
PROBABILISTIC FREQUENCY ESTIMATION OF BOILING LIQUID EXPANDING VAPOUR EXPLOSION IN A LIQUEFIED PETROLEUM GAS ADD-ON SKID SYSTEM USING INTEGRATED FAULT TREE AND EVENT TREE ANALYSIS

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

The catastrophic failure of LPG storage tanks is considered to be one of the most catastrophic hazards in the downstream segment of the gas sector but frequency calculations for LPG facilities in Africa are seldom carried out using formal reliability studies. In this paper, the frequency of occurrence of Liquid Expanding Vapour Explosion (BLEVE) accident of a small-scale 8.85 m³ LPG add-on skid unit has been determined using integrated Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) via Isograph Reliability Workbench v15.0 software package. A 12 basic event fault tree was developed for the top event of catastrophic rupture of the LPG bullet tank, utilizing mechanical, electrical and human errors based on failure statistics available from Offshore and onshore reliability data (OREDA), IEEE Std 493 and IEC 61511-1 standards in conjunction with AND and OR gate operations. Five simulation runs have resulted in the top event frequency of 0.7322 per year with main contributing factors being fire detector failure (FR=0.88/yr), gas detector failure (FR=0.41/yr) and pressure-safety-valve (PSV) failure (FR=0.017/yr). The event tree derived from the initiating event of a pressure-induced loading-line defect (frequency = 9.999×10^{-5} per year) had five different pathways to either a safe dispersion, a flash fire, a vapour cloud explosion, a jet fire, and a BLEVE, with the BLEVE pathway having a conditional frequency of 4×10^{-21} per year if all active barriers fail in sequence. It can be seen that it is not enough for any single element to fail to cause the top event, but rather degradation of several barriers at once is necessary.

Keywords: Fault tree analysis; Event tree analysis; BLEVE; LPG storage; Reliability data; Isograph Reliability Workbench

1. INTRODUCTION

Nigerian's LPG usage has increased to become one of the critical components of their domestic and industrial energy sources. LPG is stored in the form of a pressurised liquefied gas, and the failure of containment from a pressurised vessel results in a high hazard risk known as Boiling Liquid Expanding Vapor Explosion (BLEVE), being the worst-case scenario of accident in the downstream gas industry, causing a fireball, blast overpressure, and projectiles all at once (Zhou et al., 2022). Although the hazards associated with the physical consequence of a BLEVE have been extensively researched, there is no much information regarding the likelihood of such events happening at a particular facility.

The deficiency mentioned above is overcome with the help of quantitative risk assessment (QRA), which evaluates the frequency and consequences of hazardous events to determine numerical indicators of risk (Rausand & Haugen, 2020). As regards quantitative risk assessment, fault tree analysis (FTA) is the main approach used for frequency evaluation; it is based on the decomposition of the top event that occurs into the combinations of component and human failures that cause it (Vinnem & Røed, 2022). Where failure data are sparse or imprecise, fuzzy-set extensions of FTA have also been proposed to estimate fire and explosion frequencies in the process industry (Yazdi et al., 2020); the present study

instead adopts the conventional probabilistic FTA/ETA approach, drawing basic-event data directly from established reliability standards and handbooks.

In this study, Integrated Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), which were carried out using the Isograph Reliability Workbench (IRW) software version 15.0, will be applied to a typical LPG add-on skid system that uses an 8.85m³ bullet tank. The aim is to develop a probability for the top event of BLEVE based on standards, and the pathway to the barrier-dependent result from a pressure-induced loading-line defect.

2. MATERIALS AND METHODS

2.1 Study system and software

This analysis was conducted on a Metrix LPG add-on skid which has a horizontal bullet tank of diameter 1.6 m and length 4.4 m (volume 8.85 m³) as its main storage for LPG at 25 °C. The reliability analysis was conducted using Isograph Reliability Workbench version 15.0, with the use of the fault-tree and event-tree analysis modules. The top event chosen for the fault tree was the catastrophic failure of the bullet tank.

