Original Article

Application of the Cause and Consequence Diagram to MLA Active Safety Barrier System

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Article history

Received 07/08/2023
Accepted (Panel 1) 05/12/2023
Accepted (Panel 2) 27/02/2024

ABSTRACT: *Safety barriers to Liquefied Natural Gas (LNG) systems can be physical and engineered systems or human actions based on specific procedures or administrative controls. Studies have not sufficiently examined the integration of safety barriers, risk, reliability, and performance on the total safety of the LNG Marine Loading Arm (MLA) terminal system. Therefore, this study attempts to assess the underlying effects of the MLA safety barrier failure. To this end, a cause and consequence analysis was performed by integrating the dynamic fault tree analysis with the cause-and-consequence model of the emergency shut-down system of the MLA. The MLA unit's safety barrier consists of the emergency shut down (ESD), powered emergency release coupling (PERC), cargo control room, and fire and gas detectors. The ESD has the highest failure rate of approximately 1.56x10–6 hours, while the PERC has the lowest failure rate of 1.7x10–13 hours. The safety barrier system was found to be highly reliable, with a reliability of approximately 99%. Six scenarios were assessed for the loss of containment event. The worst-case scenario was simulated to be fire or the formation of a vapour cloud. For the safety barrier system, the probability of a worst-case scenario was estimated at 3.2x10–7/year and is improved by 62.5% when a redundant system is in place. This work shows that the integration of risk assessment and consequence modelling can provide a quantitative estimate for a system with a failed barrier. It also provides some justifications for determining the set-up of the safety barrier system for a specific unit.*

Keywords: *Cause-Consequence Diagram, Dynamic Fault Tree Analysis, Marine Loading Arm, Redundancy*

1.0 INTRODUCTION

Safety barriers to Liquefied Natural Gas (LNG) systems can take the form of physical and engineered systems or human actions based on specific procedures or administrative controls (De Dianous & Fievez, 2006; Hollnagel, 2008). The safety system is classified into high- and low-level safety systems (Aneziris et al., 2021). The low-level safety systems include boil-off removal, thermal insulation, venting pressure safety valves or rupture discs, high-pressure control systems, reduction or termination of loading, and corrosion protection (Aneziris et al., 2021).

1.1 Safety barriers

According to Aneziris et al. (2021), under their safety barriers categorisation, the current LNG high-level safety barriers design for an LNG terminal usually consist of four main parts: the emergency shut down (ESD), powered emergency release coupling (PERC), cargo control room (CCR), and fire and gas (F&G) detector.

The ESD is designed to minimise the consequences of an incident (SIGTTO, 2021). In an LNG terminal, the ESD is used to shut down, isolate the leaking pipe section, and depressurise the system by stopping the primary pumps and closing the valves to avoid large liquid spills (SIGTTO, 2021). The system is automatically activated in response to signals sent by F&G detectors, process alarms (pressure loss in a pipe), or when an operator manually pushes an ESD button (SIGTTO, 2021). This system acts in response to a loss-of-containment scenario, thus interrupting the release and affecting the consequences associated with the leakage.

The CCR monitors and controls the loading and unloading operations, pumps, heating, cargo conditions, and cargo-handling equipment (Francisco & Miguel, 2012). It is developed based on an integrated automated system that combines the reliability of both operators and stations (Sastry & Seekumar, 2012).

F&G detectors are optical detection devices that respond to the optical radiant energy emitted by fires or LNG leaks. They are responsive to infrared or ultraviolet radiation. The F&G detector system spots the release and sends a signal to the ESD system. The ESD interrupts the process to minimise the impact of the loss of containment. An analysis of the Health and Safety Executive Offshore Hydrocarbons Release Database (2001–2008) revealed that approximately 36% of major gas releases and 69% of significant gas releases were not detected by gas detectors (McGillivray & Hare, 2008).

