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LNG Accident Analysis and Implications for Long-Distance Cryogenic Pipelines

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Abstract: *Liquefied natural gas (LNG) has become an important component of the global energy infrastructure because of its high energy density and suitability for long-distance transportation. However, its cryogenic temperature, flammability, and potential for rapid vaporisation create significant safety hazards that require effective engineering design, operational control, and risk management. This study presents a global analysis of major LNG accidents, focusing on accident causes, failure modes, severity, risk assessment approaches, and their implications for the development of long-distance insulated LNG pipelines. This study examined six major LNG-related incidents between 1944 and 2014: Cleveland, Cove Point, Bontang, Everett, Skikda, and Plymouth. The study used descriptive statistics, Pareto analysis, accident severity classification, and failure-mode assessment to identify recurring accident patterns and major areas of concern. The analysis recorded 159 fatalities and 305 injuries across the six incidents, with four incidents involving LNG release. Equipment failure and operational/startup errors were the most frequently represented causes, each accounting for 33.3% of the incidents, while pressure surge and storage-tank failure each accounted for 16.7%. The results demonstrate that although major LNG accidents are relatively infrequent, their consequences can be catastrophic, as evidenced by the Cleveland accident, which recorded the highest number of fatalities. Key failure modes identified include storage-tank failure, cryogenic pipeline vacuum loss, thermal contraction, fatigue, insulation degradation, transfer-system leakage, instrumentation failure, and emergency shutdown failure. The study further highlights the importance of quantitative risk assessment, leak detection, emergency isolation, and safety-critical elements in reducing LNG accident risks. For long-distance insulated LNG pipelines, the findings emphasise the need for cryogenic-compatible materials, reliable insulation and vacuum monitoring, pressure and surge protection, thermal-expansion provisions, continuous integrity monitoring, automatic emergency shutdown, and effective emergency response. The study concludes that historical LNG accident experience provides an essential foundation for developing safer, more reliable, and economically viable long-distance LNG pipeline transportation systems.*

Keywords: *Liquefied Natural Gas; Accident Analysis; Case Studies; Failure Modes; Risk Assessment; Cryogenic Pipelines*

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1.0 Introduction

LNG has become an increasingly critical component of global energy infrastructure, driven by rising demand for clean energy and energy security concerns. However, despite its environmental benefits, LNG poses substantial hazard risks that demand rigorous safety management throughout its entire value chain (Gökcan et al., 2025). The commercialisation of LNG offers significant benefits to various industries, yet its chemical properties, particularly its cryogenic nature and flammability, pose a risk of catastrophic incidents if not adequately controlled (Półka et al., 2021). LNG is characterised by unique fire and explosion hazards that pose significant safety challenges to project managers, design engineers, safety professionals, and operators throughout all phases of LNG projects, from design through operation (Alderman, 2005).

LNG is natural gas cooled to approximately −162°C, reducing its volume by about 600 times and making long-distance transportation economically feasible. A typical LNG facility design must take into consideration the cryogenic nature of the fluid. Such a design will usually involve the provision of double containment for storage tanks, vacuum-insulated cryogenic piping, and a well-planned emergency shutdown system. The design must also include continuous gas detection, follow international engineering standards, and provide rigorous operator training. Despite the cryogenic nature of LNG, the industry has achieved a relatively good safety record due to appropriate engineering design and good operational approach (Mannan & Lees, 2014).

Historically, the LNG industry has had no recorded terrorist attacks on LNG tankers or land-based facilities, indicating a relatively exemplary safety record over the years (Parfomak, 2003). Nevertheless, public concerns about LNG safety persist, particularly for onshore terminals built near populated areas, where potentially catastrophic pool or vapour cloud fires could result from serious accidents (Parfomak & Flynn, 2004). Given the growing scale and number of LNG facilities worldwide, systematic understanding of the past safety performance, accident hazards and risk management approach has become essential for ensuring both operational continuity and public safety (Martinez & Lambert, 2010).

2.0 Primary Hazard Types and Physical Mechanisms in LNG Operations

2.1 Pool Fire and Thermal Radiation Hazards

Pool fires represent the most frequent and potentially severe consequence of LNG spills, generating extreme thermal radiation that threatens adjacent facilities and personnel. When LNG is released onto surfaces, it immediately begins to vaporise due to heat transfer, with LNG pool fires producing flame lengths up to 5 meters and generating thermal conditions that significantly exceed those from conventional hydrocarbon fires (Półka et al., 2021). Research employing computational fluid dynamics (CFD) modelling demonstrates that pool fires from LNG tank leaks achieve steady-state conditions within approximately 20 seconds, with maximum temperatures reaching 670°C and maximum thermal radiation reaching 624 kW/m², posing serious threats to personnel and adjacent assets (Li et al., 2021).

