MSE 1031 Project Report

Failure Analysis of the Kaohsiung Gas Explosion (2014)

Root Cause Investigation and Liability Assessment

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Statement of individual contributions

1. Executive summary: Tsai Tung Chiang
2. Introduction: Wei Ting Yeh
3. Investigation and key findings: Tsai Tung Chiang
4. Fishbone Diagram: Wei Ting Yeh
5. Fault tree analysis: Tsai Tung Chiang
6. Product liability: Both
7. Conclusions: Wei Ting Yeh
8. Recommendation: Both

Table of Content

1. Executive summary:

On the night of July 31, 2014, a catastrophic gas explosion struck the Cianjhen and Lingya Districts of Kaohsiung, Taiwan, killing 32 people, injuring over 300, and destroying major urban infrastructure. The explosions were caused by a prolonged leak of propylene gas from a buried pipeline, which accumulated in the underground stormwater trench network and ignited near an unsealed junction box, triggering a series of devastating blasts.

A comprehensive Root Cause Failure Analysis (RCFA) reveals that this disaster was not the result of a single fault but a convergence of technical, operational, and institutional failures. These included the unauthorized rerouting of a pipeline into a humid trench during public works construction, deterioration due to unaddressed corrosion warnings, and the failure of both LCY Chemical Corporation and China General Terminal & Distribution Corporation (CGTDC) to respond to early signs of pipeline rupture. Despite clear indicators of pressure anomalies, both companies resumed pumping, while the absence of gas detectors and real-time pressure monitoring delayed leak detection.

Compounding the crisis were errors in emergency mapping, outdated infrastructure databases, and poor coordination between private operators and city authorities. These issues obstructed timely hazard identification and allowed flammable gas to accumulate undetected beneath urban roads.

This report investigates the technical mechanisms of failure, legal liabilities under different jurisdictions (Taiwan, Canada, U.S.), and the systemic flaws in pipeline governance. It concludes with targeted recommendations for improving underground utility safety, regulatory clarity, emergency protocols, and inter-agency coordination. The Kaohsiung gas explosion illustrates how fragmented oversight, aging infrastructure, and production-first decision-making can converge into a preventable urban disaster.

2. Introduction

2.1 Overview of failure case

Incident Date	July 31st, 2014
Location	Kaohsiung, Taiwan
Pipeline Operator	(1) LCY Chemical Corporation (2) China General Terminal & Distribution Corporation (CGTDC)
Fatalities	32 deaths
Injuries	321 people
Damage	4.5 km of roads destroyed

Table 1. Incident Summary of the Kaohsiung Gas Explosion

The Kaohsiung Gas Explosion, one of the most catastrophic industrial accidents in Taiwan's history, occurred on July 31, 2014, in the Cianjhen and Lingya Districts of Kaohsiung. The incident was triggered by an underground leak of pressurized propylene gas, which later ignited and caused a series of powerful explosions. The resulting destruction affected a 4.5-kilometer stretch of roadway, caused 32 deaths, injured 321 people, and led to massive property and infrastructure damage [1].

Initial reports indicated that residents had noticed the smell of gas hours before the explosion, and emergency services were dispatched for investigation. However, before mitigation could take place, the gas ignited, presumably by an unknown ignition source, resulting in multiple fireballs and shockwaves across the area [2].

This incident raised urgent questions about pipeline safety, leak detection systems, and inter-agency coordination. Although the explosion itself was the immediate event, the underlying factors that enabled such a disaster to occur in a dense urban area warrant deeper investigation.

Figure 2. Aftermath of the Kaohsiung Gas Explosion [3]

2.2 Background of pipeline

Diameter	4 inches
Depth	Buried approximately 1 meter underground (Some buried about 0.5 meters deep)
Total Length	27 km
Year of Operation	Started in 1993, with planning initiated in 1986
Other Pipelines in the Network	Included an 8-inch ethylene line and a 6-inch propylene line, both constructed simultaneously by Taiwan CPC Corporation
Ownership Transfer	The 4-inch propylene pipeline was originally owned by Taiwan CPC Corporation before being transferred to LCY Chemical Corporation after installation

Table 2. Pipeline specifications [4]

Kaohsiung is a major industrial hub in southern Taiwan, home to several large petrochemical facilities. Among them, the Dashe Petrochemical Industrial Park is a key site for processing and distributing raw chemical materials. To support its operation, a network of underground pipelines was built in the 1990s to transport feedstocks such as ethylene and propylene from Kaohsiung Harbor and the CPC refineries to inland facilities like LCY Chemical Corporation.

