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Hazard Analysis of Crude Oil Storage Tank Farm

H. A. Ibrahim[1]*, H. S. Syed[2]

[1]Environmental Engineering Department, L.D Engineering College, Ahmadabad-India
[2]Associate Professor of Environmental Engineering, Government Engineering College, Bhuj, India

Abstract : The major accidents in petrochemical facilities occur during storage processes. Many disastrous accidents occurred in the past, causing death or injury for workers, huge economic losses and massive environmental pollution. Thus, this work aimed to conduct profound and adequate hazard analysis in the oil storage facility. Firstly, the potential undesired accidents in the oil storage farm were identified using Hazard and Operability Study (HAZOP). Secondly, Fault Tree Analysis (FTA) was carried out to analyze all the identified hazards and effectively determine the basic events (BEs) that lead to such hazards. The FT was evaluated by generating of the Minimal Path Sets (MPSs) and calculation of the Structural Importance Degree (SID) for each BE. Thirdly, Event Tree Analysis (ETA) was implemented to analyze the occurrence path of accidents and estimate their frequencies. The results revealed that the most significant accidents in the storage farm are fire and explosion. The qualitative analysis of the FT has shown that the most critical BEs for causing the tank fire and explosion are (formation of flammable cloud) and (Confinement between cloud and air).Additionally, it is found out that the occurrence frequency of pool fire is higher than other scenarios. Finally, based on the analysis, some preventive and mitigation measures have been given to reduce the consequence severity of tank accidents, which in turn improve the safety climate in the storage tank farm.
Keywords : Hazard analysis, HAZOP, Fault Tree, Event Tree, Safety measures.

1.Introduction:

Petroleum and chemical products are primary resources in our life and considered one of the most important basic building blocks for sustainable development. The growing demand of hazardous chemicals has brought a significant increase in risk to human and its environment [1].Hazardous chemicals have intrinsic hazards for the environment, which may damage it the human and properties around the accident area [2]. OSHAhas defined a hazardous chemical as any chemical, which has a physical hazard such as (fire and explosion) or a health hazard such as (acute or chronic effects) [3].The results of a historical analysis have shown that 17% of major accidents in the chemical industries were during storage processes[4]. According to the NFPA report in 2009 [5], 13% of the fire accidents that occurred in the USA took place in storage farms,

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causing death or injury for workers, tens million dollars as losses and cause huge environmental pollution. Many catastrophic accidents happened in the history such as Bhopal disaster in 1984,which caused thousands of fatalities and tens of thousands of people were injured[6]. Thepossible hazards are a function of both the inherent nature and the involved quantity of the chemical[7]**.**Therefore, it is important to conductaprofound and adequate hazard analysis of the oil storage facility to figure out the potential scenarios having damage to life and property as well as provides a clear picture for the decision makers to be satisfied with the safety levels in the storage tank farm.Hazard Analysis is animportant process and has a vital role in studies related to hazardous chemicals handling. Hazard identification(HAZID) is the initial step in any hazard analysis process and includes the identification of all possible accidents in the facility. The most used technique in HAZID is HAZOP study [8]. HAZOP is a systematic review of the design and operation of the system to predict the possible accidental leaks of hazardous material[9].

The defined hazards can be analyzed using many tools such as FTA and ETA. FTA is a systematic and deductive approach that focuses on hazardous outcomes (top event) and develops further to the basic causes (bottom event) that lead to such unwanted outcomes [10]. FTA is also used widely in hazard analysis of the various storage facilities [10-15]. ETA is agraphical and inductive tool that presents all the final consequencesresulting from a particular initiating event, with considering the states (failure/success) of the installed safety barriers [9]. The accidents frequencies can be estimated by ETA if the data about initiating and heading events are known. Otherwise, it can be derived from databases such as OGP [16]or HSE [17]. The major goals of this studyare (i) preventive goals to provide all possibilities, which assistto prevent accidents and injuries in the crude oil storage tank farm, (ii) protective goals toprovide protection for workers,equipment and maintain workplace safety.

2. Hazard Identification (HAZID):

HAZID phase involved a review of the storage conditions andthe layout of storage tanks. Using this information, a review of relevant accident histories, knowledge, experience with similar facilities, and good engineering practices, the possible hazardous events in the facility were determined. The potential hazards associated with the crude oil tank are almost same to similar facilities throughout the world. The class of hazards depends on the materials being stored (physical and chemical properties), type of storage tank, storage conditions, and protection and mitigation measures provided. HAZOP process is implemented by applying a set of guidewords to identify the potential all parameters deviations design intent, which may adversely affectpersonnel and plant safety.

