

Analysis of Safety Distances for Fire Brigade in Response to Confined-Space Hazardous Materials Accidents: A Case Study from South Korea

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Article

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Abstract

Confined-space hazardous-materials incidents generate rapid toxic exposure and secondary harm to firefighters, yet operational safety distances are typically defined qualitatively rather than based on dispersion behavior. This study evaluated firefighter safety distances using a hydrogen sulfide (H_2S) accident in a chemical storage tank in Suncheon, South Korea (2025), where 24 firefighters sustained secondary exposure and three civilians died. A case-based analysis integrated accident investigation data, reconstructed responder locations, concentration-based exposure criteria, and ALOHA dispersion simulation. The H_2S release rate was estimated at 0.25 g/s and modeled under low-wind conditions (1 m/s) using dense-gas dispersion methods. Simulation results showed H_2S remaining near the ground and spreading under limited ventilation. Maximum downwind impact distances were 4.1 m at 100 ppm, 7.4 m at 30 ppm, 30 m at 2 ppm, and 42 m at 1 ppm. Comparison with reconstructed firefighter positions revealed that command and emergency medical personnel without self-contained breathing apparatus could fall within low-concentration exposure zones. These findings demonstrate that conventional hazard-zone settings may underestimate responder exposure in confined-space toxic-gas incidents and support quantitative, concentration-based zone designation for emergency-response safety.

1. Introduction

Confined spaces represent environments in which hazardous-material releases can create rapidly lethal conditions. Such spaces have restricted ventilation, so even a brief release of a toxic gas can accumulate to dangerous levels (Interscan, 2025). In recent incidents, acute poisons such as hydrogen sulfide (H_2S) and carbon monoxide (CO) have emerged in confined vessels or sewers, posing immediate asphyxiation or poisoning risks (Rajakumar & Choi, 2023). Hydrogen sulfide, in particular, can paralyze the sense of smell and cause cellular asphyxiation at moderate concentrations (Rumbeiha & Kim, 2025) (Fatima et al., 2025). These properties make H_2S exceptionally dangerous in practice. Emergency-response procedures universally prescribe delineating hazard zones to mitigate such threats. Standard protocols typically divide the scene into Hot, Warm, and Cold zones to control access and respiratory protection (Jeon et al., 2020) (Pennardt & Schwartz, 2014). For example, a Incident Commander may treat the interior of a structure or the area around an open manhole as a Hot Zone requiring SCBA, with other crews held at a safe distance outside. However, such zone labels are often conceptual and are not explicitly tied to how far the toxic cloud can actually travel. Without measurements, Incident Commander may set arbitrary perimeters that underestimate the true extent of the hazard (Sorensen et al., 2004) (O'Mahony et al., 2008) (FEMA, 2023).

The inherently dynamic nature of confined-space releases further compounds the problem. The toxic plume can be discharged suddenly when an entry port is opened, or it may emerge gradually as fluids are agitated or pumped (Li et al., 2023) (Ni et al., 2025). Ventilation fans or thermal currents can then drive the gas unpredictably into adjoining spaces. Firefighters in backup or command roles may thus operate under the assumption of safety, only to find a toxic wave enveloping their position without warning. Even rescue actions themselves can alter airflow and gas movement (Castellnou Ribau et al., 2025) – for

example, fans used to ventilate a tank may inadvertently drive the plume into adjacent areas if misdirected. These complexities mean that support crews, Incident Commander, and even on-scene EMS personnel can all face secondary exposure risks, even if they remain outside the nominal Hot Zone (Keenan et al., 2025) (Lovén et al., 2024) (Descatha et al., 2025).

These patterns have already produced real and tragic outcomes. An analysis of South Korean confined-space hazardous-material accidents (1996–2025) identified fifteen major incidents, in which five firefighters were killed and fifty were injured, alongside thirteen civilian deaths and twenty-one civilian injuries (Do, 2024). Notably, in the 2025 Suncheon storage-tank incident the rescuers evacuated all victims, but a delayed surge of H_2S later inundated the ventilation area, exposing twenty-four firefighters outside the assumed safe zone (Son, 2025) (Song, 2025). Investigation reports of these cases repeatedly cite a common chain of failures: initial misjudgment of hazard type, inadequate exclusion zones, and insufficient gas monitoring. In one representative summary, regulators noted that crews “often did not establish a sufficiently large exclusion zone” and so even the personnel who believed they were safe were caught unaware when the gas spread.