One of the critical pipelines in this network was a 4-inch propylene line, originally installed by Taiwan CPC Corporation in 1993 and later transferred to LCY Chemical Corporation. The pipeline was buried about 1 meter underground and ran directly beneath densely populated urban areas. While such pipelines are essential for maintaining industrial supply chains, their placement under public roads introduces significant risks, particularly if monitoring, maintenance, or communication between operators and local authorities is insufficient. This background is essential to understand the circumstances under which the leak and explosion occurred. The following section will explore how design decisions, operational oversight, and emergency response may have contributed to the failure [4].

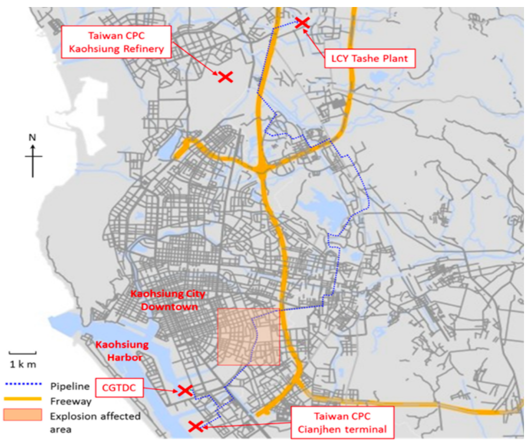

Figure 2. Route of the underground pipeline and the explosion affected area [5].

2.3 Timeline of the incident

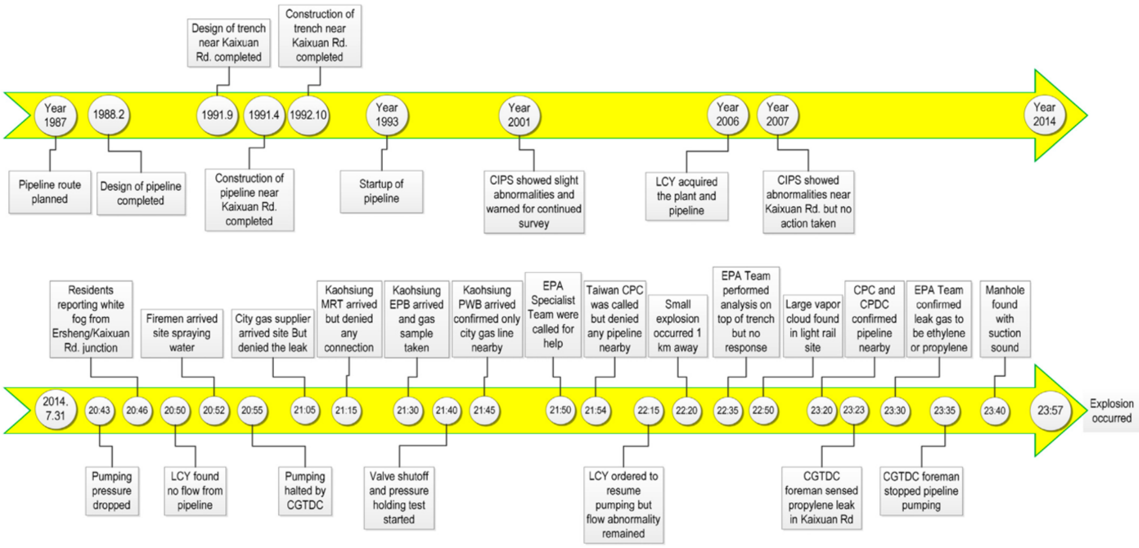

Figure 3. The timeline of the event [5]

At 20:43, the pipeline operator (CGTDC) recorded a sudden drop in pressure in the 4" propylene pipeline, indicating a possible rupture. By 20:46, residents in Cianjhen District began reporting a strong odor and visible white vapor emerging from manholes at the intersection of Kaixuan 3rd Road and Ersheng 1st Road (see Figure 4). Firefighters arrived by 20:52, set up a command post, and began water spraying. However, initial information from utility companies falsely indicated that no pipelines were present.

