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INCORPORATING TRIZ AND ISHIKAWA IN THE FORENSIC ENGINEERING CRUDE OIL STORAGE TANK FIRE AND EXPLOSION

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Abstract

A devastating fire and explosion occurred on an onshore atmospheric storage tank on Malaysia's Peninsular. Three of the storage tanks were damaged and collapsed as a result of the disaster. As a result of the intricacy of the operation, method, and human irregularity, a major fire and explosion were caused. This study addressed a TRIZ and ISHIKAWA combo to seek the probable root causes of the incident fire and explosion at an atmospheric storage tank and justified a trustworthy source of accident causers. A TRIZ, ISHIKAWA, and forensic engineering techniques were used to establish that there was a welding process with the existing and engulfing of the combustible gaseous dispersion to atmosphere that was formed from crude oil. Hence, these lethal mixtures of flammable gases and wielding activity resulted in a fire and explosion tragedy in the region. As a result, this study will provide major signs or points of caution and insight into the possibility of fire and explosion being avoided at an early stage of the refinery process.

Keywords: Catastrophic, fire and explosion; forensic engineering; flammable gas and crude oil.

1.0 INTRODUCTION

The catastrophe, like the Piper Alpha and Bhopal catastrophes, would undoubtedly result in a large number of fatalities and extensive property damage. However, there have been a few occasions in Malaysia where a storage tank has caught fire and exploded. These two incidents such as Floating Storage Tank and Fix Roof Storage Tank were reported to Malaysia's Department of Occupational Safety and Health (DOSH). In these occurrences, there was injury, death, fatality, or any combination of those three outcomes. Three atmospheric storage tanks with fixed roofs were recently involved in an accident at a respected refinery in Malaysia as depicted in Figure 1. Tank Farm 10 is the name of the tank farm owned by this reputed refining company. However, Tank 1(TK1), Tank 2 (TK2), and Tank 3(TK3) are the names of the three storage tanks that were involved in the catastrophe. Due to extensive structural maintenance, all of the tanks have temporarily suspended operation. The tanks are plagued by a number of problems like corrosion, pitting, and cracking. However, there were a lot of maintenance tasks including hot work (the process of installing insulation and cladding) at TK2, which involved using tools. Meanwhile, cold work is being done on TK3 by switching out the root wool (insulator) and arranging to tighten the wire string on the guided bar. Forensic engineering investigations involve the systematic examination and analysis of failed structures, components, or systems to determine the causes of failure. Various tools and methodologies can be utilized during these investigations to identify and analyze factors contributing to failures. Here's a brief overview of the tools mentioned.

1.1 4Ps Approach

The 4Ps approach in forensic engineering investigation refers to the examination of the four key factors that can contribute to failures: people, procedures, parts, and the environment. By analyzing these factors, investigators can identify human errors, faulty procedures, substandard parts, and environmental conditions that may have led to the failure.

1.2 Loss Causation Model

The loss causation model, commonly associated with the Swiss cheese model, is a framework used to analyze and understand how multiple failures or errors can align and lead to a catastrophic event. It visualizes layers of defenses, represented as slices of Swiss cheese, with potential holes that, when aligned, allow failures to pass through. This model helps investigators identify how failures in different layers interacted to cause the incident.

1.3 Hazard Identification Risk Assessment and Risk Control

Hazard identification, risk assessment, and risk control are fundamental steps in forensic engineering investigations. These processes involve identifying potential hazards, evaluating associated risks, and implementing measures to control or mitigate those risks. Investigators use various methods such as checklists, brainstorming sessions, and risk matrices to assess the likelihood and consequences of identified hazards.

1.4 Risk-Based Inspection

Risk-based inspection (RBI) is an approach used to prioritize inspection activities based on the level of risk associated with different components or systems. RBI takes into account factors such as the probability of failure, the consequences of failure, and the effectiveness of existing maintenance and inspection strategies. This approach helps investigators optimize inspection efforts and allocate resources more efficiently.

1.5 TIRZ

TIRZ is a concept used in forensic engineering investigations to analyze and understand the progression of failures. It considers the time duration of the failure, the potential for injuries or fatalities, the required repair or replacement efforts, and the spatial extent or zone affected by the failure. TIRZ helps investigators quantify and visualize the impact and severity of failures. (f) Ishikawa diagram, is a visual tool used to identify and categorize potential causes of a problem or failure. It provides a structured approach to brainstorm and organize various factors that may contribute to the failure. The diagram typically includes categories such as people, processes, equipment, materials, environment, and management, allowing investigators to explore multiple potential causes systematically. These tools and methodologies can be used individually or in combination during forensic engineering investigations to gather evidence, identify contributing factors, and determine the root causes of failures. However, it's important to note that the selection and application of specific tools may vary depending on the nature of the investigation and the expertise of the forensic engineers involved. However, in this case study researcher focus in search and venture for the incident's underlying causes, a large combination of TRIZ, ISHIKAWA, and thorough forensic engineering research is required. TRIZ is a problem-solving methodology and toolkit developed by the Soviet engineer and inventor Genrich Altshuller. TRIZ is designed to help individuals and teams overcome technical contradictions and find innovative solutions to complex problems. The key principles of TRIZ are based on the analysis of thousands of patents and inventions across different industries. TRIZ as a systematic approach to problem-solving, aiming to provide a structured framework for generating creative ideas and resolving contradictions. TRIZ employs several tools and techniques to support problem-solving, including: Contradiction Matrix: This tool helps identify technical contradictions and suggests inventive principles to resolve them, Inventive Principles: TRIZ defines 40 inventive principles that can be applied to overcome contradictions and generate innovative solutions, Ideal Final Result (IFR): IFR is a concept in TRIZ that encourages envisioning an ideal solution where all contradictions are resolved, Substance-Field Analysis: This technique examines the relationships between substances and fields to identify opportunities for improvement or innovation and Nine Windows: Nine Windows is a visualization tool used to explore a problem from multiple perspectives, uncovering new insights and potential solutions. TRIZ emphasizes the systematic analysis of problems, the identification of contradictions, and the use of inventive principles to find breakthrough solutions. It encourages thinking beyond traditional problem-solving approaches and promotes innovation by leveraging existing knowledge and patterns. Overall, TRIZ provides a structured framework and a set of tools to enhance problem-solving and stimulate creativity, particularly in technical domains. There a few cases of studies using TRIZ approach in accident in refinery [1], nuclear power plant solving the safe shutdown capability of fire using knowledge management of TRIZ [2] and problem solving for LPG Storage Tank using PRS-TRIZ.[3]

