the location of the vent should ensure the vented flammable material does not reach any potential ignition source and does not accumulate in any congested/ confined area where it can pose an explosion risk. It is typically also required that the flammable cloud should not reach any manned area at ground level or operator platform at an elevation. These requirements are usually achieved by studying the layout of the plant against the consequence distance of 50% Lower Flammable Limit (LFL) or sometimes 10% LFL. These dispersion criteria are relatively easy to meet as the cloud can usually rapidly disperse due to the high venting velocity and the low gas density. Nevertheless, ignition can still occur due to other sources such as a lightning strike or static electricity; hence it is relevant to discuss in detail the various thermal radiation criteria that should be applied. One of the incidents involving release LNG vapor, the officially documented cause of ignition was a spark generated by static electricity [1]. In any case, it is specifically mentioned in EN 1473 [2] that ignited vent should be considered as a credible event in the context of risk assessment.

Discussion on Thermal Radiation Criteria

EN 1473 [2] and NFPA 59A [3] are the main design standards specific to the LNG industry while API 521 [4] is the general design guideline for pressure relief systems. The thermal radiation criteria in the various standards are summarized in Table 1, while further discussion on the thermal radiation criteria is contained in the paragraphs below.

Table 1 – Summary of Thermal Radiation Criteria for Atmospheric Vent

Receptors	Maximum Allowable Thermal Radiation (kW/m^2)			
	EN 1473 Table A.3[1]	EN 1473 Table A.1[1, 2]	NFPA 59A	API 521[3]
LNG tank (concrete shell)	5	32	-	-
Equipment	5	15	-	-
Onsite buildings	5	8 or 5[4]	-	-
Within sterile area[5]	9	-	-	9.46
Edge of sterile area	5	-	-	6.31
General manned area (including roads and open areas)	5	-	-	-

Receptors	Maximum Allowable Thermal Radiation (kW/m^2)			
	EN 1473 Table A.3[1]	EN 1473 Table A.1[1, 2]	NFPA 59A	API 521[3]
Areas where emergency action is required[6]	-	-	-	4.73
Site boundary	5	5	5	-

Note 1: Radiation criteria provided in EN 1473 are excluding solar radiation.
Note 2: Table A.1 in EN 1473 is intended for LNG fire. However, it is not clear on the definition of LNG fire.
Note 3: Solar radiation should be considered. However, adjustment is allowed on a case by case basis based on numbers of factors including frequency of maximum relief, the probability of personnel within the affected area, ability of personnel to move away from the affected area, etc.
Note 4: 5kW/m2 is applicable to administrative buildings while 8kW/m2 is applicable for other buildings such as control room, warehouse, etc.
Note 5: Personnel entering area that is defined as "Sterile Area" are required to be provided with radiation shielding or appropriate PPE.
Note 6: Limited to a duration of 2min to 3min without shielding but with appropriate clothing.

EN 1473 [2]
A clear set of thermal radiation criteria for flare/ ignited vent stack is provided in Table A.3 of EN 1473. It is also explicitly mentioned in the standard that vent stack ignition shall be assumed to be a credible event. Although the criteria in Table A.3 of EN 1473 refer to an ignited vent stack, it is assumed that the same criteria are also applicable to an ignited PSV vent. Another set of thermal radiation criteria is also presented in Table A.1 for "LNG fire". Since the criteria in Table A.1 is more lenient than those of Table A.3, the criteria in Table A.1 can be treated as the upper limit in case any of the more stringent criteria in Table A.3 cannot be practically met.

NFPA 59A [3]
There are no specific design criteria mentioned for atmospheric vents except that such vents should be located at a safe location. However, the standard does provide criteria for the purpose of impoundment basin siting, which defines $5kW/m^2$ as the limit to the nearest point located outside the property line which is being used for outdoor assembly by groups of 50 or more people. In the absence of more specific criteria, it is assumed that this thermal radiation criterion for impoundment basin can also be applied to atmospheric vents inside LNG terminals. This criterion is also in line with that of EN 1473.

API 521 [4]
The standard provides a set of recommended design thermal radiation for personnel under various conditions for a flare system. Regarding atmospheric vents, the standard specifically mentions that the radiation effect from such vents should be studied as long as the vented gas is flammable and the same set of recommended design thermal radiation for flare should apply. API 521 also acknowledges that often the thermal radiation criteria are the governing factors for vent stack height rather than the dispersion criteria.