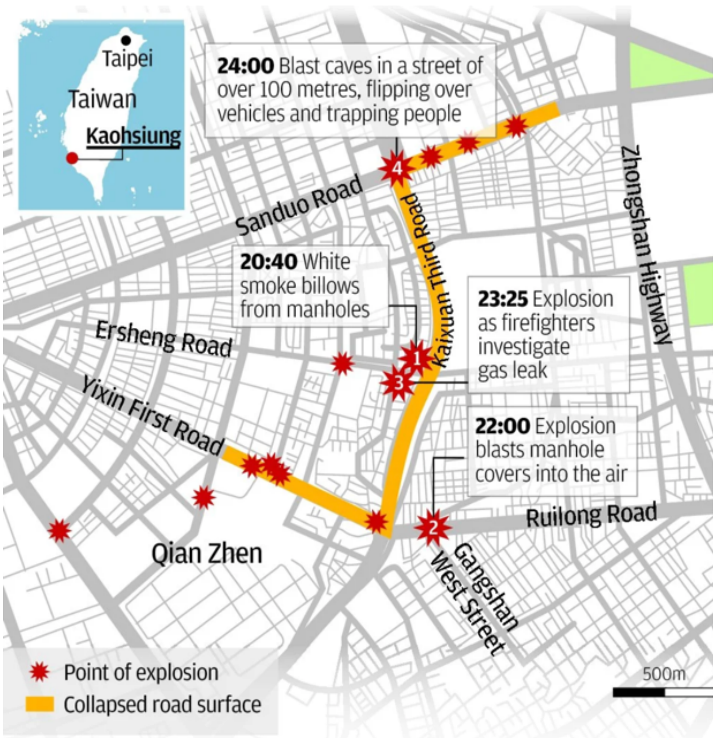

Figure 4. Map of Explosion Sites and Road Collapse [6]

From 21:00 to 23:00, field responders continued efforts to identify the gas source, while parallel pipeline operations revealed abnormal flow and pressure data. Despite CGTDC observing a flowrate surge and an electric current spike by 20:55, and both operators noting discrepancies, neither company notified emergency services. Instead, they initiated a “pressure holding test” at 21:40. Meanwhile, government agencies (EPB, MRT Bureau, PWB) arrived and began their own investigations, but conflicting information and outdated maps led to confusion.

At 22:00, a minor explosion occurred in a manhole near the leak zone, yet it did not prompt pipeline shutdown. Pumping resumed at 22:10, with propylene continuing to leak. By 23:20, CPC confirmed the presence of alkenes, and at 23:23, a CGTDC foreman finally identified a strong propylene odor onsite and ordered an emergency shutdown. Nevertheless, the gas had been leaking continuously for approximately three hours.

At 23:50, the Emergency Response Center identified the leaked substance as an olefin. CPC confirmed at 23:55 that the pipeline belonged to LCY Chemical Corporation [4]. Merely one minute later, at 23:56, a massive explosion occurred along Kaixuan 3rd Road, followed by a series of devastating secondary blasts that propagated through a 4.5 km underground trench network.

This timeline reveals a dangerous disconnect between field responders and pipeline operators. On one hand, emergency teams faced ambiguity and lacked accurate underground infrastructure information; on the other, pipeline companies failed to act upon clear signs of leakage, prioritizing production over safety. The compounded delays and miscommunications ultimately enabled a full-scale vapor explosion, underscoring critical failures in hazard recognition, inter-agency coordination, and safety culture—issues explored in greater detail in the following section.

3. Investigation and key findings

3.1 Abnormal pipeline behavior

Table 3. outlines a series of escalating anomalies and the corresponding operator responses preceding the explosion, highlighting critical failures in emergency procedures. At 20:43, the pipeline pressure at the CPC branch dropped sharply from 4.2 MPa to 1.37 MPa, a likely sign of a major rupture. However, no alert was issued to relevant emergency services. At the same time, LCY's flow meter indicated zero, confirming that propylene was not reaching the receiving plant. Meanwhile, CGTDC's pump output surged to 33,000 kg/hr, exceeding normal capacity (~23,000 kg/hr), accompanied by an electrical current spike up to 180 A, suggesting mechanical strain and probable escape of fluid [5, 7].

Despite these clear signs, the two companies proceeded with a static holding pressure test at 21:40, observing a stable pressure of around 1.3 MPa on both ends, which they deemed acceptable. Pumping resumed at 22:10, even though the root cause of pressure loss had not been investigated. A flowrate discrepancy of over 17,000 kg/hr between CGTDC and LCY indicated a significant leak [5, 7]. This sequence of events demonstrates a consistent pattern of underreaction and procedural gaps leading up to the incident.

Time	Event Description	Normal Value	Anomaly Observed	Operator Response
20:43	Pressure transmitter on CPC side dropped	~4.2 MPa	Sudden drop to 1.37 MPa	No immediate emergency notification; LCY and CGTDC continued monitoring independently.
20:50	LCY flow meter read zero flow	~23,000 kg/hr	0 kg/hr	LCY operator informed foreman, no shutdown initiated.
20:55	CGTDC pump showed Surge in output, high current	~23,000 kg/hr, 130 A	Surge in flow (33,000 kg/hr) and electric load(180A)	CGTDC shut down pump and closed isolation valves; pipeline pressure stabilized at ~1.35 MPa.
21:21	Engineers discussed pressure anomaly	-	Flow discrepancy and prior pressure drop	Decided to run a static holding pressure test; LCY requested it be brief due to high propylene demand.
21:40	Holding pressure test conducted	Should be tested under pumping pressure	Performed under static condition, both ends isolated	Observed both ends at ~1.3 MPa; deemed stable; no further investigation initiated.
22:00	LCY requested to resume supply due to low tank level	-	Supply urgency	Both parties agreed to resume pumping despite unresolved discrepancy.
22:15	Restarted pumping: CGTDC 24,500 kg/hr, LCY 6,000 kg/hr	Values should match	>17,000 kg/hr loss unaccounted for	Engineers acknowledged the discrepancy but delayed a second pressure test until after shift change.