1.6 ISHIKAWA Diagram

Meanwhile, The Ishikawa diagram is named after its shape, which resembles the skeleton of a fish. It consists of a horizontal line representing the problem or issue being investigated, with several branches extending from it like the bones of a fish. Each branch represents a category of potential causes that could contribute to the problem. The main

categories are: Manpower: People or human resources involved in the process, Method: The procedures, techniques, or processes used to perform tasks, Machine: Equipment, tools, or machinery involved in the process, Material: Raw materials, components, or supplies used in the process, Measurement: The metrics or measurements used to evaluate performance or quality and Environment: The physical or external factors that may affect the process. By brainstorming and analyzing potential causes within each category, the Ishikawa helps identify the root causes contributing to the problem. The diagram allows teams to visually map out and organize their thoughts, facilitating a structured approach to problem-solving and decision-making. Overall, the Ishikawa diagram provides a visual representation of the potential causes of a problem, enabling teams to investigate and address the root causes more effectively. It is a widely used tool in quality management, process improvement, and problem-solving methodologies.
Hence, the TRIZ and ISHIKAWA approach has been used to conduct forensic engineering on the forensic case of fire and explosion for a crude oil storage tank. Figure 1

Figure 1: Fire and Explosion –Atmospheric Storage Tank

2.0 METHODOLOGY

Forensic engineering investigation approach for this case as mentioned:

2.1 **Method of TRIZ and ISHIKAWA**

TRIZ is a problem-solving principle and tools within the broad category of TRIZ. First Principle of TRIZ approach: Increasing the degree of segmentation of an object or system, or making an object or system easier to disassemble, as demonstrated in Figure 2.

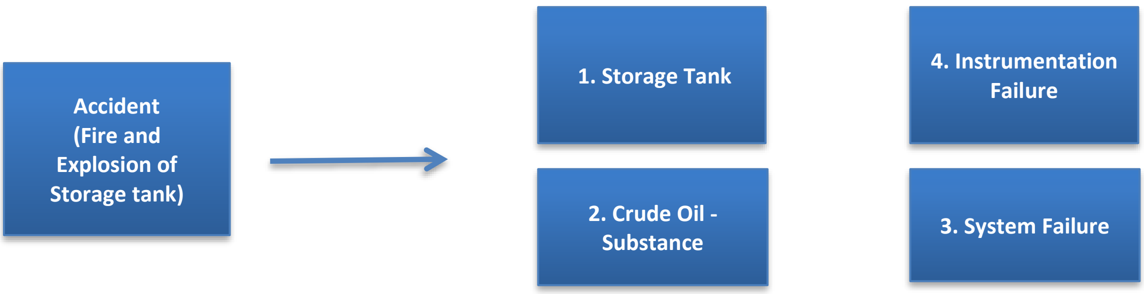

Figure 2: Segmentation of TRIZ

The System of the Accident (Fire and Explosion of Storage Tank) is divided in a few components that could contributed to the accident as such 1-Storage tank, 2-Crude Oil-substance, 3- System failure and 4- Instrumentation failure. The Segregation using TRIZ in the first layer of the forensic engineering investigation and need to go deeper on the root causes of the accidents. Hence, the Ishikawa Fishbone diagram, also known as the Cause-and-Effect diagram, is a useful tool for identifying and categorizing the potential causes of a problem or incident. It helps to visually represent the various factors that may contribute to an issue. The basic structure of the Ishikawa diagram includes a horizontal line representing the problem or incident being investigated, with several branches extending from it like the bones of a fish.

Each branch represents a category of potential causes, such as people, processes, materials, equipment, or environment. To trim down and provide detailed information on the underlying causes of the incident, incorporate additional segmentation or sub-categories within each branch. This helps to break down each category into more specific factors that could be contributing to the problem. By doing so, analyze the root causes in a more granular manner and gain a deeper understanding of the incident. For example, if the incident involves a manufacturing defect, the "Processes" branch of the Fishbone diagram could be further segmented into sub-categories like design, production, quality control, or maintenance. Explore potential causes within each sub-category and identify specific issues that may be contributing to the incident. By adopting the Ishikawa approach and incorporating detailed segmentation, systematically analyze and investigate the various factors that may have led to the incident, helping to identify root causes and develop effective solutions or preventive measures. Figure 3

