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ALOHA-Based Simulation of Safe Fire Distances for Community Safety near Industrial Production Facilities

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Abstract

Fire and explosion incidents at oil refineries in Indonesia pose serious threats to community safety, environmental sustainability, and economic stability. These risks highlight the need for a comprehensive evaluation of safe distance standards between fuel storage facilities and nearby residential areas. This study aims to assess the safe distance of thermal radiation exposure resulting from a tank fire (pool fire) scenario using the ALOHA (Areal Locations of Hazardous Atmospheres) simulation software, as well as to develop risk mitigation recommendations for surrounding communities. A quantitative, non-experimental approach was employed, utilizing secondary data from PT X and relevant literature. Simulation results indicate that areas within 32 meters of the ISO-6L T-2018 tank are exposed to thermal radiation levels of 6.31 kW/m^2, a level capable of causing skin burns, with residential settlements located within this zone. Thermal radiation exposure at 6.31 kW/m^2 may lead to first- to second-degree burns, property damage, long-term health issues, and psychological impacts on residents. Preventive measures and emergency response plans must therefore be developed and implemented to minimize risks and impacts, including community relocation, the installation of thermal barriers, safety education, regular radiation monitoring, the adoption of control technologies, and the enhancement of emergency response infrastructure.

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INTRODUCTION

Disasters at industrial facilities are classified as technological disasters because their primary causes originate from human activities (Granot, 1998; Rachmawati & Rahmawati, 2023; Setyorini, 2023). Technological failures or uncontrolled production processes can trigger non-natural disasters, commonly referred to as industrial disasters. These include explosions, fires, chemical leaks, occupational accidents, and poisoning incidents (Allyreza et al., 2022). Their impacts are extensive, ranging from casualties and material losses to ecosystem damage, public health problems, and socio-economic disruptions (Karnaji et al., 2024; Rosyidah, 2022). One example of such disasters in the oil and gas industry is oil and gas leakage due to operational failures, which can lead to environmental pollution, economic loss, and adverse effects on public health and well-being (Slack et al., 2015). Storage tank fires have frequently occurred worldwide. In 2011, the American Institute of Chemical Engineers analyzed 50 storage tank fire cases between 1959 and 2009 in China, revealing that more than 64% occurred at petrochemical plants, oil refineries, and fuel depots. The leading cause of these accidents was maintenance or repair activities, accounting for 34% or 17 cases (Zheng & Chen, 2011).

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Fire and explosion incidents at fuel storage and processing facilities have shown a concerning frequency in recent years. In 2021, a massive fire at the Balongan Refinery resulted in fatalities and residential damage, while the Cilacap Refinery experienced two fires in the same year. Utama et al. (2022) linked the Cilacap incident to lightning strikes through electrical induction. Similar fires occurred again at the Balikpapan Refinery in May 2022, causing casualties and injuries, and at the Balongan Integrated Terminal in September 2022. Previous studies emphasized that Risk-Based Inspection and HAZOP analysis are effective in minimizing potential refinery equipment failures (Dacosta et al., 2017; Sulistomo & Surjosatyo, 2023). In 2023, two more major incidents occurred: a fire at the Plumpang Depot in Jakarta that killed dozens, and an explosion at the Dumai Refinery that injured workers. Rahim et al. (2024) highlighted that crisis communication strategies and emergency preparedness (Asa et al., 2024; Jatmika et al., 2024) are critical in reducing the social and operational impacts of such recurrent incidents.

These risks are particularly significant in relation to sustainability and the SDG 11 target (Sustainable Cities and Communities), as communities living near industrial facilities are highly vulnerable to the impacts of technological disasters (Firdaus, 2024). Reducing industrial disaster risks requires enhanced risk awareness and stronger adaptive capacity among vulnerable communities (Adger, 2006; H. Jia et al., 2021; Lv et al., 2024), and the implementation of effective technical mitigation strategies (Odiase et al., 2020). Comprehensive disaster management rests on four components: mitigation, preparedness, response, and recovery (Ayuningtyas et al., 2021; Chartoff et al., 2025; Coppola, 2011).