Given these challenges, there is a critical need for evidence-based safety distances tailored to the confined-space context. Existing response guidelines give only qualitative zone definitions and offer no quantitative distances for specific conditions (Li et al., 2023) (Papadaki et al., 2025). To address this gap, the present study develops a scenario-driven analysis to define operational exclusion zones for fire brigades. We use the Suncheon incident as a case study: reconstructing the three-dimensional geometry of the tank and surrounding structure, and simulating a sudden H_2S release under realistic ventilation conditions (calibrated by on-scene measurements). From the simulated concentration field, we determine the distances at which key acute exposure limits are reached (such as the IDLH of 100 ppm for H_2S) and propose these distances as practical safety boundaries (Y. Yang et al., 2025). We then compare these computed boundaries to the perimeters actually used during the incident to identify how the responders’ estimated safety distances fell short of the true hazard extent.

The main contribution of this research is to bridge toxic-dispersion science and firefighting practice. Unlike prior studies of confined-space hazards—which have primarily focused on industrial worker safety—this work explicitly addresses the dynamic, multi-stage exposures encountered by fire-rescue teams during confined-space incidents (Zhao et al., 2025) (Xin et al., 2018) (National Institute for Occupational & Health, 2019). By operationalizing a safety distance in quantitative terms, the findings provide a concrete basis for hazard-zone delineation. In practical terms, the results can guide SOP updates and training, offering evidence-based advice on how far Incident Commander and crews should position themselves in each phase of the response (Gonzalez-Cortes et al., 2023) (C. Yang et al., 2025). Ultimately, these evidence-based criteria aim to reduce the likelihood of secondary firefighter casualties by keeping all personnel safely outside the modeled toxic-impact zones.

2. Literature Review

Confined spaces represent environments in which hazardous-material releases can create rapidly lethal conditions. Confined-space safety has been studied extensively in industrial and occupational settings, with research focusing on worker protection during planned entries (Al-Nezari, 2024) (C. Yang et al., 2025). Standard definitions of a confined space underscore the risk of oxygen depletion and accumulation of toxic atmospheres (Burke & Alnasser, 2020) (Fishwick, 2020). Many studies document that dangerous gas concentrations can accumulate in minutes if ventilation is inadequate (Yu et al., 2026) (Nasir et al., 2025) (Crow, 2025). For example, controlled experiments and field investigations have shown that even a small leak into a sealed tank can quickly yield lethal concentrations of gas. These findings underpin strict entry protocols (such as mandatory atmosphere testing and forced-air ventilation) for maintenance crews, but they assume known hazards and do not address the unpredictability of an unplanned emergency (Salamonowicz et al., 2022) (McCray & Sturtz, 2025).

Among the toxic substances encountered in confined spaces, hydrogen sulfide repeatedly emerges as a primary concern (Genjiafu et al., 2023). H_2S is heavier than air and tends to pool in low-lying pockets, and exposure above roughly 100 ppm can cause immediate respiratory paralysis and collapse (International Marine Contractors, 2023) (Cierpich et al., 2013). Moreover, H_2S rapidly induces olfactory fatigue, meaning that beyond a relatively low threshold victims lose the ability to smell it (Hedlund, 2023). These properties make H_2S especially insidious: multiple accident reports describe scenarios where entrants had little or no detectable odor present yet were abruptly overcome by an H_2S cloud (International Marine Contractors, 2023). By contrast, carbon monoxide or carbon dioxide exposures typically act more slowly or produce earlier warning symptoms (such as headache or breathlessness) (Vural & Dolanbay, 2024). Industrial accident reviews routinely find H_2S at fault in most confined-space fatalities, which is why much of the literature on tank and sewer incidents focuses on H_2S releases from waste or sludge (International Marine Contractors, 2023).

Despite the depth of industrial safety literature, there is comparatively little focus on firefighters or emergency rescuers in these scenarios. Most prior studies assume static release scenarios or controlled entry procedures rather than dynamic rescues (Safety, 2024). For instance, research on mine and sewer entry may quantify the time until a worker's air supply is depleted at a given leak rate, but such models assume a fixed hazard and do not simulate a moving rescue team. In many cases, simulations of gas accumulation and clearance treat the environment as unchanging, even though in practice firefighters may open doors, start fans, or administer victims (Parsa et al., 2025) (At Thabari, 2023). In effect, these works are worker-centric and offer no quantitative insight into how a moving chain of rescuers might be affected. To the best of our knowledge, academic journals contain no detailed analyses of how gas clouds propagate during an active confined-space incident, and incident reports usually note failures qualitatively (e.g. "inadequate exclusion zone") without measuring distances (Chen et al., 2025) (Denisenko et al., 2009).

