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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

The Evaluation of Methane Gas Explosion Risk in Confined Spaces – A Case Study in the Ship Building Industry

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Abstract

Hydrocarbon gas explosions such as methane gas in confined spaces represent a significant hazard across various industries, particularly mining, oil and gas extraction, and oxy-cutting processes. The risks associated with methane accumulation are exacerbated by the unique characteristics of confined spaces, where gas concentrations can reach explosive levels. The explosive potential of methane is primarily influenced by its concentration in the air. Understanding the conditions under which methane becomes hazardous is crucial for developing effective safety protocols and mitigation strategies.

This study is based on a truth gas leak near-miss incident in the shipyard ship building department. Before this study, there were many records of gas leaks due to hose and torch connection points and hose damage in oxy-fuel cutting operations. During the confined spaces (ballast, cargo, service, settling tanks etc.) gas free measurements on April 8, 2024, we detected a methane gas leak reaching explosive concentrations originating from a damaged welding hose. In this study, the question of what would happen if this explosive atmosphere in the confined space exploded under optimum conditions was answered. According to the results of the study, the explosive methane gas concentration in a 169 m^3 confined space (ballast tank) was approximately 10 kg methane gas mass, and the methane gas leak of 80 % of the hose cross-section diameter reached an explosive concentration within 15 minutes. The amount of 10 kg methane gas leaking into the 169 m^3 confined space was equivalent to the 95000 ppm (9.5 % v/v) methane gas concentration required to provide optimum explosion conditions. After an explosion caused by 10 kg of methane gas in the ballast tank (169 m^3), a worker standing 1 m away will be exposed to 1523 kPa of overpressure. 10 kg methane gas used for the explosion scenario represents the stoichiometric fuel/air mixture (95000 ppm). When the evaluation is made by taking into account the 1 s positive phase duration, the mortality rate due to lung damage, which is one of the organs most exposed to air, means that a person standing 1 m away is exposed to 1523 kPa overpressure and the probability of death (Pr) is estimated as 93%. This result may have more dramatic consequence depending on the number of people in the ballast tank.

Keywords: Gas explosion, Explosion risk in confined spaces, Consequence Analysis

I. INTRODUCTION

Natural gas (methane, CH_4) is a safe energy source that is extensively used in daily life particularly in residential and industrial sectors. However, it poses significiant risks in confined spaces due to its explosion potential. The risk of methane explosion increases in confined environments with limited ventilation, leading to rapid accumulation of gas within these areas. This situation presents a serious hazard for workers in industries where exposure to methane is common such as shipbuilding (Rajakumar and Choi, 2023). The research showing the fatal occupational accidents and their causes in the shipbuilding sector in Turkey is shared in Figure 1.

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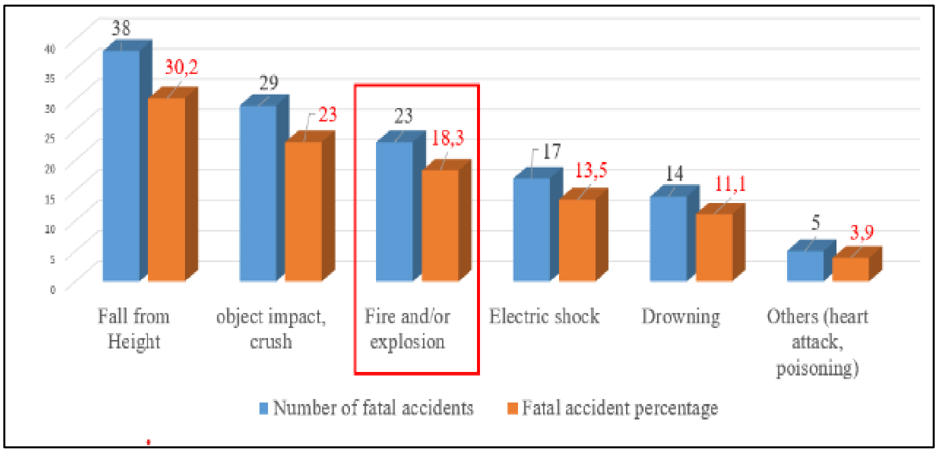

