Novel application of the bow tie technique for the analysis of the NFPA 59A standard

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The U.K. Health and Safety Executive (HSE) has worked with the U.S. Pipeline and Hazardous Materials Safety Administration (U.S. Department of Transportation) in a review of historical vapour cloud explosions (VCEs); this review was based on "very large" VCE events, which generally occur in very low wind conditions. Although there are no historical records of such severe VCEs involving LNG, there is concern about the potential for escalation to LNG equipment in LNG export terminals, which tend to use flammable products in their refrigerant systems.

The Code of Federal Regulations (CFR) 49, Part 193 [49 CFR 193], prescribes safety standards for LNG facilities in the U.S. One of the key standards that is referenced in the regulations is the National Fire Protection Association (NFPA) NFPA 59A Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG); provisions in this standard take into account the refrigerant system within its scope.

This paper describes the process followed by HSE's Health and Safety Laboratory (HSL) to examine the extent of the safeguards prescribed by NFPA 59A in LNG export terminals and also the conclusions obtained from the study. The revision of the key controls required by the standard was based on a novel design and application of a bow tie analysis, having a particular focus on the safeguards that apply to the LNG system and those that apply to the refrigerant system.

KEYWORDS: bow tie, NFPA 59A, VCE, LNG, refrigerant

Introduction

The U.S. has experienced a natural gas production growth every year within the last decade. One of the consequences of this growth is an increase in the export of natural gas, which can be conducted via pipeline or via LNG tankers [EIA, 2016]. This export increase has led to the construction of several LNG export terminals; ten terminals have been approved to be commissioned, six of which are already under construction [FERC, 2016 (A)]. There are another 16 LNG export terminals that have been proposed, but these have not been approved yet [FERC, 2016 (B)]. The Federal Energy Regulatory Commission (FERC) is responsible for authorising the siting and construction of LNG import and export terminals. Although LNG export has increased in the recent years, the U.S. is currently a net importer of natural gas. In fact, two LNG import terminals have also been approved by FERC and one of them is currently under construction [FERC, 2016 (C)].

The Code of Federal Regulations (CFR) Title 49, Part 193 (49 CFR 193) prescribes safety standards for LNG facilities. The regulations are divided into ten sections covering different areas: siting requirements, design, construction, equipment, operations, maintenance, personnel qualifications and training, fire protection and security [49 CFR 193]. Some of the requirements in the regulations make reference to a wide group of safety standards from different organisations, such as the American Gas Association and the Gas Technology Institute; the majority of external references are on the National Fire Protection Association (NFPA) standard NFPA 59A, which covers production, storage and handling of LNG. Aspects considered in NFPA 59A include siting and layout, process considerations, transfer systems, fire protection and maintenance operations [NFPA, 2016]. In addition, the 2013 version of the standard introduced risk assessment considerations, which are not mandatory for operators because these are not covered by 49 CFR 193. However, NFPA 59A suggests that new facilities or existing facilities due to undergo significant changes apply the risk assessment provisions in the standard. 49 CFR 193 states that, whenever there is a conflict between the regulations and any standard that has been referenced in the regulations, the indications in the regulations prevail.

The predicted increase of LNG export terminals in the U.S. has raised concern of the possibility of vapour cloud explosions (VCEs) occurring in this type of installation, due to the presence of flammable materials in the refrigerant system. Refrigerants that are commonly used in LNG export terminals include chlorofluorocarbons, ammonium, carbon dioxide and non-halogenated hydrocarbons. Some refrigeration units use mixed refrigerants, which can contain flammable materials such as methane, ethane, ethylene, propane and iso-pentane [Kytomaa, 2013].

To improve understanding of vapour cloud development and explosion in order to examine the potential for these hazards to exist or develop at LNG export terminals that store substantial quantities of these flammable gases for use in the liquefaction process or as a by-product from the liquefaction [Atkinson, 2016a], the U.K. Health and Safety Executive (HSE) and the Pipeline and Hazardous Materials Safety Administration (U.S. Department of Transportation) conducted an extensive review of past "very large" VCE incidents that have occurred worldwide [Atkinson, 2016b]. One of the main findings of the review was that a majority of incidents occurred in very low wind conditions, many of them due to relatively small but sustained leaks resulting in considerably big clouds in the area of the release after a few minutes.