The dominant emergency-response paradigm for toxic releases is the graduated-zone framework. National and international standards (for example, NFPA and OSHA guidelines) require responders to establish Hot, Warm, and Cold zones at any hazmat incident. Under this scheme, the Hot Zone is the

immediate release area (where entrants must wear full SCBA), surrounded by zones of progressively lower risk. Manuals advise setting a conservative initial perimeter (often a circular isolation distance) and then adjusting it as conditions change, but the standards do not prescribe specific numerical methods for determining that distance (Clawson, 2007) (United States Environmental Protection, 2025). For example, one NFPA text suggests an initial perimeter of 30–100 meters for an unknown vapor release as a rule of thumb, but notes that real-time measurement should guide any expansion or contraction of the zone (National Fire Protection, 2025). In practice, Incident Commander often rely on generic guidelines or on-the-spot judgment (for instance, using the edge of a building or 30 m as a default) rather than model-based calculations (Hiroomi et al., 1994) (American Institute of Chemical, 2026). Even when numeric suggestions are given, they are typically for outdoor releases; none of the available guidance explicitly covers confined-space plumes.

Some researchers have begun to introduce quantitative dispersion modeling into hazardous-material planning, but mostly for larger-scale or outdoor scenarios. Gaussian plume models and computational fluid-dynamics (CFD) simulations have been applied to predict the spread of major industrial leaks, railcar accidents, or pipeline ruptures (Wang et al., 2022) (Li et al., 2025). For example, the ALOHA model and similar tools allow one to input a hypothetical release scenario (flow rate, chemical properties, environmental conditions) and compute concentration contours over time (Ramli et al., 2018). Such analyses have been used to plan evacuation or shelter-in-place distances for communities near chemical facilities. However, published examples of these simulations focus on public or environmental exposures, not on tactical firefighter zones. In those studies, the output might show that a certain ppm level extends, say, 200 meters downwind, but they do not interpret that number as a responder exclusion distance. In short, dispersion modeling is acknowledged as a planning aid, but the literature does not translate model outputs into specific safe distances for emergency crews.

3. Materials

3.1. Accident data

The accident analyzed in this study was a hazardous-materials accident in a confined space that occurred in Suncheon, Republic of Korea, on 21 August 2025. The incident occurred during rescue and emergency medical operations after three civilians collapsed and lost consciousness inside a chemical storage tank. During the rescue and transport process, 24 firefighters were exposed to hydrogen sulfide (H_2S) and received hospital treatment for symptoms such as headache, dizziness, and eye irritation, while the three civilians died.

Field measurements taken at the scene indicated that the H_2S concentration around the accident site was approximately 58 ppm. Exposure occurred among various response personnel other than the SCBA-equipped rescue team, including interior command personnel, rescue support personnel, exterior command personnel, command support staff, and EMS crews. The storage tank involved in the accident

was a cylindrical structure with a height of 3 m and a diameter of 2.4 m, and the upper manhole had a diameter of 0.45 m. This narrow manhole made victim rescue difficult.

The accident investigation identified the following major contributing factors: (1) insufficient gas measurement and continuous monitoring within the hazard zone, (2) inappropriate hazard-zone setting, (3) insufficient use of personal protective equipment by some responders, (4) inadequate ventilation inside the confined space, and (5) patient transport without decontamination procedures. Figure 1 illustrates the H₂S release situation in the confined space and the positions of response personnel at the time of the accident. Panel (a) reconstructs the locations of firefighters on the basis of the official accident investigation report and related de-identified administrative records, panel (b) shows the indoor storage tank involved in the accident, and panel (c) presents the tank and surrounding structure after removal of the outer wall, thereby illustrating the structural characteristics of the confined space

3.2. Toxic properties and exposure criteria of hydrogen sulfide

Hydrogen sulfide (H₂S) is a representative highly toxic gas generated in wastewater treatment facilities, storage tanks, and environments involving organic decomposition. As summarized in Table 1, it may cause irritation even at relatively low concentrations, whereas exposure to high concentrations can result in loss of consciousness and respiratory paralysis within a short period of time. In addition, at and above certain concentrations, olfactory paralysis may occur, making the gas difficult to detect by smell.

Table 1
Characteristics and hazards of hydrogen sulfide

Category	Description	NFPA code
Chemical name	Hydrogen sulfide (H ₂ S)	
Characteristics	Colorless toxic gas with a rotten-egg odor; may not be recognized because of olfactory paralysis	
Hazards	May be fatal even after very short exposure; highly flammable; one or two breaths at high concentration may cause cellular asphyxiation and lung injury, leading to death	
* Note: Compiled from National Institute of Chemical Safety, <i>Information Book for Chemical Accident Site Response</i> (Ministry of Environment, 2024) (Lee & Kang, 2019)		

The health effects of H₂S according to concentration are summarized in Table 2. At approximately 1 ppm, the gas can be detected by odor. At 2 ppm, mild symptoms such as eye irritation and headache may occur. A concentration of 30 ppm, corresponding to ERPG-2, may cause serious or irreversible health effects after 1 h of exposure, whereas 100 ppm, corresponding to ERPG-3, is classified as life-threatening.