The PERC is a current unit used in an LNG transfer system (Manntek PERC Brochure, n.d.). In emergency cases such as tsunamis, fire catastrophes, or strong currents that force a tanker to suddenly move away from the berthing line, the PERC detaches the loading arms from the tanker. The action of the PERC combines the activation of the emergency release system valve and the release of the emergency release coupler. As a safety measure, the valves next to the PERC close quickly (usually in less than 5 seconds) after the emergency disconnection has begun. Figure 1 shows the layout of the PERC system.

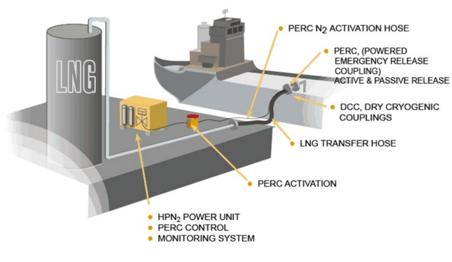


Figure 1: Layout of the PERC System (*Manntek PERC Product Data Sheet Brochure*, n.d.)

1.2 Cause and consequence analysis

Cause-consequence analysis (CCA) is an alternative assessment approach capable of modelling all system outcomes on a single logic diagram. It is a combination of event and fault tree analyses. Event tree analysis shows the consequences and fault tree analysis shows the causes. Hence, deductive and inductive analyses were combined using the CCA approach. CCA aims to identify chains of events that can result in undesirable consequences. Ortmeier et al. (2005) proposed a deductive CCA. The CCA approach has been applied by various research groups, including those in the rail industry (Güdemann et al., 2007). Vyzaite et al. (2006) combined a binary decision diagram with CCA for a non-repairable system, whereas Cleaver et al. (2007) and Woodward and Pitblado (2010) used the CCA approach to evaluate the safety barriers of LNG systems.

Most papers that have been reviewed focus on the performance of the safety barriers and qualitatively integrate them with the risk assessment (Hollnagel, 2008; Rathnayaka et al., 2012; Aneziris et al., 2021). Some studies focused only on ESD systems (Mirzaei Aliabadi et al., 2021). According to the MLA studies performed by Hanggara et al. (2017), Devianto et al. (2018), and Siswantoro et al. (2022), a gap remains in the integration of safety barriers, risk, reliability, and performance studies on the total safety of the LNG MLA terminal system. This study presents a detailed reliability analysis combined with CCA to assess safety barrier performance.

2.0 METHODOLOGY

Figure 2 illustrates the framework used in this study. Failure data obtained from the literature were calculated using the developed algorithm. Simulation results were processed to obtain dynamic failure data by incorporating the results into an Excel file. The obtained results were used to calculate the constant parameters for the reliability model and to construct and calculate the probability of failure using the dynamic fault tree approach. The total failure and reliability profiles of the entire system were then estimated using the data generated from a Monte Carlo simulation (MCS). The failure data were later embedded into a cause-consequence diagram to visualise the overall impact of the failure.

2.1. Estimation of the failure parameters

The failure probability was estimated by first collating failure data from various literature and resources, such as OREDA, SINTEF, and Faradip.Three. These data cover important components that configure safety barrier systems, including the ESD, PERC, CCR, and F&G. As the obtained failure data were based on the failure of a single unit, any component that commonly exists in redundancy is shown as two units in the table. The calculated failures for each system are listed in Tables 1, 2, 3, and 4. This assumption states that the failure of any component within the system contributes to the overall failure of the system. For a system with redundant units, failure was recalculated and later embedded in the overall failure calculation of the system. Using an MCS and the method of moment approach, the parameters of the Weibull distribution as well as the failures of the repairable components were estimated. The failure profile was assumed to be exponentially distributed, unless specified otherwise. This indicates that if the survival time is assessed up to time (t), the failure rate will be constant for all times up to t for irreparable components. The reliability of the overall system was estimated by combining the failures of the repairable and irreparable components.