Fire and Explosion Risk Analysis determines the consequences of Major Accident Events related to hydrocarbon releases. Consequence assessment is carried out by dividing process systems into isolatable sections. In the event of a failure, such as a leak, the process can be isolated using shutdown valves to minimize the release inventory. Sources of fire and explosion in oil and gas facilities have broadly driven the adoption of risk mitigation practices to avoid both physical and financial losses (Jia & Jia, 2024; Zavareh et al., 2022). Sulaiman et al. (2025) demonstrated that the HIRARC method is effective in identifying potential hazards, while Aziz & Nugroho (2023) emphasized that optimizing fire protection systems in oil and gas storage facilities plays a vital role in improving preparedness for potential incidents. Local studies, such as Supriyadi (2019) used ALOHA simulations for LNG transportation scenarios and found that pool fire radiation exposure could reach 14–39 meters, while fireball scenarios created hazard zones up to 799 meters. Alghifari et al. (2024) further highlighted the effectiveness of active and passive fire protection systems in reducing potential fire losses. Similarly, Anggraeni & Purbasari (2024) employed ALOHA simulations to evaluate fire risks in small-scale fuel storage facilities, revealing that thermal radiation exposure could extend into residential areas.

In this study, risk mitigation was conducted to manage potential hazards in order to minimize possible impacts. Prior to mitigation, risk assessment was performed to identify potential hazards associated with processes at the PT X ORF facility. Several potential accident scenarios were identified, including Jet Fire, Pool Fire, Explosion, and Dispersion. This study focuses on the Pool Fire scenario at the condensate storage tank of the PT X ORF facility. PT X develops and manages oil and gas fields involving three-phase fluid flow from reservoirs as industrial feedstock. The exploration, exploitation, and processing of oil and gas by PT X present risks of environmental pollution and health hazards caused by leaks or spills of hazardous and toxic materials.

PT X operates a critical facility in the form of a condensate tank used to store liquids resulting from gas separation due to temperature and pressure drops. This facility is located in close proximity to residential areas. The condensate tank poses the risk of a Pool Fire, which could lead to catastrophic rupture. Fires caused by leaks can generate significant thermal radiation, threatening nearby residential areas. The closer the population is to the leakage source, the higher the thermal radiation exposure. Factors influencing the impact of thermal radiation include: (1) distance from the leakage source the closer the distance, the greater the radiation intensity; (2) volume of burning material the more fuel involved, the higher the radiation output; (3) weather conditions—wind, humidity, and temperature affect the spread and intensity of radiation; and (4) fire duration—the longer the fire, the greater the accumulated heat and its environmental impacts. The modeled hydrocarbon process scenarios are presented in Table 1.

Table 1. Process Hydrocarbon Scenarios Modelled

No	Isolatable Section	Description	Phase	P (Psig)	T (F)	Potential Hazardous Outcome
1	ISO-6L	Condensate Tank - Liquid Section	Liquid	ATM	85	Pool Fire

The impacts of the pool fire scenario based on the levels of thermal radiation exposure can be seen in Table 2.

Table 2. Impacts of the Pool Fire Incident by Radiation Parameters

No	Incident	Parameter	Description of Impact
1	Pool Fire	6,31 KW/M²	Continuous exposure of personnel to radiation may cause skin burns; however, with appropriate protective clothing (e.g., uniforms), exposure may be tolerable.
		12,5 KW/M²	Extreme pain within 20 seconds; instinctive movement toward shelter; may result in death if evacuation is not possible. Indoors: 30% fatality. Outdoors: 50% fatality.
		35 KW/M²	Immediate death (100% fatality).

Previous studies have shown that the ALOHA (Areal Locations of Hazardous Atmospheres) software has been widely utilized in simulations and modeling to support industrial disaster risk mitigation. Besiktas et al. (2024) applied ALOHA in a quantitative risk analysis of natural gas pipelines in Istanbul and revealed that the intensity of thermal radiation from jet fires is strongly influenced by leakage rates and pipeline diameter. Hung et al. (2024) combined ALOHA with the Fire Dynamics Simulator (FDS) to determine safe distances for firefighters in oil tank fire scenarios, with simulation results recommending an initial exclusion zone of 62 meters. Meanwhile, Guntama et al. (2022) modeled LNG leakage scenarios in Jakarta using ALOHA, showing that fireball scenarios could generate thermal radiation reaching up to 812 meters, while fire column scenarios extended only about 29 meters. Although previous research has demonstrated the effectiveness of ALOHA in modeling fires involving flammable substances, most studies remain limited to fuel-related contexts such as LPG and LNG. To date, there has been little research specifically addressing safe distances from thermal radiation in pool fire scenarios involving condensate tanks at oil and gas facilities in Indonesia, particularly those located near residential areas. This gap underscores the need for further simulation-based industrial safety research that reflects local conditions, especially in the context of pool fire scenarios.