Table 2
Exposure levels and toxic symptoms of hydrogen sulfide (H₂S)

Exposure level	Toxic symptoms
1 ppm	Odor threshold for hydrogen sulfide detection
2 ppm	May cause irritation, including eye irritation and headache
30 ppm	Potential for serious or irreversible health effects within 1-h exposure (ERPG-2)
100 ppm	Life-threatening within 1-h exposure (ERPG-3)

* Note: Occupational Safety and Health Administration (OSHA), Hydrogen Sulfide Hazards (2026); National Institute for Occupational Safety and Health (NIOSH), Hydrogen Sulfide (2026).

3.3. Existing safety distance criteria (guideline-based)

To compare the simulation results with existing response criteria, this study referred to the safety-distance guidance presented in the Emergency Response Guidebook (ERG). The ERG provides an initial isolation distance and a protective action distance for chemical releases. In general, for a small spill, the initial isolation distance is presented as approximately 30 m, whereas the downwind protective action distance extends to several hundred meters or more. However, these criteria were developed mainly for open-space releases and therefore have limitations when directly applied to gas-release situations occurring in confined spaces.

In this study, the need for safety distances appropriate for confined-space incidents was examined by comparing these guideline-based safety distances with accident-based simulation results. In addition, the concept proposed in the related Korean materials for H₂S incidents distinguishes the hot zone, warm zone, and cold zone using concentration-based thresholds: 100 ppm for the hot zone, 30 ppm for the warm zone, and 0.1 ppm for the cold zone. Table 3 summarizes the ERG-based safety distances used as a reference in this study.

Table 3
ERG safety distances for hydrogen sulfide (applied by analogy to SOP)

Category	Safety distance		
	Initial isolation distance ³⁾	Protective action distance ⁴⁾	
		Night	Day
Small spills ¹⁾	30 m	100 m	500 m
Large spills ²⁾	400 m	2200 m	6300 m
1) Small spills: Approximately 208 liters or less			
2) Large spills: Approximately over 208 liters			
3) Initial isolation distance: All-direction distance(Life-threatening threshold)			
4) Protective action distance: Downwind distance(Health-threatening threshold)			

* Note: National Fire Agency, “Emergency Response Guidebook (ERG)”, 2022; National Fire Agency, “Standard Operation Procedures Disaster Site”, 2025.

4. Methods

4.1. Study design

This study employed a case-based methodological framework combining hazard identification (HAZID) analysis and scenario-based toxic-gas dispersion simulation. First, major hazard factors were identified through case analysis of confined-space hazardous-material accidents in South Korea. Second, the 2025 Suncheon hydrogen sulfide (H₂S) storage-tank accident was selected as the representative case for detailed analysis because it involved secondary exposure of 24 firefighters due to the absence of an appropriate safety-distance setting. Third, a scenario-based simulation using the ALOHA program was conducted for H₂S, which was identified as the highest-risk substance among the reviewed confined-space accident materials. Through this process, the study aimed to derive quantitative safety distances suitable for hazard-zone setting in actual field operations.

This study was based exclusively on the secondary analysis of retrospective, de-identified accident investigation and administrative records, together with dispersion-simulation data. The National Fire Research Institute, as the custodian of the records, authorized the use of the de-identified records for this study. Pursuant to Article 2, subparagraph 1 of the Bioethics and Safety Act of the Republic of Korea and Article 2(1), subparagraph 3 of its Enforcement Rule, human-subjects research includes research involving intervention or interaction with individuals or the use of information through which individuals can be directly or indirectly identified. This study involved no intervention or interaction with individuals and used only retrospective, de-identified records containing no directly or indirectly identifiable

information. No individuals were recruited, contacted, interviewed, surveyed, or subjected to any research intervention, and no individual-level medical records were used. Accordingly, ethics approval and the requirement for informed consent were deemed unnecessary under Article 2, subparagraph 1 of the Bioethics and Safety Act of the Republic of Korea and Article 2(1), subparagraph 3 of its Enforcement Rule, as this study involved only the secondary analysis of retrospective, fully de-identified records with no intervention, interaction, or identifiable personal information. All methods were performed in accordance with the relevant institutional guidelines and regulations and the applicable laws of the Republic of Korea.

Figure 2. Mechanism of hydrogen sulfide(H_2S) release from an indoor storage tank. (a) Pre-release condition, (Scum layer formation), (b) Internal H_2S release due to scum layer rupture, (c) External release H_2S

4.2. Accident-space modeling

The accident scene was reconstructed as a three-dimensional space model on the basis of the actual structural characteristics of the storage tank and the surrounding warehouse. The model included both the interior tank space and the adjacent indoor space in order to analyze the likely pathway of toxic-gas dispersion from the release source to the surrounding operational area. In particular, the storage tank involved in the accident was treated as a cylindrical confined space with a height of 3 m, a diameter of 2.4 m, and an upper manhole diameter of 0.45 m. Because the accident occurred in an indoor tank structure and the manhole opening was narrow, the model reflected the structural conditions that made rescue difficult and potentially limited ventilation.