Figure.1 presents a schematic diagram for the fixed roof tank. HAZOP study was conductedfor a deviation of three parameters (pressure, level,and flow). HAZOP resultsfor crude oil storage tankwere presented in **Tables** 1,2,3.

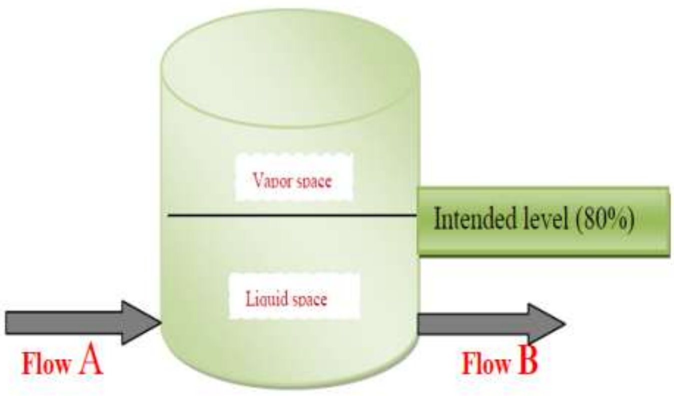

Figure1.Fixed roof tank diagram for HAZOP study.

Table 1. HAZOP (Parameter: Pressure)

Guide Word	Deviations	Possible Causes	Possible Consequences
MORE	More pressure inside the storage tank	Tank exposed toan external heat source Thermal expansion of oil in the storage tank due to fire or strong sunlight Outlet pipe ofthe storage tankblocked duringtransfer Failure of the pressurerelief valve poor ventilation Failure of the automatic pressure control system	Possible explosion due to rising build up pressure in the tank Pressure increases in the tank that could lead to fire and explosion

Table 2. HAZOP (Parameter: Level)

Guide Word	Deviations	Possible Causes	Possible Consequences
MORE	More level in the storage tank	Tank top unattended The level indicator fails The wrong valve opened The alarm doesn't work properly Expansion of oil in case of exposure to higher temperature	Crude oil leakage to the atmosphere, which may initiatethe fire if any ignition source exists. Consequently, this may heat the nearby tanks or cause burns toworkers due to exposure to heat radiation.
LESS	Less level in the storage tank	Cracking or corrosion of the tank. Damage of tank body seal Weak joints between the roof and tank shell Damage of valve and flange Rupture of a tank due to integrity loss	

Table 3. HAZOP (Parameter: the flow of crude oil to or from the storage tank)

Guide Word	Deviations	Possible Causes	Possible consequences
NO	No flow(A) of Crude oil to the Storage tank	Outlet line closed Outlet valve blocked Pump Fail Rupture of Pipeline	Pressure increases rapidly in the pipeline. Consequently,the leak and explosion probabilities grow up. Minor/major flammable liquid release
LESS	Less flow(A) of Crude oil to the storage tank	Partial opening ofthe outlet valve Inlet pipeline rupture due to mechanical damage Minor leak from thePipeline	Possibility of pressure build up in the storage line Minor release of crude oil to the atmosphere
NO	No flow (B) of Crude oilfrom the storage tank	Tank empty Outlet valve closed Line fracture Outlet line blocked rupture of pipeline	No significant hazard Pressure increase in the storage tank and probability of leak Major flammable liquid release
LESS	Less flow(B) of Crude oil from the storage tank	Partial opening of the unloading valve Minor leak from the Pipeline	Potential of excessive pressurein the storage line Minor release of Crude oil to the ambient atmosphere nearby tank

3. Hazard Analysis:

The identified hazards by HAZOP study have been analyzed by FTA to determine their root causes. FT usesBoolean logic symbols (AND gates, OR gates).FT construction [18] begins at the top event; then, it identifies level by level all the root causes that initiate the top event; after that, it determines the logical relationships between the causes and the top event.