Table 3. Key pipeline monitoring data and anomalies prior to the explosion

3.2 Operator response and human judgement lapses

Although multiple signs of pipeline malfunction emerged prior to the explosion, both CGTDC and LCY Chemical Corporation failed to respond appropriately. Rather than initiating emergency protocols or pausing operations for thorough investigation, the operators opted to maintain supply continuity in response to production pressure.

LCY Chemical Corporation, despite receiving no propylene flow at their end, proceeded with operations without identifying the cause of the supply failure [2]. The company prioritized propylene demand over operational safety, thereby allowing the leak to continue and propylene to accumulate in the stormwater trench.

Critical decisions were made based solely on visual inspection of analog gauges and manual readings, without the support of automated diagnostics, alarm systems, or a structured escalation protocol [8]. The execution of a static pressure test, interpreted as “normal” because of similar pressure readings on both ends, further reflects a fundamental misjudgment. No additional investigation followed, and the resumption of pumping only worsened the situation.

The overall operator response exhibited delayed judgment, insufficient risk awareness, and failure to apply standard precautionary principles in handling hazardous pipeline anomalies.

3.3 Mapping errors and emergency miscommunication

A critical failure contributing to the delayed response was the lack of accurate and accessible pipeline mapping. Although LCY Chemical Corporation had acquired the pipeline years earlier, the public utility database had not been updated to reflect the new ownership. As a result, the LCY pipeline was still listed under its previous owner, rendering it effectively invisible to emergency responders using the city's GIS system during the early stages of the incident [9].

Moreover, although the Kaohsiung Mass Rapid Transit Bureau and other municipal departments were aware of the pipeline's existence, having even invited LCY representatives to pre-construction meetings for the light rail project—this information was not communicated to front-line responders. When the gas leak occurred, emergency teams mistakenly focused on pipelines owned by CPC Corporation, while the actual source of propylene continued leaking unchecked beneath the stormwater trench system [8].

This misidentification delayed critical actions such as area evacuation, full system isolation, and hazard containment. In the early hours of the incident, the absence of a centralized platform for real-time information sharing among CGTDC, LCY, CPC, and city authorities compounded the confusion. As a result, response teams lacked the spatial awareness necessary to identify the leak origin and assess the scale of subsurface gas migration. These systemic failures in mapping and communication underscore the importance of centralized, real-time infrastructure data management [2].

3.4 Pipeline design & infrastructure vulnerabilities

As shown in Figure 5a, the 4-inch propylene pipeline passed through multiple trench sections beneath major roads, including Kaixuan 3rd Rd., Ersheng Rd., Yixin 1st Rd., and Sanduo 1st Rd.. In Figure 5b, a pipe break occurred near an unplanned trench branch beneath Ersheng Rd., which was not present in the original trench construction desisgn. Instead of relocating the pipeline as required, the contractor merely raised it to avoid direct intersection with the trench, despite explicit notes in the original design requiring pipeline relocation in case of overlap. Thus, the pipeline remained exposed in a humid trench environment, accelerating external corrosion.

Further compounding the risk was the insufficient burial depth—as shallow as 0.5 meters in some areas, far below the recommended 1.2-2 meters for petrochemical pipelines in mixed-use urban zones. The pipeline also lacked protective casing or isolation, and shared corridors with other utility lines, increasing its exposure to environmental stressors and mechanical damage.

Moreover, the cathodic protection (ICCP) system for corrosion prevention had previously issued warnings in 2007, identifying abnormal potential values in the pipeline section near Ersheng and Kaixuan 3rd Road junction. These warnings were not followed by remediation, and the affected segments were left unchecked in subsequent years. The pipeline's degradation continued unnoticed due to lack of regular inspection, and to make matters worse, maintenance responsibility between LCY and CPC remained ambiguous following the pipeline's ownership transfer. LCY had no formal contract in place with CPC for continued pipeline maintenance, leading to systemic neglect and confusion during critical moments [5].