Figure 1. Classification of Fatal Work Accidents in the Shipbuilding Industry [1]

According to Figure 1; the causes of fatal occupational accidents in the shipbuilding industry in Turkey, have been examined under 6 (six) main headings and the number of fatal occupational accidents caused by fire/explosion is at an alarming level. Almost all fire/explosion accidents are caused by chemicals such as gases and solvents that create flammable and explosive atmospheres in confined spaces. Methane gas can form explosive mixtures when present in the air at concentrations ranging from approximately 5% to 15% by volume, known as the lower explosive limit (LEL) and upper explosive limit (UEL), respectively (Jia, 2023). The methane gas, which is a critical concern in confined spaces, can acumulate to hazardous levels and create a severe explosion when ignited by an ignition source (such as an open flame, hot surface, sparks or static electric) at concentrations ranging from 50.000 to 150.000 ppm (lower explosive limit: 5%, upper explosive limit: 15% v/v) (Ma. Et al., 2012). Experimental studies in the literature indicate that optimum explosion conditions are achieved when the CH_4 /Air stoichiometric ratio reaches approximately 9.5%, v/v (95.000 ppm) [2]. In particular, methane gas leaks are one of the most frequently encountered major incidents in the shipbuilding sector, where methane is extensively used for processes such as oxyfuel cutting of metals and annealing.

Figure 2. Ballast Tanks – Ship Building Industry

In this study; the results of a near-miss incident that occurred on April 8, 2024 with the leakage of CH_4 gas from a torch hose connection point left open in the port side number 5 ballast tank were discussed with the Consequence Analysis Modeling Approach (CAMA). The potential for explosion is higher in confined spaces where gas concentrations may exceed safe thresholds. Research suggests that concentrations of methane above 15% in vapor form can pose explosive hazards. The most important reasons for confined space gas leaks, which are very common in the shipyard industry where the Positive Work Safety Culture is not at the expected level, are as follows;

- Lack of Training
- Torches and gas hoses forgotten/left behind at the end of work in closed areas
- Use of attached hoses in closed areas that do not comply with the TS EN 3821 standard.

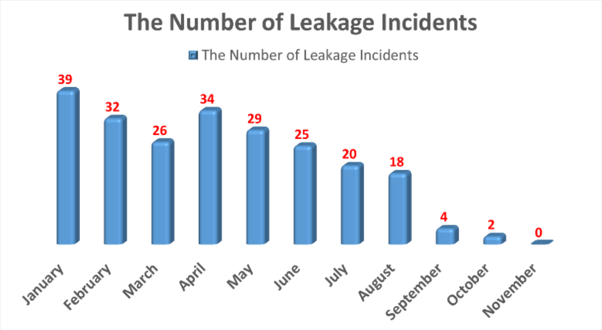

Figure 3. Methane Gas Leak Records in the Shipbuilding Projects (2024)

The flammability limits of methane gas depend on the physical and chemical properties of the gas. For example, the autoignition temperature (MIT) of methane is around 540 °C, at which temperature methane gas can combine with oxygen to undergo a combustion reaction [3]. Also, since methane gas has a lower density than air, it tends to rise in the air in the event of a leak. This can lead to methane gas accumulating in confined spaces and creating a potential explosion risk (Büyükkıdan at all., 2023). It is vital that the environment is ventilated and that the gas is safely exhausted in the event of a possible leak [4].

Table 1. The Statistics of Gas Hose Leakage in Shipbuilding Projects

Months	The Number of Leak Incidents	Leak Source	LEL (% v/v)
January	39	Torch Hose Connection	-
February	32	Torch Hose Connection	-
March	26	Gas hose joint	-
April	34	Gas hose joint	%10
May	29	Cutting Torch	-
June	25	Torch hose joint	-
July	20	Torch hose joint	-
August	18	Torch Hose Connection	-
September	4	Cutting Torch	-
October	2	Cutting Torch	-
November	0	Torch Hose Connection	-

Table 1 shows leakage statistics for approximately 126 closed areas of different volumes where gas measurements are taken every morning on a total of 4 LNG tankers in the Shipbuilding project. As a result of the gas measurement taken in the ballast tank number 5 (168 m^3) on the port side of the NB-34 project in April 2024, methane gas reaching the lower explosion limit in the closed area was detected and the closed environment was cleared of gas by means of ex-proof fans by urgently activating gas-free protocols.