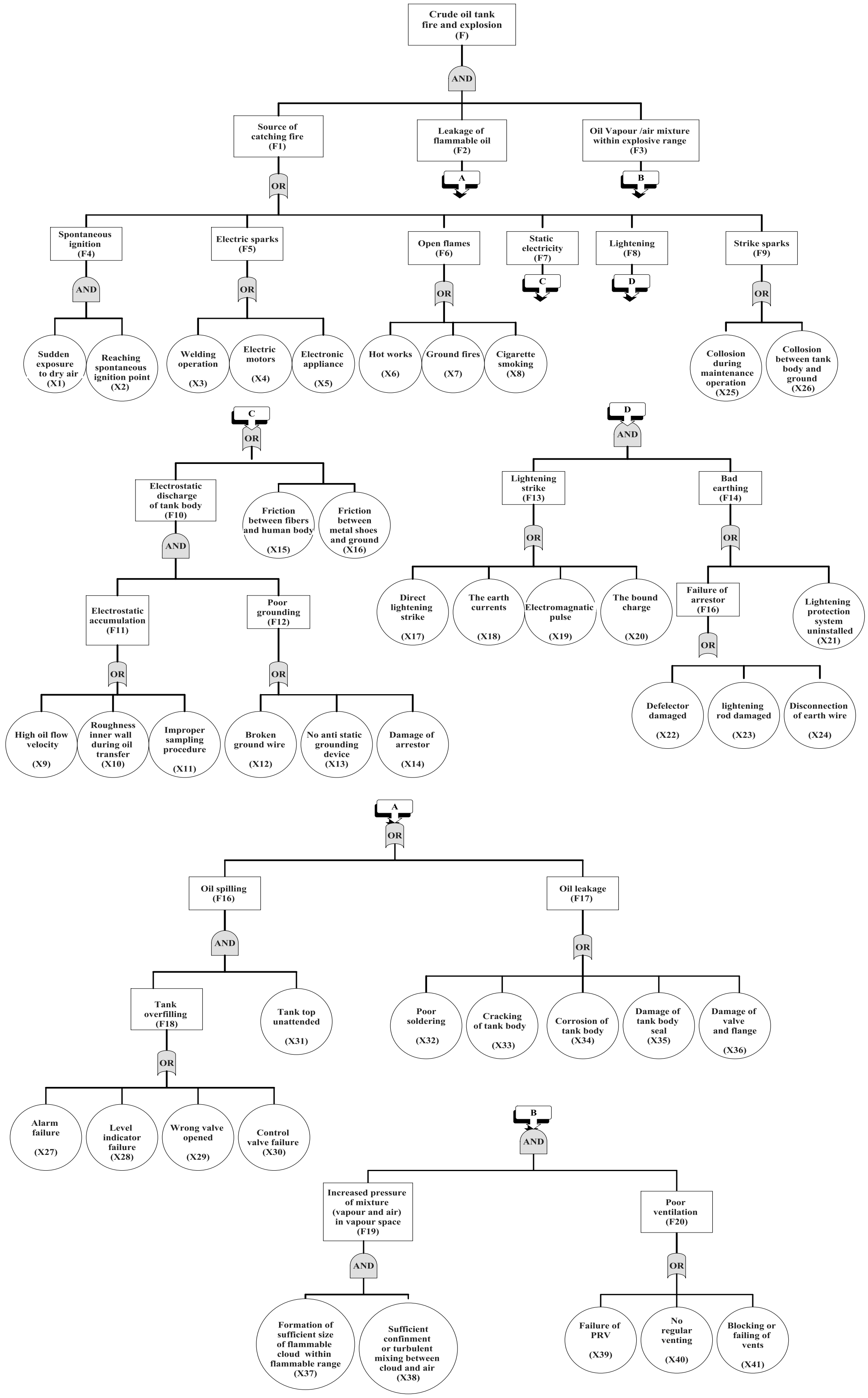

Figure 2. Fault Tree of crude oil tank fire and explosion.

Fault Tree for crude oil storage tank accidentshas constructed as shown in **Fig. 2**.In FTdiagram, there are 62 events. F stands for the top event, (F_1toF_{20}) stand for the intermediate events. ($X_1$to X_{41}) represent the BEs. The FT analysis and evaluation are generally achieved in two stages, quantitative and qualitative analysis.