In conjunction to this review of incidents, it was proposed to carry out a study to determine if LNG export terminals complying with 49 CFR 193 requirements have enough safety measures in place to prevent the occurrence of very large VCEs. HSE's Health and Safety Laboratory (HSL) had initial thoughts of conducting a review of the safety requirements prescribed in 49 CFR 193, but it was finally decided to carry out this exercise on NFPA 59A because the regulations do not take refrigerant systems into account. This paper covers an initial exercise to review NFPA 59A, but not the full set of standards that it references. The authors also acknowledge that, although specific safety requirements for the refrigerant system might not be considered in NFPA 59A, it is quite possible that the combination of NFPA 59A with the Flammable and Combustible Liquid Code (NFPA 30) would cover all relevant aspects in LNG export terminals. NFPA 30 is not referenced in the 49 CFR 193 and therefore it was not reviewed as part of this exercise.

Standards are generally written based on design requirements, which include safety features, but not necessarily in a systematic way. For the analysis of the safeguards prescribed in NFPA 59A, it was decided to explore the application of the bow tie technique; this is a tool commonly used in industry to identify the safety barriers in place against specific hazard scenarios and, if applicable, the need to implement additional barriers. The approach taken in this case implies the use of the bow tie method from a different perspective, which has particular interest on how risks coming from failures involving flammable materials are considered.

49 CFR 193 refers to previous versions of the NFPA 59A standard, in particular the versions issued in 2001 and 2006, but this study was intentionally focused on the most recent version of the standard, which was issued in 2016, because it is believed that more recent versions of a standard have a greater chance to be referenced in future editions of the regulations.

This paper is focused on the bow tie technique that was used and does not go into detail on the safeguards prescribed by NFPA 59A.

Using the bow tie method to review the adequacy of a standard, or some parts of it, is a novel application of this technique, which allows an easy understanding of the standard's strengths and weaknesses from a barrier-based perspective and, consequently, a quick identification of any areas that may need additional effort for future editions of the standard.

Bow tie methodology

The bow tie analysis is typically a qualitative technique that results in an easy way to understand how a particular hazard scenario could be influenced by the safeguards in place; for this reason, operators tend to use this method to find out if risks are adequately managed or if they should seek additional risk reduction measures.

A bow tie analysis can be described as a combination of a fault-tree analysis and an event-tree analysis [Mannan, 2012]; a fault-tree analysis is used to determine the causes of an event whereas an event-tree is focused on the possible consequences for the same event. In a bow tie diagram, the fault-tree and the event-tree elements are connected by the hazardous event of interest (top event of the fault tree), which is placed at the centre of the illustration. Fault-tree elements are placed on the left-hand side and event-tree elements on the right-hand side; by doing this, credible scenario sequences can be read from left to right.

Initiating events (threats) can lead to the occurrence of a top event; prevention barriers are any safeguards that could be used to break a link between a threat and a top event. In a bow tie, prevention barriers can intersect with the lines connecting the initiating events with the scenarios.

Outcomes (consequences) of top events can be reduced by the implementation of mitigation barriers that would break a sequence between a top event and an outcome. In a bow tie, mitigation barriers can intersect with the lines connecting the top event with the consequence.

A hazard or risk scenario is a path through the bow tie diagram from a particular initiating event, through the top event, to a particular consequence or outcome.

There are safety barriers that can influence safety for one or more items of equipment (specific barriers) and others that can affect the whole facility (general barriers). Moreover, there are safeguards that could be both prevention and mitigation barriers.

Figure 1 presents a simplified picture of the bow tie model, where "Major Hazards" correspond to the initiating events and "Loss of Control" is an example of a hazardous/top event. "Loss of containment" is the most typical top event. This figure was extracted from HSE's Hazardous Installations Directorate (HID) Regulatory Model: Safety Management in Major Hazard Industries [HSE, 2013].

