KIU
Journal of Science, Engineering and Technology

KJSET Research Article

Assessing the safety integrity level of liquefied petroleum gas refilling plants in Nigeria: A review and case study

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Paper history:
Received 12 March 2025
Accepted in revised form 14 May 2025

Keywords
Safety Integrity Level (SIL); Layer of Protection Analysis (LOPA); Consequence Modelling; LPG Plant; Areal Location of Hazardous Atmosphere (ALOHA)

Abstract
Safety is a fundamental pillar of every process, protecting the plant, personnel, community, and environment. Breaching safety protocols can lead to catastrophic events, resulting in the destruction of lives and property while polluting the natural environment. This study reviews the current knowledge on the safety integrity level (SIL) assessment of Nigerian Liquefied Petroleum Gas (LPG) refilling plants, highlighting techniques, regulatory frameworks, best practices, technological advancements, and the associated challenges. It also assesses the SIL of a case study plant to examine the level of risk reduction achieved by adhering to regulatory standards and safety guidelines from the Nigerian Midstream and Downstream Petroleum Regulatory Authority. The plant's data was analyzed using major hazard techniques, determining SIL for two credible scenarios: truck/car ignition during delivery/discharge leading to tank explosion or relief valve release. Consequence modelling was carried out for the most probable scenario, the relief valve release. Risk factors of 1.776 x 10^{-7} and 3.534 x 10^{-4}/year were identified for tank explosion and relief valve release, respectively. Consequence modelling of the relief valve release indicated a toxic effect range of 62.2 m downwind, with a flammable vapor cloud spreading 45.7 m at 60 % of the lower explosive limit. The overpressure effect ranged up to 33.8 m with a peak of 0.7 psi. After compounding the numerous LPG plants in the country, the findings show a tolerable risk for tank explosion but an alarming risk for relief valve release, emphasizing the potential for severe damage within 50 m downwind of the incident point

Nomenclature and units

k	Kurtosis
γ	Skewness
τ_{MED}	Mean Excess Delay
τ_{RDS}	Root Mean Squared Delay Spread
μ	Mean

1.0 INTRODUCTION

1.1 Overview of Liquefied Petroleum Gas (LPG) Refilling Plants

Liquefied Petroleum Gas (LPG) is a key worldwide energy source due to its cleaner and much more environmentally friendly nature (Rej *et al.,* 2022). This makes it a better alternative to conventional fuels used in households and industries such as firewood, kerosene, gasoline, and diesel (Nwosi-Anele *et al.,* 2022). LPG is produced as a by-product of crude oil and natural gas processing (Robinson, 2024). It comprises a mixture of C3 and C4 hydrocarbons, at varying compositions whose specifics vary from country to country and with season (Speight, 2022). Its major properties are summarized in Table 1.

LPG consumption in Nigeria, however, remains low, accounting for only about 15 % of the country's production capacity (Lasisi, 2021). Nigeria has about 209.16 trillion cubic feet of natural gas reserves, produces about 3 million metric tonnes of LPG annually, mainly for export, with local consumption of only about 400,000 metric tons (about 15 %) (Ukwu *et al*., 2023).

The largest energy consumer in Nigeria is household cooking, which accounts for about 80% of total domestic energy consumption (Olanrewaju & Adegun, 2021). Nigeria, being a part of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, established the National Gas Policy (NGP), which is centered on improving the use of LPG as a sustainable substitute for traditional fuels used for household cooking, among other things (Lasisi, 2021).

Sequel to the Nigerian Gas Policy, a quantum leap in LPG adoption and consumption was observed year on year, with domestic consumption surpassing 1 million metric tonnes as of December 2020 (Akpan, 2021). This brings about the expansion of domestic gas utilization, especially LPG, whose consumption is planned to increase from 500,000 metric tons per annum (MTPA) to 15 million MTPA by 2030 (US International Trade Administration, 2022). Limited distribution infrastructure is one of the major hindrances to Nigeria's LPG adoption (Agbai & Aigbedion, 2024). As such, the government directly focuses on local utilization for households, Autogas, power generation, and industries, with plans for over 60 million households to migrate to LPG by 2030 and increase their average consumption from 750,000 MTPA to about 2 million MTPA.

Table 1: Characteristic of LPG *(Balla et al., 2019; Erinle et al., 2020; Nwaokocha & Okezie, 2016; Tukiman et al., 2022)*

S/N	Property	Unit	LPG
1.	Chemical Formula	–	Butane C_4H_{10} and Propane C_3H_8
2.	Boiling Point	ºC	– 42.1 to –0.5
3.	Absolute Vapor Pressure	kPa	375 – 1510
4.	Flash Point	ºC	– 104 to – 60
5.	Density	kg/m^3	494 – 583
6.	Lower Calorific Value	MJ/kg	42.1 – 49.3
7.	Octane Rating (RON)	–	96.5 – 111
8.	Carbon Content	% w/w	82
9.	Flammability Limits	–	4.1 – 74.6
10.	Air Auto Ignition Temperature	ºC	588
11.	Flame Velocity	m/s	0.37 – 0.48
12.	Adiabatic Flame Temperature	K	2263
13.	Heat of Combustion	MJ/kg air	1.8 – 8.5

Nigeria's gas sector, however, is still underdeveloped, with gas products battling for domestic market acceptance. However, LPG assumes a different trend, with increasing domestic adoption year on year (Oyin, 2021). There are currently about 200 LPG refilling plants, mainly spanning across urban and suburban areas of the country, with prospects for more (Princewill *et al*., 2023). One of NGP's policy tools is the Domestic LPG Penetration Program (DLPGPP), which focuses on increasing LPG utilization for household activities (Lasisi, 2021). These policies bring about an increase in LPG refilling plants across the country.

An LPG refilling plant is a facility where large quantities of LPG are stored and then distributed in smaller quantities to consumer-owned storage cylinders, which are transported to other locations. However, operating an LPG refilling plant involves significant risks; during handling, storage, and transportation, various hazards are encountered (Bariha *et al*., 2023). Given that LPG is highly flammable, there are multiple potential hazards, including explosions, fires, BLEVE (boiling liquid expanding vapour explosion), and confined or unconfined vapour cloud explosions (Giannelli *et al*., 2023). These incidents can result in minor, major, or even fatal consequences, leading to the loss of both manpower and financial resources.

The major components of an LPG Refilling plant are presented on a schematic layout in Figure 1, as described by Bariha *et al*., 2023.

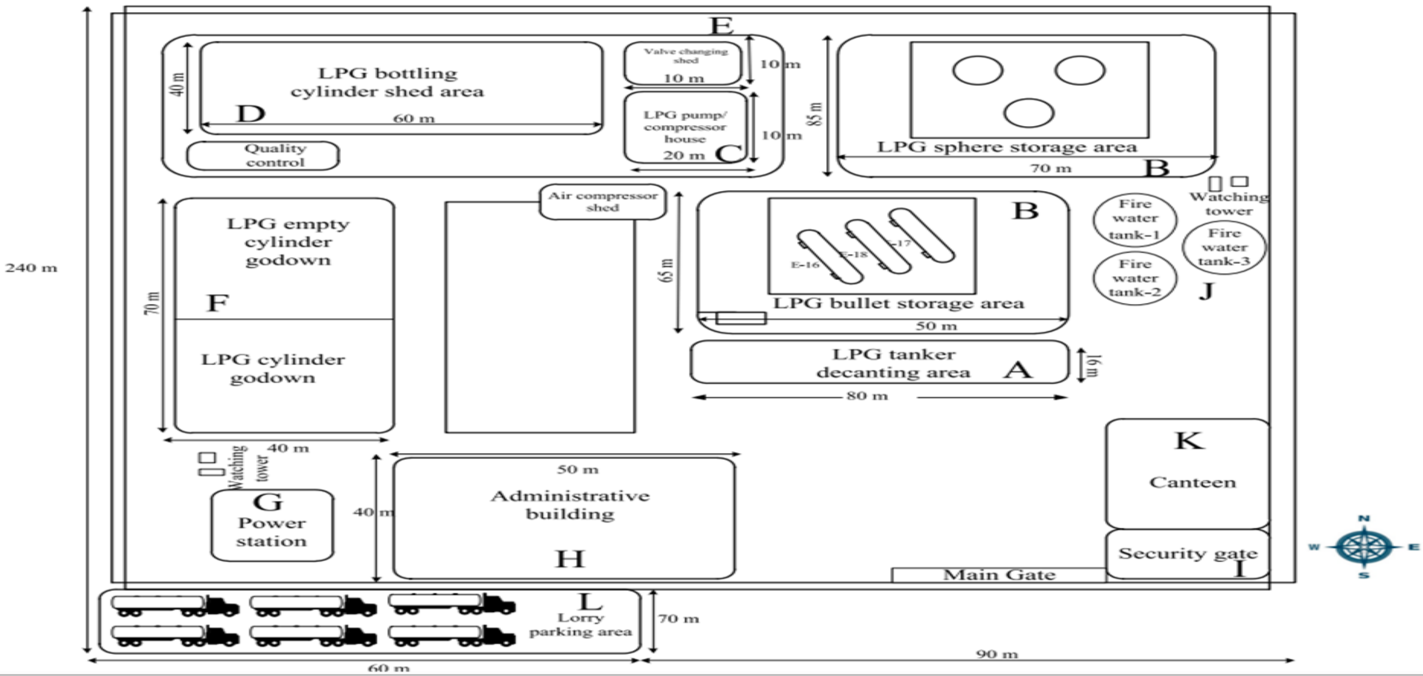


Figure 1: Schematic Layout of an LPG Plant (Bariha *et al*., 2023)

This massive promotion and adoption of LPG, bringing about numerous LPG plants within populations, ignites the need to assess the safety integrity of these plants, in efforts to establish how safe the community is from these increasing hazards. As such, this paper reviews literature to generate background on SIL of LPG plants before using a case study to assess SIL of Nigerian LPG plants.

1.2 Safety in LPG Plants

Advances in LPG adoption and utilization are not without their challenges. Several safety-related incidents have been recorded. It is worth mentioning the Baruwa incident in Lagos (October 2020), the Agbor incident in Delta (January 2022), the loss of containment in Agboju (April 2021), among others (Akpan, 2021). Safety always remains a serious concern in the LPG industry. Accidents resulting from improper handling, storage, and transportation of LPG can have deleterious consequences. handling safety problems through strict regulations, training, and public awareness campaigns is essential for the sustainable growth of the industry (Oluwabukola, 2023).

LPG is a colorless, odorless, and highly flammable gas that liquefies under pressure. Inhalation in small quantities is non-toxic; however, at reasonable quantities for a prolonged period, it can cause respiratory problems (Alkam, 2024). Its physical properties are a function of its composition. Typically, the specific calorific value of LPG is 46.1 MJ/kg. Its relative density resonates between 0.50 – 0.52 for propane and 0.56 – 0.59 for butane. When compared to other fuels, LPG is a relatively safer fuel with a high ignition temperature (Hashem *et al*., 2023). Propane ignites at about 850 – 950 ºF (450 – 510 ºC), superior to gasoline, which

ignites at about 495 ºF (257 ºC) (Ihemtuge & Aimikhe, 2020). LPG is obtained as a by-product of natural gas and crude oil processing, with a major composition of propane (C_3H_8) and butane (C_4H_{10}) (Turkiman *et al*., 2022).

LPG can potentially cause harm (hazardous) right from its production up to its end use and safe disposal of combustion products. Therefore, management of LPG risks and safety has a wide scope (Nyabuto, 2021). To effectively manage these hazards, it is important to primarily understand the product itself as well as the exercise of control under all conditions. Isolated LPG is typically not hazardous; however, even a slight loss of containment by a small leakage must be dealt with immediately and accordingly to prevent disastrous events (World LPG Association, 2014).

As a result of the nature of LPG products and the operations of an LPG refilling plant, several hazards have been identified. Table 2 gives a summary of the major hazards in an LPG plant.