The qualitative analysis includes the determination ofMinimal Path Sets (MPSs) or minimal cut sets (MCSs) of the fault tree for the storage tank.From the constructed FT, it is clear that the number of OR gates more than AND gates. Therefore, to facilitate the analysis process, FT has been transformed into the success tree. Then, the success tree has been simplified by using Boolean algebra to produce the MPSs, which represent the system safety.A MPS is thesmallest combination of basic events whose non-occurrence, it is sure that top event does nothappen. Reference to the definition of the MPS, The basic events are multiplied for OR gates and added for AND gates. The analysis of the success treeis presented in detail as follows:

$$\mathbf{F}=F_1+F_2+F_3 \quad (1)$$

$F_1= F_4 .F_5 .F_6 .F_7 .F_8 .F_9$
$F_4= (X_1 + X_2)$
$F_5=X_3 .X_4 .X_5$
$F_6=X_6 .X_7 .X_8$
$F_7= (X_9 .X_{10} .X_{11} .X_{15} .X_{16} + X_{12} .X_{13} .X_{14} .X_{15} .X_{16})$
$F_8= (X_{17} .X_{18} .X_{19} .X_{20}) + (X_{21} .X_{22} .X_{23} .X_{24})$
$F_9=X_{25} .X_{26}$

$$\boldsymbol{F_1}= (X_1 + X_2) .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .\{ (X_{17} .X_{18} .X_{19} .X_{20}) + (X_{21} .X_{22} .X_{23} .X_{24})\}. \{(X_9 .X_{10} .X_{11} .X_{15} .X_{16} + X_{12} .X_{13} .X_{14} .X_{15} .X_{16}) \} . \quad (2)$$

$$\boldsymbol{F_2}=X_{27} .X_{28} .X_{29} .X_{30} .X_{32} .X_{33} .X_{34} .X_{35} .X_{36}+X_{31} .X_{32} .X_{33} .X_{34} .X_{35} .X_{36} \quad (3)$$

$$\boldsymbol{F_3}= X_{39} .X_{40} .X_{41} + X_{37} + X_{38} \quad (4)$$

By substitution of Eqs. (2), (3) and (4) in Eq. (1), the MPSs of FT can be generated as below:

$MPS_1 =\{X_1 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{17} .X_{18} .X_{19} .X_{20} .X_9 .X_{10} .X_{11} .X_{12} .X_{15} .X_{16}\}.$
$MPS_2 =\{X_1 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{17} .X_{18} .X_{19} .X_{20} .X_{12} .X_{13} .X_{14} .X_{15} .X_{16}\}$
$MPS_3 =\{X_1 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{21} .X_{22} .X_{23} .X_{24} .X_9 .X_{10} .X_{11} .X_{12} .X_{15} .X_{16}\}.$
$MPS_4 = \{X_1 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{21} .X_{22} .X_{23} .X_{24} .X_{12} .X_{13} .X_{14} .X_{15} .X_{16}\}.$
$MPS_5 =\{X_2 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{17} .X_{18} .X_{19} .X_{20} .X_9 .X_{10} .X_{11} .X_{12} .X_{15} .X_{16}\}.$
$MPS_6 =\{X_2 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{17} .X_{18} .X_{19} .X_{20} .X_{12} .X_{13} .X_{14} .X_{15} .X_{16}\}.$
$MPS_7 =\{X_2 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{21} .X_{22} .X_{23} .X_{24} .X_9 .X_{10} .X_{11} .X_{12} .X_{15} .X_{16}\}.$
$MPS_8 =\{X_2 .X_3 .X_4 .X_5 .X_6 .X_7 .X_8 .X_{25} .X_{26} .X_{21} .X_{22} .X_{23} .X_{24} .X_{12} .X_{13} .X_{14} .X_{15} .X_{16}\}$
$MPS_9 =\{ X_{27} .X_{28} .X_{29} .X_{30} .X_{32} .X_{33} .X_{34} .X_{35} .X_{36}\}.$
$MPS_{10}=\{X_{31} .X_{32} .X_{33} .X_{34} .X_{35} .X_{36} \}.$
$MPS_{11}=\{X_{39} .X_{40} .X_{41}\}.$
$MPS_{12}=\{X_{37} \}.$
$MPS_{13}=\{X_{38} \}.$

From analysis, there are 13 Minimal Path Sets were produced for the storage tank fire and explosion.MPSs includes**4** MPS of order 19 (number of BEs), **4** MPS of order 18, **1** MPS of order 9, **1** MPS of order 6, **1**MPS of order 3, **2**MPS of order 1.This means that there are 13 possible paths to eliminate the oil tank accidents occurrence.

The quantitative evaluation of FT represents the calculation of the structure importance degree (SID) of the BEs. The SID evaluates the BE influence on the total logical structure of the top event and exclusively depends on its location in FT. The larger SID of BE, the higher effect upon the unwanted event structure.