1.1. Explosible Parameters of Methane (CH_4) Gas

Methane gas, with the chemical formula CH_4 (carbon and 4 hydrogen atoms), is a colorless and odorless energy source that exists in the gas phase under normal conditions. It is an important fuel known as natural gas in the public language. One mole of methane burns in the presence of oxygen are producing one mole of carbon dioxide, two moles of water, and 50,000 kJ/kg of heat [5].

$$CH_4\,(gas) + 2O_2\,(gas) \Rightarrow CO_2\,(gas) + 2H_2O\,(gas)\ \Delta H_E = 50.000\ kj/kg$$

The lower (LEL) and upper (UEL) explosion limit ranges of methane gas are shown in Figure 3. The optimum explosion concentration is 95,000 ppm (meaning ≈ 10 kg methane gas for 169 m^3 ballast tank)

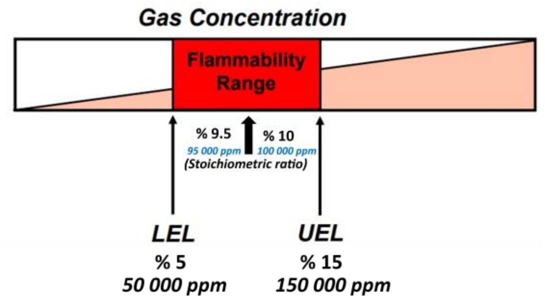

Figure 4. The Optimal Explosion Range of Methane Gas (LEL:5 % UEL: 15 %)

Specific gravity = ʎ metan = $\frac{M_{gas}}{M_{air}} = \frac{16}{29}$ = 0,552 <ʎ hava (since the specific gravity of air is about 1, methane gas accumulates near the top). Methane gas (CH_4), which is a very safe gas under normal conditions, can cause very risky situations, especially after leaks that may occur in closed areas [6]. The physicochemical properties of methane gas are shared in Table 2.

Table 2. Physicochemical Properties of Methane Gas

Chemical Formula	CH_4
Molecular Weight	16.04 g/mol
Phase	Gas
Color	Colorless
Min. Ignition Temperture (MIT)	540 °C
Min. Ignition Energy (MIE)	0.28 µJ
Odour	Odourless
Gas Density (0°C,1 atm)	0.717 kg/m³
Melting Point	-182,5 °C
Boiling Point	-161,5 °C
Explosive Range	%5- %15 (v/v)
Flammability	Yes
Heat Value	55.5 MJ/kg
Polytropic Index, γ	1.3

II. MATERYAL VE METOD

This study is based on a truth gas leak near-miss incident. According to the study results, When approximately 10 kg of methane gas leaks (within 15 minutes for 80 % leak cross-section) into a 169 m^3 confined space, the ambient atmosphere reaches the most favorable explosion conditions (LEL %9,5 v/v). The stoichiometric volume fraction in the air is 9.5 % (v/v) for methane (CH_4) gas.

This stoichiometric ratio is equivalent to approximately 10 kg of methane gas for a confined space volume of 169 m^3. Methane gas escaping from the leak cross-sectional area of approximately 80% of the hose diameter may create an explosive atmosphere (10 kg methane gas LEL 9.5 %v/v) in a confined space of 169 m^3 within 15 minutes.

The risk of confined space explosion discussed in this study occurred as a result of methane gas (CH_4) leakage at the connection point of the torch forgotten at the end of work at 08:00 p.m at the port side ballast tank number 5 in the NB-34 project (168 m^3) in April 2024 and, and the near-miss event where the stoichiometric air/CH_4 concentration exceeded the lower explosion limit (55000 ppm) was scenarioed, and the answer to the question "What would be the consequences of an explosion that could occur in a closed area as a result of contact with an ignition source (due to static electricity, open flame, hot surfaces, sparks, etc.)" was investigated.