The skid's product-transfer boundary is a single loading line connecting the bullet tank to the offloading/filling point, protected by a manually operated shutoff valve and an emergency-shutdown (ESD) system with an associated alarm; tank overpressure is protected by a pressure-safety valve (PSV) fitted to the vessel. Leak and fire hazards along this boundary are monitored by fixed gas and fire detectors that initiate the ESD sequence on confirmed detection. These loading-line, valve, instrumentation and detection elements are the physical components represented by the twelve basic events in Table 1 (Section 2.2).

2.2 Fault tree construction and failure data

A twelve basic event fault tree was constructed based on existing structures in the process safety literature and was copied into the IRW interface. The basic events included mechanical, electrical and human error. Fixed probability models were allocated to human related events while rate models were assigned to component failures. For independent basic events connected using logic gates, the gate probability is calculated using the following Boolean formulae: AND gate requires all the n inputs occurring simultaneously (Eq. 1) while OR gate occurs if at least one of the inputs occurs (Eq. 2):

$$P_{AND} = \prod_{i=1}^n P_i \quad (1)$$

$$P_{OR} = 1 - \prod_{i=1}^n (1 - P_i) \quad (2)$$

where P_i is the probability of basic event i and n the number of gate inputs. Component failure rates were taken as the ratio of observed failures to accumulated service time (Eq. 3):

$$\lambda = \frac{N_f}{T} \quad (3)$$

Table 1 reports two distinct event-probability metrics, consistent with Isograph Reliability Workbench conventions: probability type events (Q) are dimensionless failure probabilities used directly in Eqs 1-2, while rate type events (FR, per year) are converted to an equivalent probability of failure over a fixed one year mission time before being combined, using $P = 1 - e^{(-\lambda t)}$ (or the linear approximation $P \approx \lambda t$ for $\lambda t \ll 1$, consistent with Eq. 3), with $t = 1$ year matching the annualised top event probability reported in Section 3.1. Holding this mission time constant across all twelve basic events places the probability and rate type inputs on a common time basis before evaluation of the AND/OR gate logic.

Failure rate data were drawn from OREDA (2015), IEEE Std 493 (2007) and IEC 61511-1 (2016), supplemented by peer reviewed reliability sources. Table 1 lists the twelve basic events, their rates, categories and sources. The safety instrumented system function is not modelled as a single discrete basic event in this fault tree; rather, its protective role is captured through the gas detector, fire detector and emergency shutdown/alarm response basic events (Table 1, S/N 3, 4 and 9), which represent the individual detection and shutdown elements that a SIS would otherwise supervise.

Table 1: Basic events, failure-rate data and sources used in the fault tree

S/N	Basic event	Category	Rate	Unit	Source
1	Spark (ignition source)	Human/Environmental	1.0×10^{-3}	probability (Q)	Isograph RWB fault-tree output (this study)
2	Flame (ignition source)	Human/Environmental	1.0×10^{-3}	probability (Q)	Isograph RWB fault-tree output (this study)
3	Gas-detector failure to respond	Electrical	4.1×10^{-1}	per yr (FR)	Isograph RWB fault-tree output (this study)
4	Fire-detector failure to respond	Electrical	8.8×10^{-1}	per yr (FR)	Isograph RWB fault-tree output (this study)
5	Operator failure (loading-line leak)	Human error	1.8×10^{-3}	probability (Q)	Isograph RWB fault-tree output (this study)
6	Line defect due to pressure	Mechanical	1.0×10^{-4}	per yr (FR)	Isograph RWB fault-tree output (this study)
7	Failure due to collision against line	Mechanical	1.8×10^{-3}	per yr (FR)	Isograph RWB fault-tree output (this study)
8	Loading line incorrectly connected	Human error	1.8×10^{-3}	probability (Q)	Isograph RWB fault-tree output (this study)
9	Incorrect alarm response (ESD)	Human error	1.8×10^{-3}	probability (Q)	Isograph RWB fault-tree output (this study)
10	Manual shutoff valve sticking	Mechanical	1.1×10^{-4}	per yr (FR)	Isograph RWB fault-tree output (this study)
11	Fire not extinguishing (suppression failure)	Mechanical	1.0×10^{-3}	probability (Q)	Isograph RWB fault-tree output (this study)
12	Pressure-safety-valve (PSV) failure to open	Mechanical	1.7×10^{-2}	per yr (FR)	Isograph RWB fault-tree output (this study)