2.2. Application of cause consequence analysis

CCAs were performed by identifying a scenario that could occur owing to the loss of containment. In this study, the performance of safety barriers in a marine loading arm (MLA) unit was assessed. The previously calculated failure values were inserted into the scenario study, and the probability of an event occurring was evaluated. In the presented case study, the ESD was designed to have an active parallel redundant system. Six distinct scenarios, as illustrated in Figure 3, were considered and estimated as follows:

- P(Sc1&Sc2) = [(P(A)` x P(B)` x P(C)`) x P(D)`]
- P(Sc3) = [P(A)` x P(B)` x P(C)` x P(D)]
- P(Sc4) = [P(A)` x P(B)` x P(C)]
- P(Sc5) = [P(A)` x P(B)]
- P(Sc6) = P(A)

The reliability value for the identical parallel redundant system was calculated using the following equation:

$R_s = 1-((1-R_1) \times (1-R_2))$.

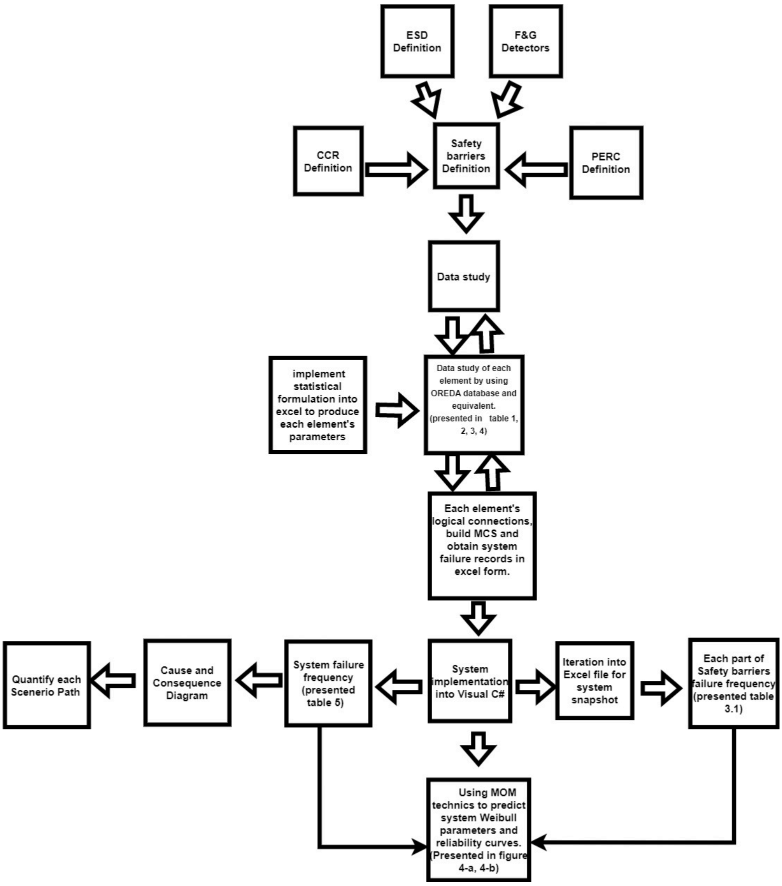


Figure 2: Methodology Framework

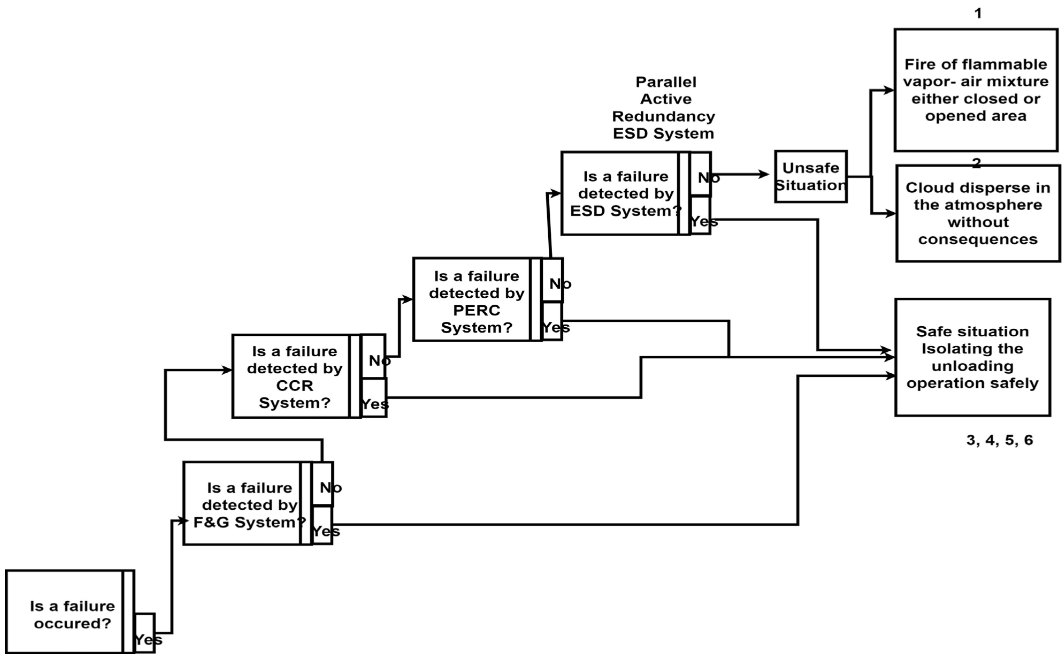


Figure 3: Cause Consequence Diagram of the Marine Loading Arm System with an ESD Redundancy

Table 1 Calculated Failure Rates for Components in Emergency Shut Down System

Component	Type	Redundancy	Failure rate (per year)	Source data	Component	Type	Redundancy	Failure rate (per year)	Source data
Flowmeter	Sensor	2	$4.2x10^{-7}$		Hard wired system (digital output)	Final element	1	$2.6x10^{-4}$	
	Logic unit	2	$2.85x10^{-5}$		Hard wired (safety system input)	Final element	1	$3.5x10^{-4}$	
	Final element	2	$4.23x10^{-6}$		Hard wired system Logic	Final element	1	$2.6x10^{-4}$	