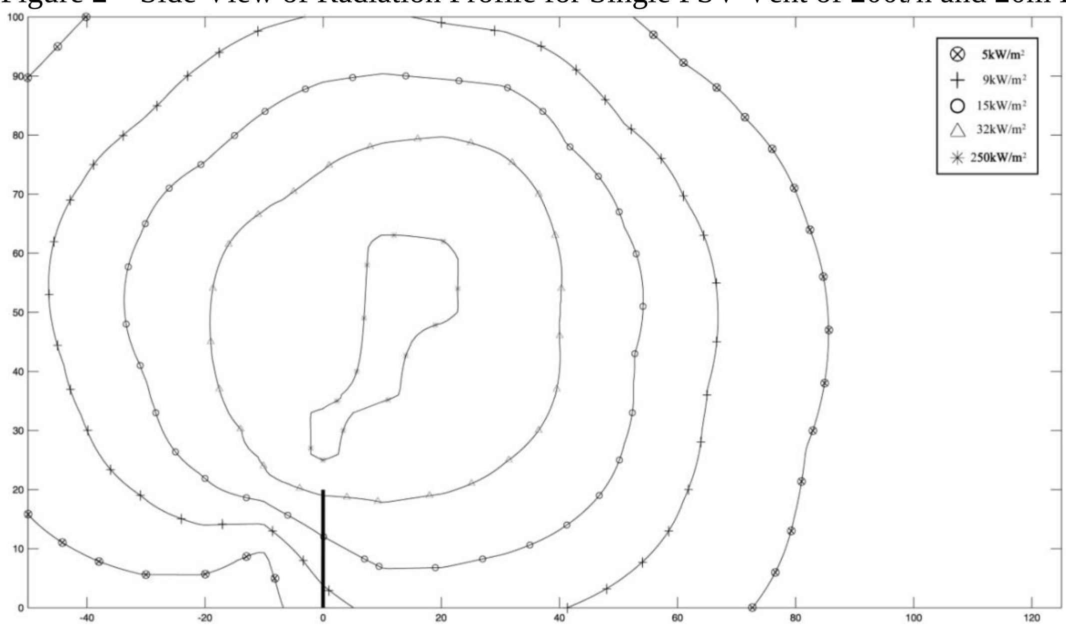
Modelling Basis for Thermal Radiation Impact Distances for PSV Vents
In this paper, all the radiation consequence modeling were performed using the chamberlain jet fire model (due to the relatively high exit velocity) in PHAST 6.7 [5] using weather condition of 10D (i.e. 10m/s wind with Pasqual Stability Class of D). Vaporizer capacity of 200t/hr and vent elevation of 20m was taken as the base case. The PSV relieving rate was assumed to be the same as the vaporizer capacity, although the rated flow of PSV may be 30% higher. It is further assumed that under gas blocked outlet condition, although the HP pump will reach shut-off condition which

is same as the set point of the PSV, the PSV will still lift due to continue vaporization as the flow of heating medium continues. The relieving rate under such circumstance is assumed to be the same as the vaporizer capacity. For the case of premature lifting of PSV during normal operation, the relieving rate is also assumed to be same as the vaporizer capacity. For comparison purpose, various other vaporizer capacities/ PSV relieving rates and vent elevations are also modeled. All results presented in this paper excluded solar radiation.

Thermal Radiation Analysis for a Single Ignited PSV Vent

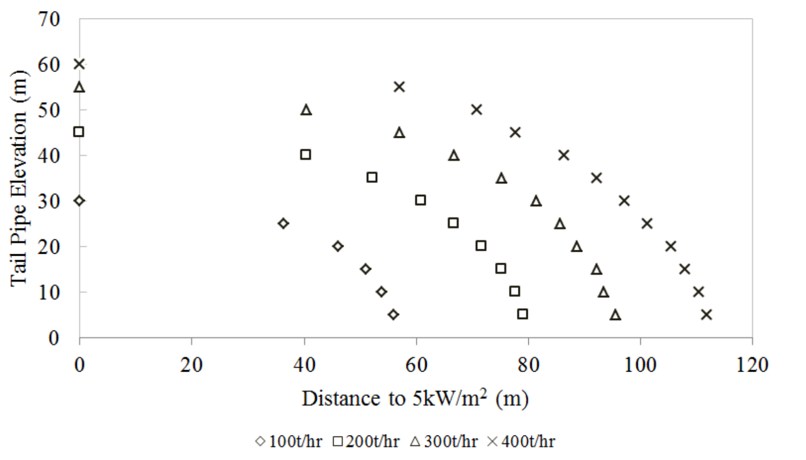
For the case of a single PSV vent ignition, the side view of the expected thermal radiation levels is presented in Figure 2.

Figure 2 – Side View of Radiation Profile for Single PSV Vent of 200t/h and 20m Elevation



It can be observed that due to the high exit velocity, flame lift-off occurs and the bulk of the flame envelope is around 40m to 60m above ground level. Also, the flame remains relatively upright even under a strong wind condition of 10m/s. A large contour of 5kW/m^2 is observed with a maximum downwind distance of 85m (75m at ground level). Based on the criteria listed in Table A.3 of EN 1473, all receptors including equipment and ground shall not be subjected to thermal radiation higher than 5kW/m^2 in the event of vent ignition. It is evident that such criteria would be difficult to satisfy. Figure 3 presents the relationship between the elevation of the vent and the extent of the 5kW/m^2 contour at ground level.

Figure 3 – Elevation of Single PSV Vent and 5kW/m^2 Distance on Ground Level



For the case of a 200t/hr release, the minimum vent elevation would have to be 45m in order to reduce the ground level radiation to below 5kW/m^2. However, other receptors such as equipment and the LNG tank would still be impaired by more than 5kW/m^2. This means that the vent should in fact be located 45m above all the adjacent equipment. Considering a typical equipment height of 10m, the elevation of the vent then has to be raised to 55m above ground. This is assuming the LNG tank can be located more than 85m away from the vent, otherwise, it may mean that the vent would have to be as tall as 100m in order to be 45m above the LNG Tank. It is apparent that the height requirement estimated from the above analysis is not practical, hence it may be necessary to study the basis of the radiation criteria in order to explore the possibility of adopting alternate criteria for design.