Through the qualitative analysis, SID values werecomputed by using the following quadratic approximate formula [13]:

$$\boldsymbol{I_{\emptyset(i)}} = \sum_{x_i \in k_j}\left(\frac{\mathbf{1}}{\mathbf{2^{ni-1}}}\right) \quad (5)$$

ni : the number of BEs in MPS that x_i belongs to.

Structural importance degree for basic events has been calculated and then the comparison between different values was obtained. For example, the SID for X9 can be achieved according to Eq. (5):

$I_{\emptyset(9)} = \frac{1}{2^{19-1}} = \frac{1}{2^{19-1}} = \frac{1}{2^{19-1}} = \frac{1}{2^{19-1}} = 1.52 * 10^{-5}$.

After that, the results were compared and arranged from highest value to lowest one.The order of BEs based on their importance degree are illustrated below:

$I_{\emptyset(37)} = I_{\emptyset(38)} > I_{\emptyset(39)} = I_{\emptyset(40)} = I_{\emptyset(41)} > I_{\emptyset(32)} = I_{\emptyset(33)} = I_{\emptyset(34)} = I_{\emptyset(35)} = I_{\emptyset(36)} > I_{\emptyset(31)} > I_{\emptyset(27)} = I_{\emptyset(28)} = I_{\emptyset(29)} = I_{\emptyset(30)} > I_{\emptyset(3)} = I_{\emptyset(4)} = I_{\emptyset(5)} = I_{\emptyset(6)} = I_{\emptyset(7)} = I_{\emptyset(8)} = I_{\emptyset(25)} = I_{\emptyset(26)} = I_{\emptyset(15)} = I_{\emptyset(16)} > I_{\emptyset(12)} = I_{\emptyset(13)} = I_{\emptyset(14)} > I_{\emptyset(1)} = I_{\emptyset(2)} = I_{\emptyset(18)} = I_{\emptyset(19)} = I_{\emptyset(20)} = I_{\emptyset(21)} = I_{\emptyset(22)} = I_{\emptyset(23)} = I_{\emptyset(24)} = I_{\emptyset(25)} > I_{\emptyset(9)} = I_{\emptyset(10)} = I_{\emptyset(11)}$.

The results indicate that the most crucial BEs for causing the fire and explosion accident are X37 (formation of flammable cloud) and X38 (Confinement between cloud and air).The second critical one is poor ventilation initiators and followed by oil leakage contributors.The control of these critical causes could considerably reduce the accidents probabilities.

4. Frequency Analysis:

The frequency of the accidents can be estimated usingETAand historical data. ET is constructed from left to right**.**The technique is initiated with selecting the appropriate initial event that could lead to unwanted consequences, the initiating event in this study is the crude oil leakage from storage tanks.The heading eventsshould describe the undesired situation. It is usually to apply NO(failure state) on the downward branch and YES(success state)on the upwardbranch. Each heading event is named with a particular letter. Every final scenario path can then be defined with a unique letters combination. Probabilities of ignition can be obtained from historical recordsand database.

Event tree for the crude oil leakage as initiating event was presented in **Fig. 3**. From ET diagram, in the case of oil leakage and immediate ignition, pool fire can occur. If there is no immediate ignition, the delayed ignition of the released oil may lead to the delayed pool fire. In some cases, due to confined space or to the large quantity of the flammable cloud involved, flame front acceleration can happen and the vapor cloud explosion (VCE)is likely to take place.The outcome frequency wasestimated by multiplying the initiating event frequency with heading events probabilities along the sequential occurrence pathof the outcome. The frequency of consequencesoccurrence can be calculated using Eqs. (6), (7) and (8).