In the study, it was assumed that optimum stoichiometric conditions were provided by exceeding the lower explosion limit of methane (CH_4) gas (95000 ppm) and the effect of an explosion in a ballast tank caused by 10 kg of methane gas on a worker weight 70 kg was evaluated.

Determining the exit characteristic of the gas from the cross-sectional area is a very important parameter in terms of the mass flow rate (kg/s) of a gas expanding from the liquid phase volume to the gas phase volume. In order to make this decision, a critical pressure assessment must be made.

The relationship between the choked pressure and the gas source (tank, collector, cylinder, etc.) based on the isentropic expansion assumption, where Po (Pascal) is the hose transfer pressure, is expressed by Equation 1.

$$P_c = P_a \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma - 1}} \qquad (1)$$

In Equation 1, Pc refers to the critical pressure (Pascal), γ refers to the polytropic index (1<γ <1.8), and Pa refers to the atmospheric pressure. When $P_o > P_c$ the flow is considered sonic, when $P_o < P_c$ the flow is considered subsonic. If the critical pressure-Pc (pascal) is greater than the atmospheric pressure- Pa (101325 Pascal); Pc> Pa the flow is expressed as sonic. In the literature, all flows at 1.9 bar and above are considered as sonic flows [8].

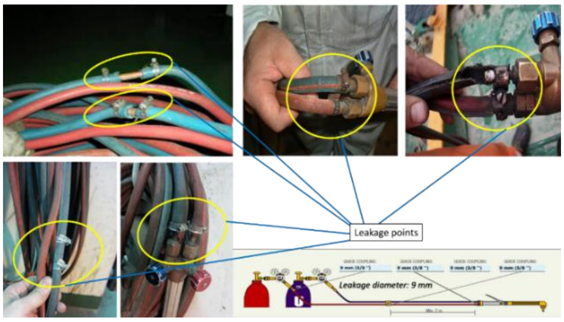

Figure 5. Leak points for flammable gases used oxy-cutting works in confined spaces

The fact that the methane gas escaping from the hose can be heard from approximately 8-10 meters indicates that the gas escaping from the hose into the enclosed space atmosphere is being emitted at sonic speed. The methodology discussed in the study can also be used with flammable gases used in other welding or oxy-cutting operations.

Equation 2 shows the mass flow equation for gas in a pressurized hose escaping from a cross-sectional area of the hose into the enclosed atmosphere.

$$\frac{dG}{dt} = C_D S P_o \psi \sqrt{\gamma \frac{M_{gas}}{Z\,R\,T}\left(\frac{2}{\gamma+1}\right)^{\gamma+1/\gamma-1}} \qquad (2)$$

for sonic flow; $\psi = 1$

In Equation 2; dG/dt: mass flow rate of the gas exit at sonic speed (kg/s), CD: (0.50 -1) discharge coefficient, S: cross-sectional area where the gas exits (m2), Po: process pressure of the gas (Pascal), ψ: dimensionless factor depending on the speed of the gas, γ: polytropic index ($1<\gamma<1.8$), Mgas: molecular weight of the gas (kg/kmol), R: universal gas constant (8314 J/kmol. K), T: temperature to which the gas is exposed (Kelvin). C_D (-) is a coefficient that takes into account that the process is not isentropic [9].

2.1. TNT (Tri Nitro Toluene) Equivalent Mass Method

The trinitrotoluene (TNT) equivalence method is a widely accepted concept for assessing the effects of explosions and is used in the related engineering field [10]. TNT is often used in equivalence calculations to measure the potency of other explosives. Other explosives are compared by "equivalent mass of TNT", usually expressed in terms of TNT. In this way; a consistent and understandable comparison can be made between the effects of various explosives. Many experiments and researches in the past have been carried out specifically on TNT. Therefore, the results of such studies provide a reliable basis when applied to other explosives. As a result, the TNT equivalent is an important tool in evaluating other high-energy substances, making it easier for engineers and scientists to analyze different materials and enable them to develop safe applications [11].