PSV	Final element	1	$2.2x10^{-10}$		PLC analog input	Final element	2	$6.1x10^{-3}$	
ESD Compressor	Sensor	2	$4.2x10^{-7}$		PLC CPU	F.E	2	$3x10^{-2}$	Faradip.Three
	Logic unit	2	$2.85x10^{-5}$		PLC digital output	F.E	2	$6.1x10^{-3}$	
	Final element	2	$1.9x10^{-5}$		Programmable safety system analog	Final element	2	$1.4x10^{-3}$	
	Sensor	2	$4.2x10^{-7}$	OREDA	Programmable safety system CPU	Final element	2	$4.2x10^{-3}$	
	Logic unit	2	$2.85x10^{-5}$		Programmable safety system digital output	Final element	2	$1.4x10^{-3}$	
	Final element	2	$1.9x10^{-5}$		Circuit breaker	Final element	2	$2.6x10^{-3}$	
CMOS Logic part	Final element	1	$6.7x10^{-5}$						
Temperature sensor	Final element	1	$5.6x10^{-08}$						
Logic unit	Final element	1	$7.5x10^{-08}$						
Pressure sensor (Electro-mechanical)	Final element	1	$5x10^{-08}$						
UV/IR sensor	F.E	1	$4.3x10^{-08}$						
ESD shut down relay (Sammarco, 2007)	F.E	1	$5.88x10^{-04}$						
Total system failure rate								**$1.56x10^{-6}$ hour^{-1}.**	

Table 2 Failure Rates for Cargo Control Room System

Component	Redundancy	Failure (λ) per year (Norsk olje & gass, 2018)
Pushbutton	2	$5.0x10^{-5}$
Redundant programmable safety system (PLC and I/O)	2	$3.5x10^{-3}$
Main bore valve incl. DCV and close assist accumulator	2	$1.2x10^{-3}$
Annulus valves and cross-over valves	2	$6.1 \cdot 10^{-4}$
PLC analog input	2	$6.1x10^{-3}$
PLC CPU	2	$3x10^{-3}$
PLC digital output	2	$6.1x10^{-3}$
Ship's pump	2	0.35
Total failure of the CCR system		$3.31x10^{-7}$ $hour^{-1}$