Discussion on Alternate Thermal Radiation Criteria

In terms of thermal radiation effect on personnel at ground level, API 521 does provide various thresholds based on different exposure durations. Assuming that all personnel working in the process area of a LNG terminal are equipped with appropriate clothing (including hard hat, long-sleeved shirts, work gloves, long-legged trousers and work shoes), the recommended design thermal radiations are given in Table 2.

Table 2 – Recommended Design Thermal Radiation for Personnel (API 521 [4])

Permissible Design Level (kW/m^2)	Conditions
9.46	Personnel with appropriate clothing cannot tolerate for more than a few seconds so can only allow for quick escape. When personnel entry is required, radiation shielding and/or special protective apparel should be provided.
6.31	Can allow for emergency action up to 30s by personnel with appropriate clothing.
4.73	Can allow for emergency action lasting 2min to 3min by personnel with appropriate clothing.
1.58	Personnel with appropriate clothing can be continuously exposed.

Based on the definition provided in API 521, the 5kW/m^2 criteria proposed in EN 1473 correspond to the allowable radiation for personnel up to three minutes of exposure. Such duration should be more than sufficient for any personnel working inside the process area to correctly assess the situation and escape to safety without suffering injury. With suitable training, increased awareness of the potential hazard (e.g. ignited PSV vents) and regular emergency drills, the reaction time required for safe escape can be shortened and a higher radiation level between 6.31kW/m^2 to 9.46kW/m^2 may be allowed.

Since 9kW/m^2 is also listed in EN 1473 as the criteria for the peak radiation inside sterile area of a flare/ vent, this paper proposes to take 9kW/m^2 as the maximum allowable thermal radiation at ground level or other manned areas such as working platforms as an alternative to the more stringent criteria of 5kW/m^2. However, before applying 9kW/m^2 to any project, proper justification should be provided to demonstrate that personnel exposed to such high radiation can still escape to safety without suffering injury. It is to be noted that 9kW/m^2 is very close to the threshold for 1% fatality based on the Purple Book thermal radiation probit after 20 seconds exposure [6].

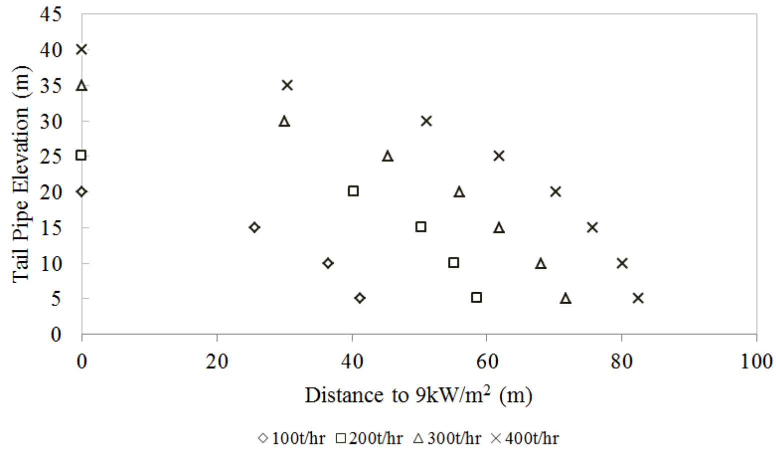
For areas where emergency actions are required such as manual firefighting provisions, the original 5kW/m^2 criteria should still be applied. Based on the definition in API 521, this would allow for a maximum safe working time of two to three minutes, which should be sufficient for actuating the emergency system. The 5kW/m^2 criteria should also be applied to the control room and other manned buildings. Although the control room is usually protected against external fire and explosion events, thermal radiation exceeding 5kW/m^2 would still prevent safe evacuation from the building, if it impinges on the means of egress. For buildings with windows facing the process area, exceeding 5kW/m^2 may also result in injury to people in the vicinity of the windows.

As for surrounding equipment and the LNG tanks, no significant damage is expected for radiation levels around 5kW/m^2. At higher radiation levels, less protected instrumentation (including cables and field instruments), piping insulation, etc. may be damaged, which would result in asset damage and a plant shutdown for a significant period to carry out repairs. Further increase in radiation may start to cause damage to equipment such as pumps and vessels. In the worst case, this may cause an increase of the vessel internal pressure and/or loss of material strength potentially leading to a loss of containment. For a full containment type LNG tank, the outer shell is a pre-stressed concrete tank which can withstand much higher thermal radiation levels than normal steel equipment. Based on EN 1473 Table A.1, 15kW/m^2 and 32kW/m^2 can be considered as limit for equipment and LNG tank, respectively.

Thermal Radiation Analysis for a Single Ignited PSV Vent based on Alternate Thermal Radiation Criteria

As shown in Figure 4, the vent elevation required to limit thermal radiation to 9kW/m^2 at ground level for a 200t/hr PSV vent is about 25m, which is much lower than the 45m requirement obtained based on the 5kW/m^2 criteria. Considering the elevation of the PSV, which is typically about 10m, designing a 15m vent is not impractical. However, if there is an operator platform in the vicinity, the same 9kW/m^2 criteria should be applied and the vent height would need to be further increased.