The thermal radiation consequences of LNG pool fires decay predictably with distance from the fire source, with fatality probabilities declining from 100% at the fire centre to approximately 2% beyond 800 meters (Chaudhari, 2016). Understanding these thermal radiation profiles is critical for determining safe exclusion zones and designing protective barriers around LNG facilities. The radiant energy from pool fires can be sufficiently high to threaten the structural integrity of facilities and potentially extend consequences beyond facility boundaries (Chaudhari, 2016).

2.2 Vapour Cloud Explosions and Deflagration-to-Detonation Transition

Vapour cloud explosions (VCE) represent a second major hazard category in LNG accidents. The dispersion characteristics of LNG vapour depend significantly on ambient conditions, with daytime dispersions generally more limited than nighttime dispersions due to atmospheric stability differences. Research on LNG bunkering operations demonstrates that release heights exceeding 10 meters significantly amplify dispersion effects, with nighttime dispersion areas at release heights of 20 meters being 3.5 times larger than daytime dispersions (Gu et al., 2025). Lower flammable limits (LFL) extend to distances of 169 meters during daytime conditions and 243 meters during nighttime conditions, defining the zones within which vapour cloud explosions could occur (Guntama et al., 2022).

Deflagration-to-detonation transition (DDT) represents a particularly severe accident scenario in vapour cloud explosions. Evidence from large-scale tests and actual VCE accidents, including incidents at Buncefield (UK), Jaipur (India), and Port Hudson (US), demonstrates that detonations have indeed occurred in prior VCE accidents, at least in parts of the combustible clouds (Oran et al., 2019). Detonation overpressures are substantially higher than those in deflagration and continue throughout the entire detonable cloud, resulting in far more severe damage compared to deflagration-only scenarios.

2.3 Rapid Phase Transitions (RPT) and Physical Explosions

Rapid phase transitions represent a unique hazard associated with LNG spills over water, arising from the violent boiling that occurs when cryogenic LNG contacts significantly warmer water. These physical explosions, termed RPTs, can generate severe but localised blast pressures and underwater shock waves capable of damaging adjacent structures and facilities (Nédelka et al., 2003). The phenomenon occurs when LNG vaporisation rates become so high due to film-boiling collapse that pressure and energy release reach explosive magnitudes. Large-scale experiments have demonstrated RPTs' capacity to produce damaging effects and the potential for escalation leading to serious accidents if initial structural integrity loss occurs (Nédelka et al., 2003).

Research distinguishes between delayed and immediate RPT phenomena, with analytical models now capable of predicting RPT onset location and timing with reasonable accuracy (Lervåg et al., 2020). Understanding RPT mechanisms is essential for assessing offshore LNG terminal safety and designing appropriate mitigation measures. Unlike LNG, hydrogen liquid spills present significantly lower RPT risks, suggesting that RPT remains an LNG-specific concern (Odsæter et al., 2021).

2.4 Cryogenic Effects and Boiling Liquid Expanding Vapour Explosions (BLEVE)

The extreme cryogenic temperatures of LNG create secondary hazards including personnel injuries from direct contact and structural brittle failure of materials not designed for such temperatures (Forte & Ruf, 2017). Additionally, catastrophic rupture of LNG tanks exposed to external fires can produce boiling liquid expanding vapour explosions (BLEVE), combining physical explosion effects with thermal and projectile hazards (Eberwein et al., 2023). Experimental studies of thermal insulation behaviour under fire conditions demonstrate that thermal exposure can cause rapid release of flammable gases and BLEVE conditions, with maximum thermal flux from BLEVE events reaching 99.8 kW/m² (Eberwein et al., 2023).

3.0 Reported Major LNG Incidents

Major LNG incident data and their investigative reports were derived from the U.S. Department of Energy, the National Transportation Safety Board (NTSB), the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA), Asia-Pacific Economic Cooperation and the International Group of Liquefied Natural Gas Importers websites for further analysis. Evidently, the major accidents have significantly influenced LNG safety regulations and engineering design.