Table 3 Failure Rates for PERC System

Component	Redundancy	Failure (λ) per year (Norsk olje & gass, 2018)
PERC logic unit (I/O)	2	0.0061
Digital output	2	0.0014
Control logic unit/Hard wired system/(analog input)	2	0.0003
PERC logic unit (I/O)	2	0.0061
ESD logic unit	2	0.0002
Circuit breaker	2	0.0026
Relay	2	0.0017
Break-away valve	2	$1.2x.10^{-7}$
Total failure of the PERC system		$1.7x10^{-13}$ $hour^{-1}$

Table 4 Failure Rate of F&G Detectors

Components	Redundancy	1/MTBF λ (/hour)	Data source
Flame detector	2	0.05×10^{-8}	Faradip.Three
Gas detector-IR (SI-111)	2	0.03×10^{-8}	
Gas detector–IR point	2	0.028×10^{-8}	
RS 232 inverter	2	5.79×10^{-6}	
Sensor loop	2	2.7×10^{-6}	
Electronic interfaces	2	2.3×10^{-6}	
Audio/video signalling device	2	4.38×10^{-6}	
Splitter board	2	2.3×10^{-7}	
Hardwire	1	10^{-9}	
Total failure of the F&G detectors		1.53×10^{-11} hour^{-1}	

3.0. RESULTS AND DISCUSSIONS

The failure data for all repairable and irreparable systems were estimated based on data collated from the literature. The failure of a single device was assumed when all the components existing in the duplicate were not explicitly described.

3.1 Failure rate of components

The failure rates of each component acting as a safety barrier for the MLA unit are listed in Table 5.

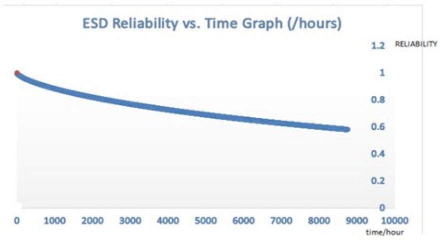
Table 5 Overall Failure Estimates for the Safety Barrier System

Safety barrier component	Overall failure (hour^{-1})	Remarks
ESD	1.56×10^{-6}	Highest failure: ESD pump
CCR	3.31×10^{-7}	
PERC	1.7×10^{-13}	
F&G detector	1.53×10^{-11}	

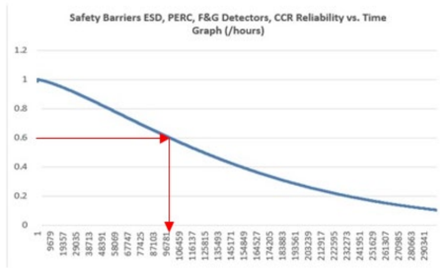
The ESD system component with the highest failure rate was the ESD pump with an estimated failure rate of approximately 0.0134 per year. LNG unloading line components, such as unloading pumps and valves, contribute significantly to the pressure during ESD activation. Regarding the CCR system, the failure of all redundant pump units is required for overall system failure to occur. However, because most components of a CCR system involve fluid movement, a higher probability of failure may occur. The most reliable component of the safety barrier of an MLA unit is the PERC system. These components are mostly electronic components that have high reliability and exist in redundancy, making failure almost impossible.

3.2 Reliability estimation of the MLA system

An MCS was used to assess the reliability of the MLA system because it can generate random numbers that can imitate the failure behaviour in real processes. The simulation was integrated into the Visual Studio C# algorithm, and the risk frequency was assessed. In this study, an MCS was performed for a one-year service period. As shown in Figure 4-a, within the one-year service period, approximately 8760 iterations were performed, and a reliability curve for each safety barrier was generated. The ESD system with repairable components failed 24 times within 8760 iterations. The samples of time extracted for the failures were 3, 6, 1921, 4163, 4882, and 6918 hours. With these data, the Weibull parameter estimates were determined; the values were β equals 0.6970 and α equals 21761 h. The reliability of the ESD system at the end of its one-year service life was estimated to be 60%. Similar reliability calculations were performed for the CCR, PERC, and F&G systems to obtain their reliability data; they obtained 99% (CCR), 98% (PERC), and 99% (F&G). These data were embedded in the CCD to identify the overall impact of the leakage scenario. For the overall safety barrier system shown in Figure 4-b, a longer service period of 300,000 hours (32.5 years) was assessed. The reliability of the safety barrier system decreased to 60% at the end of 96,000 service hours.



