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Dynamic Analysis of Multiple Fire Domino Effects for Better Environmental Safety and Health Management

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Abstract

Fire is a major hazard which frequently occurs in any flammable chemical processing industry leading to severe injuries, fatalities and environmental pollution. Fire induced domino accidents are of serious concern since its escalation to multiple target equipment results in more severe multiple fire scenario. Such multiple fire scenario in industrial clusters located at densely populated environment is a major threat to health and safety of human. Dynamic analysis of multiple fire domino effects is significant since the time to failure and start of fire at each equipment occurs at different times. A quantitative analysis of the dynamic variation in time to failure and failure probabilities of storage tanks during multiple fire domino effects is done. The concept of critical thermal dose is applied in this study for the estimation of dynamic time to failure of each vulnerable storage tank considering maximum synergistic effects based on the temporal variation in the intensity of heat radiation received by them. Improved probit equations are utilised for the calculation of failure probabilities of vulnerable storage tanks as a function of dynamic time to failure. The obtained results enhance timely implementation of accident mitigation measures to reduce associated health, safety and environment issues.

Keywords

Critical Thermal Dose, Domino Accident Analysis, Environmental Safety and Health, Multiple Fire Scenario

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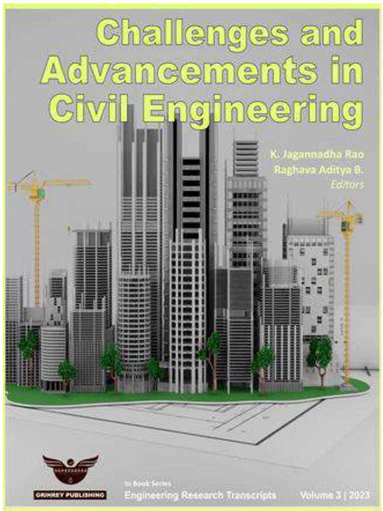

1. Introduction

Fire and explosion are major primary accidents in any flammable chemical storage tank facilities which result in catastrophic domino accidents by escalating towards nearby vulnerable storage tanks due to escalation vectors like heat radiation or overpressure [1]. Fire induced domino accidents are of serious concern in any hazardous chemical process industry. The prolonged duration of primary fires enhances its escalation to multiple target equipment to result in more severe multiple fire scenario [2]. Domino effects involving multiple fires are a major threat to environmental safety and health of people as it involves multiple heat radiation sources. This leads to severe injuries, fatalities and environmental pollution due to the production of irritating, corrosive and toxic gases along with heat radiation. Domino accidents are time-dependent processes. In case of multiple fire related domino effects, the intensity of heat radiation incident on a vulnerable unit and its time to failure (ttf) varies with time. The intensity of thermal radiation emitted and incident on a chemical storage tank depends on the tank diameter, burning rate of the chemical released, flame height etc. As stated in [3] and [4], once the intensity of heat radiation incident on a vulnerable equipment is greater than or equal to the damage/escalation threshold, the accident escalates to result in further domino accidents which are more severe than the initiating event i.e.; fire/explosion. The escalation of an accident through heat radiation from pool fire or tank fire is time-dependent which takes about a few minutes or even hours to cause damage to nearby storage units [2]. Thus, the time to failure /damage and consequent start of fire in each storage tank varies temporally especially during multiple fire domino accidents.

In this work, the concept of critical thermal dose is used to estimate dynamic ttf of vulnerable equipment according to temporal evolution of multiple fire scenario and temporal variation in the intensity of heat radiation received by it [5]. Improved probit equations are used to calculate failure probabilities of storage tanks incorporating the temporal variation in the thermal radiation incident on a vulnerable storage tank and its dynamic time to failure. The dynamic analysis of domino effects involving multiple radiation sources during a multiple fire scenario is significant for the estimation of dynamic time to failure and failure probabilities since the failure and start of fire at each at each storage tank occurs at different times. The estimation of dynamic time to failure of vulnerable storge tanks plays a major role in realistic implementation of accident escalation mitigation and protective measures to reduce health, safety and environmental issues. It also helps in realistic scheduling of emergency shutdown and fire control operations.