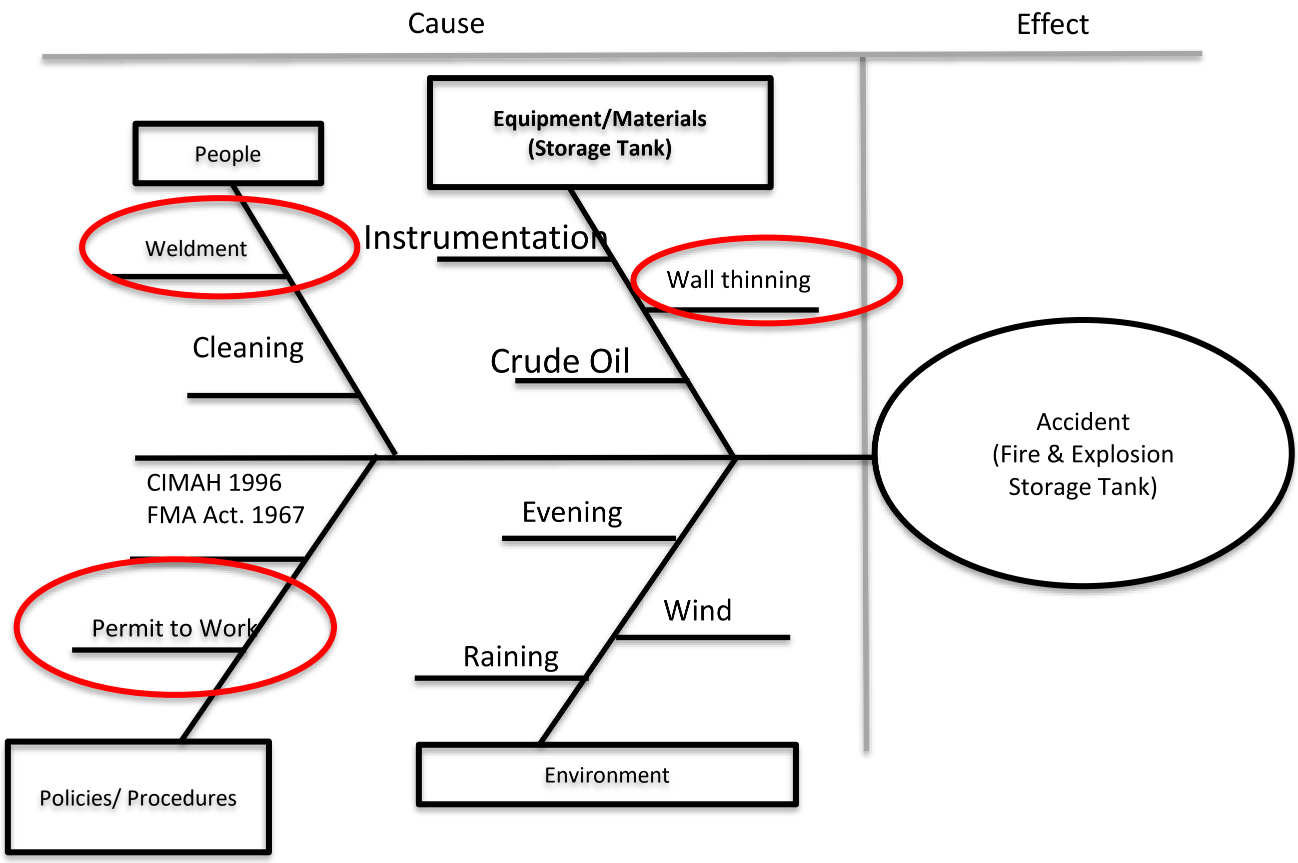

Figure 3: ISHIKAWA for Storage Tank's Fire and Explosion

To reflect this, Figure 4 shows that the TRIZ subcomponents have been rearranged in the ISHIKAWA diagram with four principal pieces (Elements). The ISHIKAWA as such equipment consists of 4 parts. Resources, People, Environment, and Policy Procedure. So, the 2nd layer of the process of investigation will indicate the multiple of causes of the Accident (Fire and Explosion storage tank) most probably due to the heating up of crude oil in which, still operated in the tank that causes vaporisation of hazardous gaseous, support with the severe corrosion and thinning of the storage tank which causes the hazardous gaseous could penetrate outwards of the tank, and the lack of procedure of welding and PTW and late evening wind which propagate the fire and explosion. In summary, TRIZ and ISHIKAWA is the early screening of the most probable causes of the accident. However, to go deeper in analysis on how the most probable causes of the accident affected. Therefore, the approach of forensic engineering investigation as 3rd layer of inspection is needed to justify comprehensively the complexity and robustness nature of the accident that occurred.

2.2 Forensic Engineering Approach

Forensic investigators will abide by the code of investigation [4], which involved the scientific method of gathering and screening information. The activities, related to the investigation of failure and assistance of investigation by creating a sequence of photos of the accident. Therefore, for this case of an accident, the storage tank's information of the tanks and substance must be investigated and verified. [5].

2.2.1 Storage Tank Specification

The premise involved has about 6 storage tanks in tank farm 10 that located nearby to each other. Those storage tanks were known as fixed atmospheric storage tank. Most of the storage tanks are occupied /stored with crude oil. The specification and location of the storage tank shown as:

Table 1: Specification of Storage Tank of Crude Oil

	TK3	TK1	TK2
Capacity (Working volume)	24000m^3	45813 m^3	27559 m^3
Material	SA 36		
Shell	7.46mm (top) 8.52mm (Middle) 16.35mm (Bottom)	8.1mm (top) 10.46mm (Middle) 20.67mm (Bottom)	7.46mm(top) 8.52mm (Middle) 16.35mm (Bottom)
Roof	4.75mm (Nominal Thickness)		
Effect from Fire	100%	100%	*Flash fire* at edge of roof top
Diameter (m)	46.81	60.43	46.81
Height (m)	16.17	16.17	16.17

Extracted data above table showed that tanks of TK3 and TK2 have similar specification in diameter and height. Meanwhile, TK2 has a little different in terms of diameter. However, tank 1 and tank 3 were badly damaged in the fire and explosion compared with tank 2(flash fire). The location of the affected tanks displayed in the Figure 4.