This study aims to fill that gap by evaluating safe distances from thermal radiation in a condensate tank fire scenario at PT X facilities using ALOHA simulations. It is expected to provide quantitative information on the environmental impacts of such fires and contribute technically to risk mitigation efforts for communities living near industrial facilities. The novelty of this research lies in integrating ALOHA modeling into a specific process failure scenario at oil and gas facilities located adjacent to residential areas. The findings are expected to serve as a scientific basis for safe distance planning, support industrial safety policy-making, and strengthen community protection in line with sustainability principles and disaster risk management.

METHOD

In its operations, PT X develops and manages oil and gas fields involving the transportation of three-phase fluids from the reservoir as industrial raw materials. These raw materials are then processed to separate oil, gas, and produced water. PT X also operates a gas receiving facility, where the produced gas is directly delivered to the Onshore Receiving Facility (ORF) in Gresik before being distributed to domestic industries. However, exploration, exploitation, and processing activities in oil and gas operations carry potential risks of environmental pollution and health hazards, particularly from leaks or spills of hazardous and toxic materials. Figure 2 presents a satellite image of the PT X processing area, which serves as the primary focus in the pool fire risk analysis.

This study employed a quantitative, non-experimental method using the ALOHA (Areal Locations of Hazardous Atmospheres) software, developed by NOAA and EPA, to model hazardous material releases and predict their atmospheric dispersion (U.S. & NOAA, 2020). ALOHA was selected because it is widely recognized as effective for simulating toxic gas incidents and mapping hazard zones, serving as a valuable tool for emergency response planning (Fatemi et al., 2017; Tseng et al., 2012). The research was conducted using secondary data obtained from PT X and relevant literature, without any direct intervention in the research object (non-experimental design). In this study, ALOHA was applied to:

1. Fire Simulation: Modeling a pool fire scenario and calculating the distribution of thermal radiation generated from the fire.
2. Risk Assessment: Identifying high-risk areas based on the intensity of thermal radiation and their distance from the fire source.
3. Decision Support: Assisting in planning evacuation measures and risk mitigation strategies based on the radiation data produced by the simulation.

Figure 2. Satellite Image of the PT X Processing Area

The data obtained were used to analyze potential exposures using ALOHA (Areal Locations of Hazardous Atmospheres) software and complementary methods, providing an overview of the impacts at the location where operational failures occur. The exposure resulting from an operational failure was assessed based on a failure scenario leading to a pool fire at the ISO-6L T-2018 tank, which generates thermal radiation affecting surrounding populations. The findings of this health and safety impact assessment, focusing on individuals within the production facility and nearby public facilities, can serve as a reference for prevention and mitigation efforts aimed at reducing the risk associated with a pool fire at the ISO-6L T-2018 tank in the ORF. The research steps are illustrated in Figure 1.