2.3 Simulation procedure and event tree

Crosschecking the input values and re-running the simulation helped to debug the fault tree and get it simulated to convergence. The simulation was performed five times to ensure that consistent results have been obtained. The event tree analysis was next carried out using the IRW event tree analysis module, with a pressure induced loading line defect (frequency $w = 9.999 \times 10^{-5}$ per year) as the initiating event, and gas detection, open flame/ignition, fire detection, fire suppression and pressure relief (PSV) as the branch barriers. This initiating event corresponds to the "line defect due to pressure" basic event of the fault tree (Table 1, S/N 6; EV49 in Figure 1) rather than to the fault tree's combined 0.7322/yr top event probability: the event tree traces one specific leak initiating pathway through the barrier sequence, while the fault tree separately aggregates all twelve basic events into the overall BLEVE top event probability. The two analyses are therefore complementary rather than sequential, and the resulting pathway frequencies (including the 4×10^{-21} /yr BLEVE branch) should be read as barrier performance outcomes conditional on this specific initiating pathway, not as a further breakdown of the 0.7322/yr top event figure. The non-realistic pathways were removed. The frequency of an outcome pathway k , given initiating event frequency f and barrier branch probability sequence $\{m\}$, can be expressed using Eq. 4:

$$F_k = f \times \prod_{j=1}^m p_j \quad (4)$$

where p_j is the conditional branch probability at barrier j along the pathway.

3. RESULTS AND DISCUSSION

3.1 Fault tree: BLEVE top event probability

The fault tree analyzed twelve basic events at the bottom of the tree, logically connected with the BLEVE top event via OR and AND gates (see Figure 1). Using the probability values from Table 1 in conjunction with the logic gates of Equations 1 and 2, the probability of the top event for a year was found to be 0.7322, invariant throughout all five runs of the simulation. This was strongly influenced by the three most probable contributors, namely fire detector failure to respond (FR=0.88/yr), gas detector failure to respond (FR=0.41/yr), and pressure-safety valve failure to open (FR=0.017/yr). The AND gate logic of the upper levels implies that the simultaneous failure of several protection layers is

3.2 Event tree: outcome pathways

Five branches of outcomes were derived from the pressure induced loading line defect event, including safe dispersion, flash fire, vapour cloud explosion (VCE), jet fire and BLEVE (see Figure 3 below). The PSV failure branch probability was $Q=0.017$, consistent with the pressure safety valve failure rate reported in Table 1 (S/N 12). The application of Equation 4 to the various probability values for the barrier branch led to a conditional frequency of 4×10^{-21} per year for the fully-protected BLEVE branch, accounting for the highly unlikely probability of having the initiation event occur together with failure of all active barriers simultaneously. Safe dispersion was found to be the most likely outcome when all safety barriers operate as planned.