The simulation input parameters used in the ALOHA model are summarized in Table 4.

Table 4
Simulation input parameters

Division	Input Values
Atmospheric Stability Class ¹⁾	D
Leak Amount	0.25 grams/sec
Leak Source Height	0 m
Wind Speed	1 m/s
Temperature	34 °C
Measured Height	2 m
Humidity	50%
Ground Roughness	urban or forest
Cloud Cover(0 ~ 10) ²⁾	5
1) Atmospheric stability class : A(Very unstable), B(Unstable), C(Slightly unstable), D(Neutral), E(Slightly dStable), F(Stable)	
2) Cloud cover: 10 (Complete cover), 7·5 (Partly cloudy), 3 or 0 (Clear) tenths	

4.3. Hydrogen sulfide release and dispersion simulation

Based on the representative accident scenario, H₂S release and dispersion were analyzed using a scenario-based simulation approach. The simulation conditions were established to reflect the possibility that gas accumulated inside the confined space could be rapidly released to the outside when the internal environment was disturbed. In particular, the so-called soda-can phenomenon, defined in the supporting materials as the sudden release of high-concentration H₂S dissolved in wastewater when agitated, was considered as the conceptual basis for rapid release. The simulation focused on the temporal change in concentration and the spatial accumulation characteristics of H₂S after release, with particular attention to dispersion from the tank interior through the manhole and into the surrounding response area.

Measured accident data were incorporated as reference information for scenario construction and model validation. According to the accident investigation materials, the H₂S concentration measured around the accident site was approximately 58 ppm. The simulation was therefore designed to reproduce the confined-space release situation on the basis of the actual accident structure, the measured field concentration, and the recorded response process.

4.4. Safety-distance evaluation criteria

Safety-distance evaluation was conducted by applying acute-toxicity criteria for H₂S to the simulated concentration field. As indicated in the study materials, toxic thresholds used for operational zone

setting were 100 ppm for the hot zone, corresponding to ERPG-3 or IDLH, 30 ppm for the warm zone, corresponding to ERPG-2, and 0.1 ppm for the cold zone, corresponding to ERPG-1. In addition, the draft methods outline states that IDLH concentration and short-term exposure criteria were applied to define firefighter exposure-risk zones. Based on these criteria, the study estimated the boundary of the exposure-risk area for firefighters and evaluated whether personnel engaged in command, rescue support, suppression support, and emergency medical activities could remain within or beyond an appropriate safety distance.

4.5. Model validation

Model validity was assessed by comparing the simulation results with the actual exposure locations and damage range observed during the accident. The draft manuscript specifies that firefighter exposure locations and operational segments were compared with the simulated impact zone. Accordingly, the validation process examined whether the predicted H₂S influence area spatially overlapped with the positions of injured firefighters, including personnel outside the nominal hot zone such as command staff, support personnel, and EMS crews. Through this comparison, the study evaluated the appropriateness of the simulated hazard zone and the applicability of the derived safety distance to actual confined-space emergency response.

5. Results

Figure 3 presents the simulated dispersion pattern of hydrogen sulfide (H₂S) generated using the ALOHA model under an estimated release rate of 0.25 g/s. The dispersion contours were delineated according to concentration thresholds associated with human health effects, thereby enabling interpretation of the spatial extent of potential exposure under the representative low-wind condition of 1 m/s. The figure specifically illustrates the maximum downwind distances reached by each concentration level and provides the basis for evaluating the adequacy of existing operational hazard-zone settings

5.1. Gas dispersion characteristics in the confined space

The simulation indicated that H₂S released from the storage tank dispersed rapidly into the adjacent warehouse space immediately after release. Owing to its higher density relative to air, the released gas showed a clear tendency to remain near the ground rather than disperse vertically. This behavior is particularly important in confined or semi-confined environments, where limited ventilation can delay dilution and allow the gas to accumulate within the breathing zone of nearby responders.

The results further showed that, under restricted ventilation conditions, H₂S was not dispersed uniformly but instead formed localized high-concentration regions during the early stage of release. Following this initial accumulation, the gas plume gradually expanded outward, resulting in a broader zone of lower-concentration exposure. This pattern suggests that the release generated two simultaneous hazards: first, a localized zone of potentially severe exposure close to the source, and second, a wider area of lower-concentration exposure extending into surrounding operational spaces. From a response

perspective, this finding indicates that confined-space H₂S incidents may threaten not only entry teams operating near the source but also personnel positioned farther away in adjacent areas.

5.2. Hazard-zone analysis

The concentration-based dispersion analysis showed distinct differences in the maximum downwind extent according to exposure threshold. The simulated impact distance was approximately 4.1 m at 100 ppm, corresponding to ERPG-3, and 7.4 m at 30 ppm, corresponding to ERPG-2. At lower concentrations, the affected area expanded substantially, reaching approximately 30 m at 2 ppm and 42 m at 1 ppm.