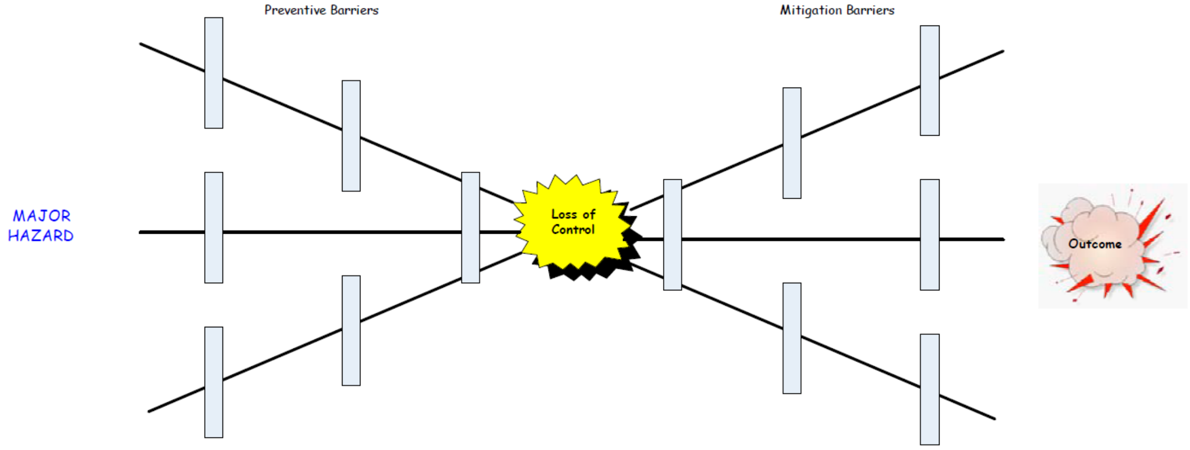

Figure 1. Bow tie diagram (from HSE's HID Regulatory Model [HSE, 2013])

The main reason why a bow tie analysis is a very useful tool is that placing the existing safeguards at both sides of the diagram allows a visual identification of any gaps along paths, and therefore the need for further risk reduction measures to reduce or eliminate these gaps. The bow tie shows whether a particular hazard is prevented or mitigated by only a single barrier or by multiple barriers, i.e. it can be used to check for defence in depth. More significantly, the presence of any gaps along paths can also be rapidly detected leading to the implementation of appropriate safety measures. The bow-tie also allows easy identification of particularly significant barriers, e.g. the possibility of a single barrier failure leading to various major accident hazards. Because of their graphical format, bow tie diagrams are very good tools for communication of the hazards, potential consequences and how this is managed [Forbes, 2014].

Review of the NFPA 59A standard

The review of NFPA 59A was carried out at a high level and started with the identification of equipment items or process blocks in generic LNG export terminals, which were considered as initiating events. Generic process blocks that were identified comprised storage, pipelines, pumps, refrigeration units, vaporizers and transport.

Secondly, credible scenarios for LNG export terminals were analysed. Conducting a high level study, all scenarios were grouped, ending up with two main types of event: catastrophic loss of containment (events leading to sudden loss of containment of the whole inventory) and continuous loss of containment. As there were two main scenarios to consider, it was decided to incorporate the two scenarios in the same diagram. The double-node bow tie design used in this case allows the user to explore the LNG export terminal as a whole by looking at a single figure.

The next step was focused on the identification of consequences of each top event; outcomes identified were VCE, flash fire, fireball, pool fire, jet fire and unignited/asphyxiation.

Having identified generic initiators in LNG export terminals, the two main top events and the possible outcomes, an initial bow tie diagram was drafted, with no accounting for safeguards at this stage. To develop the diagram, all possible links were studied and those that were considered to be credible were drawn. Figure 2 shows the bow tie diagram that was initially drafted, where links to a catastrophic loss of containment are represented by orange lines whereas links to a continuous loss of containment are represented by purple lines. Figure 2 also illustrates a possible way to introduce safety barriers in the diagram: dark red colour bars represent general barriers and light red colour bars represent specific barriers.