The first LNG incident occurred at Cleveland East Ohio Gas Company in 1944 (APEC, 2011). In the report, a cylindrical LNG storage tank constructed from low-nickel steel failed catastrophically because the material became brittle at cryogenic temperatures. Approximately 4.5 million litres of LNG escaped into surrounding streets, rapidly vaporised, ignited, and produced widespread fires, leading to 128 fatalities and 200 injuries (APEC, 2011).

Another incident was reported at Cove Point LNG Terminal, USA, in 1979. It was reported that LNG leaked through an inadequately sealed electrical conduit, associated with an LNG pump. The vapour travelled through underground electrical conduits into a substation, where it ignited from normal electrical switching equipment, causing an explosion (APEC, 2011).

In 1983, a heat exchanger ruptured at the Bontang LNG Plant because of severe over-pressurisation during commissioning. Notably, LNG itself was not released because the accident occurred before LNG entered the system (APEC, 2011). The report indicated that 3 lives were lost as a result of the failure of the pressure protection system.

Five years after the Bontang occurrence, a pressure surge incident occurred at the Everett LNG import terminal during an LNG transfer, causing flange gasket failure. The 1988 Everett LNG Terminal incident is regarded as one of the best-documented examples of an LNG spill that did not escalate into a fire or explosion because of effective facility design and emergency response (Parfomak & Flynn, 2004).

Davis **(2020)** provided an analysis of the Skikda LNG plant explosion, which occurred in Algeria in the year, 2004. The report stated that the leaked gas entered the air intake of a steam boiler where it ignited, causing a boiler explosion followed by a massive vapour cloud explosion and fire, leading to 27 fatalities and 74 injuries.

Yoshida (2017) reported the Plymouth LNG Peak Shaving Plant incident, which occurred in 2014, where debris punctured the outer shell of a large LNG storage tank, resulting in leakage of perlite insulation and damage to the tank structure. The consequences of this incident included 7 injuries, damaging of three liquefaction trays, a total economic loss of about US$900 million, and a 2% reduction in global liquefaction capacity.

3.1 Accident Trends Analysis

The table (Table 1) presents the six major LNG-related incidents occurring between 1944 and 2014 in the United States, Indonesia, and Algeria. The incidents demonstrate that LNG accidents have resulted from both technical failures and human/operational errors, with consequences ranging from minor injuries to major fatalities. The Cleveland LNG Plant accident in 1944 was by far the most severe, resulting in 128 fatalities and 225 injuries, while the 2004 Skikda incident caused 27 fatalities and 74 injuries. The remaining incidents had comparatively lower consequences, although they still provide important lessons for LNG facility design and operation.

A clear pattern in the table is the importance of equipment and infrastructure integrity. The Cleveland accident was associated with storage-tank failure, while the Everett incident involved transfer-piping failure and the Cove Point incident involved LNG leakage into an electrical conduit. These events demonstrate that LNG containment systems, pipelines, storage tanks, electrical systems, and associated components must be designed to withstand cryogenic temperatures, pressure variations, thermal stresses, and other operating conditions. For long-distance LNG pipelines, this emphasises the importance of appropriate cryogenic materials, effective insulation, expansion provisions, pressure and surge protection, leak detection, and automatic isolation systems.

The table also demonstrates that process control and operational management are critical to LNG safety. The Bontang incident was associated with overpressure during commissioning, while the Plymouth incident was linked to a startup error. These incidents indicate that even when equipment

is appropriately designed, inadequate commissioning, startup, or operating procedures can create significant hazards. Consequently, LNG facilities require carefully developed operating procedures, competent personnel, systematic commissioning protocols, pressure-relief systems, process monitoring, and emergency shutdown arrangements.

Another important observation is that LNG release does not necessarily mean that the accident is caused directly by LNG leakage. For example, the Skikda incident was associated primarily with a hydrocarbon refrigerant leak rather than an LNG release. This illustrates that LNG facilities contain several hazardous systems beyond the LNG containment system itself, including refrigerant systems, fuel-gas systems, compressors, utilities, and electrical equipment. Therefore, safety assessments should address the entire process system, rather than focusing exclusively on LNG storage and transfer.

The progression of the incidents also suggests an increasing emphasis on preventive and protective safety measures. Earlier incidents highlighted fundamental issues such as tank integrity and material selection, whereas later incidents emphasise gas detection, emergency shutdown, process control, startup management, and system protection. This reflects the evolution of LNG safety engineering toward a more comprehensive risk-management and layers-of-protection approach involving inherently safer design, detection and monitoring, automatic isolation, fire and explosion protection, emergency response, and rigorous operational control.