Among the following sections Section 2 defines the case study area and methodology used in this work. Section 3 provides various results along with a brief discussion on the major observations and output. Section 4 briefly conclude the significance of dynamic analysis of multiple fire domino effects for better health, safety and environment management.

2. Methodology

2.1 Study Area

In the present study, a Benzene storage tank farm from a petrochemical industry in South Asia. It is located at a densely populated industrial cluster with a potential for multiple fire domino effects leading to health, safety and environmental issues is selected. It consists of 8 storage tanks of Benzene at atmospheric condition as shown in the google earth image in Figure.1. Schematic representation of storage tanks is given in Figure. 2. Diameter (m) and total volume (m^3) of each tank are given in Table. 1.

Fig. 1. Google Earth image of the Benzene storage tank farm (Courtesy: Google Earth)

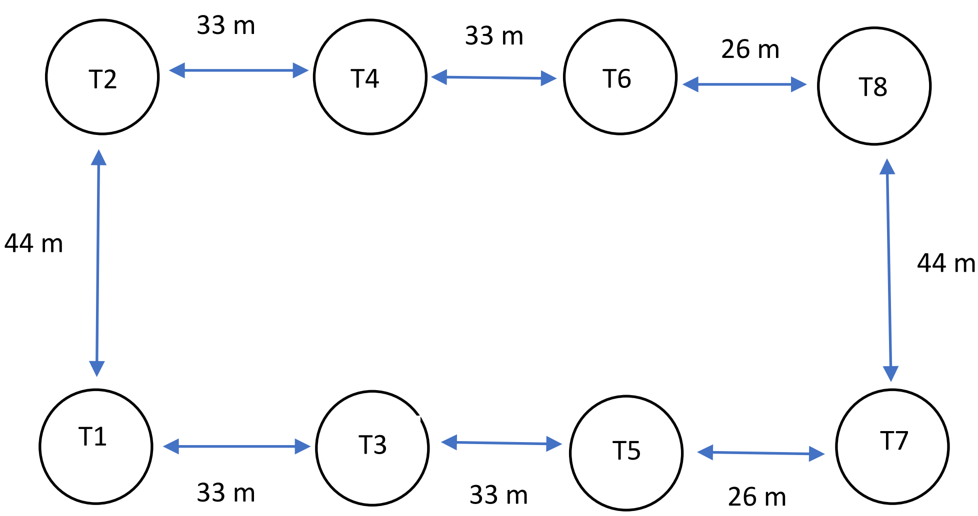

Fig. 2. Schematic representation of centre-to-centre distance between storage tanks

Table 1. Diameter and Volume of Storage Tanks

Tank Name	Diameter (m)	Volume (m^3)
T1	14	1000
T2	21	3300
T3	14	1000
T4	21	3000
T5	21	3000
T6	21	3000
T7	10.5	690
T8	10.5	690

2.2 Dynamic Time to Failure

In case of fire related domino effects, the heat radiation from multiple fires; especially at higher order domino effects, causes synergistic effects which increases the failure probability of a vulnerable storage tank [5]. Many researchers adopted the probit equations indicated in [6] and [7] for the calculation of damage probability of a vulnerable equipment. However, these probit equations do not consider dynamic ttf. In this study, we used improved probit equations (1) and (2) for the calculation of escalation/damage probability of a vulnerable equipment by considering its dynamic ttf [5]:

For all heat radiation scenarios:

$$Y = 9.25 - 1.85\ln(ttf)\,;\; ttf\ (min) \quad (1)$$

$$\ln(ttf) = -1.128\ln(I) - 2.667\times 10^{-5}V + 9.877;\; ttf\ in\ seconds \quad (2)$$

P_0 denotes intensity of overpressure (Pa), ttf is time to failure, V is volume of storage tank (m^3) and I is intensity of heat radiation (9 kW/m^2).

The domino affected accident escalation/damage probability of a vulnerable equipment is estimated from the Standard Normal Cumulative Distribution Function *φ(Y-5)*, where Y is the probit value obtained from Equation (1).