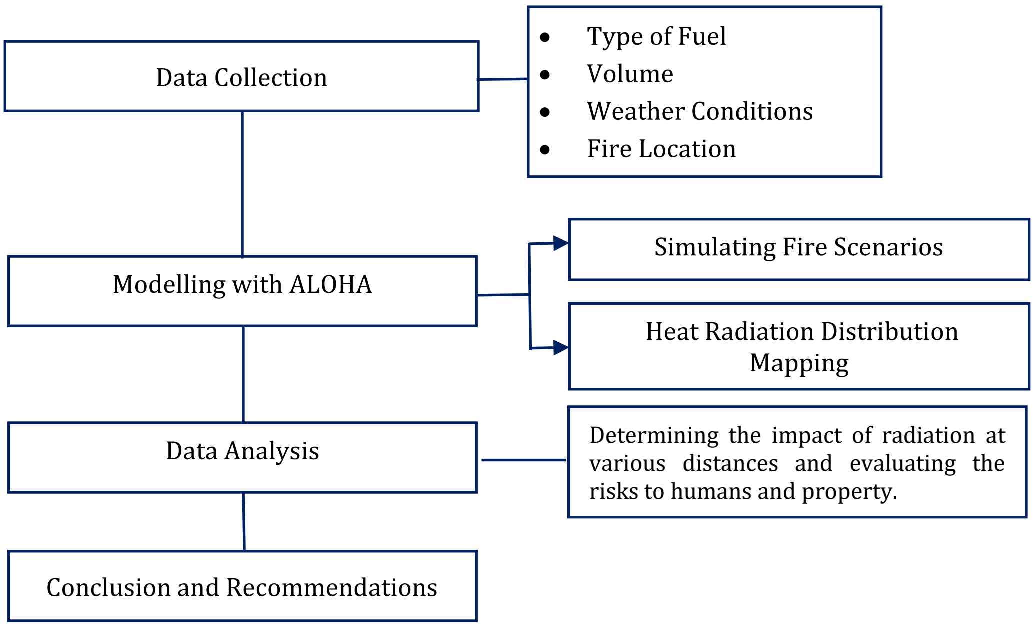

Figure 1. Research Steps

With this approach, the study can provide comprehensive and reliable information regarding the impact of thermal radiation from a pool fire scenario, as well as the necessary measures to protect nearby residents and property. Benefits of Using This Method. Accuracy and Precision: Enables researchers to obtain accurate estimates of thermal radiation distribution. Efficiency: Accelerates the risk analysis process compared to manual methods. Decision-Making Support: Provides robust data to inform fire risk management and emergency planning.

Specification Data

The tank specification data are presented in Figure 3.

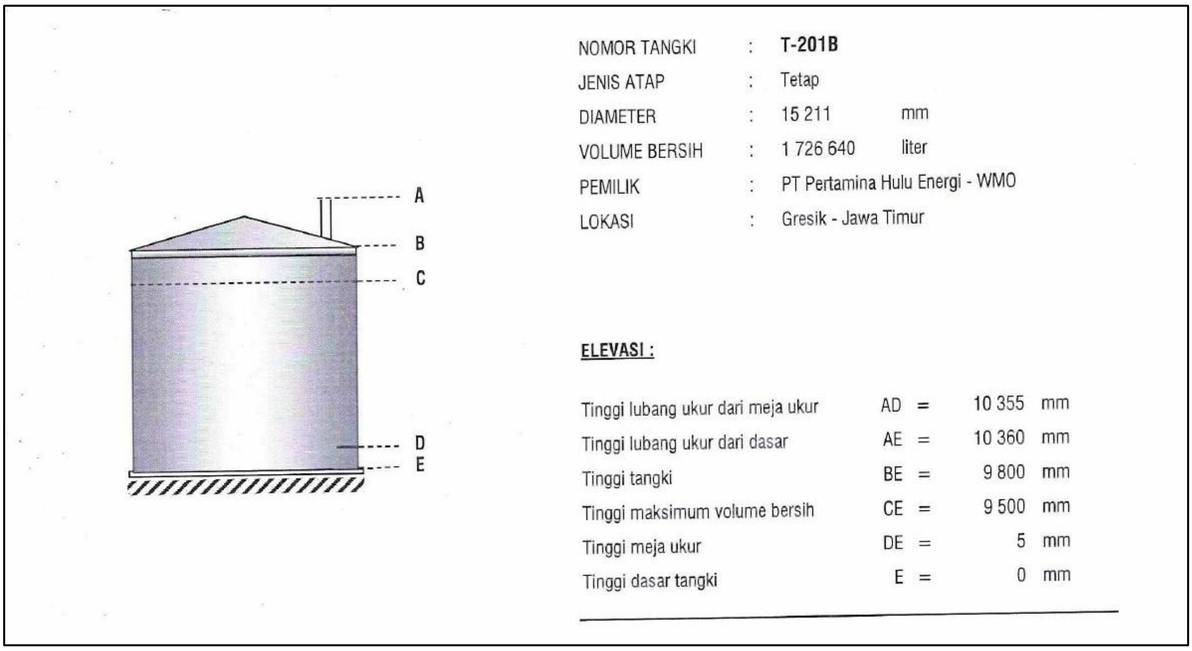

Figure 3. Specifications of ISO-6L T-2018 Tank

The chemical and atmospheric data are presented in Figure 4.