An important aspect of safety in LPG plants is the assessment of process safety risks. Maduabuchi (2023 A) discusses the ongoing challenges in the Nigerian petroleum industry regarding the assessment of cumulative process safety risks. The study indicates that the management and monitoring of asset integrity systems are often inadequate, which leads to increased vulnerability to accidents. Maduabuchi (2023 B) emphasizes that the accumulation of process safety risks significantly influences major accident prevention in petroleum operations, highlighting the importance of real-time risk assessment models that account for deviations in safety-critical barriers.

Table 2: Major Hazards in an LPG Refilling Plant (Singh & Premi, 2015)

S/N	Hazard	Occurrence Factors	Measures
1.	Explosion	Rapid oxidation.	
2.	Fire	Ignition by any external source.	Fire hydrant system, extinguisher
3.	BLEVE (boiling liquid expanding vapor)	It occurs when LPG containers are accidentally surrounded by fire.	BLEVE can only be controlled by fire prevention (initial start-up of fire), sprinkler systems, and a fire hydrant system.
4.	Confined and unconfined vapor cloud explosion	Confined explosions occur within a containment, such as a vessel or pipework. Unconfined explosions occur in the open air.	For controlling unconfined Vapour cloud explosions, use proper ventilation, and GMS for vapor and gas detection.
5.	Gas leakage	The bursting of the storage tank, leakage of liquid LPG from the bottom line, or rupture of any cylinder	Gas monitoring system, frisking gate, proper handling of cylinders during filling and transportation
6.	Carousel	Carousel failure during the filling of cylinders	Proper usage of the carousel and continuous maintenance

Moreover, industrial hazard identification and safety measures assessment are crucial for mitigating risks in LPG facilities. Afube & Nwaogazie (2019) conducted a study that identified various hazards within the chemical industry, which is relevant to LPG operations due to the similarities in handling hazardous materials. Their findings indicate that high noise levels, explosion risks, and inadequate safety measures contribute to workplace injuries and fatalities. This highlights the necessity for rigorous safety protocols and training for personnel working in LPG plants to reduce the risk of accidents.

The most common hazards relating to LPG are fire and explosion (Servestani *et al*., 2023). Since any uncontrolled release of LPG can have serious consequences, the LPG safety programme, therefore, aims to prevent uncontrolled releases by containment. However, other hazards are prevalent in the refilling plant, arising from storage, handling, distribution, and use (WLPGA, 2019).

Jia *et al*. (2022) evaluated fire risk for petroleum product handling facilities in the Niger Delta region and revealed a history of fire and explosion incidents in LPG stations. The study emphasizes the need for improved fire safety measures and emergency preparedness plans to protect both workers and the surrounding communities. Additionally, Akpi (2023) assessed disaster risk preparedness in LPG stations in Port Harcourt, identifying key measures such as safety training, emergency response plans, and leak detection systems as essential for enhancing safety in these facilities.

To ensure safe operations, the facility layout of the LPG refilling plant should be well-designed and clear from other buildings with enough space to allow operations without risk (Kolawale *et al*., 2020). Tanks, pumps, and pipelines should be designed according to approved standards. Tanks should be equipped with temperature and pressure indicators and a sprinkler system to regulate temperature and pressure automatically (Jegede, 2024).

1.3 Regulatory Guidelines

The following are regulatory guidelines of the Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA), 2020, for the establishment of LPG refilling facilities in Nigeria (DPR, 2020):

Minimum Design, Construction, and Installation Requirements (DPR, 2020)

i. Generally, all design, construction, installations, and operations must comply with Mineral Oils Safety Regulations (MOSR, 1997) and other applicable codes and standards from bodies like the Standard Organization of Nigeria (SON), American Society of Mechanical Engineers (ASME), National Fire Protection Authority, American Welding Society as well as other standards recognized by the NMDPRA Chief Executive officer.

ii. All design, construction, installations, and mitigation measures shall be applied to reduce hazards of transfer, storage, and use of LPG to as low as reasonably practicable (ALARP).

iii. Active engagement of authority representatives in all activities and mandatory witnessing of project milestones, including tank burial, integrity tests, and tank calibration by the authority representatives.

iv. Commissioning of all critical equipment and piping according to the manufacturer's specifications after installation.
v. Any site chosen for the application should be wide enough to ensure a safe distance between the facilities from other structures.
vi. The site should be accessible by the roadside and away from physical hazards such as gridlines, pipelines, and other rights of way (ROW). It should be a minimum of 100 m radius away from other third-party LPG refilling plants.
vii. Pressurized storage vessels should be 7.5 – 50 m away from adjoining properties, depending on the capacity and nature of the installation. Drainage from plants should not be channeled to the water body, and contaminated water must be treated before release.
viii. Proper risk assessment and hazardous area classification must be carried out to ensure a safe layout design and daily operations of the facility.
ix. Tank farms, refilling shades, dispensers, vent pipes, road tankers, and buildings must be properly laid out to protect hazardous areas from ignition sources, provide escape routes in case of emergency, and ensure safe access to road tankers and service vehicles.
x. All dangerous areas should be in open-air ventilation and away from other buildings. Electrical connections shall be made following the manufacturer guidelines and be of integrity to safeguard from explosion.
xi. Storage tanks and vessels should be located in places with safe access and clear surroundings of other buildings. The fill point for the tank should be located such that the movement of other vehicles does not pose a risk to the dispensing tanker.
xii. Materials of construction for tanks and piping should be strong enough to provide a good level of safety and environmental protection. Materials such as carbon steel, reinforced fiberglass, and other acceptable materials by NMDPRA should be employed.
xiii. Pressure safety valves, pressure and temperature gauges, and other important safety equipment should be fitted on all storage tanks. Over-pressure protection devices, which work under normal and emergency conditions, should be fitted. Each tank shall be provided with a sprinkler system for temperature control.
xiv. Manually controlled relief valves should be provided on each tank to release pressure during maintenance. Storage tanks shall be separated by a distance of 1 – 1.5 m for capacities below 60 MT and ¼ the sum of the diameters of two adjacent tanks for capacities above 60 MT. Relief valves should be 3 m away from adjoining properties for a capacity of 10 MT and below, or 7.5 m for higher capacities.
xv. All pumps that are not submersible should be secured and mounted on a concrete stand or bolted to a rigid frame. Product dispensers should be mounted, secured, and in an open, ventilated area where cylinders can be easily filled.
xvi. Installations should have electrical continuity and be bonded and earthen to comply with international standards, i.e., the Petroleum Model Code of safe practice, part 1, and other equivalent international standards.
xvii. Buildings, canopies, and other installations should be made in accordance with building standards. Refilling shade and signage should be made of inflammable material, and their height should not obstruct ventilation.
xviii. Crucial points such as electrical wiring/distribution systems, luminaries, and lighting signs should be protected from incandescent. Appropriate industrial colors should be used to paint piping, and specified fire extinguishers by the Federal Fire Service should be kept at strategic locations.
xix. Cylinders should not be stored in the refilling area. A fire safety mat should be used to protect the floor of the refilling shed to prevent spark ignitions from accidental cylinder falls.
xx. Customers should be separated and kept away from the refilling area. Routes and parking areas should be marked, and alternative escape routes away from LPG facilities should be provided for both staff and customers.
xxi. The fire protection system should be designed to prevent fire and explosion and minimize as much as possible its impact should it occur.
xxii. A minimum of 15 cubic meters of clean water should be made available, firefighting gadgets kept on alert and at least two fire extinguishers with minimum ratings of 21A and 183B as defined by MSA EN 3-7:2004, applicable for gaseous fire should be available at accessible locations.
xxiii. Where a firewall is used, it shouldn't be more than two sides (usually one side is sufficient), should be solid and made using masonry or reinforced concrete, capable of resisting 30 minutes of fire. Shall not be less than the vessel height and shall not be less than 3 m away from the vessel. It should not impair natural ventilation and should provide 60-minute protection where it shields the population.

The above are some of the major regulatory requirements for the establishment and operations of LPG plants in Nigeria. These guidelines will be used as a yardstick for the evaluation of SIL in the LPG plants.

2.0 UNDERSTANDING SAFETY INTEGRITY LEVEL (SIL)

2.1 Definition of SIL

The International Electrotechnical Commission (IEC) defined safety as liberty from undesirable risks in its 61508 standards. However, this definition provides no measurement scale, and since safety and reliability are different, accurate safety measurement cannot be established by only assessing the system's overall reliability. The standard, therefore, proposes a rate of dangerous failure as a means to measure the efficiency of a safety function. Within the same standard, safety integrity is defined as the propensity of safety-related systems to adequately discharge their required function at all stated conditions within a specific time interval. It further defines SIL as a discrete level for defining safety integrity requirements of safety functions (Redmill, 1999).

SIL is defined as a score of probability that the SIF operating within a unit process effectively delivers its function in a certain range of time (Dan *et al*., 2015). Safety integrity levels are classified according to the probability of failure on demand (PFD) for a given safety instrumented function (SIF). ANSI/ISA84.01-1996 classifies this PFD in the range of one to three, while IEC 61508 and 61511 are in the range of one to four (Marszal & Scharpf, 2002).

2.2 Standards Governing SIL

OSHA 29 CFR Part 1910.119 in the United States, under its Process Safety Management (PSM) section, requires mechanical integrity assurance from organizations for all their safety-critical controls and emergency shutdown systems. Seveso Directive (96/82/EC) promulgates similar requirements in the European Union (Marszal & Scharpf, 2002). These are requirements that set the path for SIL assessment.

Instrumentation, Systems, and Automation (ISA) Society promulgated industry standard ANSI/ISA-84.01-1996 to promote compliance with the PSM regulation. This standard aligns closely with IEC 61511 and focuses on the application of safety instrumented systems (SIS) in the process industries. Its scope covers the design, implementation, and maintenance of SIS to ensure safety in chemical and petrochemical industries. It emphasizes a lifecycle approach to managing safety and specifies targets for SIS based on the required SIL level (ISA, 2018).

The International Electrotechnical Commission (IEC) created a similar document, IEC 61508, which is an umbrella standard that covers numerous industries (Marszal & Scharpf, 2002). Often referred to as the "mother" standard, it establishes the foundation framework for functional safety applicable across industries. The scope of IEC 61508 provides a comprehensive guide for the design, development, and operation of electrical, electronic, and programmable electronic (E/E/PE) safety-related systems. With a lifecycle approach, it introduces methodologies for SIL determination, such as risk graphs, fault tree analysis, and layer of protection analysis (LOPA), as well as hardware and software requirements (International Electrotechnical Commission, 2010).

IEC standard 61511 is the process-sector-specific standard that falls under the IEC 61508 umbrella (Marszal & Scharpf, 2002). Its scope addresses the design and management of SIS in sectors like oil and gas, pharmaceuticals, and food processing. These standard stresses the importance of conducting thorough hazard and operability studies (HAZOP) and LOPA for effective risk reduction and emphasize functional safety assessments and periodic testing to ensure continued compliance with SIL requirements. It also tailors the generic requirements of IEC 61508 for easier application in process industries, making it more user-friendly for industry professionals (International Electrotechnical Commission, 2016).

Other standards include IEC 62061 on the safety of machinery, and functional safety of safety-related electrical, electronic, and programmable electronic control systems. ISO 138498-1 on machinery-safety-related parts of control systems, the non-technology dependent standard for the control system, EN 501529, EN 50495, and EUROCAE ED-12B (Gabriel *et al.,* 2018)

2.3 SIL Levels and Their Implications

Based on the guidelines for SIS by IEC 61508, SIL is categorized into four grades. The Center for Chemical Process Safety (CCPS) defines these four categories as thus (Dan *et al*., 2015):

SIL 1: ordinarily, SIFs with SIL 1 are used employing a unit sensor, a unit SIS logic solver, and a unit final control element.

SIL 2: The SIFs under this level are normally fully independent, from the sensor to the SIS logic solver and the final control element.