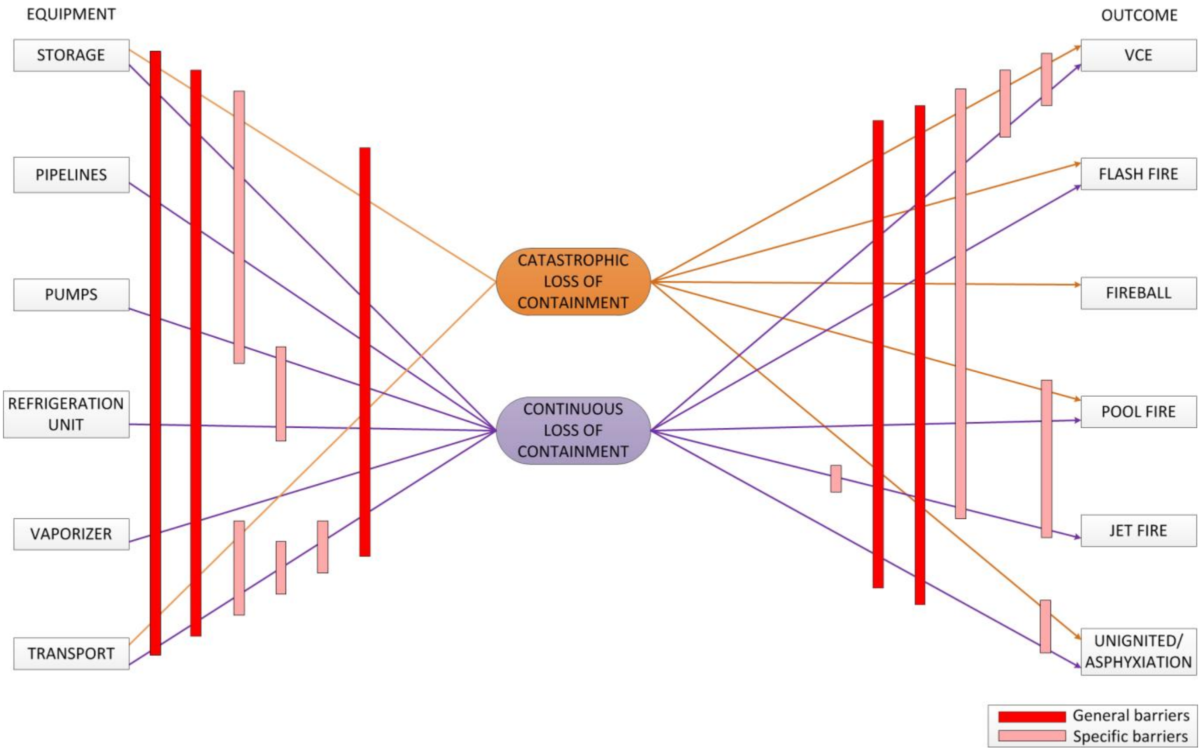

Figure 2. General overview of a double-node bow tie diagram

On the left-hand side of the diagram, it was observed that only equipment items involved in storage and transport can lead to catastrophic loss of containment events, whereas continuous loss of containment events could be caused by a failure of any equipment item. Referring to the outcomes from top events, jet fires cannot be derived from a catastrophic failure and fireballs cannot be derived from a continuous failure.

The following stages of the bow tie analysis aimed to identify all the requirements (barriers) cited in NFPA 59A and to allocate them in the bow tie diagram. It was then necessary to go through each barrier and to define its purpose: for prevention barriers, this means determining what equipment items the barrier could be installed in and what top events it would help prevent; for mitigation barriers, it means what outcomes a barrier would help in reducing the likelihood and/or severity.

Due to the substantial number of barriers described in NFPA 59A, it was decided to break down the standard using a supporting matrix. In this matrix, all safeguards were referenced by numbers together with an indication of the corresponding section reference in the NFPA 59A code and a brief description of what the code states. Other columns of the matrix were used to indicate what equipment items and what outcomes the barriers could have any impact on. An additional column was included in the matrix to indicate if barriers are generic (G) or specific (S).

Figure 3 presents an extract of the supporting matrix produced, where green boxes represent prevention barriers and yellow boxes represent mitigation barriers (barriers that were both preventive and mitigating were also identified and represented by a different colour, although none of them are shown in the extract shown in Figure 3).