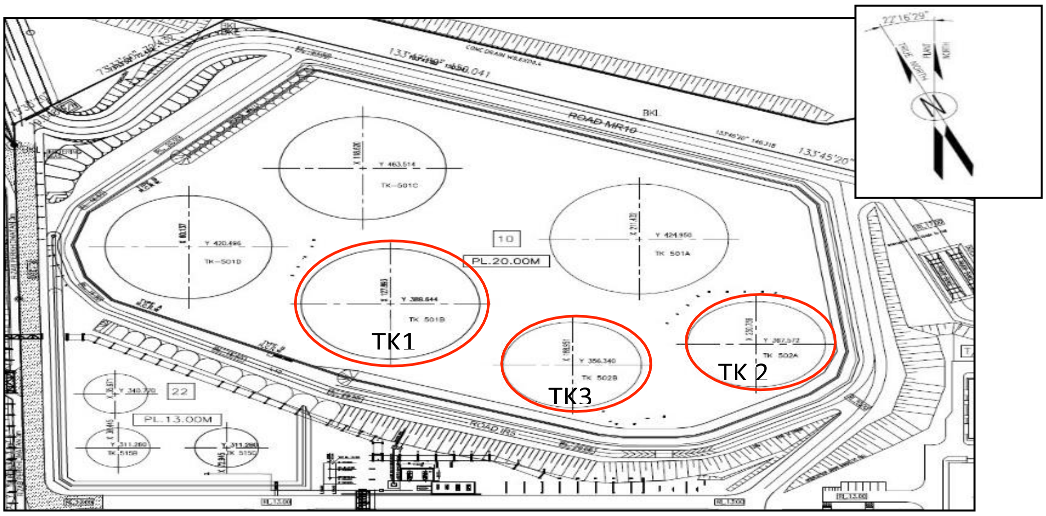

Figure 4: The location of TK1, TK2 and TK3 involved in the incident (red colour)

Figure above, shown that red circular notified as TK3, TK2 and TK1 were those tanks that engulfed in the disaster of fire and explosion. The location of those 3 tanks was very near to each other in distance. Figure 5 indicated for the capacity of substance in the tank for further forensic investigation.

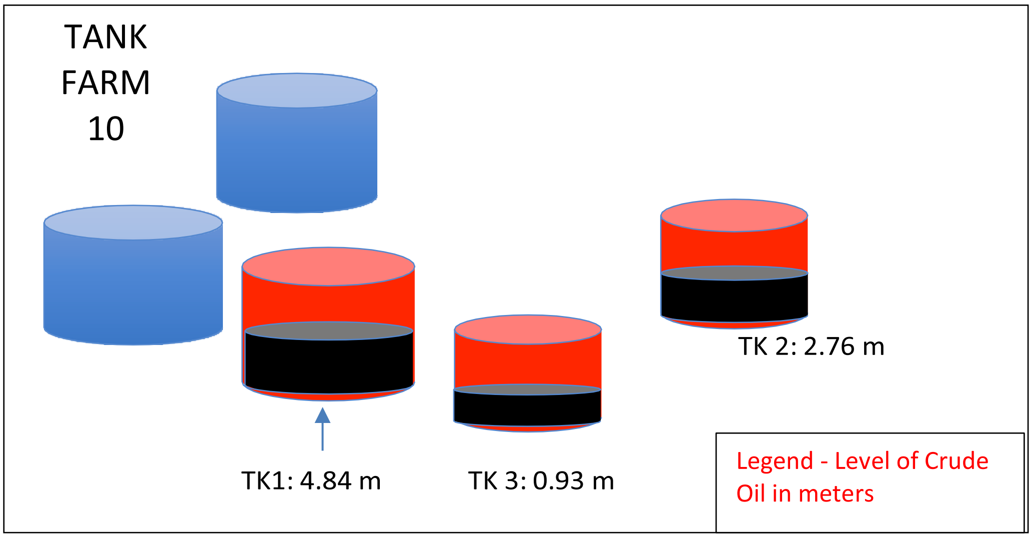

Figure 5: Arrangement of Storage Tank at Tank Farm 10(TK1:4.84 m, TK2:2.76 m and TK3:0.93 m)

Description of the substance or chemical that is kept in the storage tank, for example, what type it is. What are the substance's temperature and pressure inside the tank? Consequently, a detailed investigation into the substance's details is required.

2.2.2 Crude Oil Specification

The substance stored in the storage tank for this particular case of the incident was crude oil. The detail of the crude oil has been established through the documentation received from the company. Therefore, the detail of the crude oil was profoundly reliable on the forensic engineering investigation [6]. The detail of the crude oil stated as per shown in Table 2.

Table 2: Crude Oil

COMMERTIAL NAME	**BOSCAN**
SUBSTANCE PROPERTIS	UNITs
Density of Specific Gravity (15.4 ^{o}C)	0.9079
Gravity according API (60^{o}F)	10.3
Kinematic of viscosity (100^{o}F)	12432
Kinematic of viscosity (140^{o}F)	2236
Kinematic of viscosity (210^{o}F)	205
Sulphur Content (%)	6.26
Pour Temperature (^{o}C)	18.3
H_2S Content (ppm)	< 1
Flash Point-Temperature (^{o}C)	59
Asphatlene (%wt)	12.39
Vapour Pressure (P)	0.89

Boscan was the commercial name for the crude oil that been stored in the storage tank. However, the chemical substance prevails in the Boscon Crude oil can be justified through the chemical safety data sheet as shown in the Table 3.