Figure 4 – Elevation of Single PSV Vent and 9kW/m^2 Distance on Ground Level



For the 15kW/m^2 radiation level, which is the criterion for surrounding equipment, the contour extends to a maximum downwind distance of about 55m but does not impact any area below 5m elevation (refer to Figure 2). This may impact adjacent vaporizers, recondenser and the associated piping. One mitigation measure would be to increase the separation distance between the vent and these equipment, but this is impractical at least for the adjacent vaporizers. On the other hand, the elevation of the vent can be placed 15m above the highest equipment within a 55m radius. In order to avoid the vent pipe being too high, which may require an expensive design of the support structure, the vaporizer PSV vent can be installed on top of the pipe rack or the highest structure rather than close to the vaporizer itself. This design would be able to limit the height of the vent to 15m above the highest structure. As for 32kW/m^2, which is the criteria for the LNG tank, the maximum downwind distance is about 40m. This should not pose any significant issue since this separation distance should be easily achievable.

However, even after limiting the application of the 5kW/m^2 criteria to only safety critical elements that require manual intervention (such as fire monitors, other firefighting equipment and manual call points), meeting such criteria could still prove to be a challenge. Typical firefighting equipment will be about 20m from the vaporizer, hence the PSV vent located on top of the vaporizer would require minimum elevation of 45m (refer to Figure 3). Even if the separation distance can be increased to 40m by other means such as installing the vent on top of the pipe rack, this would still require the vent elevation to be 40m.

To summarize, with the alternate criteria, the elevation of the PSV vent for a 200t/hr vaporizer would likely be between 25m to 40m above ground. In the case of larger vaporizers, the various thermal radiation criteria would be even more difficult to meet. For example, a 300t/hr vaporizer would likely require the vent elevation to be around 35m to 55m. Another factor is the rated capacity of the PSV, which can sometimes be much higher than the calculated flow rate or the vaporizer capacity. Including safety margins and other design considerations, a PSV on a 300t/hr vaporizer may well be able to relieve close to 400t/hr. This would increase the requirement of PSV vent height beyond 60m.

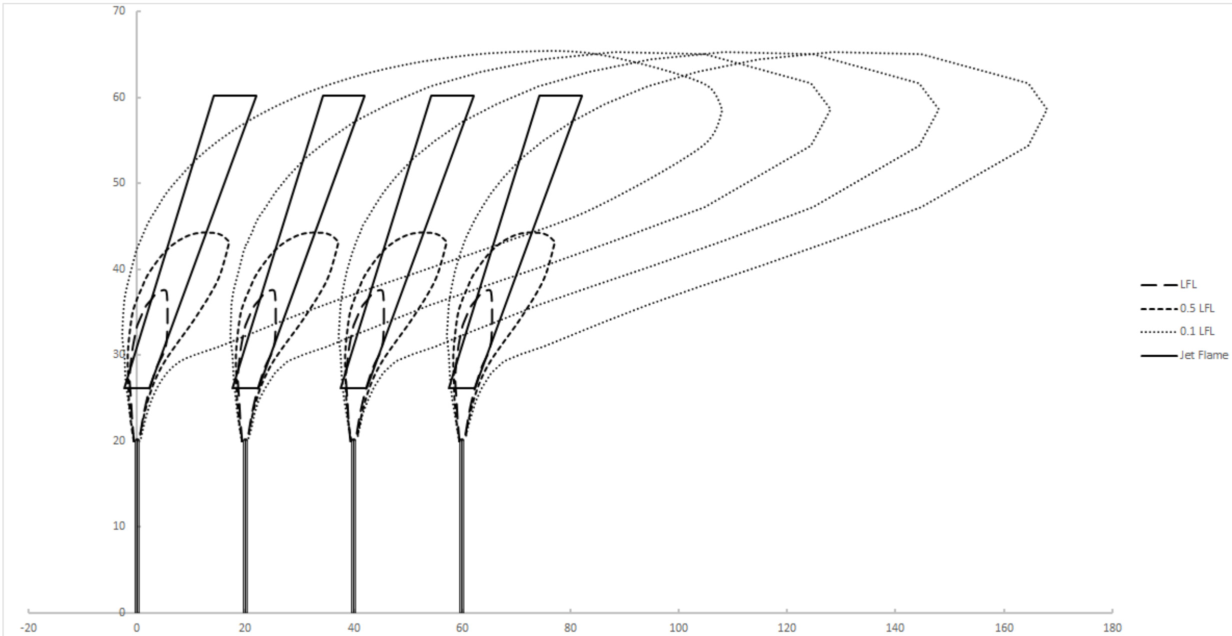
Ignition of Multiple PSV Vents

As mentioned earlier, under some circumstances such as blockage on the common header, all PSVs can relieve at the same time, hence the possibility of ignition of multiple vents also needs to be studied as the combined radiation effect would be more severe than ignition of a single vent.

Birch et al. (1989) [9] has shown that a gas jet in a cross wind could lead to flame flash back upon ignition in a region with flammable concentrations below the LFL. This is due to high turbulence producing local pockets of the combustible fuel-air mixture at the edge of the gas plume where the mean concentration is below the LFL. Furthermore, dispersion models often only calculate the mean values of concentration at a point. Concentration fluctuations as a result of turbulence, terrain, surface roughness, solar radiation and wind variation etc. are "averaged out" leading to uncertainties in ignition likelihood. API 521 [4] suggested the uncertainty in a lower threshold for flammability can be addressed by ensuring the concentration at potential sources of ignition, personnel location, or other vulnerable areas does not exceed 0.1 times to 0.5 times the LFL.