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CHEMICAL DATA:
  Chemical Name: N-HEPTANE
  CAS Number: 142-82-5                   Molecular Weight: 100.20 g/mol
  PAC-1: 500 ppm      PAC-2: 830 ppm     PAC-3: 5000 ppm
  IDLH: 750 ppm       LEL: 10500 ppm     UEL: 67000 ppm
  Ambient Boiling Point: 96.3° C
  Vapor Pressure at Ambient Temperature: 0.092 atm
  Ambient Saturation Concentration: 98,266 ppm or 9.83%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 2.5 meters/second from E at 2 meters
  Ground Roughness: urban or forest      Cloud Cover: 0 tenths
  Air Temperature: 34° C                 Stability Class: D
  No Inversion Height                    Relative Humidity: 50%

SOURCE STRENGTH:
  Leak from hole in vertical cylindrical tank
  Flammable chemical is burning as it escapes from tank
  Tank Diameter: 15.2 meters             Tank Length: 9.8 meters
  Tank Volume: 1,778 cubic meters
  Tank contains liquid                   Internal Temperature: 30° C
  Chemical Mass in Tank: 1,062 tons      Tank is 80% full
  Circular Opening Diameter: 10 centimeters
  Opening is 100 centimeters from tank bottom
  Max Puddle Diameter: 58.79 meters
  Max Flame Length: 20 meters
  Burn Duration: ALOHA limited the duration to 1 hour
  Max Burn Rate: 337 kilograms/min
  Total Amount Burned: 20,063 kilograms
  Note: The chemical escaped as a liquid and formed a burning puddle.
  The puddle spread to a diameter of 8.7 meters.
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Figure 4. Chemical and Atmospheric Data

RESULTS AND DISCUSSION

The results of the ALOHA simulation show that the thermal radiation generated from the pool fire scenario can be seen in Figure 5.

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THREAT ZONE:
  Threat Modeled: Thermal radiation from pool fire
  Red   : 11 meters --- (35 kW/(sq m))
  Orange: 23 meters --- (12.5 kW/(sq m))
  Yellow: 32 meters --- (6.31 kW/(sq m))

THREAT AT POINT:
  Thermal Radiation Estimates at the point:
  Downwind: 59.6 meters                 Off Centerline: 69.6 meters
  Max Thermal Radiation: 0.558 kW/(sq m)
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Figure 5. Thermal Radiation Results from the Pool Fire Scenario

The impact of the pool fire scenario indicates that thermal radiation of 35 kW/m^2 affects an area with a radius of 11 meters, while radiation of 12.5 kW/m^2 extends up to 23 meters. Meanwhile, radiation of 6 kW/m^2 reaches a distance of 32 meters. A detailed illustration of the radiation impact at these intensity levels is presented in the figure below, showing radiation of 35 kW/m^2 at a distance of 11 meters.

Health Impact: Exposure to thermal radiation of 35 kW/m^2 can cause severe skin burns within a short period (less than 20 seconds). Third-degree burns are highly likely, requiring immediate medical attention and potentially resulting in extensive tissue damage. Material Damage: Radiation at this level can trigger secondary fires in flammable materials and cause significant damage to buildings, vehicles, and equipment in the affected area. Evacuation: Areas within an 11-meter radius must be evacuated immediately to prevent severe injuries.

At a distance of 23 meters, exposure to thermal radiation of 12.5 kW/m^2 can cause second-degree burns within approximately 20–30 seconds, leading to blistering and damage to deeper skin layers. Although less intense than 35 kW/m^2, this radiation level remains strong enough to ignite flammable materials and damage nearby property. Therefore, immediate evacuation of residents within a 23-meter radius is necessary to prevent potential injuries.

At a distance of 32 meters, exposure to thermal radiation of 6 kW/m^2 can cause first-degree burns, characterized by skin redness and pain, within approximately 30–60 seconds of exposure. Prolonged exposure may also result in second-degree burns. While this radiation level is sufficient to damage heat-sensitive materials, it is unlikely to directly trigger large-scale fires. Residents within a 32-meter radius should be alerted and may need to be evacuated depending on the duration of the fire and surrounding conditions.