Overall, the table shows that the major lessons from historical LNG accidents can be grouped into five interconnected areas: (1) appropriate material and equipment selection, (2) containment and piping integrity, (3) pressure and process control, (4) leak detection and emergency isolation, and (5) effective commissioning and operational procedures. These lessons are particularly relevant to the development of long-distance insulated LNG pipelines, where failure of containment, insulation, pressure control, or monitoring systems could lead to LNG release and potentially hazardous vapour-cloud formation. Historical accident experience therefore provides an important basis for identifying failure modes and establishing appropriate design and safety requirements for future LNG transportation infrastructure.

Table 1: Table showing reported LNG accident data

Incident	Country	Year	Fatalities	Injuries	Main Cause	LNG Release	Key Lesson
Cleveland LNG Plant	USA	1944	128	225	Storage tank failure	Yes	The need for proper material selection at the design stage
Cove Point LNG	USA	1979	1	1	LNG leak into electrical conduit	Yes	The need to improve facility design
Bontang LNG	Indonesia	1983	3	–	Overpressure during commissioning	No	Pressure protection and commissioning controls
Everett LNG Terminal	USA	1988	0	0	Transfer piping failure	Yes	Surge protection and piping design improvement envisaged
Skikda LNG Plant	Algeria	2004	27	74	Hydrocarbon refrigerant leak	No	The need to improve Gas detection and emergency shutdown procedure
Plymouth LNG Plant	USA	2014	0	5	Startup error and explosion	Yes	Startup procedure should be properly managed

3.2 Pareto analysis of LNG accident causes: The Pareto analysis identifies the relative contribution of different initiating causes among the six LNG accidents considered. The results indicate that equipment failure and operational/startup errors are the two most frequently represented causes, each accounting for 2 of the 6 incidents (33.3%). Together, these two categories account for 66.7% of the recorded incidents, indicating that technical reliability and human/operational performance represent the dominant areas requiring attention.

A breakdown of the analysis shows that the equipment failure category is ranked first and accounts for 33.3% of the incidents. Failures involving transfer piping, containment systems, or other equipment demonstrate the importance of mechanical integrity throughout the LNG value chain. In particular, cryogenic equipment must be capable of operating reliably under extremely low temperatures, pressure variations, thermal contraction, and repeated thermal cycling. Consequently, equipment selection, inspection, preventive maintenance, integrity management, and condition monitoring are important controls for reducing LNG accident risk.

Operational and startup errors also account for 33.3% of the incidents. This finding demonstrates that LNG safety cannot depend exclusively on equipment reliability. Errors during startup, commissioning, or operation can create abnormal pressure conditions, release hazards, or ignition opportunities. Effective operating procedures, competency-based training, permit-to-work systems, pre-startup safety reviews, process monitoring, and strict commissioning procedures are therefore essential.

The remaining causes, pressure surge and storage tank failure, each represent 16.7% of the incidents. Although individually less frequent, both can have potentially severe consequences. Pressure surges can arise from rapid valve operation, flow changes, or transient conditions and may damage pipelines or associated equipment. Storage-tank failure, meanwhile, represents a particularly important containment hazard because a large LNG release can rapidly generate a flammable vapour cloud.

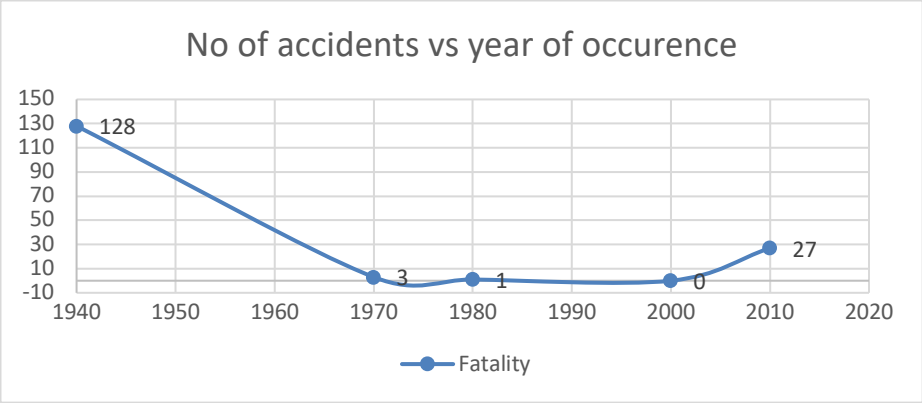


Figure 1: Chart showing fatality trend

The result of the Pareto analysis suggests that safety improvement efforts should initially prioritise: (1) Equipment reliability and mechanical integrity (2) Startup, commissioning, and operational control (3) Pressure and surge management and (4) Storage-tank integrity and containment.