SIL 3: The SIFs here are also fully independent as in SIL 2. To achieve low PFD, cautious design and regular proof tests are required. Due to the high cost associated with this architecture, only a few SIL 3 SIFs are available in most companies.

SIL 4: The SIFs under SIL 4 are uncommon due to their difficulty in design and maintenance. Table 3 shows the different ranges of PFD for determining SIL.

Table 3: Safety Integrity Level Categorization *(Dan et al., 2015; Hidayatullah & Musyafa, 2015; Marszal & Scharpf, 2002)*

SIL Category	PFD	Risk Reduction Factor (RRF)
Not Recommended (NR)	$1 \leq PFD$	$RRF \leq 1$
SIL 0	$10^{-1} \leq PFD < 1$	$1 < RRF \leq 10$
SIL 1	$10^{-2} \leq PFD < 10^{-1}$	$10 < RRF \leq 100$
SIL 2	$10^{-3} \leq PFD < 10^{-2}$	$100 < RRF \leq 1000$
SIL 3	$10^{-4} \leq PFD < 10^{-3}$	$1000 < RRF \leq 10000$
SIL 4	$10^{-5} \leq PFD < 10^{-4}$	$10000 < RRF \leq 100000$
No Standard Safety Requirement (NSSR)	$PFD < 10^{-5}$	$RRF > 100000$

3.0 RISK ASSESSMENT IN LPG REFILLING PLANTS

3.1 Hazard Identification and Risk Assessment (HIRA)

To identify potential hazards and provide measures based on individual risk priorities, industries use the tool HIRA. After hazard identification, to establish the significance of the hazards, qualitative and quantitative risk assessment techniques are used. The blend of quantitative, deterministic, and probabilistic methods made up HIRA. Deterministic methods are concerned with measuring risk receptors like people, environment and equipment, the products, and the equipment used. The probabilistic methods capitalize on the tendency or recurrence of incidents or the occurrence of potential incidents. Finally, quantitative methods provide a numerical assessment of data (Saisandhiya & Babu, 2020).

Hazard identification is often considered the identification of hazardous characteristics and the risk that is of concern (Wells, 1997). The proactive procedure of recognizing hazards and eliminating/reducing the risk of occupational injury or damage to property, equipment, and/or the environment is termed hazard identification. Hazards and potential hazards in the workplace must be identified to effectively eliminate or control them, and to demonstrate commitment to occupational safety and health. Hazard identification is the process of investigating individual work areas and tasks to identify all the hazards that are intrinsic to the job. It is the initial phase in the risk assessment of a process (Saisandhiya & Babu, 2020).

Two possible reasons for hazard identification are obtaining an array of hazards for further investigation using other risk assessment techniques, which is often termed "failure case selection". And secondly, to carry out a significant study qualitatively and identify mitigation measures, which is termed "hazard assessment". To effectively conduct hazard identification, a review of potential incidents and hazardous

Scenarios must be conducted after establishing a screening procedure (Saisandhiya & Babu, 2020).

Be it a process plant or any type of facility, identification of hazards is essential in its safe design and operations. The method or tools used in hazard identification vary depending on the situation. However, they are all rigorous, systematic, and a function of the know-how of the team directly or indirectly (Crawley & Tyler, 2003). Different techniques are used in the oil and gas industry for hazard identification, which include hazard identification (HAZID), hazard analysis (HAZAN), hazard and operability study (HAZOP), Dow fire and explosion index, Mond index, checklist, and what-if analysis (Gabhane & Kanidarapu, 2023).

The risk of an event is the probability or likelihood of an unwanted event occurring in a particular circumstance, within a given time frame. Risk assessment, on the other hand, is a composite process of establishing the worth of identified hazards and risk to the parties affected by the decision. It is multifaceted, comprising the identification of hazards, estimation of their frequencies, analysis of their consequence, evaluation of the risks, and analysis of sensitivity to prioritize risks for further studies before decision-making (Wells, 1997). Risk assessment is also defined as the method of assessing the risks of identified hazards to better understand the nature of these risks (Sandeep & Rajiv, 2015).

HIRA in liquefied petroleum gas (LPG) refilling plants is crucial to ensure safety and prevent accidents. Different methodologies have been proposed to enhance HIRA processes in such facilities. Kwon (2024) emphasizes the importance of a structured framework for hazard identification during simultaneous operations, which is particularly relevant in complex environments like LPG refilling plants, where multiple tasks occur simultaneously. Furthermore, Gabhane & Rao (2023) propose the use of neural networks in environmental risk assessments, highlighting the potential of advanced computational techniques to model and predict hazardous scenarios effectively. This approach aligns with the findings of Terzioglu and Iskender (Terzioglu & Iskender, 2021), who stress the necessity of accurate modeling to predict the consequences of gas leakages and explosions, thereby underscoring the importance of predictive analytics in HIRA.

Different authors have also explored specific tools and methodologies for conducting HIRA in LPG refilling plants. Rajakarunakaran *et al*. (2015) introduce fuzzy fault tree analysis combined with the experience of experts as a robust method for evaluating risks, which allows for the incorporation of uncertainties inherent in hazard assessments. This method contrasts with traditional approaches, providing more understanding of potential risks. Additionally, the work of Bariha *et al*. (2016) discusses the significance of incident analysis in identifying failure modes and their consequences, advocating for a comprehensive review of past incidents to inform future safety measures. The integration of these diverse methodologies provides a multifaceted perspective on HIRA, suggesting that a combination of predictive modeling, expert input, and historical analysis may yield the most effective risk assessment strategies in LPG refilling operations.

3.2 Tools and Techniques for Risk Assessment

Risk assessment as a methodical process is used in various activities, particularly in industrial settings such as liquefied petroleum gas (LPG) refilling facilities to identify, evaluate, and prioritize risks. The tools and techniques for risk assessment can be categorized into three main types: qualitative, semi-quantitative, and quantitative methods. Qualitative techniques, such as Hazard and Operability Study (HAZOP) and Failure Mode and Effects Analysis (FMEA), rely on expert judgment and descriptive analysis to identify potential hazards and their consequences without numerical data (Oliveira *et al*., 2017).

Semi-quantitative methods, like the Risk Matrix, assign numerical values to the likelihood and severity of risks, allowing for a more structured approach to risk prioritization (Raso, 2023). Quantitative techniques, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), utilize mathematical models to calculate the probabilities of different failure scenarios and their impacts, providing a more precise assessment of risk levels (Waziri *et al*., 2017).

In the context of LPG refilling facilities, several techniques are commonly employed to assess SIL. The use of the IEC 61508 standard for functional safety is prevalent, which incorporates both qualitative and quantitative assessments to determine the necessary safety measures for systems handling hazardous materials (Choi *et al*., 2020).

Additionally, LOPA is frequently utilized to evaluate the effectiveness of existing safety measures and to identify any gaps in risk management strategies (Moolla *et al*., 2015). In Nigeria, the application of these techniques is particularly relevant due to the increasing number of LPG refilling stations and the associated risks. Studies have shown that the integration of local knowledge and expert opinions into risk assessment processes enhances the effectiveness of these evaluations, particularly in the context of developing economies with limited resource distribution (Olumide, 2023; Anigilaje, 2024).

Furthermore, the Analytic Hierarchy Process (AHP) has gained attention as a decision-making tool in risk assessment, allowing stakeholders to prioritize risks based on multiple criteria (Oliveira *et al*., 2017). This method is particularly useful in Nigeria, where diverse factors such as economic conditions, regulatory frameworks, and environmental considerations must be taken into account. The combination of qualitative, semi-quantitative, and quantitative techniques, along with localized approaches, provides a comprehensive framework for effectively managing risks in LPG refilling facilities. With continuous changes in the industry, the adoption of these methodologies will be essential for ensuring safety and compliance with international standards.

Hazard and Operability Study (HAZOP)

HAZOP stands for hazard and operability study and is defined as a qualitative risk assessment technique that is structured and uses "guide words" along with "parameters" to assess possible deviations in a process node (Vijay & Sankar, 2023). It is conducted by a set of experts who scrutinize the LPG refilling process to identify deviations from the intended design (Oubellouch & Aziz, 2024). HAZOP as a systematic hazard identification method is thorough and structured to pinpoint different challenges that can hinder the operations of a process, and the risks equipment holds that can affect humans/facilities in the system. It is a proactive method to ensure systems run smoothly and safely. HAZOP systematically integrates the search for causes of incidents, and consequences resulting from them and provides recommendations to minimize the impact of potential risks identified (Suryadi *et al.,* 2023).

Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a systematic, inferential failure analysis technique using a top-down strategy to identify the root causes of an undesired event or failure in a system using Boolean logic. In FTA, a principal event of concern is identified, which is then broken into intermediate and basic events, which are connected using logical operators (Zacchaeus *et al.,* 2023). FTA is more useful in highly hazardous industries like nuclear, aerospace, oil & gas, and chemicals. Kim & Lee (2024) used FTA as part of a probabilistic safety assessment to identify the risk of seismic events on gas plants. This helped them identify components at high risk and the quantification of such hazards.

In contrast to other methods like HAZOP, Quantitative Risk Assessment (QRA), LOPA, Bow-Tie Analysis, and ETA, which are either focused on qualitative analysis, require extensive data, or analyze consequences rather than causes, FTA blends root causes abilities with quantitative risk evaluation, making it instrumental in drafting preventative plans (Yousfi *et al.,* 2012).

Layer of Protection Analysis (LOPA)

According to the IEC61511 standard, LOPA is a semi-quantitative method that is primarily aimed at estimating the level to which independent protection layers (IPLs) are enough to prevent or contain risk to a tolerable limit for a particular harmful scenario by analyzing and rating the risk (Eltahan *et al*., 2024). LOPA is a simple method of risk assessment that shows the qualitative and quantitative ability of protection layers to prevent or mitigate danger from happening (Hidayatullah & Musyafa, 2015).

LOPA is a semi-quantitative risk assessment technique that is utilized to calculate risk frequency for decision-making (Ghasempour *et al*., 2021). LOPA is carried out to group incidents according to the views of specialists and to determine failure rate frequency as well as the probability of failure on demand (Dan *et al*., 2015). It evaluates risks according to the order of magnitude for selected incident scenarios and develops information derived from qualitative risk assessment techniques like HAZOP. It is usually carried out for a single-hazard consequence pair (Fayyaz, 2022).

LOPA techniques grew from the late 1980s to the 1990s to help in evaluating major protection layers that can avert consequences from incidents such as fire, explosion, or release. It is an all-inclusive method that identifies major safeguards, categorizes them, determines their adequacy and dependency, as well as assesses their ability to act when demanded (Sibilski, 2020). It is a semi-quantitative technique used to examine whether mitigation measures existing for a specific process safety incident (i.e., Initiating Event, or I.E.) are adequate. LOPA gives an order-of-magnitude assessment of a particular hazard (Olsen, 2024). It determines the level of efficacy of existing IPLs to prevent/mitigate an I.E., whose frequency is denoted "IEF". LOPA provides only two outcomes, i.e., either the protective measure works when demanded or not. These possible outcomes are denoted either by the probability to work on demand (PWD) or the probability to fail on demand (PFD), whose sum is unity for any independent protection layer (IPL). In LOPA analysis, Equation 1 is the key (Sibilski, 2020).