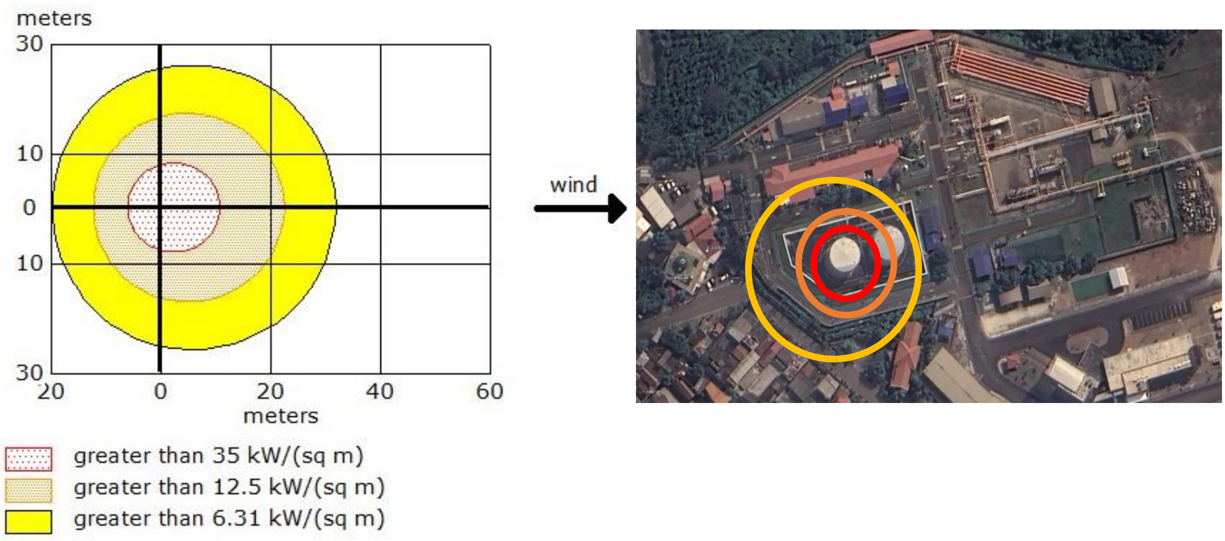

Figure 6. Thermal Radiation

The results indicate that residents located within 32 meters of the tank are exposed to thermal radiation of 6.31 kW/m^2, as shown in Table 2. According to the parameters of incident impact, continuous exposure to this level of radiation may cause skin burns. These findings are consistent with the results of Zárate et al. (2008), who stated that exposure to thermal radiation above 6 kW/m^2 can cause first-degree burns within a short time and second-degree burns with prolonged exposure. In the industrial context, this highlights the urgency of establishing emergency evacuation zones and strengthening fire mitigation systems, particularly in areas with a high risk of direct impact. Compared to previous studies, such as those conducted by Mitu et al. (2021) and Ramesh & Gopalan (2022), this research offers a more specific approach by incorporating actual site data, local weather conditions, and the physical characteristics of the tank under investigation. Moreover, it provides a direct linkage between radiation levels, health impacts, and material damage, which adds practical value to emergency planning.

The strength of this study lies in the use of locally based simulation data that realistically represent field conditions, as well as the application of ALOHA as an efficient predictive tool in fire risk management (Pouyakian et al. 2023; Jones et al., 2013). This aligns with studies emphasizing the importance of spatial predictive modeling in risk-based emergency planning for densely populated industrial areas (Yoo & Choi, 2019; Hung et al. 2024). Accordingly, the findings of this research not only illustrate the potential impacts of a pool fire scenario but also provide a novel contribution by integrating spatial modeling and site-specific data for risk management, an approach that has been rarely applied in industrial facilities in Indonesia. The study contributes both practically and academically by offering a scientific basis for determining safety distances, supporting industrial safety policy-making, and enhancing community protection strategies.

LIMITATION

Nevertheless, this study has certain limitations. The simulations rely on secondary data and model assumptions, which may not fully capture dynamic real-world conditions such as variations in equipment reliability, emergency response capabilities, and socio-environmental factors. Moreover, the study is limited to pool fire scenarios in condensate tanks and does not cover other potential hazards such as explosions or toxic gas dispersion. Future research should therefore integrate multi-hazard scenarios, on-site validation, and a broader assessment of community resilience to strengthen the comprehensiveness of risk management strategies.

CONCLUSION

This study found that a pool fire scenario involving the ISO-6L T-2018 tank generates thermal radiation of 6.31 kW/m^2 at a distance of 32 meters, which includes residential areas. Such exposure has the potential to cause first- to second-degree burns, structural damage to buildings and flammable materials, as well as long-term health impacts such as dehydration and skin tissue damage. In addition, this threat may trigger psychological distress and anxiety among nearby residents.

The findings directly address the research problem, confirming that residential settlements fall within the hazard zone of thermal radiation. The key result of this study is that thermal radiation exposure of 6.31 kW/m² reaching residential areas within 32 meters of the ISO-6L T-2018 tank represents a serious threat that requires immediate intervention to safeguard public health and safety. Therefore, urgent measures are needed, including relocation, community protection and education, continuous monitoring, implementation of heat-control technologies, and enhancement of emergency response infrastructure to minimize the associated risks and impacts.

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