Figure 5 presents the side profile of the steady state flammable gas cloud that is formed by venting from four PSVs (200t/hr from each vent with 20m separation distance). The footprints are illustrated at LFL, 0.5 LFL and 0.1 LFL. A jet flame under the same release condition is also modeled and superimposed on the gas cloud to depict the shape of the jet flame in case a flashback occurs. It can be seen that the 0.1 LFL contour extends over a distance of more than 100m downwind, overlapping with the 0.1 LFL concentration produced from the release of other PSVs. Although the interaction between overlapping gas clouds is not modeled, it can be postulated that the 0.1 LFL contour would extend even further and the concentration within the overlapping volume would be higher than predicted from single release source. It can be concluded that in case one of the vents is ignited, it may result in ignition of all the surrounding vents; hence it is important to study the cumulative thermal radiation from multiple PSV vents.

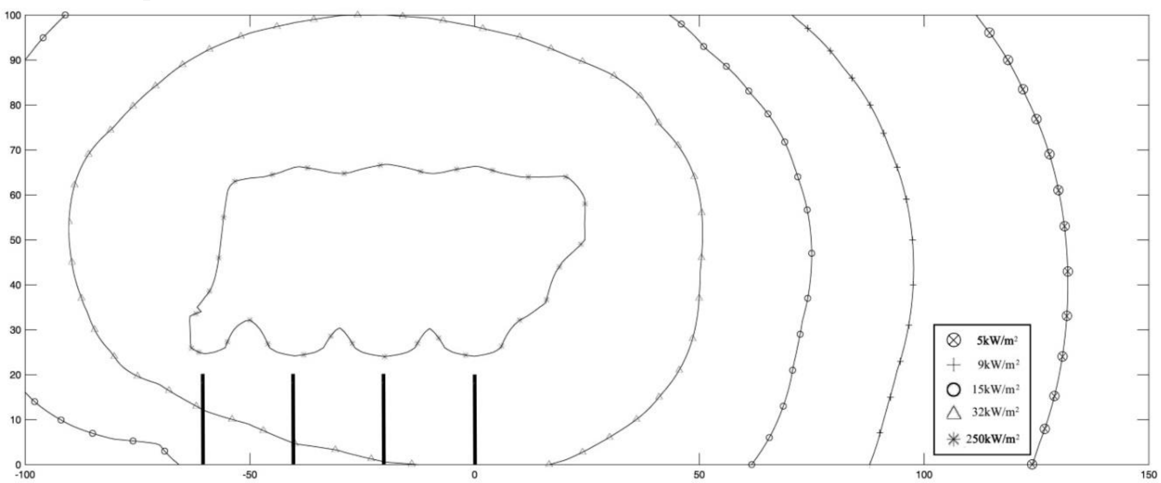
Figure 5 – Side View of Flame and Dispersion Envelope for Four 200t/hr Vents



Thermal Radiation Analysis for Multiple Ignited PSV Vents based on Alternate Thermal Radiation Criteria

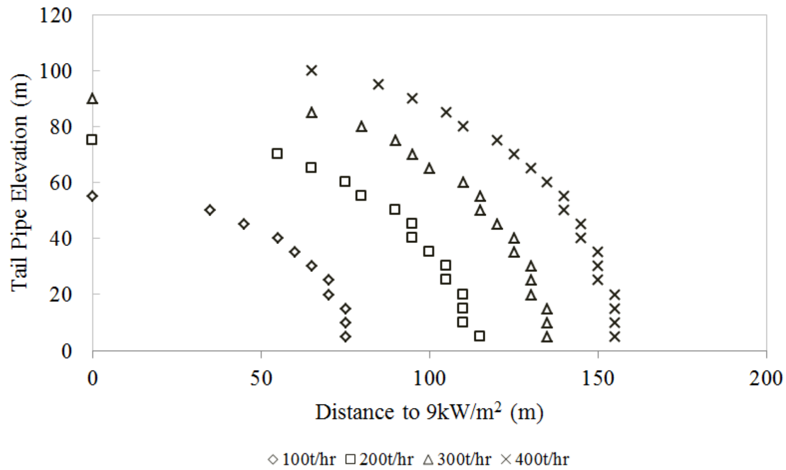
Considering 200t/hr vaporizer, a 5MMTPA terminal would require up to 4 vaporizers in parallel. The combined radiation contour for 4 PSVs assuming a separation distance of 20m is provided in Figure 6.

Figure 6 – Side View of Radiation Profile for Four PSV Vents of 200t/h each at 20m Elevation and 20m Apart



It can be observed that the region of very high radiation (i.e. greater than 100kW/m^2) remains above the vent elevation. The maximum downwind distance for 32kW/m^2, which is the criteria for the LNG tank, is about 50m which should not pose much of a constraint. However, the combination of 4 PSVs together is able to emit up to 38kW/m^2 of radiation at ground level. This level of radiation corresponds to 100% lethality level for a human after just 20 seconds of exposure. To meet the alternate criteria of 9kW/m^2, as per Figure 7, would require the height of the vent be raised to 75m.