$$M_{TNT} = \emptyset \text{ x } \frac{M_{gas\ x}\,\Delta H_{gas}}{\Delta H_{TNT}} \qquad (3)$$

In Equation 3, M_{TNT} represents the mass amount of TNT equivalent to the amount of explosive gas (kg), Ø represents the explosion efficiency (0.01 – 0.10), ΔH_{gas} represents the explosion energy of the gas (kJ/kg), ΔH_{TNT} represents the explosion energy for explosive TNT (kJ/kg). CCPS (Center of Chemical Process Safety) recommends that an explosion efficiency of 0.03 be taken into account in hydrocarbon gas explosions.

2.2. Direct Effects of Explosion on Humans

The effect of blast waves on humans is based primarily on the sudden increase in pressure that occurs at the moment of explosion. These pressure waves can cause damage to various parts of the human body. Direct damage from pressure is usually concentrated in body parts that contain air pockets, such as the ears and lungs. In particular, the lungs are extremely sensitive to overpressure because of they contain air pockets. The overpressure wave created during an explosion can cause lung tissue to rupture or internal bleeding. The concept of scaled distance "Z" is a parameter used in the calculation of overpressure caused by explosions.

This concept was developed to better understand the effects of explosive charges and their impact on the surrounding air environment. Calculating overpressure (P_s) is of great importance in assessing the safety risks of such events and taking appropriate protective measures. Equation 4 helps to scale down the effects of larger explosive charges and compare the effects of smaller charges.

$$Z = R / W_{TNT}^{1/3} \quad \text{m.kg}^{-1/3}$$

$$0.3 \le Z \le 1.0 \text{ for;}$$

$$P_s = \frac{619.4}{Z} - \frac{32.6}{Z^2} + \frac{213.2}{Z^3} \qquad (4)$$

$$\acute{P}_s = \frac{8P_s^2 + P_s\,14 \text{ x } 10^5}{P_s + 7 \text{ x } 10^5} \qquad (5)$$

In Equation 4; R represents the real distance (m), W: TNT equivalent mass amount (kg), Z: scaled distance(m.kg-1/3), P_s: overpressure (kPa).

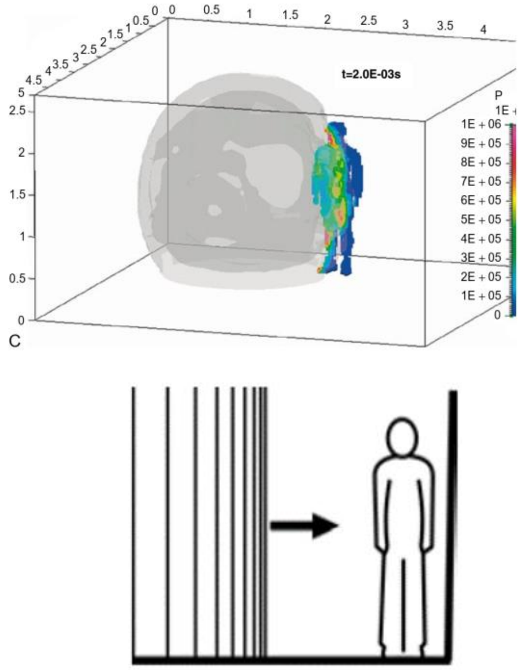

Figure 6. Effects of explosion overpressure wave on humans in confined space [13]

Figure 6 shows how an explosion in a closed space engulfs a person and the blast wave that the worker will be exposed to, using the Ansys-LS DYNA software. The position of people at the time of the explosion (e.g. sitting, standing or lying down) and environmental factors (e.g. confined space) may affect susceptibility to overpressure. Figure 6 shows the overpressure wave-body interactions that occur after a methane gas explosion in a confined space such as a ballast tank. The explosion overpressure wave occuring on humans can be calculated theoretically with equation 5.