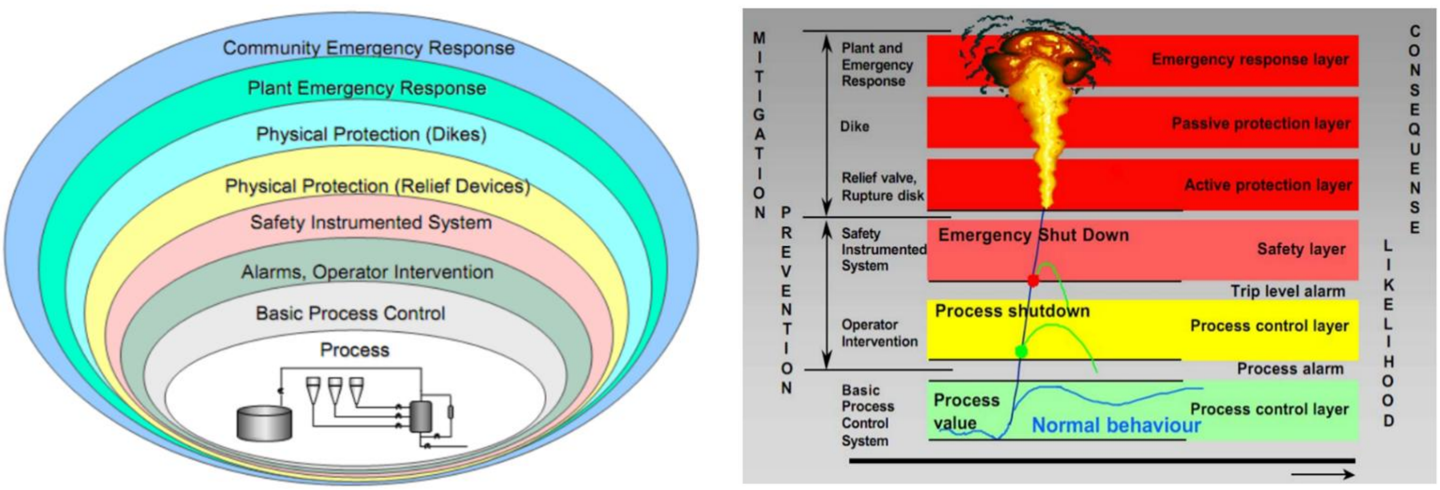
$$f_i^c = IEF_i \times PFD_{i1} \times PFD_{i2} \times \ldots \times PFD_{ij} \qquad (1)$$

Where f_i^c is the residual frequency occurrence for scenario "i" per time, which is a number relatively used for the comparison of different layers and scenarios. IEF_{i1} is the frequency of the initiating event for scenario "i" per time, PFD_{i1} is the probability of failure on demand of the independent protection layer "1" for scenario "i" and PFD_{ij} is the probability of failure on demand of the independent protection layer "j" for scenario "i".

4. SIL ASSESSMENT FRAMEWORK

4.1 Independent Protection Layers (IPLs)

Independent protection layers are safeguards used to avert or minimize the consequences of an incident scenario. The scenario is the product of cause and consequence (Lyon & Popov, 2020). The key characteristics of an IPL are its effectiveness in preventing the scenario from ensuing a negative consequence, and its independence from the initiating event as well as other IPLs. An IPL can be preventive, as in alarms and emergency shutdown, when it stops the hazardous scenario from occurring, or mitigative, as in containment and emergency response, when it minimizes the damage caused by the unwanted scenario (Fayyaz, 2022). Figure 2 (A & B) shows the major IPLs used in chemical process industries and whether they are preventive or mitigative.



(A) (B)

Figure 2: (A) Typical independent protection layers used in chemical process industries, (B) IPL functions, preventive or mitigative (Fayyaz, 2022).

4.2 Identifying Safety Instrumented Functions (SIFs)

Functional safety is defined as the capacity of a system to reduce safety risks in the event of a breakdown (Tchórzewska-Cieślak *et al.,* 2021). When such a breakdown occurs, the process or machine might become hazardous to personnel, equipment, or the environment. To simplify, functional safety ensures the safe operation of a process throughout its entire cycle of operation against all risks (Kallambettu & Viswanathan, 2018).

Functional safety is getting critical as systems become automated, and technology now spearheads industrial processes. The goals of functional safety in machinery are avoiding and controlling recurring and non-recurring faults (Niazi, 2022).

Functional safety systems are active systems. Active systems react based on input signals they receive to trigger actuators, motors, or other devices to achieve safety (Tchórzewska-Cieślak *et al.,* 2021). They are active rather than passive, in that they listen for signals and then react to them. A safety function (SF) is a complete arrangement that comprises a sensor, logic solver, and actuator, married together to solve a particular safety challenge. If the safety function employs instrumentation to achieve this task, it is termed a safety instrumented function (SIF). Figure 3 shows the typical design architecture of a safety instrumented function. A safety instrumented system (SIS) is an aggregation of SIFs stacked together to guarantee the safety of a process. SIS should not be misinterpreted as a logic solver, as popularly believed in some circles. Logic solver is a part of the SIS as shown in Figure 4, and the same logic solver can be used for different SF within the same SIS (Abhisam, 2021).

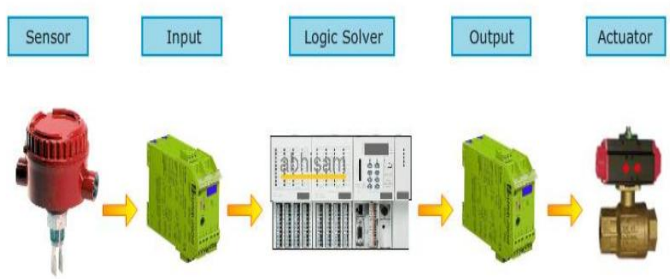


Figure 3: Typical design architecture of a safety instrumented function (Abhisam, 2021)

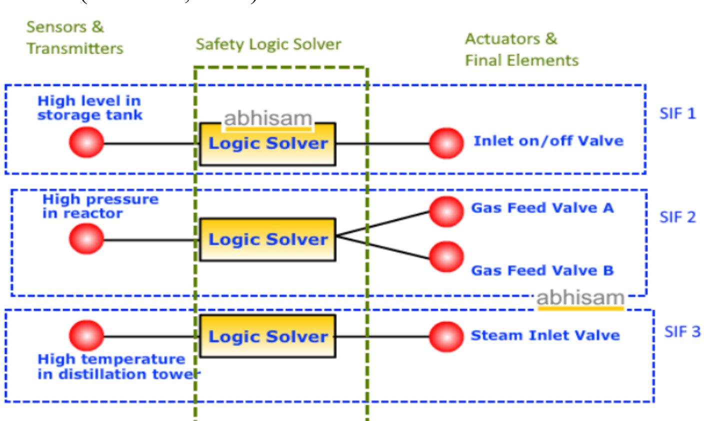


Figure 4: Diagrammatic Representation of a Safety Instrumented System (Abhisam, 2021)

International Electrotechnical Commission's (IEC) standards classify safety instrumented functions into two categories depending on the frequency of demand for the specified safety function. SIFs working on low demand are expected to be called upon less than once per year. An example is an overfill protection or an emergency shutdown system. On the other hand, high-demand SIFs are required to act more than once per year, in some cases, continuously present. A good example is the brake of a car, which is applied frequently whenever the car is operated (Abhisam, 2021).

4.3 Determining Risk Reduction Requirements

Determining risk reduction requirements in SIL assessments is essential for ensuring the safety of operations in liquefied petroleum gas (LPG) facilities (Attia & Sinha, 2020). The SIL assessment process typically follows a structured methodology as outlined in the IEC 61508 standard, which emphasizes the importance of hazard identification, risk assessment, and necessary determination of safety measures to realize a tolerable level of risk (IEC, 2010). A key technique used in this process is LOPA, which determines the efficacy of existing protection layers and identifies further risk reduction measures needed to meet the desired SIL (Chastain-Knight, 2019). This method allows for a systematic assessment of both the probability of hazardous events and the effectiveness of safety systems in place, thus providing a clear pathway for determining risk reduction requirements.

In Nigerian LPG plants, the implementation of SIL assessments often incorporates local operational challenges and regulatory frameworks. For instance, the use of HAZOP studies is prevalent, where multidisciplinary teams analyze processes to identify deviations that could lead to hazardous situations (Hidayatullah & Musyafa, 2015). Additionally, Fault Tree Analysis (FTA) is frequently employed to quantitatively assess the probability of failure events and their consequences, providing a detailed understanding of risk factors associated with LPG operations (Attia & Sinha, 2020). The integration of these techniques is crucial in Nigeria, where the LPG sector is rapidly expanding, and the need for robust safety measures is heightened due to the potential for catastrophic incidents related to gas handling and storage.

Furthermore, the assessment of risk reduction requirements in Nigerian LPG plants emphasizes the importance of regulatory compliance and stakeholder engagement (Oubellouch & Aziz, 2024). Local regulations often dictate specific safety standards that must be met, and involving stakeholders, including employees and local communities, is important in risk identification and the development of effective preventive strategies (Nwapi, 2020). The combination of international standards, local practices, and stakeholder involvement creates a comprehensive framework for determining risk reduction requirements in SIL assessments, ultimately enhancing the safety and reliability of LPG operations in Nigeria. As the industry continues to evolve, ongoing training and capacity building for personnel involved in risk assessments will be crucial for maintaining high safety standards and adapting to emerging risks.

4.4 Assigning SIL Levels

Assigning Safety Integrity Levels (SIL) during SIL assessments in liquefied petroleum gas (LPG) plants is a critical process that ensures the safety and consistency of an SIS. SIL is a scale of the dependability of safety functions provided by these systems, and it is determined based on the risk associated with the hazardous events that the SIS is designed to mitigate. The IEC 61511 standard provides a structured approach for assigning SIL levels, which involves identifying potential hazards, assessing the associated risks, and comparing these risks against predefined risk tolerance criteria Baybutt (2013). This process typically includes qualitative and quantitative risk assessments, such as HAZOP and LOPA, to assess the efficacy of existing safety measures and identify any necessary enhancements (Wang *et al*., 2022).

In practice, the assignment of SIL levels involves a systematic methodology that includes several steps. First, a comprehensive hazard identification process is conducted to determine the potential failure scenarios that could lead to hazardous events. Following this, a risk assessment is performed to assess the probability and consequences of these events, often utilizing tools such as Fault Tree Analysis (FTA) or Failure Mode and Effects Analysis (FMEA) (Feng *et al*., 2016). The results of these assessments are then used to determine the required SIL for each SIF based on the severity of the consequences and the rate of occurrence of the identified hazards. This approach ensures that the SIL assigned reflects the extent of risk reduction necessary to realize an acceptable safety level (Feng *et al*., 2016).

In Nigerian LPG plants, the assignment of SIL levels is particularly important because of the rising demand for LPG and the associated safety risks. The application of international standards, such as IEC 61511, is complemented by local regulations and practices that consider the unique operational challenges faced by these facilities. For instance, the integration of local knowledge and expertise in the risk assessment process enhances the effectiveness of SIL assignments, ensuring that they are contextually relevant and adequately address the specific risks present in the Nigerian LPG sector (Gabhane & Rao, 2023). Furthermore, stakeholder engagement, including input from operational personnel and regulatory bodies, plays an important role in the SIL assignment process, fostering a culture of safety and continuous improvement within the industry. As the LPG sector in Nigeria continues to grow, the ongoing refinement of SIL assessment methodologies will be essential for maintaining high safety standards and preventing incidents.

4.5 Verification and Validation

Verification and validation (V&V) of Safety Integrity Level (SIL) assessment results are crucial steps in ensuring that safety instrumented systems (SIS) in liquefied petroleum gas (LPG) plants function reliably and effectively mitigate risks. Verification involves checking that the SIL assessment process has been conducted correctly, ensuring that all necessary steps are followed, and that the results are consistent with the established methodologies (Gabriel *et al.,* 2018). Validation, on the other hand, assesses whether the SIL levels assigned accurately reflect the safety requirements needed to manage identified risks (Chastain-Knight, 2019). This dual approach helps to ensure that the safety measures implemented are not only theoretically sound but also practical and effective in real-world scenarios.