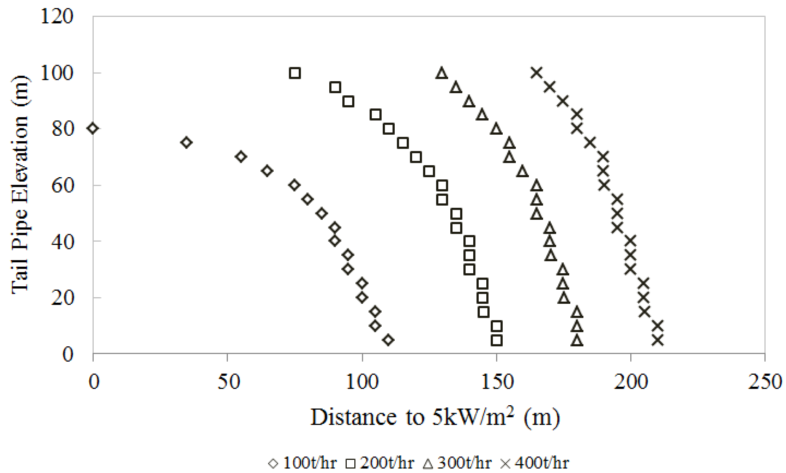
Figure 7 – Elevation of Four Parallel PSV Vents and 9kW/m^2 Distance on Ground Level



Apart from the safety concern, the potential damage to other surrounding equipment may also be significant. The adjacent vaporizers are most likely to be within 20m which means it would be exposed to radiation of 32kW/m^2 or above. This will cause damage to the external surface of the equipment, field instruments and piping. For the radiation level to below the recommended threshold of 15kW/m^2, the height of the vent would have to be more than 50m above any equipment.

As shown in Figure 8, even if the vents are located at an elevation of 100m, it is not possible to reduce the radiation at the ground level to below 5kW/m^2 for a vaporizer that is larger than 200t/hr. At this point it is obvious that adopting an atmospheric vent as the disposal method for the vaporizer PSV does not allow any of the radiation criteria to be met, for the case of multiple PSV vent ignition.

Figure 8 – Elevation of Four Parallel PSV Vents and 5kW/m^2 Distance on Ground Level

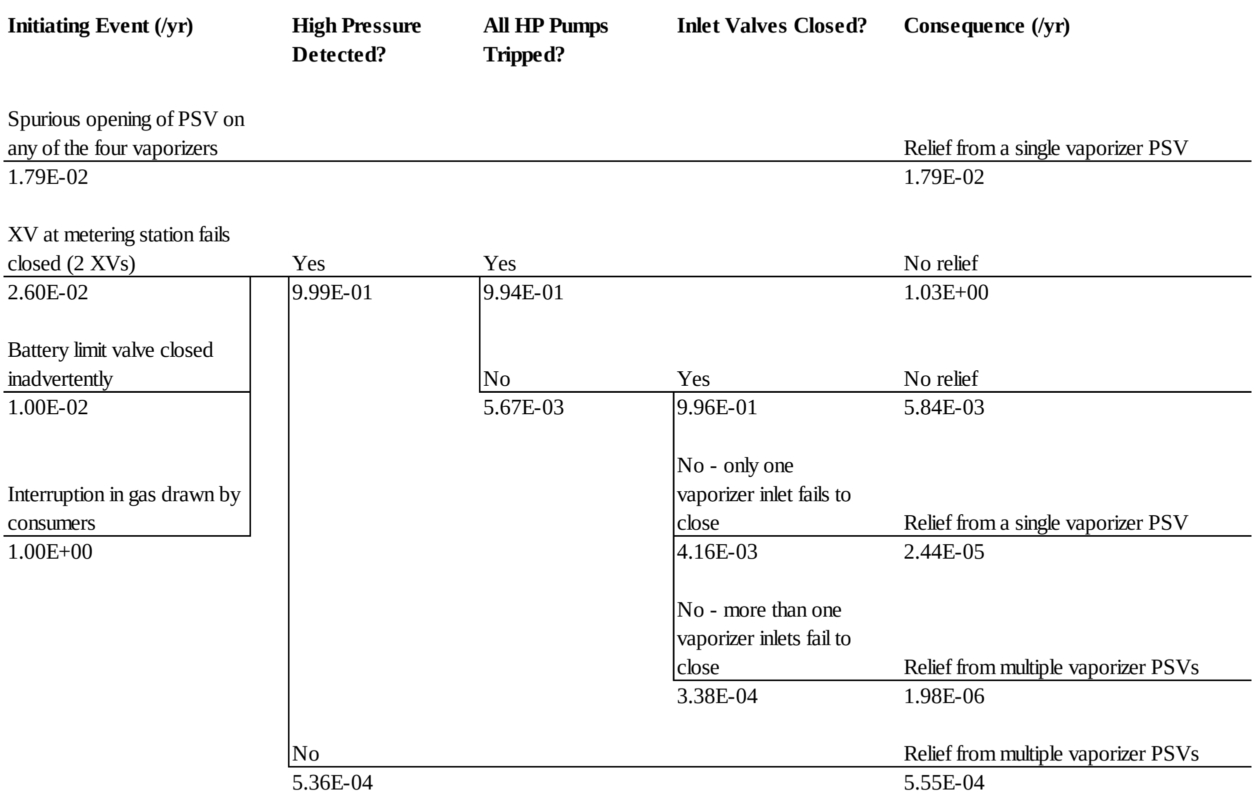


Frequency Analysis of Ignited PSV Vents

A sample frequency analysis based on a typical LNG terminal design is presented here for single as well as multiple ignited PSV vents. All the data provided in this section is for illustration only.