2.3. Probit Functions

The overpressure that occurs during an explosion causes the pressure difference between the air inside the lungs and the outside environment to change suddenly. This can lead to tears or bleeding in the lung tissue. Due to the impact of the explosion, the body is suddenly exposed to a high external pressure, and this overpressure exposure makes it difficult for the lungs to expand, causing the air inside them to become compressed. These pressure differences caused by the high-intensity explosion can cause blood vessels to rupture, resulting in bleeding. Probit analysis, proposed by Eisenberg et al., is a statistical method used to estimate the risk of death from a particular event.

Based on the data obtained from equations 6, 7, 8, 9 the risk of death of individuals exposed to a certain overpressure is calculated.

$$Y = -5.0 + 5.74 \ \text{In}\ S \qquad \textbf{(6)}$$

$$\mathbf{S} = \frac{\mathbf{4.2}}{\overline{\mathbf{P}}} + \frac{\mathbf{1.3}}{\bar{\mathrm{I}}} \qquad \textbf{(7)}$$

$$\overline{\mathbf{P}} = \frac{\acute{\mathbf{P}}_{\mathbf{s}}}{\mathbf{P_a}} \quad \textbf{and}\ \bar{\mathrm{I}} = \frac{\mathbf{i}}{\mathbf{m^{1/3}}\sqrt{\mathbf{P_a}}} \qquad \textbf{(8)}$$

$$\bar{\mathrm{I}} = \frac{\mathbf{i}}{\mathbf{m^{1/3}}\sqrt{\mathbf{P_a}}}\left(\frac{\mathbf{1}}{\mathbf{2}}\ \mathbf{P'_S}\ \mathbf{t_p}\right)$$

$$\mathbf{P_r} = \frac{\mathbf{1}}{\mathbf{2}}\left[\mathbf{1} + \mathbf{erf}\left(\frac{\mathbf{Y-5}}{\sqrt{\mathbf{2}}}\right)\right] \qquad \textbf{(9)}$$

Blast pressure difference-induced lung injury usually occurs as a result of explosions that create high overpressure, and calculating such injuries is a complex process. The probability of death due to lung injury caused by the application of explosion pressure difference, Pr (%), can also be estimated theoretically by the following procedure [14]. According to the assumption in Figure 6; after an explosion caused by 10 kg of methane gas in the ballast tank, a worker standing 1 m away will be exposed to 1523 kPa of overpressure. When an evaluation is made with a 1 s positive phase duration, the mortality rate due to lung damage, one of the most important air-entering body organs, is estimated as 93%. This situation may have more dramatic consequences depending on the number of people in the ballast tank.

It was assumed that there was no ventilation in the environment and the explosion was analyzed for a 1 second positive phase duration based on the representation given in Figure 7.

- The physical formulas and parameters are used to calculate the overpressure; Ps (Pa) and death propability (Pr); at a given distance from the explosion center.
- The total overpressure Ps' (Pa) is calculated for the position of the human body in the confined space given in Figure 7.
- For a 70 kg human body, the scaled impulse ($Pa^{1/2}$ s $kg^{-1/3}$) and the scaled pressure, $\overline{P}$ (-), are calculated by Equation 7.
- The probability of death is calculated with the Probit function (Pr) given in Equation 8.

It should be emphasized, however, that the results of these calculation procedures are not fully quantitative or binding.

2.4. Consequence Analysis Modeling Approach (CAMA) Method

Consequence analysis modelling approach (CAMA) is an important tool that comprehensively evaluates the situations and consequences that may cause a possible industrial accident in the chemical process industry and contributes to the planning of reinforcement and redevelopment works to eliminate the potential accident risk or reduce it to an acceptable level [7].

Usually, their purpose is primarily to estimate the effects and consequences of an event, so that contingency plans of hypothetical scenarios can be drawn, discussed and dealt with. The CAMA (Consequence Analysis Modeling Approach) given in Figure 7 was used in this study to evaluate the confined space explosion risk of methane gas. The framework of the study procedure is given in Figure 7. The Consequence Analysis Approach is defined as the estimation of the expected effects of event consequences, regardless of the frequency or probability of the expected event occurring (CCPS-Center for Chemical Process Safety).