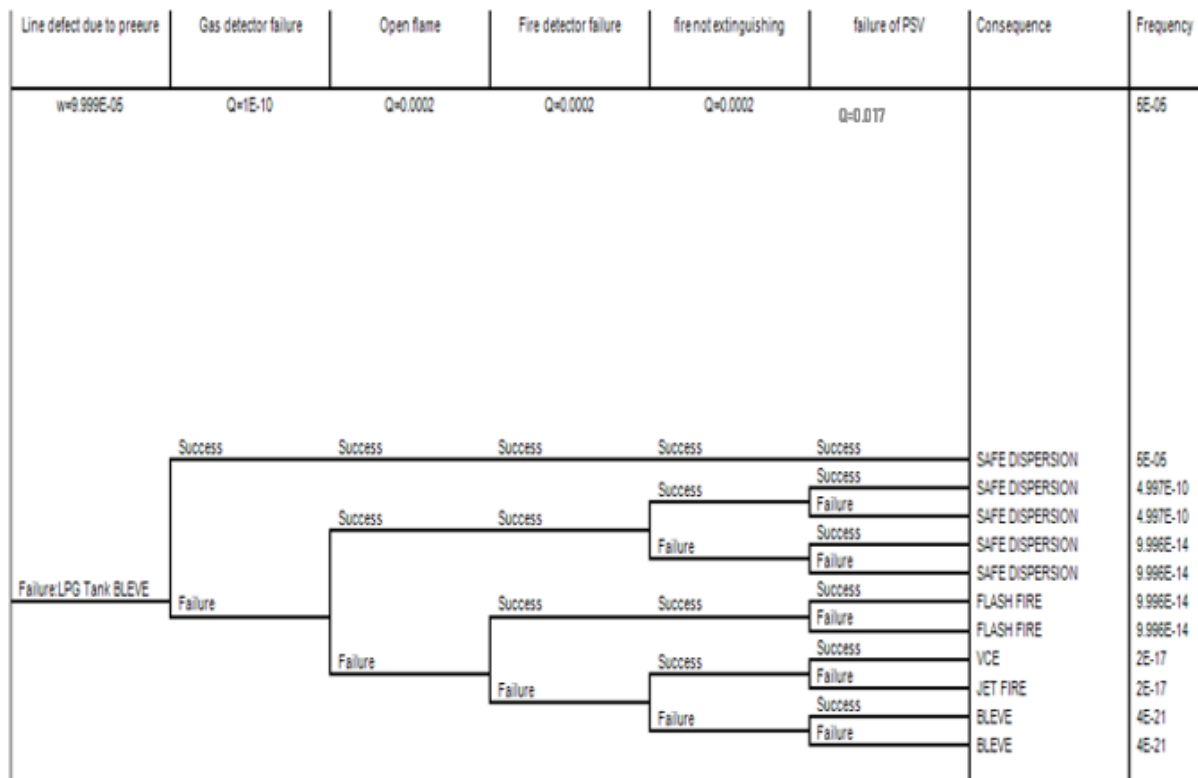


Figure 3: Event tree mapping the pressure-induced loading line defect initiating event to five outcome pathways.

Although the fault-tree top-event probability (0.7322/year, aggregated across all twelve basic events) and the event-tree's protected BLEVE branch frequency (4×10^{-21} /year, conditional on the single loading-line-defect initiating pathway) come from two separate analyses and are not directly derived from one another, the several orders of magnitude gap between them illustrates the benefit of safety barriers and highlights that keeping the barriers intact, rather than lowering the frequency of any single initiating event, is what controls the BLEVE hazard. This means that reliability centered maintenance focused on the three basic events with the highest frequencies will provide the largest reduction in the top event probability.

4. CONCLUSIONS

A joint study of fault tree and event tree analysis on an exemplary LPG add-on skid resulted in a BLEVE top event probability of 0.7322 per year, mainly due to fire detector, gas detector, and pressure safety valve failures. Five possible consequences of an event tree progression for a pressure induced loading line defect were found, out of which the fully protected BLEVE scenario has a probability of 4×10^{-21} per year, while the safest dispersion of gas in case of all barriers' functioning is the most probable consequence. A single failure does not suffice to trigger the top event, which makes barrier availability more significant than the initiating event frequency in managing LPG risks. The reliability data based on international standards presented in the paper and methodology can be applied to similar plants that lack failure rate data in their country, and it is proposed to concentrate maintenance efforts on the three leading basic events.

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