These results are significant because they demonstrate that the spatial extent of the hazard increases markedly when lower, yet still operationally relevant, concentration thresholds are considered. In particular, the 2 ppm threshold is associated with irritation and headache and therefore represents a meaningful exposure level for firefighters engaged in prolonged command, support, or EMS activities. The simulated 30 m reach of this threshold indicates that even low-concentration exposure may extend to the boundary of, or beyond, the initial isolation distance commonly applied in field operations. Similarly, the 1 ppm contour extended to approximately 42 m, suggesting that the detectable influence of the release may persist well beyond the area typically regarded as the immediate hazard zone.

Taken together, these findings show that reliance solely on conventional initial isolation distances may underestimate the operational exposure range in confined-space H₂S incidents. While high-concentration zones remained relatively close to the release source, lower-concentration zones extended considerably farther, creating the potential for exposure among personnel who might not ordinarily be classified as operating within a high-risk area.

5.3. Firefighter exposure-risk assessment

A comparison between the reconstructed firefighter locations shown in Fig. 1 and the simulated dispersion pattern shown in Fig. 3 indicated that firefighters performing rescue-support and command functions were positioned within relatively higher exposure-risk areas. In particular, exterior command personnel and EMS crews who were not wearing self-contained breathing apparatus (SCBA) appeared likely to fall within the low-concentration exposure zone of 2 ppm or greater.

This result is operationally important because it suggests that the risk of firefighter exposure was not limited to personnel directly involved in tank entry or immediate rescue actions. Rather, responders performing supporting functions outside the nominal hot zone may also have been vulnerable to H₂S exposure, especially in areas where gas accumulated near the ground and dispersed outward under weak ventilation conditions. The findings therefore indicate that secondary exposure may remain possible even after the primary rescue phase has been completed.

More broadly, the results suggest that low-concentration, longer-range exposure may represent an under recognized hazard in confined-space toxic-gas incidents. Existing response systems often focus on acute high-concentration risk near the source; however, the present simulation indicates that lower-

concentration exposure zones may extend into areas occupied by command and medical personnel. This implies that hazard-zone designation, responder placement, and respiratory protection strategy should account not only for immediate life-threatening concentrations but also for the wider operational footprint of lower-level toxic exposure.

6. Discussion

The present findings suggest that conventional operational distances may not adequately capture firefighter exposure risk in confined-space hazardous-material incidents (Lee & Kang, 2019) (Iarc, 2023). Under the representative release scenario, hydrogen sulfide (H_2S) dispersed to approximately 4.1 m at 100 ppm, 7.4 m at 30 ppm, 30 m at 2 ppm, and 42 m at 1 ppm. The simulation further showed that, after release from the storage tank, H_2S rapidly spread into the indoor warehouse space, accumulated under limited ventilation, and remained near the ground because of its dense-gas behavior (Sorensen et al., 2004) (Bain et al., 2014).

This pattern is consistent with the assumed release mechanism of the present case. The scenario was based on a rapid release associated with disturbance of tank contents, analogous to the soda-can phenomenon described in the supporting materials (Ishihara & Iyi, 2020) (Lim et al., 2022). From an operational perspective, this means that the hazard is not limited to interior entry teams. Personnel engaged in command, support, and EMS activities may also remain within the exposure zone if they operate near the release pathway or adjacent poorly ventilated spaces (Rajakumar & Choi, 2023).

The firefighter-location comparison supports this interpretation. Responders performing rescue-support and command functions were reconstructed within relatively higher exposure-risk areas, and exterior command personnel and EMS crews without SCBA were found to have a high likelihood of falling within the zone above 2 ppm (Woodbury & Merrill, 2026). This finding is important because it indicates that secondary exposure may persist even after the rescue phase has been completed. It also suggests that non-entry personnel positioned outside the nominal hot zone may remain vulnerable when hazard zones are established qualitatively and gas monitoring is not sustained (Cierpich et al., 2013).

The case also reflects a broader operational pattern documented in Korean confined-space hazardous-material accidents (Lee & Kang, 2019). Across the 15 reviewed cases, recurrent contributing factors included inadequate hazard-zone setting, insufficient gas measurement, incomplete PPE use, and inadequate ventilation, with a cumulative toll of five firefighter deaths and 50 injuries (Kwon, 2016). The Suncheon accident therefore represents not an isolated event, but a severe example of a recurring weakness in confined-space response management.

Methodologically, the combined use of Gaussian plume back-calculation and DEGADIS-based ALOHA simulation provided a practical framework for estimating leak behavior and exposure range under limited field-data conditions. Although uncertainty remains because the analysis was based on constrained accident-scene information, this approach offers an operationally useful basis for interpreting firefighter safety distance in real incidents. Overall, the results support a shift from purely conceptual zone

designation toward quantitative hazard-zone setting coupled with continuous gas monitoring and stricter control of responder placement throughout the incident.