A common technique for V&V in SIL assessments is the use of independent reviews and audits. These reviews often involve multidisciplinary teams that evaluate the SIL assessment process, including hazard identification, risk assessment, and the rationale behind the assigned SIL levels. The use of structured methodologies such as LOPA and FTA can facilitate this process of verification and validation by providing clear documentation of the assumptions and calculations made during the assessment (Cialkowski, 2016). Additionally, the application of the SecureSafety (SeSa) methodology, which integrates security aspects into functional safety analysis, has been shown to impact SIL calculations directly, thereby necessitating thorough validation of the results (Grøtan *et al.,* 2007).

5. TECHNOLOGICAL AND METHODOLOGICAL ADVANCEMENTS

Safety Integrity Levels (SIL) in Liquefied Petroleum Gas (LPG) refilling plants continue to witness technological advancements such as Artificial Neural Networks (ANN), Internet of Things (IoT) applications, and digital simulation techniques. These advancements are essential in enhancing safety assessments and operational efficiency in the LPG sector.

Artificial Neural Networks (ANN) have become powerful tools for predicting failure pressures and assessing the integrity of infrastructure in LPG facilities. Kumar *et al*. established how blending ANN with Finite Element Analysis (FEA) significantly reduces the time required for accurate failure pressure predictions in corroded pipelines, which is directly applicable to the integrity assessments of LPG storage and distribution systems (Kumar *et al*., 2021). This integration allows for rapid analysis of complex data sets, enabling stakeholders to make informed decisions regarding maintenance and safety protocols.

Various studies explored the application of ANN in risk assessment frameworks. Hà *et al*. in their study proposed a comprehensive risk assessment framework that utilizes ANN to analyze risk factors determined via FMEA (Hà *et al*., 2018). This approach can be adapted to LPG refilling plants to systematically evaluate potential hazards and their impacts on safety integrity. The predictive abilities of ANN can enhance the accuracy of risk assessments, allowing for proactive safety measures to be implemented.

Artificial Intelligence (AI) has been recognized as a transformative tool in the assessment of safety integrity in the Nigerian LPG sector. Maduabuchi highlights the development of a conceptual framework that integrates AI into the visualization of cumulative process safety risk for petroleum operations (Maduabuchi, 2024 A). This framework aims to address the complexities of managing safety-critical barriers, which are often in a state of flux, making it difficult to maintain an objective and auditable risk management system (Maduabuchi, 2024 B). By utilizing AI, the framework can identify probable risks and generate real-time insights by assessing large amounts of data, thereby facilitating more informed decision-making in safety management.

Moreover, the integration of AI with existing risk assessment methodologies can enhance the predictive capabilities of safety evaluations. The application of AI algorithms in conjunction with traditional methods like FMEA can improve the identification of hazards specific to LPG operations. This is particularly relevant in Nigeria, where the LPG industry has faced numerous safety incidents, including explosions and fires at refilling stations (Jia *et al*., 2022). By employing AI-driven analytics, stakeholders can better anticipate and mitigate risks associated with LPG handling and storage.

The Internet of Things (IoT) is also another tool bringing revolution to safety monitoring in LPG operations. IoT applications facilitate real-time monitoring of gas levels and leak detection, which are critical for maintaining safety in LPG refilling plants. Espinoza discusses how IoT technology can be employed for continuous monitoring of LPG distribution, thereby enhancing safety through timely detection of leaks (Espinoza, 2024). Additionally, Rahman *et al*. present a combined hardware prototype that utilizes IoT for supervising gas leaks and fires, showcasing the potential for remote control and immediate response to safety incidents (Rahman *et al*., 2022).

The work by Sutikno *et al*. illustrates an IoT-based LPG pressure monitoring system that uses sensors to transmit real-time data on gas pressure, thereby ensuring safe operational conditions (Sutikno, 2023). Such systems can significantly reduce the response time to gas leaks, thereby minimizing the risk of accidents. Implementation of IoT-based monitoring systems can provide continuous data on operational conditions, allowing for immediate responses to potential hazards (Maduabuchi, 2023 A). This proactive approach is essential in a country where the management of cumulative risks in the petroleum industry remains a significant challenge (Maduabuchi, 2024 B).

Digital simulation techniques also play a crucial role in enhancing SIL assessments. These techniques enable the modelling of various operational scenarios, allowing for the evaluation of safety measures under different conditions. By integrating digital simulations with AI and IoT data, operators can create comprehensive safety models that account for the dynamic nature of LPG operations in Nigeria. This integration can lead to improved safety protocols and more effective training programs for personnel, ensuring that they are well-prepared to handle emergencies (Ekong, 2023).

Furthermore, the cultural aspect of safety in the Nigerian LPG industry cannot be overlooked. Ekong emphasizes the importance of promoting a robust safety culture within organizations, which is crucial for the successful implementation of advanced safety technologies (Ekong, 2023). Training programs that incorporate AI and IoT technologies can enhance employee engagement and compliance with safety protocols, ultimately leading to a safer working environment.

Integration of Artificial Intelligence, Internet of Things applications, and digital simulation techniques is vital for enhancing the assessment of Safety Integrity Levels in LPG refilling plants in Nigeria. These technologies not only improve the accuracy and efficiency of safety evaluations but also facilitate proactive measures to mitigate risks associated with LPG operations. As the industry keeps changing, embracing these advancements will be vital for ensuring the safety and sustainability of LPG usage in Nigeria.

6. CHALLENGES IN SIL ASSESSMENT FOR LPG REFILLING PLANTS

The assessment of Safety Integrity Levels (SIL) in Liquefied Petroleum Gas (LPG) plants faces numerous challenges, both globally and specifically within the Nigerian context. These challenges stem from a combination of technological, regulatory, and cultural factors that complicate the effective implementation of safety measures in the LPG sector.

Globally, the LPG industry battles with the need for standardized safety protocols and assessment methodologies. Lack of uniformity in safety regulations across different countries can lead to inconsistencies in SIL assessments. Rosenthal *et al*. discuss integrated analytical approaches for energy interventions, their focus is primarily on clean cooking technologies rather than directly on SIL assessments in LPG operations (Rosenthal *et al*., 2018). This study does not adequately highlight the need for a cohesive framework for assessing safety in LPG operations.

Another significant global issue is the integration of advanced technologies in SIL assessments. While innovations such as IoT and AI have the potential to enhance safety monitoring and risk assessment, their implementation is often hindered by high costs and the need for specialized training. Espinoza's work discusses the design of IoT-based models for LPG distribution monitoring, highlighting the potential benefits of these technologies in improving safety outcomes (Espinoza, 2024). However, the disparity in technological adoption between developed and

developing countries further exacerbates this challenge, as many regions lack the infrastructure and resources necessary to implement these advanced systems effectively.
The identified challenges below are some of the major factors hampering effective SIL assessment in Nigeria.

6.1 Regulatory Challenges

The lack of a robust regulatory framework governing the LPG industry is one of the major challenges in Nigeria. Maduabuchi highlights that the cumulative assessment of process safety risk is weighty and continuous, with management and monitoring of asset integrity systems often lacking objectivity and audibility Maduabuchi (2023 B). This regulatory gap leads to inconsistent safety practices across various LPG facilities, increasing the risk of accidents and incidents. The absence of stringent enforcement mechanisms further escalates this issue, as operators may not feel compelled to adhere to safety standards.

6.2 Technological Challenges

Globally, the unification of innovative technologies such as AI and IoT into SIL assessments is gaining traction. However, in Nigeria, the adoption of these technologies is hindered by several factors. The high costs associated with implementing IoT systems for real-time monitoring and AI-driven analytics pose significant barriers, particularly for small-scale operators who dominate the Nigerian LPG market (Oluwabukola, 2023). Additionally, the lack of technical expertise to operate and maintain these advanced systems limits their effectiveness in enhancing safety assessments.

6.3 Infrastructural Challenges

Infrastructural deficiencies are another critical challenge facing the Nigerian LPG industry (Agbai & Aigbedion, 2024). The reliability of electric supply and internet connectivity is often inadequate, which hampers the deployment of IoT-based monitoring systems that are essential for real-time safety assessments (Moore *et al.,* 2020*)*. This lack of infrastructure not only affects the operational efficiency of LPG plants but also compromises the safety measures that can be implemented.

6.4 Cultural Challenges

Cultural attitudes towards safety in Nigeria significantly impact the effectiveness of SIL assessments. There is often a perception that safety is a secondary concern, leading to insufficient training and engagement of personnel in safety practices. Ekong emphasizes the importance of promoting a robust safety culture within organizations, as employee engagement is crucial for the successful implementation of safety measures (Ekong, 2023). However, in many LPG plants, safety protocols are not prioritized, resulting in a lack of adherence to established safety standards.
Conclusively, the challenges of SIL assessment in LPG plants in Nigeria are multifaceted, ranging from regulatory and technological, to infrastructural, and cultural dimensions. Concerted efforts from different stakeholders are needed to tackle these challenges; by fostering a culture of safety, investing in infrastructure, and enhancing regulatory frameworks, the Nigerian LPG industry can improve its safety integrity and reduce the risks associated with LPG handling and distribution

7. CASE STUDY OF A.A. RANO NIGERIA LIMITED LPG PLANT

7.1 Related Works

Table 4 summarizes relevant key studies conducted relating to the safety integrity level of LPG refilling plants in Nigeria. It highlights the gap in these studies, which forms the basis for the aim of this study: to assess the effectiveness of regulatory standards in safeguarding the community.

Table 4: Contributions of some Authors in Oil and Gas Safety

S/N	Author & Year	Title	Key Findings	Limitations
1.	Ayakpo *et al*. (2023)	Liquefied Petroleum Gas Stations Disaster Risk Preparedness Assessment of Port Harcourt City, Nigeria	- 96.2% of LPG stations are stand-alone; tanks are above-ground. - High levels of safety training, emergency planning, and leak detection were observed. - Significant correlation between station type and risk.	- Focus is limited to Port Harcourt. - Data largely self-reported. - Does not assess the implementation and effectiveness of regulatory standards.
2.	Ogbette *et al*. (2018)	Continuous Gas Explosions in Nigeria: Causes and Management	- Gas explosions are mainly due to poor maintenance, inadequate gas detection, and non-compliance with safety protocols.	- Reliance on secondary data. - Lacks quantitative SIL assessment. - Minimal discussion on regulatory enforcement.

			- LPG stations, often located in residential areas, increase risk.	
3.	Park (2017)	Simplified Risk Assessment on Fire Hazard of LPG Filling Station	- Presents a simplified risk assessment framework for LPG filling stations. - Identifies key hazards and risk factors affecting LPG operations.	- Generic methodology not fully tailored to the Nigerian context. - Limited focus on the role of regulatory standards.
4.	Maduabuchi (2023 A)	Needs and challenges of Nigeria's petroleum industry in assessing process safety cumulative risk	- Reveals significant gaps in asset integrity and overall process safety risk management. - Highlights challenges in cumulative risk management in Nigeria.	- Broad industrial focus; not isolated to LPG-specific issues. - Does not assess regulatory standard effectiveness.
5.	Maduabuchi (2023 B)	Assessment of factors influencing process safety risk accumulation in petroleum operations in Nigeria.	- Emphasizes the need for real-time risk assessment models for cumulative risk. - Suggests improvements in safety barrier monitoring.	- Theoretical model with limited empirical validation in LPG plants. - Regulatory effectiveness is not specifically evaluated.
6.	Afube & Nwaogazie (2019)	Identification of industrial hazards and assessment of safety measures in the chemical industry, Nigeria using proportional importance index	- Identifies major hazards (e.g., explosion risks, inadequate safety measures) affecting chemical processes similar to LPG operations. - Underlines the importance of robust safety protocols.	- Broad focus on the chemical industry. - Not specific to LPG refilling plants. - Lacks discussion on enforcement of regulatory standards.
7.	WLPGA (2019)	LPG Safety Programs: A Global Perspective	- Provides an overview of safety practices and risk reduction measures in the LPG industry globally. - Summarizes best practices from multiple regions.	- Global scope with little emphasis on Nigerian-specific challenges. - Does not assess local regulatory standard effectiveness.
8.	Jia *et al*. (2022)	Fire Risk Evaluation for Petroleum Product Handling Facilities in the Niger Delta Region, Nigeria	- Documents frequent fire incidents and stresses enhanced emergency preparedness. - Highlights risk factors specific to the Niger Delta region.	- Focuses on fire risk rather than full SIL assessment. - Regulatory standard effectiveness not addressed.
9.	Bariha *et al*. (2023)	Fire and risk analysis during loading and unloading operation in liquefied petroleum gas (LPG) bottling plant	- Identifies best practices in facility design and layout that reduce risks in LPG plants. - Emphasizes the role of physical safety measures.	- Focuses on technical and design aspects. - Limited discussion on regulatory enforcement.
10.	Spellman (2023)	Physical hazard control: preventing injuries in the workplace	- Proposes a methodology for classifying hazardous zones in LPG plants to improve risk management. - Offers a structured approach to area control.	- Primarily theoretical with limited field validation in Nigeria. - Does not evaluate how regulations ensure proper area classification.
11.	Redmill (1999)	Understanding safety integrity levels.	- Provides a foundational framework for assessing SIL using PFD metrics. - Establishes basic concepts for functional safety.	- Outdated and generic. - Not specific to LPG plants or Nigerian regulatory environments.
12.	Dan *et al*. (2015)	Integrated framework for determining the safety integrity level for improved process safety	- Details SIL ranges and methods for risk reduction based on the probability of failure on demand (PFD). - Offers quantitative guidelines for safety improvements.	- Broad focus on chemical processes. - Limited direct application to Nigerian LPG operations and regulatory effectiveness.