Table 3: Physical and Chemical Properties of BOSCON Crude Oil

Physical & Chemical Properties	Light Naphtha	Medium Naphtha	Heavy Naphtha	Kerosene	Light Diesel	High Diesel	Gasoline
Starting Temp. (°C)	158	212	302	374	455	536	650
Last Temp. (°C)	212	302	374	455	536	650	1049
Specific Gravity	0.7188	0.7570	0.7980	0.8380	0.8739	0.8998	0.9503
API	65.4	55.4	45.8	37.4	30.4	25.8	17.4
Sulphur Content	0.2450	0.7556	1.4360	2.5816	3.6957	4.3964	4.9749

Table above indicated that the BOSCAN Crude Oil consists of chemical substances as Light Naphtha, Medium Naphtha, Heavy Naphtha, Kerosene, Low and High Diesel and Gasoline. Those chemical substances have differences in flash point of temperature respectively. Those were under the category of flammable substances. Hence, that information must be adequately justified and verify with an addition from the finding gathered from forensic engineering investigation.

3.0 FORENSIC ENGINEERING INVESTIGATION

Forensic engineering investigation must be profoundly reliable in the process of the justification and verification of the actual scene of the incident in finding of the root causes of the disaster. The approach of the forensic engineering normally consists of 3 stages:

3.1 **Onsite Investigation**

The approach of forensic engineering investigation as such:

a. **Welding Activities**

Information that gathered from this stage found that there was a significant photos and debris of so call the vital part of the investigation which verify the existence of welding activities occurred on the TK 3. Those items used for wielding activities founded near the TK3 such as:

1. Welding Set.
2. Grinder.
3. Genset (Diesel)
4. Oxy Acetylene Cutter.
5. Electrical Wire and Appliances.

Those, above items have been identified and verified at the location of the items (near to TK 3) and supported with the statements of the welders themselves. Thus, effectively information that agreed of the welding events has been carried throughout the incident. The location of the welding event is shown in Figure 6.

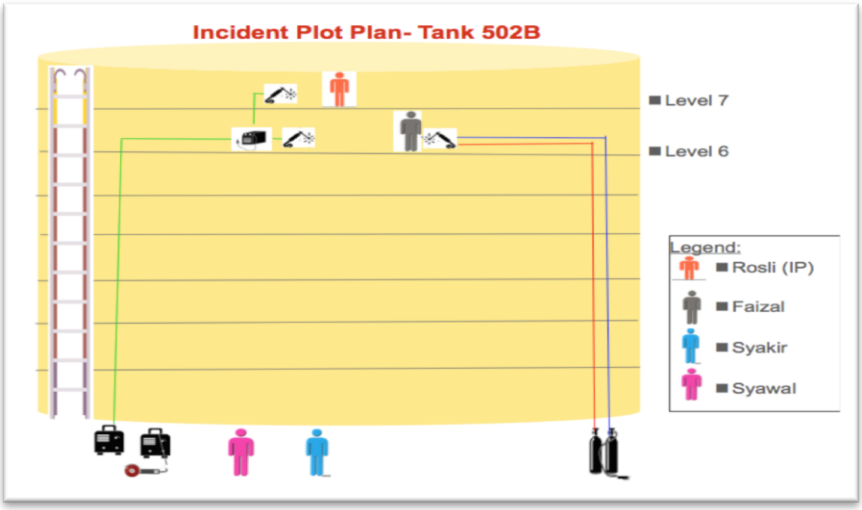

Figure 6: Location of the Wielding Activities at Tank 502B -TK3

The location of the welding event justified by the welders and helpers of the event was carried out at the platform level 6 and 7. These events were involved of grinding and welding process on the guide bar of the scaffold at level 6 and 7. That event can be illustrated in below Figure 7.

Figure 7: Welding Spot

This welding event has profoundly created extremely high temperatures and significant existence of flammable gaseous into the atmospheric explosion area around the platforms 6 and 7. [7] Thus, atmospheric explosion will be triggered with the sufficient of chemical substances that fall under the range of flammable and explosion limit.

Furthermore, due to the sign of severe corrosion process and pitting occurred because of the wielding events that produced high temperature iron ore, the temperature of 520^{O}C [8]. Thus, welding iron ore as a source of trigger plus with the accumulation of the flammable of gaseous (Naphtha, AGO, LGVO and HGVO) could cause of fire and explosion. The welding's event is drawn in Figure 8.

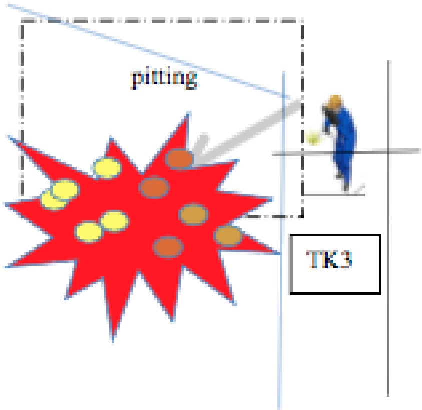

Figure 8: Welding event, which involved of welding iron ore (high temperature)

3.2 **Wall Thinning at Tank TK3**

According to the Risk Based Inspection (RBI 581) by the plant Inspector of the company earlier indicated that the area top wall of the tank has been propagated of the thinning process especially severe corrosion. [9] The crude oil in which stored in the tank has a high content of sulphur has worsened the propagating process of the corrosion event on the wall of the tank. Hence, data gathered from the usage of Ultrasonic Thickness Gauge (UTG) has vividly proven of the significant data of thinning event which affected top wall's thickness of tank TK3. Location and data measured as shown in Figure 9 and Table 4. Therefore, gaseous will go into the tank through the pitting (small hole) and in contact with flammable gaseous.