(a)



(b)

Figure 4: Reliability Profiles for (a) ESD System and (b) Safety Barrier System

Based on the iterations performed, the ESD system had 24 failures in 8760 iterations (0.27 failures per iteration), while CCR and PERC had one failure each in 15000 iterations (6.67×10^{-3} failures per iteration). The F&G detectors had no failures within a one-year period. For an ESD system, electronic parts have high reliability, whereas mechanical parts fail more frequently. For the overall safety barrier system, the MCS was regenerated 300,000 times, where each iteration was considered as a one-hour service time. The system failed 193 times in 32.5 years. Some time failures were 4, 28, 86 132, 95 118, 162 305, 205 836, 212 940, 285 804, and 299 977. Using the method of moments approach, the parameters for the Weibull distribution of the total system were estimated, and the values obtained were α = 163372 h, and β = 1.35.

3.3 Cause and consequence analysis of the MLA system

The previously calculated reliability values for each system were integrated into the CCD diagram and equations, as described in Section 2.2. Six different failure scenarios or series of events were assessed, and the probability of an event occurring was estimated based on the given scenario.

The first path, designated as Scenarios 1 and 2 and classified as unsafe conditions, can occur when there is a leak or failure that can lead to a loss of containment event. None of these safety barriers can detect failures sequentially. Triggering events can lead to consequences such as fire in either closed or open areas or cloud dispersion in the atmosphere. If there is no ignition source, there might be no further consequences; however, if the wind speed is high and the cloud is moved to a place with a possible fire source, it can be ignited, leading to a vapour cloud explosion. The probability of Scenarios 1 and 2 occurring was estimated at 3.2×10^{-7} (per year).

With the exception of the previously described event, the other event paths were considered safe because at least one safety barrier component could detect the system. The probability of safe events occurring was calculated as follows:

- Event 3: 1.68×10^{-6} (per year). Leak or release events were only detected by the ESD (fourth tier) system.
- Event 4: 1.98×10^{-4} (per year). The event was detected by the PERC (third tier) system and quickly isolated.
- Event 5: 9.8×10^{-3} (per year). This event was detected early by the CCR system and subsequently isolated.
- Event 6: 0.99 (per year). Loss of containment was detected using the F&G system and directly isolated.

From the above scenario, it is evident that for any event detected, the system will be isolated, operation will be stopped, and pressure will be reduced. A sequence of safe operations is important such that the leak source can be identified and repaired accordingly. When the ESD was run in a redundant active parallel system, the reliability value was recalculated; the reliability of the ESD was increased to 84%. With the improvement in the reliability of ESD, the overall probability of an event occurring in Scenarios 1 and 2 was also reduced by a factor of 2.5.

4.0 CONCLUSION

The application of the MCS and adaptation of the method of moments approach were successfully presented in this study when preventive maintenance was not considered. In other words, research can estimate the number of failures that a system will experience if it does not intervene in preventive maintenance. Another important factor in failure is the human factor, which was omitted from this study. With the integration of failure and CCAs, the quantitative values of the event probability with its respective event scenario were assessed under these circumstances. The ESD had the lowest reliability among all safety barrier components in the MLA system. When designed as an active parallel redundant system, the overall reliability of the ESD system improved from 60% to 84%. With this improvement, unsafe conditions such as fire or vapour cloud formation can be prevented by a factor of 2.5. This study demonstrated that predicting the reliability or failure probability of a system by incorporating the failures of basic components and performing simulations over a service period is possible. Comparing the reliability of the safety barrier systems, valves are the most reliable components, whereas mechanical parts, especially diesel engines, are the least reliable. The degree of importance of each element should be investigated in future studies. Finally, by embedding the CCA in the analysis, safety analysts can define and defend the requirements of certain safety barrier components.

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