13.	Marszal & Scharpf (2002)	Safety Integrity Level Selection	- Presents quantitative methods for SIL determination using historical failure data and probabilistic models. - Offers a statistical foundation for SIL assessment.	- Based on historical data that may not reflect current practices in Nigeria. - Limited discussion on regulatory frameworks.
14.	Abisam (2021)	The Abhisam Quick Guide to Basic Functional Safety and SIL	- Outlines design architectures for safety instrumented functions (SIFs) to reduce hazards. - Emphasizes the importance of robust safety system design.	- Focused on technical design aspects. - Does not address regulatory oversight or enforcement of safety standards.

7.2 Methodology

Sampling

A purposeful sampling method was employed to select A. A Rano Nigeria Limited, an LPG plant located opposite Aviation Quarters on Sokoto Road in Samaru, Kaduna State, is the subject of this case study. This selection was influenced by practical considerations and specific constraints, including limited availability of time and resources that hindered the examination of multiple plants or those situated at a significant distance. Also, the selection was informed by the company's demonstrated adherence to regulatory compliance standards. The proximity of this plant facilitated efficient data collection and ensured timely access to requisite information and personnel. Furthermore, A. A Rano is recognized as a reputable petroleum marketer, characterized by its strict compliance with established regulatory frameworks.

Data Collection

Two sets of data were collected: regulatory standards from NMDPRA and study data from the plant, which was collected through site inspection and interviews with personnel. Table 5 is a summary of the data collected.

Table 5: Plant's Inspection Data Sheet

No. of Tanks		1		
Combined Capacity (MT)		22		
No. of Dispensing Pumps		4		
No. of Staff		17		
S/N	**ITEM**	**AVAILABILITY**	**QUANTITY**	**NMDPRA STANDARDS**
Layer 1 (Process Design and Operation)				
1.	Operating Temperature (°C)	-20 to 50	-	Not Specified
2.	Operating Pressure (bar)	10	-	Not Specified
3.	Operators Training	Yes	Every 2 Years	Required
4.	Plant Layout Design and Good Housekeeping	Excellent	-	Excellent
Layer 2 (Basic Process Control and Alarms)				
5.	Tank Temperature Indicator	Yes	1	Required
6.	Tank Pressure Gauge	Yes	1	Required
7.	Temperature/Pressure Alarm	No	-	Not Specified
8.	Automatic Sprinkler System	Manual Available	1	Required
Layer 3 (Critical Alarm with Operator Intervention)				
9.	Gas Detectors	Yes	3	Required
10.	Emergency Shutdown Switch	Yes	2	Required: at least two locations
Layer 4 (Safety Instrumented System)				
11.	None	-	-	Not Specified
Layer 5 (Relief device)				
12.	Pressure Relief Valve	Yes	2	Required
Layer 6 (Containment of Release)				
13.	Containment Device/equipment	No	-	Not Specified
Layer 7 (Plant's Emergency Response)				

14.	Emergency Plan	Yes	-	Required
15.	Emergency Response Team Training	Yes	-	Required

Source: Author's Survey, 2023

Hazard Identification

Hazard identification was conducted using the major hazard analysis (MHA) technique to identify hazards that can lead to loss of containment of LPG. MHA is one of the Process Hazard Analysis (PHA) techniques whose scenarios of interest are those that result in significant danger. The structured technique is employed by dividing the process into parts, upon which brainstorming is carried out for major hazards using the typical what-if technique. To keep focus and narrow the scope, brainstorming is focused on the group of initiating events that can lead to loss of containment. Results of MHA are arranged in a table with fields: scenario, cause, consequence, enablers, safeguards, severity, likelihood, and risk factor (Baybutt, 2003). Table 6 gives the severity, likelihood, and risk factor scales adopted, where risk factor is determined by multiplying severity and likelihood.

Table 6: Severity, Likelihood, and Risk Factor Scales (Singh & Premi, 2015)

Severity (S)		**Likelihood**	
Scale	**Interpretation**	**Scale**	**Interpretation**
1	Very Slightly Harmful	1	Very unlikely
2	Slightly Harmful	2	Unlikely
3	Harmful	3	Likely
4	Very Harmful	4	Very Likely
Risk Factor			
Category of Risk		**Tolerability**	
Very low (Level 1, 2, 3, 4)		Acceptable (or Negligible)	
Low (Level 5, 6)		Require risk reduction to be tolerable (unwanted)	
Medium (Level 8, 9)		Require risk reduction to be tolerable (unwanted)	
High (Level 10, 12)		Require risk reduction to be tolerable (unwanted)	
Very high (Level 15, 16)		Unaccepted	

SIL Assessment

Hazard-consequence pair with the highest risk factor from hazard identification were selected for SIL assessment. Data from design specifications as well as case study inspection were used to identify existing safeguards or protection layers in the LPG refilling plant. LOPA, as a semi-quantitative technique, was used to determine the SIL of the plant. This was achieved by determining the initiating event frequency from literature, design specifications, metrological data of the area, incident registers, and operating procedures. Subsequently, the PFD for each IPL was determined from the instrument's manufacturer specifications and reference texts. Where a particular protection layer is absent, maximum probability (1) was used as the PFD. Equation 1 was then employed to calculate the risk factor of the plant and assess whether this risk is within tolerable limits or not by comparison with acceptable risk standards.

Consequence Modeling

Based on LOPA study results, consequence modeling was carried out using Areal Location for Hazardous Atmosphere (ALOHA) software for the most probable scenario, in order to identify levels of concern with respect to toxicity, flammable vapor cloud extent, and overpressure. The scenario chosen was released from a pressure relief valve resulting from the ignition of leakages during delivery and retail discharge operations. This scenario was selected as human error either due to negligence or absence of training and awareness is a major source of incidents globally (Alonso *et al., 2017)* and most especially in Nigeria. Data from tank and valve manufacturer specifications as well as atmospheric data from the Nigerian Metrological Agency (NIMET) was used for modeling.

Mitigation Measures

Results of the LOPA study and consequence modeling were analyzed to identify key areas in need of additional safeguards that will improve the overall safety and sustainability of the refilling facility.

7.3 Results and Discussion

Result of Hazard Identification

Table 7 presents the result of hazard identification conducted on the LPG refilling plant.

The results of the major hazards analysis (Table 7) revealed four hazardous scenarios that can result in the loss of containment of LPG in the plant. Minor leakages are a group of hazards resulting from pipeline or equipment failure due to defects, aging, corrosion, or the use of substandard equipment. These hazards bring about minor releases of LPG into the environment that can result primarily in fire with available ignition sources, explosion by transfer of thermal radiation to pressurized vessels, and environmental pollution with or without ignition.

Fire resulting from these hazards has a risk factor of 6 (low) because, despite its harmful consequences, the chances of leakages in the plant are low. After all, standard equipment was used. Factoring in the tendency of ignition sources, the presence makes fire hazards unlikely.

Table 7: Responses from Major Hazard Analysis

S/N	Scenario	Cause	Consequence	Enablers	Safeguards	Severity	Likelihood	Risk Factor
1.	Minor Leakages	Leakages along pipeline joints (flanges and elbows) Leakages at valves Crack in the tank due to aging or substandard fabrication A faulty relief valve due to using substandard equipment Broken/worn-out pump seals Corrosion of equipment	Fire, leading to damage to equipment and injury to personnel	Ignition Source Personnel presence	Fire Extinguishers Gas detectors Fire alarm Fire hydrant Fire Safety Mat Personnel access restrictions	3	2	6
			Explosion, leading to loss of personnel, equipment, and buildings.	Ignition Source Personnel presence	Fire Extinguishers Gas detectors Fire alarm Fire hydrant Personnel access restrictions	4	1	4
		Cylinder Refilling Process	Air pollution	Air Current	None	2	4	8
2.	Overpressure of the tank	High ambient temperature Incident within the plant or adjacent processes Utility failure Ignition of minor leakages Tanks overfill	Tank Explosion, leading to loss of personnel, equipment, facilities, the nearby community, and environmental pollution	Absence of operator intervention. Absence of a cooling system Failure of the relief device	Safety instrumented system (water sprinkler) Pressure relief valve	4	2	8
			Vapor cloud explosion leading to loss of personnel, equipment, facilities, the nearby community, and environmental pollution	Ignition source Personnel/ customer presence	Sprinkler system Emergency plan	4	3	12
3.	Major Leakages	Relief valve release Rupture of the tank from crack propagation Leakages from delivery hoses during offloading.	Vapor cloud explosion leading to Loss of lives, equipment, facilities, the nearby community, and environmental pollution	Ignition source Personnel/ customer presence	Sprinkler system Emergency plan	4	3	12
			Tank Explosion leading to Loss of personnel, equipment, facilities, nearby community, and environmental pollution	Personnel/ customer presence	Sprinkler system Fire hydrant system	4	3	12

			Serious pollution of the ambient air in nearby communities	Air Current Absence of containment devices	None	3	4	12
4.	Incorrect /Inaction of Operator	The operator is failing to shut off the delivery valve after offloading	Major leakage, leading to fire, explosion, loss of life, damage to equipment, and environmental pollution	Ignition source	Gas detectors A routine check by the safety supervisor before and after product delivery	3	2	6

If eventually a fire starts, the chances of an explosion from minor leakages are very unlikely due to the available firefighting gadgets within the plant.

However, whenever a release occurs, environmental pollution is inevitable. Though a minor leakage may not result in severe damage at that instant, there is a frequent minor release of LPG during unmounting of the refilling nozzle, which results in a risk factor of 8 (medium).

Overpressure of the LPG storage tank is another scenario that can result from minor leakages, ignition within the plant, fire incidents from nearby facilities, for example, the FASADA petrol station adjacent to it, or a rise in ambient temperature. In Nigeria, ambient temperature can rise to 47 °C in areas like Sokoto and up to about 45 °C in the northeastern part, such as Borno state. This high ambient temperature may run daily for up to three months in a year, with the peaks varying. Overpressure can result in a catastrophic disaster (explosion), costing lives, equipment, and facilities, and damaging the environment. Due to the existence of safeguards, especially a pressure relief valve, the likelihood of an explosion is low and hence a risk factor of 8 (medium).