Table 2: Table showing Pareto analysis of LNG accident causes

Rank	Cause	Number of Incidents	Percentage	Cumulative (%)
1	Equipment failure	2	33.3	33.3
2	Operational/startup error	2	33.3	66.7
3	Pressure surge	1	16.7	83.3
4	Storage tank failure	1	16.7	100.0
Total		**6**	**100.0**	

3.3 Accident Severity Metrics

The classification table (Table 2) shows that catastrophic LNG accidents are relatively infrequent but can produce extremely severe consequences. The Cleveland LNG Plant accident represents the catastrophic category because of its exceptionally high number of fatalities and injuries. This demonstrates the importance of preventing low-frequency, high-consequence events through robust containment, appropriate materials selection, structural integrity, and comprehensive hazard assessment.

The major category is represented by the Skikda LNG Plant accident, which resulted in substantial loss of life and injuries. Although its initiating event differed from the Cleveland accident, the consequences demonstrate that failures involving associated hydrocarbon-processing systems can escalate into major incidents. This reinforces the need to consider secondary and supporting systems, such as refrigerant systems, compressors, gas detection, fire protection, and emergency shutdown systems, in LNG risk assessments.

The moderate category includes Bontang and Cove Point. These incidents illustrate that failures involving overpressure, leakage, electrical systems, and commissioning can have serious consequences even when they do not produce catastrophic loss of life. They therefore highlight the importance of pressure-relief systems, electrical segregation, leak detection, safe commissioning procedures, and automatic isolation.

The Everett and Plymouth incidents fall into the minor category based primarily on their reported human consequences. However, classifying an incident as minor should not imply that the underlying failure mechanism is unimportant. Transfer-piping failure and startup errors can potentially escalate under different circumstances. Thus, these events are valuable for identifying precursor conditions and implementing corrective measures before more severe accidents occur.

Table 3: Table showing accident severity metric

Accident Severity Metric	Severity	Frequency	Representative Incidents
Catastrophic	Very high — multiple fatalities and extensive injuries	Rare	Cleveland LNG Plant
Major	High — significant fatalities and injuries	Occasional	Skikda LNG Plant
Moderate	Moderate — limited fatalities/injuries or significant process consequences	Occasional	Bontang LNG, Cove Point LNG
Minor	Low — no fatalities and limited injuries	Rare	Everett LNG Terminal, Plymouth LNG Plant

3.4 Descriptive Analysis of global LNG accidents

The descriptive statistics as shown in Table 4 demonstrate that global LNG accidents exhibit a highly uneven severity distribution. Although the mean number of fatalities is 26.5 per incident, the median is only 2, indicating that the mean is substantially influenced by a small number of

catastrophic events, mainly the Cleveland disaster. In particular, the maximum of 128 fatalities accounts for approximately 80.5% of the total fatalities recorded in the six incidents. Furthermore, four of the six incidents involved LNG release, suggesting that loss of containment remains an important accident mechanism. Nevertheless, the occurrence of two major incidents without a major LNG release highlights the importance of considering other hazards, including explosions, structural failures, equipment failures, and operational errors, when evaluating LNG safety.

3.5 Common LNG Failure Modes

In the reported global LNG accident data sheet, the following failure modes have been identified, and they provide a pointer to areas of focus during risk assessment.

Storage Tanks: Brittle fracture, Foundation settlement, Overpressure and Thermal stress

Cryogenic Pipelines: Vacuum loss, Thermal contraction, Pipe fatigue, Weld cracking, Insulation degradation, and Mechanical damage

Transfer Systems: Flange leakage, Valve failure, Pump seal leakage, and Hose rupture

Instrumentation: Gas detector failure, Pressure transmitter failure, Temperature sensor malfunction, and Emergency shutdown failure

Table 4: Table showing the descriptive analysis of global LNG accidents

Parameter	Value
Number of major incidents	6
Total fatalities	159
Total recorded injuries	305
Mean fatalities per incident	26.5
Median fatalities	2
Maximum fatalities	128
Minimum fatalities	0
Incidents involving LNG release	4
Incidents without major LNG release	2

3.6 Human Factors

The historical LNG data sheet shows that many LNG incidents involve operational shortcomings rather than design deficiencies. Related human shortcomings in LNG operations include Inadequate operator training, Failure to follow procedures, Poor maintenance planning, Weak permit-to-work systems, Insufficient hazard communication, and Deficient safety culture.