(a)

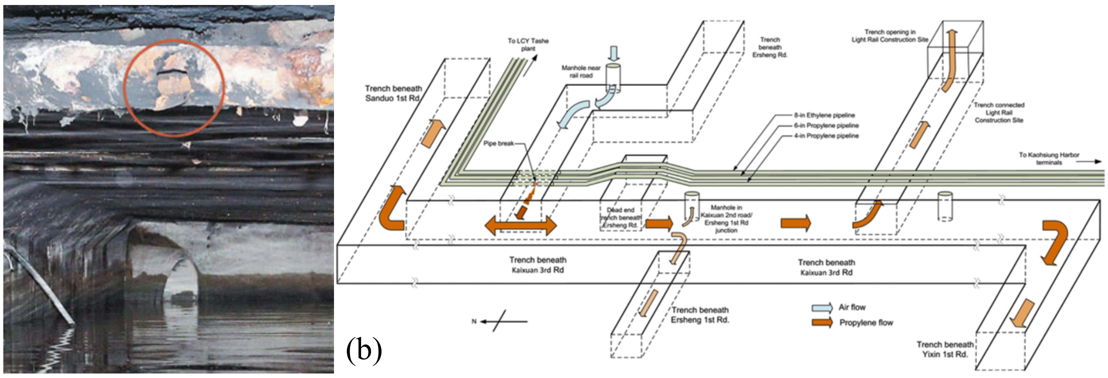

Figure 5. (a)The storm water trench, the 4-in propylene pipeline and the break [9], (b) Schematic diagram of trench, pipeline, and the spread of the leak propylene [5].

3.5 Environmental amplification factors

The characteristics of Kaohsiung's subterranean infrastructure significantly intensified the spatial reach and destructive power of the explosion. This incident produced a planar, multi-point explosion pattern, and was largely due to the presence of an interconnected network of stormwater trenches, sewer lines, and utility corridors, which enabled leaked propylene vapor to migrate across several intersections [2]. The absence of sealed compartments or gas barriers between pipeline zones allowed vapor to accumulate and disperse without restriction. Once ignition occurred, the distributed gas pockets ignited almost simultaneously, amplifying the blast radius and intensity [4]. Furthermore, the trench system lacked venting mechanisms, which led to dangerously elevated vapor concentrations in confined underground spaces [5].

The design of surface infrastructure also contributed to damage escalation. Roads and sidewalks were not engineered to relieve overpressure, lacking blast-resistant joints or sacrificial layers. Consequently, explosive force was transmitted directly to the surface, causing significant ground deformation and structural failures above ground [10].

3.6 Conclusion

This investigation reveals that the incident was not the result of a single technical fault, but a cascading systems failure. Abnormal pressure and flow data prior to the explosion provided early warnings, yet no alarms were triggered, and operators failed to escalate the situation. Misjudgments were driven by production pressure, lack of automation, and misreading of field data, allowing gas to leak for over two hours. Simultaneously, mapping errors and fragmented emergency coordination delayed identification of the leaking pipeline. Without real-time data integration or centralized response among CPC, LCY, and city authorities, initial shutdown efforts targeted the wrong infrastructure. Structurally, the pipeline's shallow burial, inadequate corrosion protection, and absence of shutoff mechanisms left it highly susceptible to failure. Its placement in a stormwater trench enabled rapid subsurface vapor migration, transforming a localized leak into a multi-point urban disaster. Together, these findings reveal a systemic breakdown across technical, human, and organizational domains.