Major leakages are hazardous sources leading to large amounts of LPG release, such as the pressure relief valve or the propagation of cracks on the storage vessel. The available safety instrumented system (automated sprinkler system) in the plant is operated manually, which defeats the aim of safety layer 4, increasing the chances of a relief valve trigger. These hazards can result in a vapor cloud explosion because LPG is denser than air, and therefore, when released, it takes a longer time to disperse, especially under low air currents. Any potential ignition sources a few meters away from the plant may result in a vapor cloud explosion. This plant is by the roadside with nearby quarry/stone breakers and auto mechanics often using an open flame to patch vehicle tire tubes, cumulatively resulting in an available ignition source. The absence of a containment device and the severity of explosions result in a risk score of 12 (high).

Ignition of vapor clouds or propagation of cracks could lead to a tank explosion, resulting in wanton consequences. Considering the likelihood of LPG vapor cloud release by the relief valve and the presence of an ignition source, a risk factor of 12 (high) was assigned to this hazard. A scenario might occur where large LPG vapors were released by the relief valve, however, no ignition source is present to trigger an explosion. In such cases, major air pollution is inevitable since no containment measure is available. This leads to a risk factor of 12 (high).

Another important scenario is incorrect action by personnel. This plant employs a single pumping system for discharge and delivery using a network of valves. Delivery valves are shut off during discharge and vice versa. If the personnel in charge forget to shut off delivery valves, and discharge is started, a major release of LPG will occur. Adherence to standard operating procedures and strict monitoring by supervisors reduces the risk factor to six (low).

Determination of Safety Integrity Level

Hazards with alarming risk factors are those from scenarios of tank overpressure and major leakages, which could lead to both explosion and hazardous release, with the chances of vapor cloud explosion. However, for this study, two scenarios will be considered:

A tank lorry starts during unloading or a vehicle starts during dispensing, leading to a tank explosion.

The tank lorry starts during unloading or the vehicle starts during dispensing, leading to hazardous release.

During unloading, the tank lorry's ignition will create an ignition source and disturb the delivery hose connections, leading to leakages. Similarly, a lot of LPG vapor is released during dispensing while coupling/decoupling the dispensing nozzle. A car ignition will create an ignition-leading incident scenario. The following data will be used for SIL evaluation (Table 8).

Table 8: LOPA Study Data

S/N	Parameter	Value	Source
1.	Initiating Event frequency (Tank lorry starts during unloading or vehicle starts during offloading)	3/year	Park (2017)
2.	Enabling Condition Probability (Immediate Ignition)	0.296	Park (2017)
3.	Conditional Modifier (Immediate Extinguish)	0.04	Park (2017)

4.	PFD for IPL 1 (Process Design)	0.1	Sibilski, (2020)
5.	PFD for IPL 2 (Sprinkler System)	0.1	Park (2017)
6.	PFD for IPL 3 (Alarms & Operator Intervention)	1	No Critical Alarms Available in the plant
7.	PFD for IPL 4 (Pressure Relief Valve Aev1100)	0.005	(Gross, 2004)

Where IPL is an Independent Protection Layer

Scenario One

For an LPG tank explosion, the scenario in question is overpressure of the tank resulting from fire caused by vehicle ignition during discharge. The thermal radiation raises the tank temperature, causing overpressure and an explosion. For this to happen, immediate ignition of LPG vapors with vehicle ignition is required. Plant firefighters must also fail to immediately extinguish the fire. Figure 5 shows the Swiss cheese model of the scenario. The overall probability of this scenario is determined by employing Equation 1 as thus:

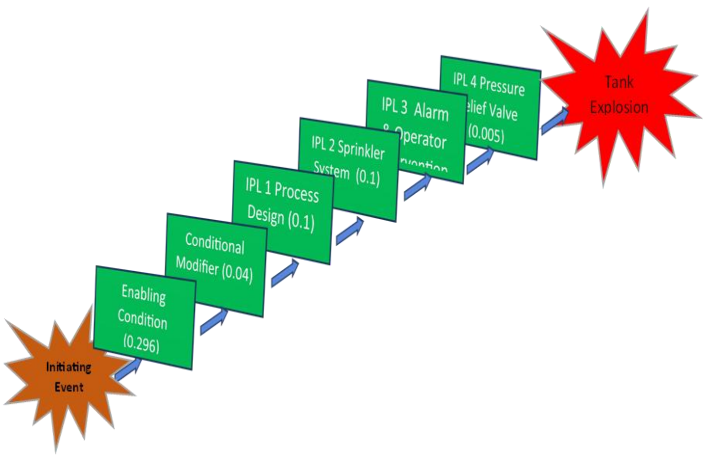


Figure 5: Swiss Cheese Model of Scenario One with PFD for IPLs

$$F_i = IEF \times EC \times CM \times \left(\prod_{j=1}^{j} PFD_j\right) \quad (2)$$

Where IEF is the frequency of initiating event, PFD is the probability of failure on demand, i is the scenario in question, j is the IPL, EC is the enabling condition, and CM conditional modifier.

$$F_1 = 3 \times 0.296 \times 0.04 \times 0.1 \times 0.1 \times 1 \times 0.005$$
$$= 1.776 \times 10^{-6}/year$$

The likelihood of Scenario One occurring is quantified at 1.776 x 10^{-6} events per year, which corresponds to a risk reduction factor exceeding 100,000. Under this scenario, the integrity level of the plant is classified as exceeding SIL 4. When this probability is extrapolated to a national scale, particularly in the context of increasing adoption of LPG and the corresponding rise in refilling facilities, an illustrative case involving 1,000 facilities results in an estimated probability of approximately 1.776 x $\times 10^{-3}$ events per year. This elevated probability aligns with a classification of SIL 3, which is within tolerable limits.

Scenario Two

This scenario is similar to the first scenario, considering initiating events, conditional modifiers, and enabling conditions. The difference arises in that, for the incident to occur, the final independent protection layer (IPL 4) is not required to fail; rather, it must be activated. This implies that IPL 4 has changed into an enabling condition (EC_2) since hazardous release via the pressure relief valve hinges on the valve activation. The Swiss Cheese model of this scenario is in Figure 6. The total probability of this unwanted event is as follows:

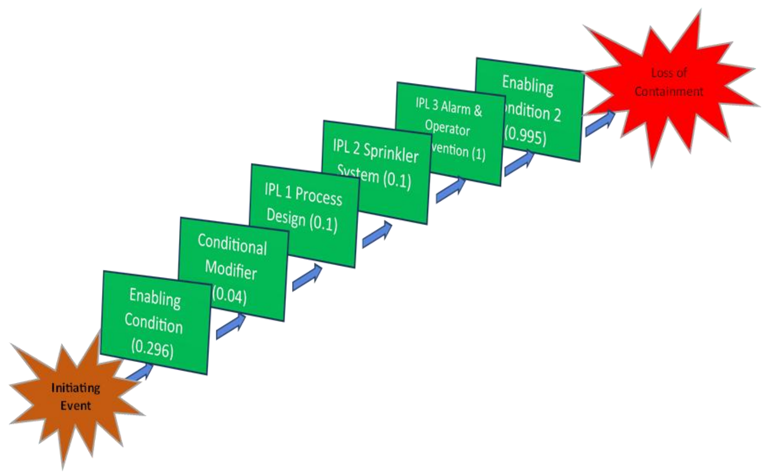


Figure 6: Swiss Cheese Model of Scenario Two with PFD for IPLs

Probability of EC_2 = 1 – PFD of IPL 4 (3)

= 1 – 0.005

= 0.995

Subsequently, the overall probability of scenario two becomes:

$$F_2 = 3 \times 0.296 \times 0.04 \times 0.1 \times 0.1 \times 1 \times 0.995$$
$$= 3.534 \times 10^{-4}/year$$

Scenario Two has an overall likelihood of 3.534 x 10^{-4} events per year. This scenario renders the integrity level of the plant to be SIL 4, which is considered tolerable. However, extrapolation to the national scale in this case, using the same illustrative case, increases the risk to a significant level ($3.534 \times 10^{-1}/year$). This corresponds to SIL 1, which is not acceptable considering the potential negative penalties of the scenario.

Consequence Modeling

To better understand the extent of risk posed by scenario two, consequence modeling of the pressure relief valve was carried out using the ALOHA software. The data used for this modeling is shown in Figure 6, which is a text summary of the ALOHA model. The software is designed to model a single compound only, and hence, LPG was modelled as butane. Discussion of the results follows.

ALOHA 5.4.7 - [Text Summary]

File Edit SiteData SetUp Display Sharing Help

```
SITE DATA:
  Location: SAMARU ZARIA, NIGERIA
  Building Air Exchanges Per Hour: 0.69 (unsheltered single storied)
  Time: July 25, 2024  0728 hours ST (user specified)

CHEMICAL DATA:
  Chemical Name: BUTANE
  CAS Number: 106-97-8                   Molecular Weight: 58.12 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 53000 ppm
  LEL: 16000 ppm     UEL: 84000 ppm
  Ambient Boiling Point: 27.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3.33 meters/second from SW at 3 meters
  Ground Roughness: urban or forest      Cloud Cover: 3 tenths
  Air Temperature: 25° C                 Stability Class: D
  No Inversion Height                    Relative Humidity: 50%

SOURCE STRENGTH:
  Leak from short pipe or valve in horizontal cylindrical tank
  Flammable chemical escaping from tank (not burning)
  Tank Diameter: 2.776 meters            Tank Length: 6.94 meters
  Tank Volume: 42,004 liters
  Tank contains liquid                   Internal Temperature: 25° C
  Chemical Mass in Tank: 22000 kilograms
  Tank is 91% full
  Circular Opening Diameter: 2 inches
  Opening is 0 meters from tank bottom
  Release Duration: ALOHA limited the duration to 1 hour
  Max Average Sustained Release Rate: 667 pounds/min
     (averaged over a minute or more)
  Total Amount Released: 39,202 pounds
  Note: The chemical escaped as a mixture of gas and aerosol (two phase flow).
```

Figure 6: Data for Consequence Modeling of LPG Release

Toxicity Effect

Modeling of toxic effects according to Acute Exposure Guideline Levels (AGELs), considering three levels of concern (LOC), plotted threat zones and their extents as shown in Figure 7.

For sixty minutes of exposure, individuals within 21 yards (19.2 m) downwind of the release point will experience a toxicity effect at a concentration of 53000 ppm (AEGL-3). At this concentration, the chances of fatality or life-threatening health damage or death are high. An effect of 17000 ppm (AGEL-2) concentration is expected to be 36 yards downwind (32.9 m) of the release point.

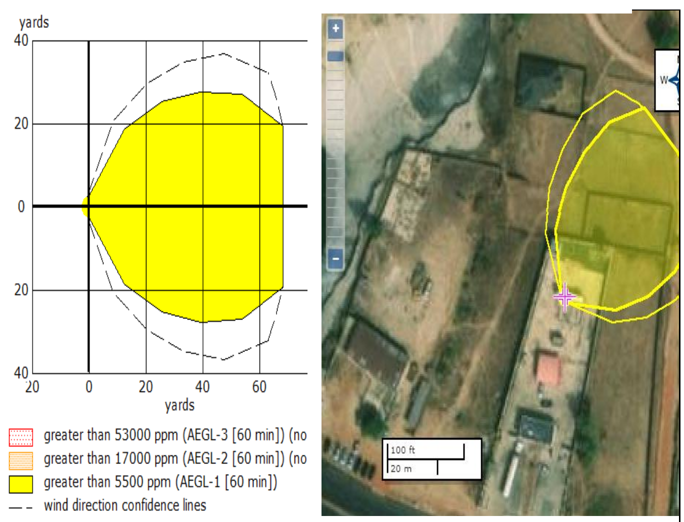


Figure 7: Toxic Effects Levels of Concern

Under this effect, the tendency of long-term health injury and impaired ability to avoid danger is very high. These areas cover part of the facility, putting personnel as well as nearby commercial facilities at great risk. These two threat zones were not indicated in Figure 7 due to limitations of ALOHA's dispersion prediction model and its attempt to provide reliable information.