Figure 9 shows the possible sequence of events that could lead to a fire at a single PSV vent or at multiple PSV vents. A number of potential initiating events have been considered, as discussed earlier in the paper, that would result in the opening of PSVs. The initiating event frequencies are estimated based on data given in the Safety Equipment Reliability Handbook [10] and OREDA [11]. The overall reliability of the PAHH trip was assumed to be meeting SIL 3 (with RRF of 1,600). The expected frequency of any significant interruption in the consumption of gas due to an upset at the downstream user end can range from once in 10 years to once per year depending on the configuration such as number of consumers, the ratio of consumption by the different users, pipeline inventory etc.

Figure 9 Frequency Estimation of Release from Single/ Multiple PSV Vent(s)



Based on the analysis, the total probability of relief from a single PSV vent is 1.79×10^{-2}/yr while relief from multiple PSVs is estimated as 5.57×10^{-4}/yr. Following the initial release, the flammable cloud can be ignited by various mechanisms. Based on the hydrocarbon vapor release in a large plant model published by UKOOA IP Research Report [12], releases in the range of 200t/hr to 800t/hr would result in an ignition probability between 0.4 and 0.6. This value might be conservative for release from PSV vents since the associated flammable cloud is not expected to reach any ignition source. Therefore a reduction factor of 0.1 or lower might be applied; however, the minimum ignition probability should not be less than 0.001 [12].

The likely ignition sources for release from vents are lightning strikes or static electricity. The frequency of a lightning strike is estimated based on the method provided in BS EN 62305-2:2006 [13]. Based on a typical LNG terminal footprint and a lightning ground flash density of 15 strikes per km^2 per year (a typical value for tropical coastal regions [14]), the ignition probability due to a lightning strike on the PSV vent is about 3.3×10^{-3}. Considering all potential ignition sources, the best estimate of ignition probability for any PSV relief scenario is expected to be in the range of 0.005 to 0.05. Combining with the relief frequency, the frequency of fire from a single PSV vent would therefore be in the range of 9×10^{-4}/yr to 9×10^{-5}/yr. The frequency of fire from multiple PSV vents would be slightly lower and in the range of 3×10^{-5}/yr to 3×10^{-6}/yr.

In case any or all of the thermal radiation criteria discussed in this paper are not applied to the plant design, the facility owners have to review whether the risk associated with a PSV vent fire is tolerable from the perspective of both personnel safety and supply reliability. Based on the example presented in this paper, the risk of production loss leading to gas supply interruption for several days due to damage caused by single / multiple PSV vent fire will also in the order of 1×10^{-3}/yr. For multiple PSV vent fire scenario, the radiation on the ground level can exceed $38kW/m^2$. The risk of causing a fatality can be assumed to be same as the associated fire frequency which is about 3×10^{-5}/yr. Although the fire is expected to be of short duration, about 10 to 15 minutes, assuming manual intervention to shut off power to all LNG pumps, damage and potential fatality is likely.

Mitigation Options

One option is to provide a reliable suppression/ snuffing system for all atmospheric vents since the primary concern is thermal radiation effect following ignition. The effectiveness of this measure needs to be investigated further.

The second option is to provide a High Integrity Pressure Protection System (HIPPS) to shut off LNG inlet flow to vaporizer through dual shutdown valves at each vaporizer inlet. This will minimize the probability of overpressure in multiple vaporizers during common blocked outlet condition and the risk of simultaneous discharge from multiple PSVs. This may allow the design to only consider radiation effect from single PSV relief, which is mainly due to premature lifting. To mitigate the impact due to single ignited PSV, the vent has to be elevated to minimum 15m above the top of any equipment/piping and 40m from ground level if the impact on manual firefighting provisions is also considered

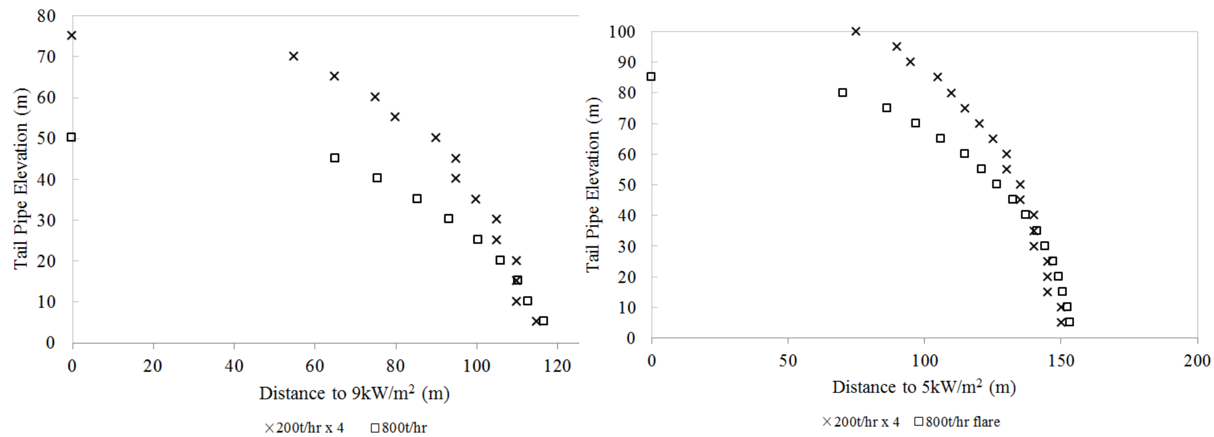
Alternately, all the hazards associated with ignited PSV vents can be mitigated by routing the discharges to a dedicated High Pressure (HP) flare or a HP vent stack. With the provision of a HP flare system, any entrained LNG from a PSV release will also be separated safely in the knockout drum.