LNG Risk Assessment and Quantification Approaches

4.1 Quantitative Risk Assessment (QRA) Frameworks

Systematic risk assessment of LNG facilities requires a comprehensive quantitative evaluation that combines frequency and consequence analyses. The Formal Safety Assessment (FSA) framework prescribed by the International Maritime Organisation provides structured approaches to hazard identification (HAZID), risk analysis, and evaluation of risk control options (Čapalija et al., 2025). For LNG-fuelled cruise ships, a comprehensive FSA application that combines existing safety data, regulatory standards, and probabilistic risk modelling is important as it reveals critical accident-escalation pathways, particularly in scenarios involving passenger evacuation and port operations areas that remain under-researched in current practice (Čapalija et al., 2025).

Quantitative risk assessment studies of LNG facilities employ integrated Bayesian network approaches combined with catastrophe theory to develop comprehensive causal structures for

hazard identification and risk assessment (Wu et al., 2021). These models provide novel perspectives for identifying hazards and assessing the evolution process from accident causes to consequences. For floating storage and regasification units (FSRUs), comprehensive index hierarchy systems addressing human, equipment, environmental, and management aspects enable refined risk assessment and prioritisation (Xiao et al., 2024).

4.2 Dynamic Risk Assessment for Simultaneous Operations

Dynamic risk assessment is crucial in LNG operations because traditional static risk assessment approaches fail to capture the dynamic nature of LNG bunkering simultaneous operations (SIMOPs), where occurrence probabilities of potential consequences change at different times as specific operations commence or complete (Fan et al., 2022). Dynamic quantitative risk assessment (DQRA) methodologies based on Bayesian networks overcome this limitation by modelling time-varying risk characteristics inherent in complex LNG operations. These approaches demonstrate efficiency in probability calculations and flexibility in conducting causal diagnosis, enabling identification of critical time periods when risks peak.

4.3 Hazard Identification and Prioritisation

Hazard identification and prioritisation in the LNG industry are very important due to their potential to provide firsthand information to enhance informed decision-making. A comprehensive hazard identification in LNG operations employs multiple methods, including hazard and operability (HAZOP) analysis, failure mode and effects analysis (FMEA), and fault tree analysis (FTA). In port areas engaged in LNG operations, functional analysis identifying 20 distinct functions can systematically categorise hazards into high-risk (7 functions), medium-risk (5 functions), and low-risk (8 functions) categories, enabling prioritised safety measure implementation (Gökcan et al., 2025). The Functional Resonance Analysis Method (FRAM) provides an alternative approach for examining accident processes and their resonance patterns.

Atypical scenario identification represents an increasingly recognised challenge, as demonstrated by the DyPASI (Dynamic Procedure of Atypical Scenarios Identification) tool developed specifically to address unexpected scenarios not identified by conventional hazard identification processes (Paltrinieri et al., 2011). Application of the DyPASI methodology to LNG regasification terminals reveals comprehensive identification of potential risks across different facility layouts, including onshore terminals, offshore gravity-based structures, and floating storage and regasification units.

5.0 Safety Management Systems and Regulatory Framework

5.1 Safety Critical Elements (SCE) and Process Safety Management

Accurate identification of safety-critical elements (SCEs) provides an essential foundation for effective safety management and risk mitigation (Heldiansyah, 2026). Analysis of numerous process safety management incident investigation reports reveals that critical contributors to accidents frequently involve SCEs, with effective identification and implementation of safety-critical tasks substantially mitigating catastrophic incident risks. The identification of SCEs enables more effective prioritisation of ongoing asset management efforts for hardware barriers, while human barriers require specific interventions to operate successfully and prevent top events or minimise consequences.

5.2 International Standards and Regulations

International maritime regulations and standards establish minimum requirements for LNG safety, though challenges persist in achieving comprehensive regulatory alignment for emerging technologies like LNG-fuelled ships and floating LNG facilities. International Maritime Organisation (IMO) regulations establish a framework through the MARPOL Protocol Annex VI,

implementing Emission Control Areas (ECAs) from 2010 that restrict ship exhaust gases and have driven adoption of LNG-fuelled systems (Nubli et al., 2022). Directive 2012/18/EC (Seveso III) establishes European requirements for major accident prevention involving hazardous substances, including LNG (Półka et al., 2021).