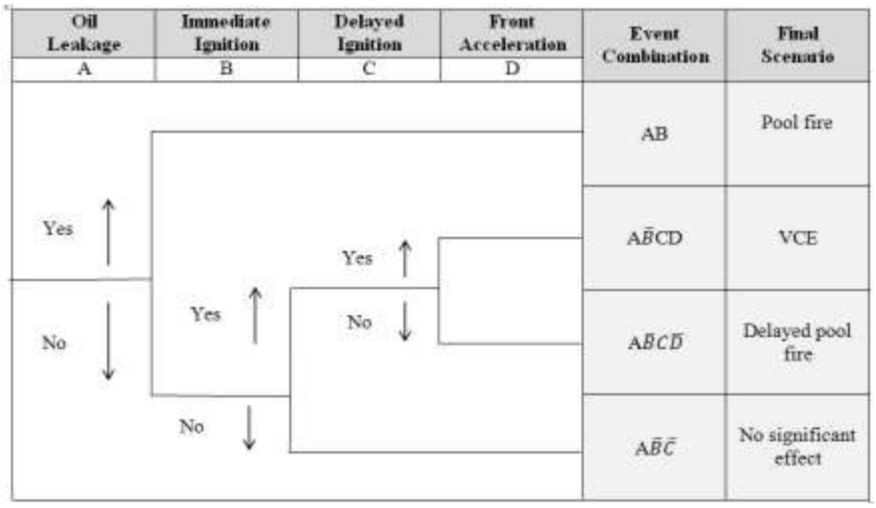

Figure 3.Event Tree for the crude oil leakage from the storage tank.

$$F_{(pool\ fire)} = F_{(A)} * P_{(B)} \quad (6)$$

$F_{(VCE)} = F_{(A)} * [1 - P_{(B)}] * P_{(C)} * P_{(D)}$ (7)

$F_{(delayed\ fire)} = F_{(A)} * (1 - P_{(B)}) * P_{(C)} * [1 - P_{(D)}]$ (8)

Leak frequency according to OGP is $1*10^{-3}$ [16]. The probability of ignition for storage tanks are given according to the Purple book [19], as below:

$Probability\ of\ immediate\ ignition = P_{(B)}$ = 0.065.

$Probability\ of\ immediate\ ignition = P_{(C)}$ = 0.065.

$Probability\ of\ front\ acceleration = P_{(D)}$ = 0.1.

Substitution of ignition probabilities values in Eqs. (6) up to (8), we can calculate the frequency of final scenarios as follows:

Pool fire frequency = $1*10^{-3}$ *0.065 = $6.5*10^{-5}$ per tank per year.

VCE frequency =$1*10^{-3}$ *(1-0.065)* 0.065*0.1 =$6*10^{-6}$ per tank per year.

Delayed pool fire frequency = $1*10^{-3}$*(1- 0.065)*0.065*(1-0. 1) =$5.4*10^{-5}$ per tank per year.
From the results, it is apparent that the frequency of pool fire is higher than the frequency of explosion.

5. Preventive and Mitigation Measures

Based on FTA of crude oil storage tank, the most critical basic events which may lead to oil fire and explosion has been identified. Therefore, to prevent or reduce the accidents probabilities and severities, common preventive and mitigation measures must be taken into consideration.

5.1. Preventive measures:

- Regular inspection and maintenance must be carried out of all components in the control system.Moreover,the filling ratio of the tank must be obeyedto avoid the overfilling incidents.
- Good policy regarding periodic maintenance for all equipment utilized in the storage farm.
- Pipe joints/flange should have copper bonding to maintain electrical continuity; flange guard is useful to divert the leakage of oil.
- Fixed roof tank must be provided with pressure relief valves and breather vents placed on the top of the tanks.
- Conventional lightning protection system for storage tanks involves installing the lightning masts around the tank and shield wires above the tank as well as ensuring the tank is well earthed.

5.2. Mitigation measures:

The mitigation measures must be done to limit and minimize the magnitude of the incident.Safety supporting systems must ensure a continuous supply of basic requirements to the storage tank farm, these systems comprised of the following:

- Automatic detection systems such as fire detectors, alarm system, heat Sensing and flame Sensing.
- Foam supply and production system for the tank fire protection.
- Tank cooling system that mounted on every tank in order to prevent its exposure to an adjacent fire
- The using of personal protective equipment must be strictly worn by all workers in the storage farms.
- Development of a green belt around the installation area will help in preventingthe spread of fire to other areas.

6. Conclusions:

The conclusions of the study can be summarized in the following points:

- Hazard analysis study has been conducted for the crude oil storage tank farm.

- HAZOP study has identified all possible deviations in parameters from design intent (level,flow, and pressure), which could finally lead to oil leakage or extra pressure and consequently result in undesirable events such as fire and explosion.
- Fault Tree of crude oil storage tank fire and explosion has been drawn.The qualitative and quantitative evaluationswere carried out. The results indicate that the most crucial BEs for causing the occurrence of fire and explosion accident are X37 (formation of flammable cloud) and X38 (Confinement between cloud and air).The second critical one is poor ventilation initiators and followed by oil leakage contributors.
- The identified critical causes must be given more attention to minimize the probabilities and mitigate the severity of the accidents.
- The frequency analysis for a crude oil leakage was carried out using ET. The results indicated that the frequency of pool fire is higher than other accidents frequencies.

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