4. Root Cause Failure Analysis

4.1 Fishbone diagram

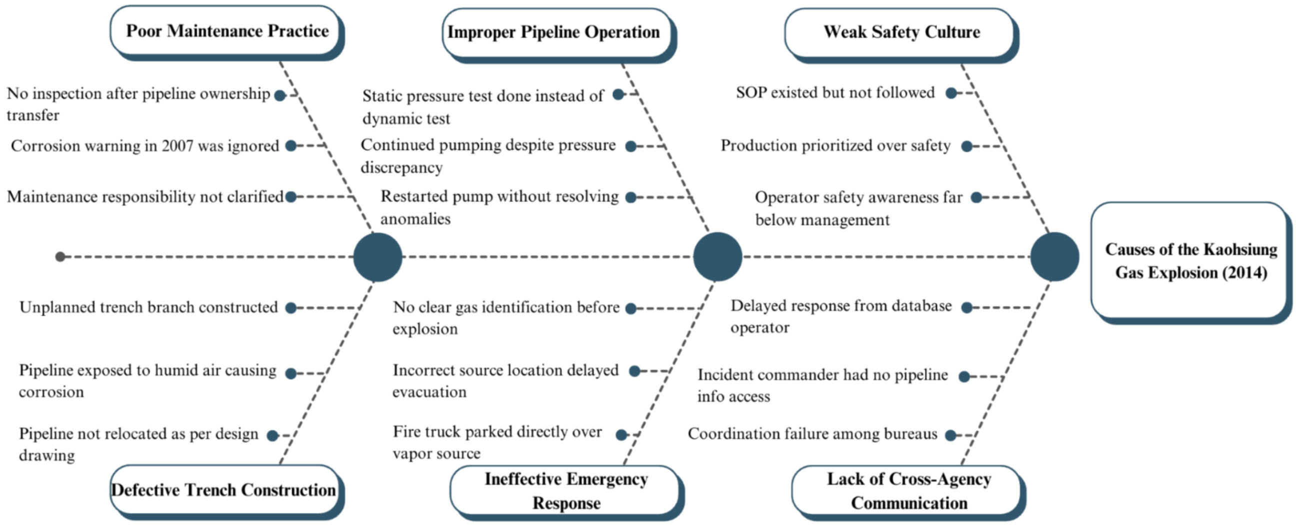

Figure 6. Fishbone diagram

Building on the investigation findings presented in the previous section, the fishbone diagram identifies six major root causes that contributed to the Kaohsiung gas explosion: poor maintenance practice, improper pipeline operation, weak safety culture, defective trench construction, ineffective emergency response, and lack of cross-agency communication. These categories capture both technical failures such as corrosion, misaligned pressure monitoring, and missing safety systems, and organizational issues including miscommunication and regulatory oversights. Together, they reflect a systemic breakdown rather than an isolated error. The fishbone structure clarifies how multiple factors interacted to allow undetected gas leakage, delayed containment, and ultimately an uncontrolled ignition in a densely populated area. These identified root causes now form the basis for the fault tree analysis, which further decomposes the top event, the explosion, into its necessary conditions and logical failure paths.

4.2 Fault tree analysis

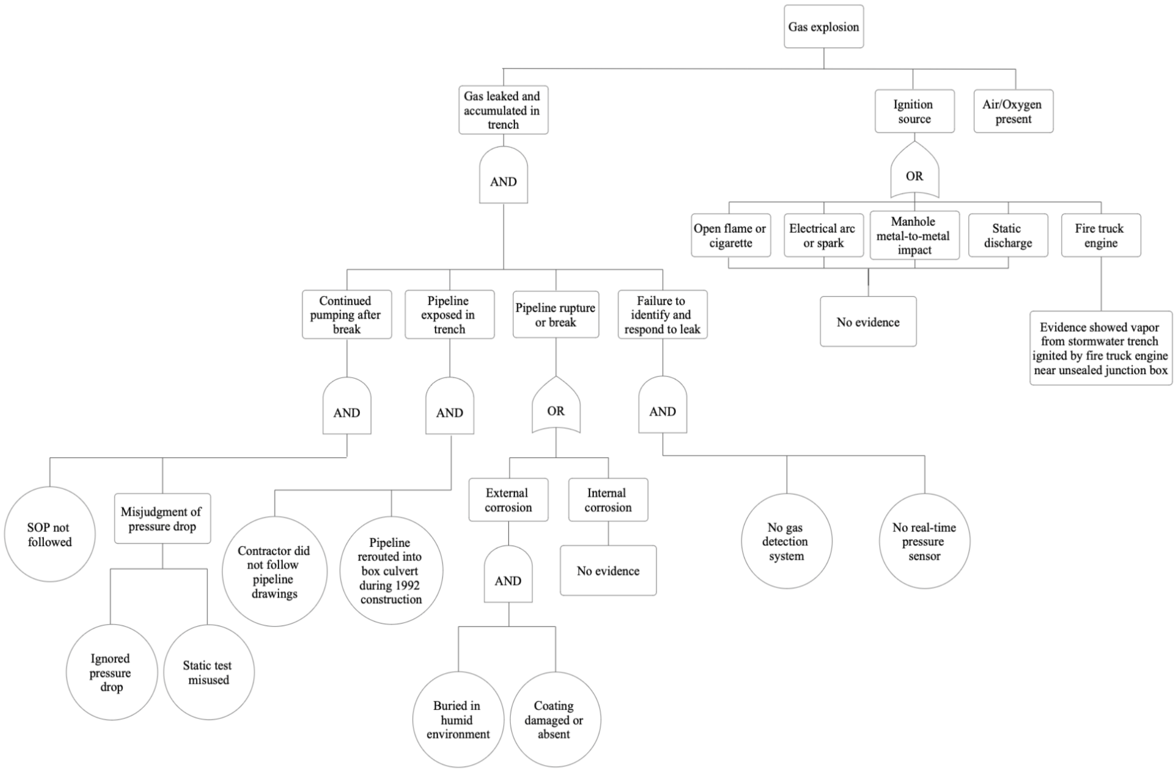

Figure 7. Fault tree analysis

The fault tree analysis further decomposes the gas explosion into its necessary preconditions, offering a structured logic-based approach to understanding how multiple systemic failures converged to cause the disaster. Building on the root causes identified in the fishbone diagram, this FTA outlines the specific failure events and their logical relationships that led to the explosion.

For the explosion to occur, three conditions had to be simultaneously met: the presence of a flammable gas-air mixture, an ignition source, and the availability of oxygen. The most critical one was the prolonged accumulation of leaked propylene gas within the stormwater trench system. This condition emerged from a sequence of cascading failures, including pipeline rupture, continued pumping after the break, the pipeline's exposure within the trench, and the failure to identify and respond to leak.