The equations (3) to (8) are used for the calculation of dynamic ttf as a function of critical thermal dose D_{th} [5]:

The critical thermal dose D_{th} required to cause tank failure:

$$D_{th} = Q^{\alpha}\ \times ttf; ttf\ in\ seconds, \alpha \text{ is a constant} \quad (3)$$

For atmospheric equipment,

$$D_{th} = Q^{1.128}\times ttf = e^{-(2.667\times 10^{-5}\times V - 9.877)};\; ttf\ (sec), V\ (m^3), Q\ (\frac{kW}{m^2}) \quad (4)$$

Q is the constant value of thermal radiation incident on the vulnerable equipment, V is the constant volume of vulnerable equipment. Q and ttf are inversely proportional.

While considering a time-dependent variation in the thermal radiation incident on the vulnerable storage tank,

$$D_{th} = \int_0^{ttf} Q^{\alpha} \times dt \tag{5}$$

During a stationary pool fire, the thermal radiation incident on a vulnerable storage tank is a step function which remains constant until a new fire occurs and changes temporally once a new fire occurs. Thus, the critical thermal dose can be simplified as:

$$D_{th} = \sum_{i=1}^{n} Q_{0,i}^{\alpha} \,.\, \Delta t_i \tag{6}$$

$Q_{0,i}^{\alpha}$ denotes the total heat radiation incident on a vulnerable equipment at each time interval, Δt_i denotes the length of each time interval and n denotes the total number of time intervals.

A vulnerable storage tank fails at the end of n^{th} time interval to start a fire. Thus, the dynamic ttf of a vulnerable storage tank, when the ttf of other tanks are known:

$$ttf = \sum_{i=1}^{n-1} \Delta t_i + \Delta t \tag{7}$$

Where,

$$\Delta t = \frac{D_{th} - \sum_{i=1}^{n-1} Q_{0,i}^{\alpha} \,.\ \Delta t_i}{Q_{0,n}^{\alpha}} \tag{8}$$

Dynamic ttf of a vulnerable equipment in (7) accounts for the effect of thermal radiation from multiple fires which initiate at different points of time [5]. The time-dependent estimation of ttf is more realistic as it maximizes synergistic effect during multiple fire scenario. Thus, it helps to implement a more realistic environmental safety and health protection measures. The damage threshold of the atmospheric units is taken as 15kW/m^2 [3], [4] and [8]. Mass burning rate and flame height during a pool fire are calculated for each tank the estimation of emitted and received heat radiation using classical empirical equations from TNO multi-energy models are well discussed in [9] and [10]. TNO is the Netherlands Organization for Applied Scientific Research.

The mass burning rate of a liquid is calculated as

$$\frac{dm}{dt} = \frac{0.001\, H_C}{C_p(T_b - T_a) + H_{vap}} \quad \text{When } T_b > T_a \tag{9}$$

And

$$\frac{dm}{dt} = \frac{0.001\, H_C}{H_{vap}} \quad \text{When } T_b < T_a \tag{10}$$

Where T_a is the ambient temperature (K), T_b is the boiling point (K) of the liquid, H_C is the net heat of combustion (energy/mass), H_{vap} is the heat of vaporization of the liquid at T_a, (energy/mass).

The total heat radiation emitted from a pool of radius 'r' is given as

$$Q = \frac{(\pi r^2 + 2\pi r H) \cdot \left[\frac{dm}{dt}\right] \cdot \eta\, H_C}{72 \cdot \left[\frac{dm}{dt}\right]^{0.61} + 1} \tag{11}$$

η is the efficiency factor (0.13 to 0.35), H is the flame height (m)

$$H = 84\, r \left[\frac{\left(\frac{dm}{dt}\right)}{\rho_a\, (2gr)^{\frac{1}{2}}}\right]^{0.6} \tag{12}$$

ρ_a is the air density (1.2 kg/m^3 at 20°C and 1 atm.) and g is the acceleration of gravity (9.81 m/s^2). The heat radiation received by a storage tank at a distance R from the centre of pool fire is,

$$I = \frac{TQ}{4\pi R^2} \tag{13}$$

T is the transmissivity of the air path (Approx. 1).