A cost-benefit analysis may be carried out to determine the most cost-effective safeguard.

HP Flare or Vent Stack Option

The HP flare or vent stack option provides the flexibility to be located in an area far away from the process area and buildings, thus providing adequate separation distance to any sensitive receptor. Based on Figure 10, terminal of 5MMTPA capacity with a 800t/hr flare would only require to be 50m in order to limit the ground level radiation to no more than 9kW/m^2, which is much lower than the 75m required for four separate 200t/hr vents. In addition, with a sterile zone of 90m, the flare elevation of about 70m would be sufficient to meet the 5kW/m^2 criteria. For higher terminal throughput, the flare design option needs to be further examined.

Figure 10 – Distance to 9kW/m2 and 5kW/m2 on Ground Level for Flare vs Four Individual Vents



Conclusion

This paper has reviewed the fire hazards due to ignited PSV vents on single/ multiple vaporizers. Based on the review of various industry standards, this paper has proposed a set of practical thermal radiation criteria to be adopted for any ignited vents in LNG terminals, which are 5kW/m^2 for location of manual emergency access (such as firefighting provisions), 9kW/m^2 for personnel exposure, 15kW/m^2 for process equipment, piping and instruments/cables and 32kW/m^2 for concrete LNG tank. Applying the above criteria to the case of single ignited PSV vent, it is found that the vent has to be elevated to minimum 15m above the top of any equipment/piping and 40m from ground level if the impact on manual firefighting provisions is also considered, for a 200t/hr vaporizer. For the case of ignition of multiple PSV vents, the radiation at ground level could exceed 38kW/m^2 which could cause severe injuries or fatality and significant damage to equipment. To avoid these impacts, each PSV vent will need to be elevated to more than 50m above surrounding equipment and more than 100m from ground, which is considered as impractical. Any fire damage could result in the unavailability of gas supply for several days or weeks which could have a significant impact on both industrial consumers and domestic gas consumers.

A sample frequency analysis was performed to estimate the probability of ignited vent scenario. The risk associated with ignition of multiple vents is in the order of 3 x 10^{-5}/yr, which also corresponds to the risk of a single fatality. Facility owners and designers may carry out a cost-benefit analysis to determine the requirement for mitigation measures. These may include a dedicated HP flare or vent stack to handle all vaporizer PSV discharges or a High Integrity Pressure Protection System (HIPPS) to trip the LNG flow to the vaporizer in order to minimize PSV lifting frequency or a reliable fire suppression system to minimize the fire hazards.

The risk of production loss leading to gas supply interruption for several days due to damage caused by single PSV vent fire will be in the order of 1 x 10^{-3}/yr. This is dominated by the premature lifting of PSV which can only be mitigated by elevating the vent to the required height mentioned above for single PSV case or by routing to HP flare.

Acknowledgement

The authors wish to acknowledge the support received from IRESC including some of the information included in this paper, as well as contributions from Jason Fung and Arjan Abeynaike.

Reference

[1] CH.IV International, *Safety History of International LNG Operations*, TD-02109, Rev. 13, March 2014
[2] European Standard, *Installation and equipment for liquefied natural gas – Design of onshore installations*, EN 1473:2016, May 2016
[3] National Fire Protection Association (NFPA), *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*, NFPA 59A, 2013 Edition
[4] American Petroleum Institute (API), *Pressure-relieving and Depressuring Systems*, API 521, 6th Edition January 2014
[5] DNV GL, PHAST Version 6.7
[6] RIVM, *Reference Manual Bevi Risk Assessments*, Version 3.2, 2009
[7] Woodward, John L., *Estimating the flammable mass of a vapor cloud*, CCPS, 1998
[8] Mannan, Sam, Lees' *Loss Prevention in the Process Industries Hazard Identification, Assessment and Control. s.l. : Butterworth-Heinemann, 2012. Vol. 1*, ISBN 978-0-12-397210-1
[9] Birch, A.D., Brown, D.R., Fairweather, M., and Hargrave, G.K, *An experimental study of a turbulent natural gas jet in a cross-flow*, Combust. Sci. and Tech., 1989
[10] Exida, *Safety Equipment Reliability Handbook*, 3rd Edition, 2007
[11] SINTEF, *Offshore Reliability Data (OREDA), Volume 1 – Topside Equipment*, 6th Edition, 2015
[12] Energy Institute, London, IP Research Report – Ignition Probability Review, Model Development and Look-up Correlations, January 2006
[13] European Standard, *Protection against lightning – Part 2: Risk management*, EN 62305-2:2012, May 2012
[14] Hong Kong Observatory, *Lightning density map for Hong Kong*, http://www.hko.gov.hk/wxinfo/llis/llis_map.htm, September 2016