The rupture was most likely caused by external corrosion, exacerbated by prolonged burial in a humid environment and inadequate protective coating. Despite evident pressure drops and operational anomalies, operators continued pumping due to misjudgment and procedural lapses, such as the misuse of static pressure testing and failure to follow standard operating procedures. Simultaneously, flawed trench construction and rerouting of the pipeline into a box culvert during earlier construction exposed the pipe to further environmental stressors. Compounding these issues was the absence of a gas detection system and real-time pressure sensors, which prevented early leak identification.

On the ignition side, multiple potential sources were considered, including open flames, electrical arcs, and static discharge. However, investigation evidence pointed most strongly toward the fire truck engine, which likely ignited vaporized propylene near an unsealed junction box. This confirms that ignition was not a random occurrence but the result of uncontrolled access and equipment placement near an undetected hazard zone.

Overall, the FTA illustrates how technical deficiencies, misaligned human decisions, and inadequate regulatory oversight interacted across domains. These interdependencies reflect a systems-level failure, where multiple lower-level faults propagated upward and converged into a catastrophic event. The next section summarizes the most critical failure paths and examines their implications for infrastructure safety and accountability.

4.3 Summary of critical failure paths

The critical failure paths of the Kaohsiung gas explosion can be traced through multiple interacting causes identified in both the fishbone and fault tree analysis. Poor maintenance practices, such as failure to act on corrosion warnings and unclear ownership responsibilities, led to external corrosion on the buried pipeline. The rupture was worsened by defective trench construction, where the pipe was rerouted into a humid box culvert without sufficient protective coating. Despite signs of pressure anomalies, operators continued pumping due to misjudgment and violation of standard operating procedures, including the misuse of static testing. Meanwhile, the lack of a gas detection system and inaccurate pipeline mapping delayed response. This allowed gas to accumulate in the stormwater trench system over several hours. The most probable ignition source was the engine of a fire truck positioned directly above an unsealed vapor source. These failure paths reflect a systemic breakdown across technical, operational, and organizational layers, each of which contributed to a preventable industrial disaster.

5. Product liability

5.1 Identification of liable parties

The Kaohsiung gas explosion constitutes a textbook case for analyzing corporate and institutional liability through the lens of product liability and tort law. While the propylene pipeline does not represent a traditional consumer product, its function as a high-risk industrial component falls within the scope of both strict and negligence-based liability frameworks across legal jurisdictions. The parties involved—LCY Chemical Corporation, China General Terminal & Distribution Corporation (CGTDC), and government agencies—bear differing levels of responsibility depending on the legal system applied.

5.2 Comparative perspective: Canada & U.S. & Taiwan

Liable parties	Canada (Negligence-Based Tort Law)	United States (Strict Product Liability)	Taiwan (Civil Code + Product Liability Act + Judicial Ruling)
LCY Chemical Corp.	Liable if negligence is proven, such as failure to monitor pipeline conditions or act on warnings. Courts require breach of duty of care and causation. Civil liability likely.	Strictly liable under Restatement §402A if the pipeline is deemed defective. Liability applies even without fault. Subject to tort claims and potential punitive damages.	Held civilly liable for 30% in 2024 ruling. Although criminally acquitted, the court cited failure to manage known operational risks under Civil Code §184.
CGTDC (Port Operation)	Potential shared liability for negligent operation, such as failure to stop pumping during abnormal pressure events. Liability depends on foreseeability and duty of care.	May be liable under co-operator and failure-to-warn doctrines. Contributory negligence can result in civil liability.	Held civilly liable for 30%. Court found its decision to resume pumping significantly contributed to the explosion. No criminal charges filed.
Government (Municipal and Central)	Can be held liable only if gross negligence or breach of statutory duties is proven. Courts generally defer to governmental immunity unless systemic failure is evident.	Generally protected under qualified immunity. Civil suits are possible only if clear, willful disregard for safety is shown.	Held civilly liable for 40%. Court emphasized trench design flaws, outdated GIS data, and oversight failures. Criminal convictions imposed on three public officials.
CPC Corporation (former pipeline operator)	Liability requires proof of original design or maintenance negligence. Rarely held liable after ownership transfer unless continuing duty is breached.	May be liable under product origin theory if design defects are proven to have caused harm. Must demonstrate causation.	Not held liable. No civil or criminal responsibility found due to lack of causal connection between prior work and incident.

Table 4. Liability Analysis [11]

5.2.1 LCY Chemical Corporation

In the United States, LCY would likely be held strictly liable under Restatement (Second) of Torts §402A for distributing a defective and unreasonably dangerous product. The pipeline, having corroded significantly due to poor maintenance and lacking essential safety mechanisms such as real-time pressure monitoring, can be interpreted as defective in its condition and use. Furthermore, the decision to continue pumping after signs of rupture constitutes a failure to warn or mitigate harm, reinforcing tort-based liability and potentially triggering punitive damages.