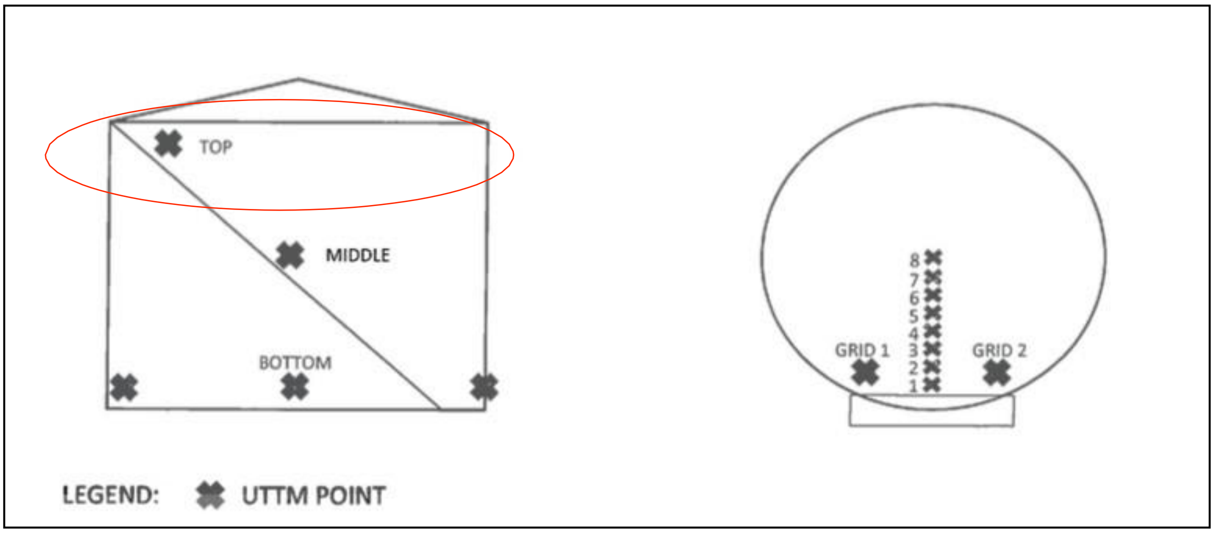

Figure 9: Point Location of the Ultrasonic Thickness Tank Gauge Measurement (UTTM) at TK 3

Those locations have been planned strictly according to API RBI 581 in seeking to verify the integrity of the tank. Hence, data measured stipulated and displayed in the Table 4.

Table 4: Data Measurement of Top Window (Red Circle: Data of wall thickness less than nominal)

No.	LOC	NOM. THICKNESS	C/A	UTTM Point				
1.	Top Window	**7.94**		7.04	7.05	6.89	7.02	6.98
				7.15	7.19	7.06	6.97	7.28
				7.29	7.31	7.13	7.07	7.28
				7.18	7.20	7.11	7.36	7.15
				7.32	7.18	7.16	7.28	7.10

Analysis of the data captured by using UTTM on the top wall thickness (red circle) portrayed significant evidence that, this area top wall of tank TK3 was severely damaged, badly corroded and thinning process at specific wall.

This cause propagation of cracking and pitting. As the data measured mostly less than the nominal thickness wall, 7.94 mm. This process will considerably contribute to the outward flow of the flammable gaseous out of the tank. Thus, created an excessive flammable gaseous at topside of the tank.

3.3 **Hazardous Chemicals Substance**

The scenario of flammable gaseous existed and was exposed to the air that was believed accumulate of the combination of vapour cloud of the flammable gaseous maneuver downward towards the welding activities [10]. Those flammable gaseous exited outflow from the open gooseneck. Then, it's created a significant combination of vapor cloud of flammable gaseous in contact and reacted with welding activities that create fire and explosion. This condition in which existence of 3 elements in fire triangle such as vapor gaseous, oxygen and welding activities (spark) will trigger the scene of fire and explosion depicted in Figure 10.