7. Conclusion

This study quantitatively evaluated firefighter safety distance using a real confined-space hydrogen sulfide accident in Suncheon, South Korea. The results showed that H₂S released in a confined space tended to remain near the ground and disperse beyond the range commonly assumed in field response, reaching approximately 30 m at 2 ppm and 42 m at 1 ppm under the representative scenario. These findings indicate that the actual exposure range may exceed the conventional hazard zone applied in practice.

Comparison of the simulated plume with reconstructed firefighter locations further showed that personnel other than the entry rescue team, particularly command, support, and EMS personnel, could also be included in the exposure area. This finding underscores that secondary exposure risk may remain even after rescue activities have ended.

From a theoretical perspective, this study demonstrates the value of quantitatively interpreting confined-space gas dispersion through a combined Gaussian plume and DEGADIS-based ALOHA approach under limited field-data conditions. From a practical perspective, the findings support improvement of hazard-zone setting, continuous gas monitoring, and stronger PPE control in confined-space hazardous-material response. However, because the analysis was based on a single case and limited input data, future studies should incorporate multiple accident cases and higher-resolution CFD-based modeling to improve generalizability and precision.

Declarations

Competing Interests:

The authors declare no competing interests.

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Author Contribution

J.-c.Y.: Conceptualization, methodology, software, formal analysis, investigation, resources, data curation, writing—original draft preparation, funding acquisition. J.-c.P.: Validation, writing—review and

editing, supervision.J.-c.K.: Investigation, resources, funding acquisition.All authors have read and agreed to the published version of the manuscript

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Data Availability

The data supporting the findings of this study are not publicly available because they contain sensitive and non-public operational and administrative information related to an official hazardous-materials accident investigation. Owing to institutional confidentiality and information-security restrictions, the underlying accident-investigation records cannot be shared or made available for external use. All non-sensitive data necessary to understand the study methods and reported findings are included in the manuscript.

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Figures

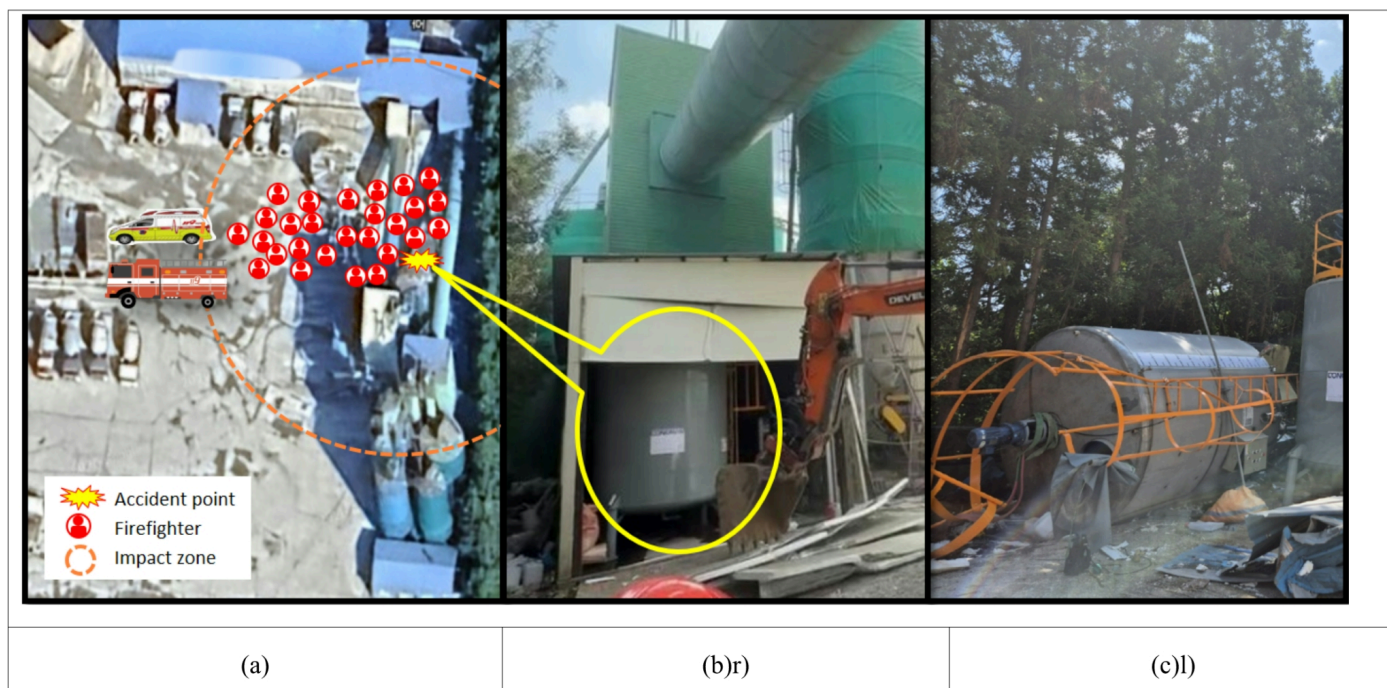


Figure 1

(a) Reconstructed firefighter locations within the impact zone

(b) Confined-space tank involved in the accident (indoor)

(c) Confined-space tank involved in the accident (after removal of the outer wall)

Schematic illustration of the hydrogen sulfide release in the confined space and the locations of response personnel at the time of the accident, showing the spatial relationship between the release source and exposed personnel.