The quantitative modeling approach applied for methane gas explosion in confined spaces in this study can be applied to different explosive gases in different industries. The key point is to construct integrity loss scenarios and predict their consequences.

The selection of the release case depends on the requirements of the consequence study. If an internal company study is being complete to determine the actual consequences of plant releases, then realistic cases should be selected such as this study.

Uncertainties that arise during the consequence modeling procedure are treated by assigning conservative values to some of these unknowns.

By doing so, a conservative estimate of the consequence is obtained, defining the limits of the design envelope. This ensures that the resulting engineering design to mitigate or remove the hazard is overdesigned. Every effort, however, should be made to achieve a result consistent with the demands of the problem.

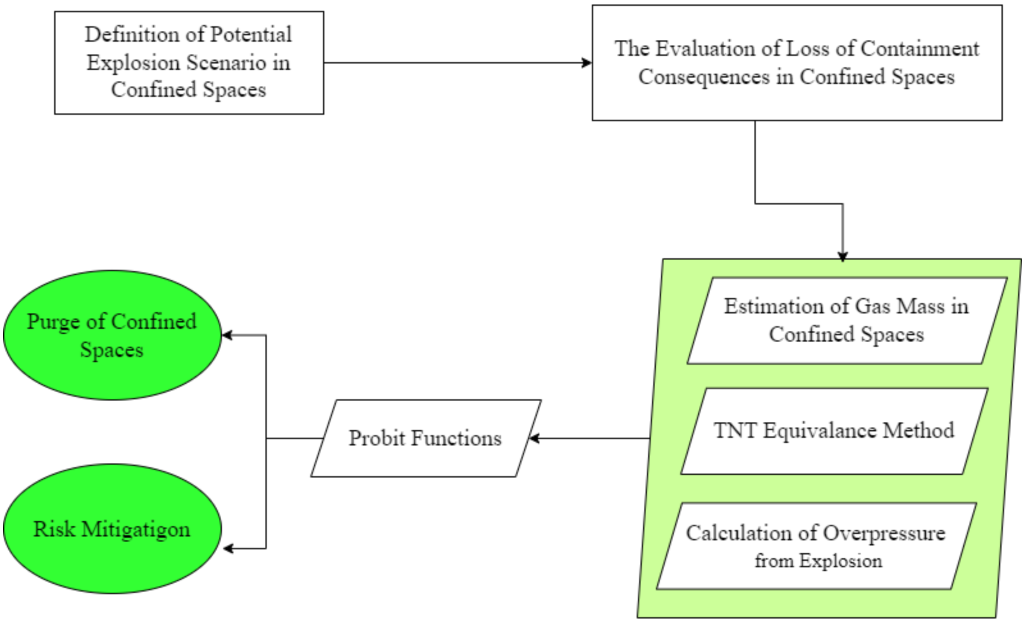

Figure 7. Study Framework [CAMA]

According to the study details given in Figure 7; According to the study details given in Figure 7; an explosion scenario was created based on near-miss records, the stoichiometric methane gas amount was converted to TNT equivalent mass and the equivalent overpressure was calculated. The obtained overpressure value was matched with probit functions and the probability of death of the worker in the ballast tank was estimated.

III. RESULTS and DISCUSSION

According to the consequence analysis evaluation; the explosion mass of 10 kg methane gas may be fatal in 169 m^3 confined space. When this amount of methane gas accumulated in a confined space explodes under the influence of an ignition source, it creates an overpressure of approximately 1523 kPa on the worker at a distance of 1 meter.