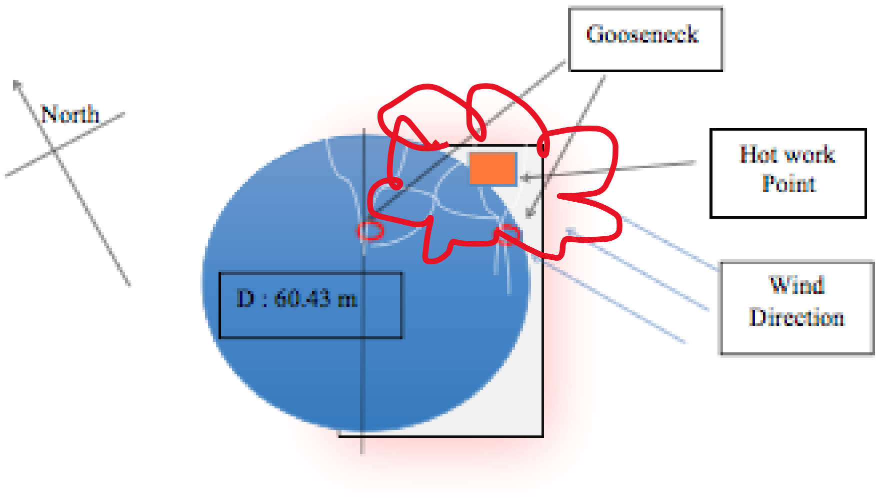

Figure 10: Scenario of Fire and Explosion

As the activities of hot work has been carried out more than 3 months prior of the incident whereby the maximum of pressure in the tank estimated around 4-5 bar acted as operation pressure cum with the temperature of 172^{O}C. Thus, because crude oil's physical and chemical qualities might progressively transform from liquid to hazardous chemical and flammable gaseous, this could happen. Furthermore, there was no proof of record about the gas detector measurement were done prior, during and after welding event at platform 6 and 7. The accumulation of the combination vapors and flammable gaseous will create a Hazardous Atmospheric or Atmospheric Explosion.

Meteorological data on that date of the incident indicated that with the air wind flows movement at 4.00 pm, 5.00 pm and 6.00 pm cum at 130^{O} and 140^{O}. Data recorded that wind speed of 3.0–3.1 m/s will intensify instantly the process of fire and explosion [11]. Eventually, this situation will occur with the combination of the existing flammable gaseous as a trigger of source, chemical substance and oxygen.

Hence, its signified that crude oil can easily transformed shape thorough the process of vaporisation into vapors especially to high flash point temperature calculated as 850^{O}C compare to it flash point of temperature at 60^{0}C. As a result, it indicates that crude oil can easily change into vapors through the process of vaporisation, notably at higher flash points than its flash points at 60^{O}C and 850^{O}C, respectively. As compared to crude oil, naphtha, atmospheric gas, and high-volume gas oil all have greater flash points. Vaporisation is easily caused by differences in the flash temperatures of the various chemical components in crude oil. Table 5 shows the separation of the gases.

Table 5: Physical and Chemical Properties

ChemicalSubstance	Flash Point	Quantity(tonnage)	Threshold Quantity(tonnage)	Hazardous Behaviour(liquid)
Naphtha	< 0^{o}C	8430.75	5000	Highly Flammable
Atmospheric Gas Oil (AGO)	60^{o}C	164000	N/A	Medium Flammable
High Volume Gas Oil (HGVO)	87.8^{o}C	128000	N/A	Medium Flammable

Asphalt (Bitumen)	> 225ºC	47000	N/A	Liquid
Crude Oil	60ºC	221000	N/A	Liquid

Those 3 top chemical substances are easily contributed to the scenario of the fire and explosion as their flash point temperature was less than the crude oil (60^{O}C). Thus, a simulation of the vaporisation of gaseous in the large room inside the tank will create the combination of the flammable gaseous inside the tank as shown in Figure 11.

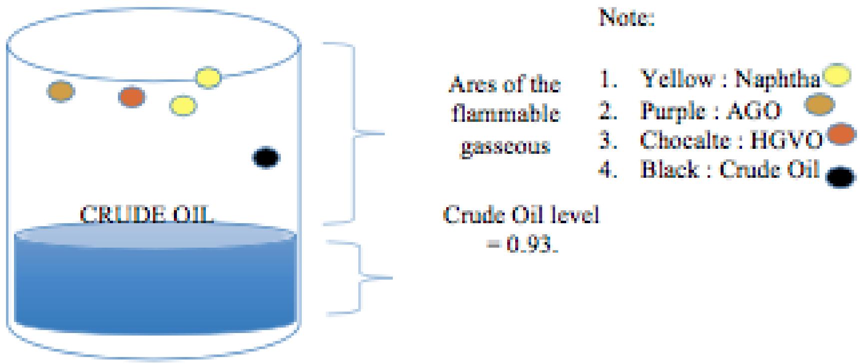

Figure 11: Simulation of the Vaporisation the Flammable gaseous

According Jerome Tavaeu, 2011[12] indicated that the larger room inside of the tank will increase the rate ofvaporisation of the flammable gaseous generated from the crude oil. The vaporisation of gaseous will fill up the empty space in the tank till it push outwards the flammable gaseous through the open venting gooseneck and mix up with the air which eventually created Hazardous Atmosphere or Atmosphere Explosion. In addition, on the welding event will rapidly increase the chance of fire and explosion. As a result, the tremendous pressure and temperature caused tank TK3 to catch fire and explode. All of the debris and pieces that were flown to the nearby tank. Both TK2 and TK1 experienced a tiny explosion and flash fire. This nightmare of fire and explosions will produce energy when under excessive pressure.

Meanwhile other Noret et al., 2014 [13] stated that the prediction of the analytical model could be justified by the source of overpressure and projectile that significant enough with the probability analysis and deterministic. It's shown in Table 6.

Table 6: Maximal Overpressure and Damage Scale

Overpressure Maximal Value (MPa)	Damage	Reference
0.007	Failure of the tank	[14]
0.0075	Minor leak in the tank shell	[15]
0.016	Substantial leak in the tank shell	
0.020	Major leak in the tank	
0.020 to 0.05	Failure of atmospheric storage tank	[16]
0.025	Failure of atmospheric storage tank	[17]
0.0205 to 0.0275	Failure of atmospheric storage tank	[18]

Hence, the highest overpressure will be 0.0205–0.0275 MPa in which could pose damage as to failure of atmospheric storage tank. However, for TK3, analytical analysis and calculation done at 1.5 bar with pressure data of 0.15 MPa. If refer to the table, TK3 pressure was more that the highest overpressure maximal value. Therefore, TK3 will engulf with severe damage for the tank. Meanwhile, TK2 and TK1 will go under the domino effect as such flown fragments and debris.