Formal Safety Assessment frameworks continue to evolve, with applications to diverse LNG scenarios, from cruise ships to alternative fuels requiring periodic updates to address emerging technologies and operational patterns (Čapalija et al., 2025). Classification society rules require alignment for consistency, though floating LNG facilities present novel challenges requiring coordination between offshore platform rules and ship design standards (Aronsson, 2012).

5.3 Integrated Safety and Security Risk Management

LNG ports and marine terminals require integrated approaches to safety and security risk management, particularly given increased post-9/11 security concerns and growing LNG demand worldwide (Briouig, 2014). Holistic approaches combining risk prevention, mitigation, emergency planning and response, and port business continuity prove more cost-effective than disciplinary approaches marked by traditional silos between safety and security functions. Practical frameworks for LNG ports risk and emergency management prove applicable across diverse geographic contexts, from the Middle East and North Africa regions to Asian markets experiencing rapid LNG development.

6.0 Engineering Improvement and Implications for Long-Distance Insulated LNG Pipelines

6.1 Engineering Improvements Since Major Accidents

The LNG industry has incorporated several important safety enhancements since the first major LNG incident took place. Such enhancements include full-containment and double-containment storage tanks, the use of high-performance cryogenic materials (e.g., 9% nickel steel and stainless steel), distributed temperature sensing, continuous methane detection, and automatic emergency shutdown systems (Fulford & Slatter, 1988). Other measures include provision of fireproof supports, Computational Fluid Dynamics (CFD)-based hazard analysis, Quantitative Risk Assessment (QRA), Hazard and Operability (HAZOP) studies, Layers of Protection Analysis (LOPA) and Risk-Based Inspection (RBI). A combination of these enhancements has led to excellent safety performance in the LNG industry (Mannan & Lees, 2014).

The major technological shift in the 21st century has been toward energy efficiency and integrated boil-off-gas (BOG) management. Modern LNG carriers increasingly employ dual-fuel propulsion, BOG reliquefaction systems, advanced cargo-management systems, and improved containment insulation. These technologies allow BOG to be used as fuel or returned to the cargo tanks through reliquefaction, thereby reducing cargo losses and improving overall energy efficiency (Kochunni & Chowdhury 2022).

The current technological frontier is moving toward smart, low-loss and highly monitored LNG transportation systems. Digital-twin technologies, artificial intelligence, real-time monitoring, and predictive-maintenance approaches are being investigated and increasingly demonstrated for maritime systems and LNG carrier operations. For example, recent research has examined digital twins for fault diagnosis, while industry demonstrations have applied digital-twin technology to LNG carrier gas-management and cargo-handling systems (Hasan et al., 2024).

For land-based transportation, cryogenic LNG pipelines represent an emerging alternative for continuous transportation of LNG in its liquid state. Recent research has developed mathematical and optimisation frameworks for long-distance LNG pipelines that account for cryogenic insulation, heat transfer, flow behaviour, intermediate cooling and pressurisation. These developments indicate potential for long-distance liquid-state LNG transportation, although the technology remains less

mature and less widely deployed than conventional LNG shipping and gaseous natural-gas pipelines (Zhang et al., 2024).

In parallel, advanced leak-detection technologies, including distributed fibre-optic temperature sensing, have been demonstrated for cryogenic LNG pipelines. Such systems can detect temperature changes associated with LNG leakage and integrate with emergency shutdown systems. Together with improved containment systems, insulation, automation, FLNG, FSRUs and small-scale LNG infrastructure, these developments are contributing to a more integrated, efficient and digitally monitored LNG supply chain (Tanimola & Riesner, 2010)

6.2 Implications for Long-Distance Insulated LNG Pipelines

Before presenting the engineering design recommendations for long-distance insulated LNG pipelines, it is important to recognise that historical analyses of LNG accidents have consistently demonstrated that the safety of LNG transportation systems depends more on the integrity of engineering design, operational controls, and maintenance practices than on the inherent hazards of LNG itself. As reviewed, the case studies indicate that accidents were primarily initiated by equipment failures, loss of containment, material deficiencies, pressure transients, or operational errors rather than catastrophic failures of LNG storage systems. These events have shaped modern LNG engineering standards and reinforced the need for multiple layers of protection throughout the lifecycle of LNG facilities and transportation infrastructure.