Under Canadian law, a negligence-based tort analysis would require the plaintiff to prove that LCY breached its duty of care. This includes failures such as ignoring cathodic protection warnings (2007), neglecting maintenance post-ownership transfer, and prioritizing production over safety. The factual record demonstrates that such breaches were material contributors to the accident.

In Taiwan, LCY was held 30% civilly liable under Civil Code §184, which governs liability arising from intentional or negligent unlawful acts. Although LCY was acquitted in criminal proceedings, the court acknowledged its partial fault for failing to mitigate operational risk and for not clarifying pipeline maintenance responsibilities after acquiring ownership [11].

5.2.2 China General Terminal & Distribution Corporation (CGTDC)

CGTDC's liability primarily stems from operational negligence. The company's decision to resume pumping despite clear pressure anomalies and flow mismatches constitutes a breach of duty under both Canadian and Taiwanese negligence standards. In U.S. tort law, CGTDC may be liable under the failure-to-warn doctrine and could be viewed as a co-operator in a defective system, justifying inclusion in a strict liability claim.

In Taiwan's actual court ruling, CGTDC was found 30% civilly liable, acknowledging its role in enabling the leak through inappropriate responses and delayed shutdown actions. The court's decision reflects the principle of contributory negligence in industrial operations [11].

5.2.3 Government agencies (municipal & central)

The Kaohsiung City Government was ultimately held 40% liable for the gas explosion, making it the party with the highest share of responsibility. The court found that the city failed to fulfill its duty of care in overseeing trench construction, maintaining accurate infrastructure mapping, and ensuring effective emergency response coordination. Specifically, it neglected to enforce the relocation of a hazardous pipeline during public works, permitted the pipeline to remain exposed in a humid trench environment conducive to corrosion, and relied on outdated or inaccurate utility records. These institutional oversights directly contributed to the rupture and significantly delayed emergency mitigation efforts.

In comparative terms, while governments in Canada and the United States often benefit from doctrines such as qualified immunity or judicial deference—unless gross negligence is demonstrated—Taiwanese civil law (Civil Code §184) imposes liability for administrative omissions resulting in harm. The Kaohsiung case thus reinforces the principle that municipalities may be held primarily accountable when systemic failures lead to widespread public damage. In the final ruling, the Kaohsiung City Government was held civilly liable for 40% of the total compensation, reflecting the judiciary's assessment of its pivotal role in trench design failures, GIS data mismanagement, and oversight deficiencies [11].

6. Conclusions

The 2014 Kaohsiung gas explosion was not caused by a single technical fault but by a combination of operational errors, infrastructure flaws, and governance failures. Early warning signals—such as abnormal pressure and flow readings—were ignored by LCY and CGTDC, who resumed pumping despite indications of a leak, directly contributing to the explosion.

Structurally, the pipeline's placement in a moist, shallow, and altered trench led to corrosion, while the absence of cathodic protection and poor enforcement of design standards reflected broader oversight failures. The city's interconnected utility corridors allowed leaked gas to spread and ignite across multiple points.

From a governance perspective, outdated GIS data, poor inter-agency communication, and unclear emergency protocols delayed leak identification and response. The disaster revealed a lack of coordinated infrastructure management and crisis leadership.

Legally, the civil court assigned 40% of liability to the city government, and 30% each to LCY and CGTDC. Three public officials were convicted, while CPC was cleared due to no causal link with the incident. This case underscores the need for integrated risk governance combining technical, legal, and institutional reforms to prevent future urban industrial disasters.

7. Recommendation

7.1 Governance and policy recommendations:

1. Clarify institutional responsibility: Clearly assign maintenance and emergency roles to municipal, central, and private pipeline stakeholders. Avoid ambiguous ownership during handovers.
2. Integrated GIS pipeline database: establish a 3d citywide underground pipeline map with regular updates, enforced by legislation and managed by an independent regulatory body.
3. Public participation and transparency: require petrochemical operators to disclose underground infrastructure layouts to the public. Create community-based disaster education and pipeline safety awareness programs.
4. Disaster preparedness framework: institutionalize petrochemical-specific disaster drills and decision protocols that involve multi-agency coordination.

7.2 Engineering and urban resilience recommendations:

1. Hazard-resistant trench and pipeline design: All pipeline-containing trenches must be sealed, vented, and equipped with real-time gas detection. Reinforce trenches in high-density zones.
2. Emergency isolation technology: Install automated shutoff valves and pressure sensors on all high-risk pipelines, with fail-safe mechanisms linked to centralized control systems.
3. Redundant detection networks: Develop sensor networks to detect pressure, leak rate, and vibration, connected to emergency response systems.
4. Separate hazardous industrial zones: Plan future petrochemical facilities in isolated industrial zones with minimum proximity to residential areas, reducing composite disaster risks.

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