3.0 RESULTS AND DISCUSSION

As a result, TRIZ, ISHIKAWA, and forensic engineering inquiry were the best approach used in which was important in the early ways of justifying the causes of accidents. Furthermore, a thorough strategy was combined with an audit of the documentation and the collection of numerous analyses, including storage tank and crude oil specification data. Data and onsite extended to forensic investigation onsite of the incident's premises, where investigation onsite data and scene were gathered and significant probable causes were identified, particularly with regard to the welding event. The thinning condition of the wall thickness by measurement on TK3 adopting RBI Assessment and data using UTTM showed severe damage, and the existence of Hazardous Chemical Substance in contact with the welding activities was likely what caused the fire and explosion to break out. Therefore, the probable combination causes, including the discharge of combustible material into the air that comes into contact with a spark, severely thinned walls, welding activity, and the presence of oxygen, all contributed to the fire triangle, which in turn caused an explosion and fire. With the use of these combinations of strategies, the underlying causes of events such as fires and explosive disasters will be justified and proved.

4.0 CONCLUSION

Eventually, the incident's hypothesis has been confirmed: the welding event on platforms 6 and 7, in particular at the top rim wall of storage tank TK3, combined with the presence of the flammable gas vaporisation process through open venting of gooseneck, severely thinned walls, presence of oxygen that significantly accelerated the fire and explosion scenario for TK3, TK1, and K2. These factors contributed to the disaster that led to worker injuries. Limitations of this research include the use of inappropriate tools and evidence that has been damaged by the fire of a search and rescue team while doing on-site forensic engineering examinations, particularly when trying to find hazardous gases after an incident. However, the greatest instrument for a scene investigation should be in the hands of the forensic engineering investigator to provide the most thorough comprehensive investigation.

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REFERENCES

[1] Risza Rusli, Azmi Mohd Shariff 2009. Qualitative Asessment for Inherently safer Design (QAISD) at Preliminary Design Stage, Journal of Loss Prevention in the Process Industries. Volume 23, Issue 1, January 2010, Page 157-167.
[2] Wang, C.-N., Chen, H.-P., Hsueh, M.-H. and Chin, F.-L.. "The application of knowledge management and TRIZ for solving the safe shutdown capability of fire alarms in nuclear power plants" Kerntechnik, vol. 82, no. 5, 2017, pp. 552-561. https://doi.org/10.3139/124.110794
[3] Leem, S., Huh, Y., Lim, J., Kim, I., & Jeong, S. 2011. Problem Solving for LPG Storage Tank using RPS-TRIZ.
[4] Prosidur Kerja Penyiasatan Aduan dan Insiden (PK04) Pindaan 08 (2018). *Prosidur kerja Sistem Pengurusan Kualiti, Keselamatan & kesihatan Pekerjan*; Jabatan Keselamatan dan Kesihatan Pekerjaan Malaysia.
[5] Rui Lui, Micheal P. Lester, Alicia E. Diaz & de Leon. 2018. *Forensic Engineering 2018, Forging Forensic Frontier*, American Society of Civil Engineer (ASCE), 2018/1173 pp.1-5
[6] Material Data Sheet for Crude Oil (BOSCAN) from TESORO.
[7] Directive 94/9/EC.1994. *Atmosphere Explosion*, ATEX, 23 Mac 1994
[8] Haz et al., 1089. *Resistance Spot Wielding A Heat Transfer*.
[9] RBI 581. 2000. *Risk Based Inspection Technology*, Third Edition.
[10] Directive 94/9/EC 1004: *Atmosphere Explosion* ATEX 23 Mac 1994
[11] Department Meterology of Malaysia, 2018, *Report on the Meteorology* (wind speed).
[12] Jerome Tavaeu. 2011. *Explosion of Fixed Roof Atmospheric Storage Tanks Part 1: Banckground and Review of Case Histories.*
[13] Noret et al., 2014. *Safety of Atmospheric Storage Tank During Accidental Explosion*. European Journal of Environmental and Civil Engineering, Ed. Lavoisier, 2012 16 (9), pp 998-1022.
[14] TNO. 1989. CPR 16E. *Method for the determination of Possible Damage*, First Edition 1992.
[15] Valerio Cozzani, Ernesto Salzo. 2004. *The Quantitative Assessment of Domino Effecta Caused by Overpressure Part I. Probit Models. Dipartimento di Ingegneria Chimica*, *Mineraria E Delle Tecnologie* Ambientali, Universita di Bologna, Viale Risorgimento 2, 40136 Bologno, Italy, Istituto di Ricerche Sulla Combustione, CNR, via Diocleziano 328, 80125 Napoli, Italy, Journal of Hazardous A107 (2004) 67-80.
[16] Le Petit G., Cagniant A., and Morelle M., 2013. *Innovative Concept for a Major Breakthrough in Atmospheric Radioactive Xenon Detection for Nuclear Explosion Monitoring*. Journal of Radioanalytical and Nuclear Chemistry 298, 1159-1169 (2013).
[17] Lannoy, A.,1984. *Analysis of Unconfined Air Hydrocarbon Explosion: Deterministic an Probabilistic Studies of the Accident Scenario Prediction of the Ovepressure Effect*. Num 4, XVIII-390 p; Ref:Dissem, ISSN:0013-449X.
[18] Le Roux, Thomas 2011. *Accident Industriels Et Regulation Des Risques: I'explosion De la Poudrerie De Grenelle En 1974*. Dan revenue D'Historie Moderne-Contemporaine 2011/3. No 58- 3), page 34A62.