Advances in cryogenic engineering, process safety management, and digital monitoring technologies have significantly improved the reliability of LNG systems over the past several decades. International standards, including those published by the International Organisation for Standardisation, National Fire Protection Association, and the American Petroleum Institute, emphasise the application of defence-in-depth principles through robust containment systems, continuous monitoring, emergency shutdown capabilities, and rigorous inspection programmes. Similarly, modern risk assessment methodologies such as Hazard and Operability (HAZOP) studies, Layers of Protection Analysis (LOPA), Quantitative Risk Assessment (QRA), and Risk-Based Inspection (RBI) have become essential tools for identifying potential failure scenarios and implementing preventive and mitigative safeguards before incidents occur. These approaches are particularly important for long-distance LNG pipelines, where the consequences of a loss of containment may extend over significant distances.

The development of long-distance insulated LNG pipelines introduces additional engineering challenges associated with cryogenic temperatures, thermal contraction, insulation performance, hydraulic transients, and pipeline integrity over extended routes. Consequently, pipeline systems must be designed not only to minimise heat ingress and maintain LNG in its liquid state but also to ensure rapid detection, isolation, and mitigation of any abnormal operating conditions. The integration of advanced sensing technologies, automated control systems, high-performance insulation materials, and predictive maintenance strategies is therefore fundamental to achieving safe, reliable, and economically viable LNG transportation.

7.0 Emerging Applications and Future Challenges

7.1 LNG as Alternative Marine Fuel

LNG adoption as marine fuel for both cargo vessels and cruise ships represent a major industry transition, driven by emissions regulations and environmental concerns. The safety of LNG-fuelled vessels requires comprehensive evaluation of bunkering and onboard fuel gas supply systems, with specific attention to credible accident scenarios and their expected consequences (Iannaccone, 2021). CFD modelling of cryogenic tank behaviour under accidental hydrocarbon fires provides precise data for tank structural integrity analysis, while LNG fire scenario consequence modelling within fuel preparation rooms quantifies heat flux received by ship structure.

7.2 Regulatory Gaps and Future Research Needs

Current knowledge gaps persist regarding LNG transportation safety, particularly concerning limited incident history and sparse accident frequency data. The field of LNG transportation research has undergone minimal accident frequency analysis compared to liquefied petroleum gas (LPG) transportation, with consequence analysis studies remaining inadequately explored (Huffman et al., 2024). Future safety research priorities should include: (1) enhanced understanding of boiling liquid expanding vapour explosion (BLEVE) potential in LNG systems, (2) improved characterisation of rapid phase transition severity and likelihood, (3) extended consequence analysis methodologies for diverse LNG operational scenarios, and (4) development of standardised assessment frameworks for LNG spills over water.

7.3 Cyber Security and Emerging Threats

Cyber security threats to LNG infrastructure have emerged as an increasingly acute concern given the digital investment in LNG operations and geopolitical tensions (Jao & Chuah, 2023). Protection of cyber-physical systems managing LNG operations requires integration with traditional physical security and process safety approaches to ensure comprehensive risk management.

8.0 Conclusions and Recommendations

The global LNG industry has experienced relatively few major accidents given its scale of operations. From the presented incidents, the most severe event which was the 1944 Cleveland disaster, led to major advances in cryogenic storage design, while later incidents such as Cove Point, Skikda, and Plymouth reinforced the importance of gas detection, emergency shutdown systems, safe commissioning practices, and robust process safety management.

A review of these accidents has indicated that LNG itself rarely causes catastrophic failures. Instead, they typically result from equipment failures, operational errors, inadequate maintenance, or failures in associated hydrocarbon systems. The accident severity metric also highlights an important characteristic of LNG safety. It shows that low-frequency events can have disproportionately high consequences. Therefore, LNG pipeline and facility design should not rely solely on historical accident frequency. Instead, it should combine probabilistic risk assessment (PRA), quantitative risk assessment (QRA), failure-mode analysis, consequence modelling, and layers of protection to address both frequent lower-consequence failures and rare catastrophic events.

Consequently, for a long-distance insulated LNG pipeline, the principal risk-control measures should include cryogenic-compatible materials, reliable insulation and vacuum monitoring, leak detection, pressure and surge protection, automatic emergency isolation, thermal-expansion provisions, pipeline integrity monitoring, and well-defined emergency response procedures. Hence, the design and operational strategies should incorporate these risk measures.

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