			EQUIPMENT										OUTCOME						
Reference	NFPA59A BARRIERS	General (G) Specific (S)	1. Refrigerant storage	2. Refrigerant delivery	3. Natural gas pipeline	4. Refrigeration Unit	5. LNG Storage Double (D) Full (F) Membrane (M)	6. LNG line and transfers	7. LNG pumps	8. Transfer to/from ship	9. LNG storage on ship	10. Re-gasifier	A. VCE (Congested)	B. Severe VCE (Non-congested)	C. Flash fire	D. Fireball	E. Pool fire	F. Jet fire	G. Unignited/ Asphyxiation
CHAPTER 4 - GENERAL REQUIREMENTS																			
1	NFPA59A 4.2 Corrosion control overview *Repair, replacement, or significant alteration of components due to a change in the original materials, a corrosion failure or significant deterioration due to corrosion*	G																	
2	NFPA59A 4.6 Noncombustible material	S																	
	NFPA59A 4.7 Ignition source control																		
3	NFPA59A 4.7.1 Smoking permitted in designated areas	G																	
4	NFPA59A 4.7.2 Welding, cutting and hot work according to NFPA 51B *NFPA 51B: Standard for fire prevention during welding, cutting, and other hot work*	G																	
5	NFPA59A 4.7.3 Portable electric tools and extension lights in free of flammable fluid areas	G																	
6	NFPA59A 4.7.4 Vehicles and other potential ignition sources shall be prohibited within diked areas or within 50ft of LNG containers or other flammable fluids	G																	

Figure 3. Extract of the supporting matrix produced to generate the bow tie diagram

According to Figure 3, reference number 1 corresponds to NFPA 59A code section 4.2 that refers to the requirement of having a set of corrosion control measures in place. As this requirement applies to all equipment items in a LNG export terminal and it would help preventing the occurrence of a catastrophic or a continuous loss of containment, this requirement would be considered as a generic prevention barrier. Measures referring to the control of ignition sources fall under section 4.7; all these measures have been identified as mitigation barriers because they cannot prevent a loss of containment event, but they certainly can reduce the likelihood of the possible outcomes.

With the information collated in the supporting matrix, the final bow tie diagram was produced. Firstly, all relevant items and event sequences (scenario lines) were drawn. Then, each prevention barrier was represented on the left-hand side of the top event by a line that vertically crosses the diagram (barrier line) and each mitigation barrier was represented the same way on the right-hand side. For each barrier, the corresponding reference in the supporting matrix was added at the top and at the bottom of the vertical line. Finally, scenarios affected by a safety barrier were indicated by a thicker vertical line at the intersection between the barrier line and the scenario line.

Figure 4 shows a simplified incomplete version of the bow tie diagram that was developed for one scenario, catastrophic loss of containment (LOC). Equipment items shown on this simplified diagram are grouped under three main plant areas: refrigerant, LNG and ship. To generate the illustration presented in Figure 4, a representative set of safety measures was addressed; generic barriers are represented in grey whereas specific barriers are represented in black. Dotted lines are added at the bottom of the diagram as an indication that this is not a complete version of the bow tie analysis results.