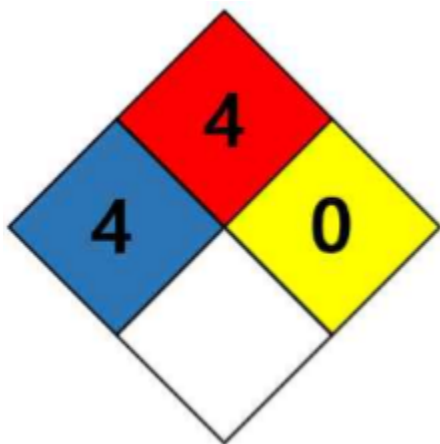


Figure 2

(a) Pre-release condition

(Scum layer formation)

(b) Internal H_2S release due to scum layer rupture

(c) External release H_2S

Mechanism of hydrogen sulfide(H_2S) release from an indoor storage tank

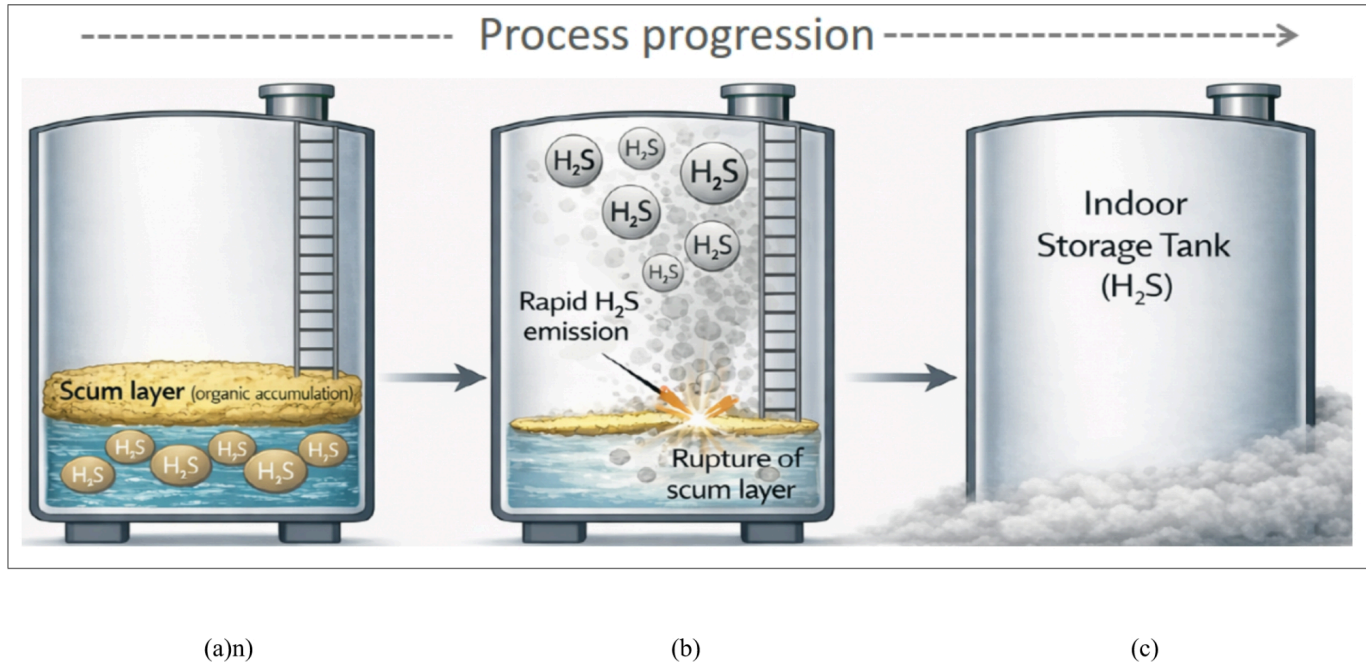


Figure 3

Dispersion of hydrogen sulfide (H_2S) simulated using the ALOHA model under a release rate of 0.25 g/s. The contour lines represent concentration thresholds associated with health effects, and the distances indicate the maximum downwind extent under low wind speed conditions (1 m/s).