The yellow area visible in Figure 7 represents a region where the toxic effect has a concentration of 5500 ppm (AGEL-1). This level of concern stretches 68 yards (62.2 m) downwind of the release point and can cause irritation, discomfort, and short-term injury that is transient and reversible after exposure ceases. The broken line indicates a limit of confidence in wind direction due to its variation over time.

Flammable Vapor Cloud

The extents of the flammable vapor cloud from the point of release are shown in Figure 8. The model accounts for three LOCs, which consist of areas where the concentration of flammable vapor is at the lower explosive limit (LEL) of LPG (red zone), 60 % of LEL (orange zone), and 20 % of LEL (yellow zone). The presence of ignition in the red zone will ignite the flammable vapor since the air-fuel ratio is adequate for combustion. Within the orange and yellow zones, typically, the air-fuel ratio is not sufficient to start combustion. However, because of uneven distribution of flammable vapor in air, termed patchiness, flame pockets are formed, which are points in space where a significant concentration of flammable vapor sufficient for ignition accumulates. Orange zones have a higher probability of flame pocket formation compared to yellow.

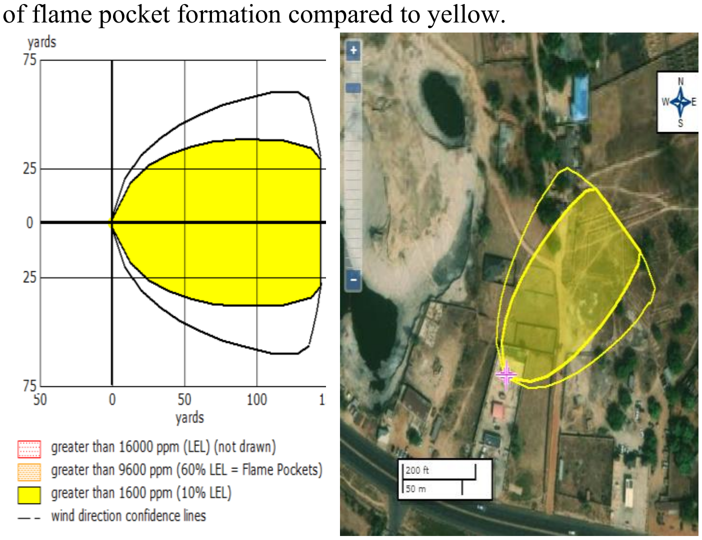


Figure 8: Flammable Vapor Cloud Limits

The red zone extends 37 yards (33.8 m) downwind of the release point. The orange zone extends 50 yards (45.7 m) downwind, and the yellow zone 145 yards (132.6 m). This threat zone reaches the vicinity of a dispersed population, a potential source for ignition.

Overpressure from Vapor Cloud Explosion

The level of pressure received by objects when a vapor cloud explosion occurs at different distances from the release point was modeled and presented in Figure 9. The Red zone represents overpressure intensity greater than 1.0 psi, capable of house demolition. The orange zone, an intensity above 0.7 psi, is capable of minor damage to house structures, and the yellow zone, an intensity above 0.5 psi, is capable of shattering windows with minor damage to window structures.

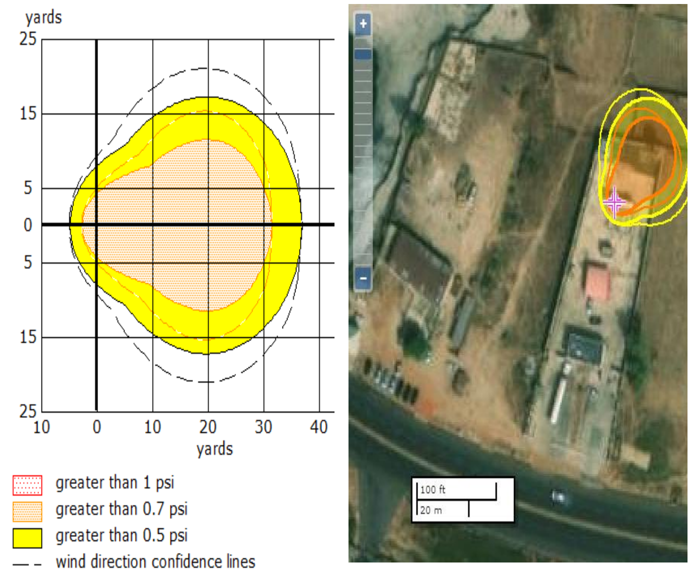


Figure 9: Overpressure Threat Zones

Based on the scenario, the red LOC was not exceeded. The yellow LOC stretches 32 yards (29.3 m) downwind, about 2 yards (1.8 m) upwind, and about 24 yards (21.9 m) wide from the explosion center, while the yellow LOC stretches 37 yards (33.8 m) downwind, 5 yards (4.6 m) upwind and about 34 yards (31.1 m) wide from the explosion center.

Mitigation Measures

The following measures are proposed to minimize risks of identified hazards, increase the safety integrity level of the facility, and prevent/minimize loss of valuable products:

i. A feasibility study for a containment tank to capture the relief valve release should be conducted.
ii. Water sprinkler systems should be made safety instrumented rather than manually operated to annul the effect of human error.
iii. An alarm for critical temperature and pressure should be installed to alert customers and personnel of hazardous scenarios in case of sprinkler failure.
iv. Technological advancements should be integrated to aid real-time monitoring and better risk assessment.

8. BEST PRACTICES FOR SIL ASSESSMENT IN LPG REFILLING PLANTS

The assessment of Safety Integrity Levels (SIL) in Liquefied Petroleum Gas (LPG) refilling plants is crucial to guarantee safety and minimize risks associated with hazardous materials. This review outlines best practices for SIL assessment, integrating insights from various studies to improve the reliability and effectiveness of safety measures in LPG operations, particularly in Nigeria.

Comprehensive Risk Assessment Frameworks

A structured risk assessment framework is fundamental to effective SIL evaluation. Maduabuchi emphasizes the essence of a systematic approach to assessing process safety cumulative risk in Nigeria's petroleum industry, Abdulai *et al*. (2018). This framework should incorporate methodologies such as FMEA, LOPA, and HAZOP, which methodically identify potential hazards and their impacts. The integration of these methodologies allows LPG plants to develop a comprehensive understanding of the risks associated with their operations, facilitating better decision-making regarding safety measures (Gabhane & Rao, 2023). The regulators need to ensure that such a robust framework is established, which should enable continuous risk assessment.

Integration of Advanced Technologies

The integration of innovative technologies such as AI and IoT can significantly enhance SIL assessments. AI can analyse historical data to predict potential failures, while IoT devices can provide real-time supervision of critical parameters such as pressure and gas levels. Gabhane and Rao demonstrate the use of neural networks for environmental risk assessment in LPG terminals, highlighting the potential for advanced modelling techniques to improve safety evaluations (Gabhane & Rao, 2023). Additionally, the use of IoT sensors in LPG refilling plants can facilitate continuous monitoring, enabling operators to detect anomalies and respond promptly to potential safety breaches. Currently, Nigerian LPG plants use very less of these technologies to the extent where most plants operate their water sprinkler systems manually.

Regular Training and Capacity Building

Training and capacity building are vital components of effective SIL assessment. Personnel involved in LPG operations must be adequately trained in safety protocols, risk assessment methodologies, and emergency response procedures. Ekong emphasizes the essence of promoting a robust safety culture within organizations, as employee engagement in safety practices is crucial for the successful implementation of safety measures (Ozoh *et al*., 2018). Regular training sessions, workshops, and simulations can enhance employees' understanding of safety measures and their roles in maintaining operational integrity. This is particularly relevant in Nigeria, where misconceptions about LPG safety can hinder its adoption (Ozoh *et al*., 2018). While NMDPRA enacted the minimum industrial safety training for downstream operators as a means for continuous training, strict measures must be taken to ensure that this training is well implemented and functional.

Continuous Monitoring and Evaluation

Continuous monitoring and evaluation of safety systems are essential for maintaining SIL. This involves not only the use of IoT technologies for real-time data collection but also the establishment of key performance indicators (KPIs) to assess the efficacy of safety measures. The dynamic nature of barrier data makes it challenging to manage cumulative risk continuously. Therefore, implementing a systematic approach to monitoring safety performance can help identify areas for improvement and ensure compliance with safety standards (Jia *et al*., 2022).

Stakeholder Engagement and Communication

Stakeholder engagement and effective communication are critical for successful SIL assessments. Engaging with all stakeholders, including employees, management, regulatory bodies, and the local community, can foster a collaborative approach to safety. Community-based participatory research methods can be employed to understand the perspectives and needs of various stakeholders regarding LPG safety. This inclusive approach can lead to more effective safety interventions and policies that address local concerns (Ekong, 2023). In the current standards, this is carried out before the establishment of these plants; however, even during and after operations, stakeholder engagement is key to understanding the prevailing risks and assessing them.

Regulatory Compliance and Best Practices

Adhering to national and international safety regulations is paramount for SIL assessment in LPG plants. In Nigeria, compliance with the regulations set forth by the Department of Petroleum Resources (DPR) and other relevant authorities is essential for ensuring operational safety. Regular audits and inspections can help ensure that LPG facilities meet safety standards and identify areas for improvement. Additionally, adopting best practices from global leaders in the LPG industry can provide valuable insights into effective SIL assessment methodologies (Princewill, 2023 A).

Emergency Preparedness and Response Planning

To effectively mitigate risks associated with LPG operations, it is crucial to develop robust emergency preparedness and response plans. These plans should outline procedures for responding to various emergency scenarios, including gas leaks, explosions, and fires. Training employees on these procedures and conducting regular drills can enhance readiness and ensure that personnel are well-prepared to handle emergencies effectively (Princewill, 2023 B).

In conclusion, best practices for SIL assessment in LPG refilling plants encompass a comprehensive risk assessment framework, the integration of advanced technologies, regular training, continuous monitoring, stakeholder engagement, adherence to regulatory standards, and emergency preparedness. By implementing these practices, LPG facilities in Nigeria can enhance their safety integrity, reduce risks associated with LPG handling, and contribute to a safer operational environment. As the industry continues to evolve, ongoing investment in safety technologies and practices will be essential for maintaining high safety standards.

9.0 CONCLUSION

The assessment of the Safety Integrity Level (SIL) in Nigerian Liquefied Petroleum Gas (LPG) refilling plants reveals critical gaps and significant potential for improvement in ensuring plant safety and environmental sustainability. The study underscores that while adherence to regulatory standards and safety guidelines has mitigated certain risks, challenges such as inadequate technology adoption, regulatory enforcement, and cultural perceptions towards safety are persistent. It also highlighted artificial intelligence, IoT, and ANN as technological tools for real-time monitoring and risk prediction. Effective integration of these tools will enhance the overall safety integrity of the plants and their assessment.

The case study results identified that NMDPRA-recommended safety guidelines effectively protect against plant risks. However, when cumulative societal risks are considered, there is a need for improvement, as the case study revealed an alarming risk of hazardous release, which can create toxic effects extending 62 m downwind, stressing the urgent need for enhanced safety protocols. The study, therefore, emphasizes the need to review the Nigerian LPG regulations and incorporate more safety layers to minimize societal risks and improve the safety integrity level. Case-specific recommendations include the use of an automatic sprinkler system, installation of critical alarms, and a feasibility study for a containment layer to contain hazardous releases.

Future research should consider a cross-functional study consisting of multiple plants from different locations to assess the impact of the degree of compliance with regulatory guidelines on the safety integrity level of the plants. Other incident scenarios should also be considered in the assessment.

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Declaration of Funding

No funding.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

The authors thank the Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA) for providing regulatory standards and support in securing the approval of the case study plant (A.A. Rano Refilling Gas Plant, Zaria Along Sokoto Road). They also thank the staff and management of the case study plant for their cooperation and seamless access to information.

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