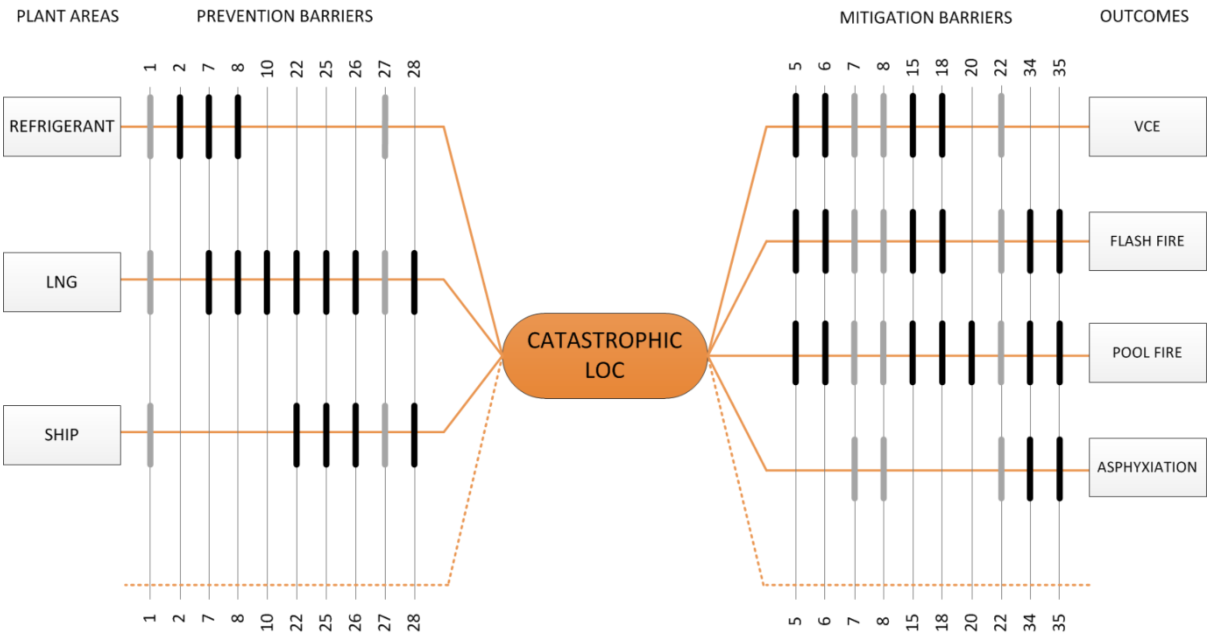

Figure 4. Simplified version of the bow tie diagram for a catastrophic loss of containment scenario

Taking the matrix extract in Figure 3 as a reference, barrier number 1 corresponds to corrosion control measures, which is a generic prevention barrier. Consequently, this safeguard is identified in Figure 4 on the left-hand side of the diagram by grey coloured barriers that are applicable to the three plant areas that were considered.

Some barriers that are both prevention and mitigation measures are identified in Figure 4, i.e. barriers 7, 8 and 22; these safeguards are allocated at both sides of the bow tie. An example of such types of measures could be any kind of emergency shutdown device.

Despite the fact that Figure 4 shows only an extract of the bow tie produced, this extract is representative of the conclusion drawn from the full bow tie diagram: NFPA 59 A requires plant areas involving LNG to have more safeguards in place than other plant areas involving refrigerant products. However, as stated in the introduction, the analysis did not include the requirements of 49 CFR 193, NFPA 30 (a specific standard for flammable materials with a broad scope) nor other standards referenced by NFPA 59A. Figure 4 also shows some gaps in the ship areas; however, this is due to the extract taken for the illustration. In actual fact, NFPA 59A includes all requirements for any type of transfer system in chapter 11.

The analysis performed did show, as expected, that there were no specific barriers for the hazard of large-scale VCE initiated by loss of containment of refrigerant, as discussed by Atkinson [2016b]. However, a number of generic barriers, particularly gas detection and isolation, have potential for mitigating many such hazard scenarios.

Conclusions

The forecasted increase of LNG export terminals in the U.S. has raised concern about the potential for very large VCEs occurring in this type of facility due to the use of flammable products in the refrigerant system.

A modified bow tie diagram approach has been developed and demonstrated to be a novel and useful technique for examining the coverage of safety standards for all types of hazard.

The bow tie technique was successfully used to review the requirements prescribed by the NFPA 59A standard, which is a generic standard that covers different sorts of installations having LNG on site.

The analysis only considered the requirements of NFPA 59A itself, and not the 49 CFR 193 regulation nor other standards that are referenced by them. A more complete review of the requirements of all relevant standards and regulations would add value.

The analysis did show, as expected, that there were no specific barriers for large-scale VCE hazards initiated by loss of containment of refrigerant. However, a number of generic barriers, particularly gas detection and isolation, have potential for mitigating many such hazard scenarios.

As well as identifying missing barriers, the technique can also prioritise the importance or criticality of particular barriers, for example if the barrier is the only one identified against a particular initiator, or to mitigate a particular top event. A barrier's importance can also be assessed from the number of different scenarios that it protects against.

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