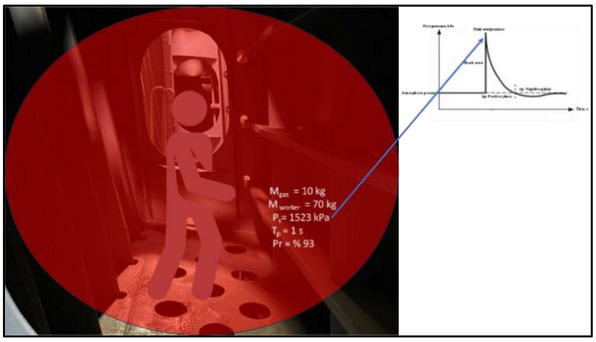

Figure 8. Possibility of Death Due to Overpressure in Ballast Tank

The findings obtained in this study are very important in terms of emphasizing why flammable gas leaks that may occur from welding gas hoses should be prevented. It is scientific evidence that demonstrates the importance of the risk for employers. The findings obtained through the CAMA were a driving force in eliminating the risk of gas leaks occurring in the confined spaces between January 2024 and November 2024. Although the resulting overpressure value varies according to different calculations, the occurrence of fatal consequences is an indisputable fact.

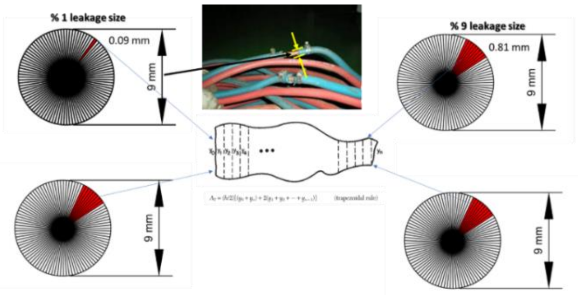

Figure 9. Non-regular Leakage Cross-section on Gas Hoses

The majority of leaks that may occur in gas hoses do not occur in smooth cross-sectional areas. For irregular leak holes, the "trapezoidal rule" can be applied [15]. Although assumptions made based on hose diameter for leaks make it difficult to estimate the amount of leaked gas, it will help us have an idea about the risks of gas leaks that may occur at between 1% and 100% of the hose diameter (Figure 9).

In the literature, the studies on methane gas explosion experiments in confined spaces show that the most favorable conditions are 9.5% (95000 ppm). [16]. For this reason, the reference was taken as 10 kg explosive gas mass, which is the equivalent of the explosion in the 169 m^3 ballast tank in the scenario.

The explosive methane gas concentration in a 169 m^3 confined space (ballast tank) was approximately 10 kg mass, and the methane gas leak of 80% of the hose cross-section diameter reached an explosive concentration in approximately 15 minutes. The amount of 10 kg of methane gas leaking into the 169 m^3 confined space was equivalent to the 95000 ppm (9.5% v/v) methane gas concentration required to provide optimum explosion conditions.

Explosion accidents (Figure 1), which are one of the main causes of fatal occupational accidents in the shipbuilding industry, are a problem that should be given serious consideration, especially when evaluated in terms of confined spaces.

In this study, the effects of possible methane gas explosions in confined spaces on workers were investigated using the QRA method. As is known, the explosion phenomenon is far from the field of experimentation and observation due to the risks it involves. Therefore, This theoretical study provides an important perspective to theoretically reveal the risk of confined space gas leakage, which is frequently encountered in the shipbuilding industry.

- It is important that the hoses used in closed areas comply with the TS EN 3821 standard in order to prevent the fluid from damaging the hose and causing leakage as a result of deformation.
- Gas purification measurements must be well disciplined before entering the closed area, and closed areas containing gas must be exhausted with ex-proof fans.
- Combustible gas hoses and oxygen cutting torches should be checked regularly.
- During the shipbuilding phase, it is necessary to establish a technological infrastructure to continuously monitor flammable and toxic gas concentrations in closed areas (ballast tanks, cargo tanks, void spaces, cofferdams, bow thrusters, settling tanks, service tanks, etc.), which are quite numerous.

Additionally, attached hose connections should not be allowed in closed areas, and in cases where attachment is necessary, double clamps should be used on both sides.

Future work will focus on experimental and theoretical purge times, positioning of fan suction points and appropriate fan designs for ballast tanks containing flammable gas.

IV. CONCLUSION

Eliminating methane gas leaks, which cause serious losses in terms of explosion risk in confined spaces, is a very important action. A possible methane gas explosion in a confined space can have fatal consequences. Therefore, confined space gas leaks must be continuously monitored and effective purge systems must be used.

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