3. Results and Discussions

The vertical burning rate of Benzene is generally 6 mm/min or 0.0001 m/s as per the safety datasheet of Benzene. Further, the mass burning rate is calculated as 0.0876 kg/m^{2}s by multiplying the vertical burning rate with the density of benzene (876 kg/m^3). The flame height and emitted heat flux from each storage tank are obtained as shown in Table. 2.

Table 2. Flame Height and Emitted Heat Radiation of each storage tank

Tank Name	**Flame Height (m)**	**Emitted Heat Flux (kW/m^2)**
T1	26.54	53721.9
T2	35.19	108481
T3	26.54	53721.9
T4	35.19	108481
T5	35.19	108481
T6	35.19	108481
T7	21.73	32666.4
T8	21.73	32666.4

The intensity of thermal radiation incident on each storage tank estimated using classical empirical equations from TNO multi-energy models [9] and [10] are given in Table. 3.

Table 3. Intensity of Incident Thermal Radiation

Heat Radiation Incident on Each Target Tank (kW/m^2)								
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
T1	X	3.81	6.32	1.49	1.39	0.64	0.57	0.35
T2	6.31	X	6.31	17.05	3	2.80	1.33	1.15
T3	6.32	3.81	X	3.81	8.44	1.48	1.48	0.66
T4	2.64	17.05	6.3	X	7.7	17.05	2.99	2.99
T5	2.48	3	12.77	7.69	X	7.69	20.05	2.99
T6	1.19	2.8	2.64	17.05	7.69	X	6.43	20.05
T7	0.36	0.46	0.96	1.11	10.82	2.64	X	1.73
T8	0.22	0.39	0.42	1.105	1.11	10.82	1.73	X

From the values of heat radiation intensities given in Table. 3, it is identified that:

- The heat radiation from T1, T3, T7 and T8 did not exceed the escalation/damage threshold (15 kW/m^2) of any of the tanks.
- The thermal radiation incident on T4 from T2 was greater than the escalation/damage threshold (17.05 kW/m^2).
- The heat radiation incident from T4 was greater than the escalation/damage threshold (17.05 kW/m^2) of T2 and T6.
- T5 affected T7 by a thermal radiation of 20.05 kW/m^2.
- The heat radiation received by T4 (17.05 kW/m^2) and T8 (20.05 kW/m^2) from T6 exceeded the escalation/damage threshold.

According to the above observations, T2, T4, T5 and T6 are found to be critical storage tanks. It is to be noted that T4 and T6 affected more than one storage tank at a time. So, these tanks are considered as most critical storage tanks. However, in this study, T2 is chosen as the primary tank in which the fire is assumed to be initiated.

However, all the storage tanks except the primary tank T2, are preheated by the heat radiation below their damage threshold before receiving an overall heat radiation which exceeds their damage thresholds either from an individual source or through synergistic effects. This time dependent variation in the incident heat radiation necessitates the estimation dynamic ttf as a function of tank volume as well as critical thermal dose. Dynamic ttf of each vulnerable storage tank from the beginning of initial fire is utilised for the estimation of dynamic accident escalation probabilities using the improved probit models [5].

When T2, T4 and T6 are damaged consecutively, the overall thermal radiation incident on T3 (15.25 kW/m^2) exceeded the damage threshold to catch fire. Also, the overall thermal radiation incident on T5 (18.39 kW/m^2) exceeded the damage threshold to catch fire. The overall thermal radiation incident on T1 (16.46 kW/m^2) through the synergistic effects of T2, T3, T4 and T6 exceeded the damage threshold to catch fire. It is also identified that the damage of T3 is essential to cause the damage of T1 through synergistic effects. Table. 4. shows the ttf of vulnerable storage tanks from the beginning of initial fire calculated using the simple summative methods discussed in [6] and [7]. In simple summative method only the total sum of thermal radiation received by a target tank is considered while calculating ttf. This method does not consider the time dependent variation in the intensity of heat radiation received by a target tank from multiple fire sources. Table. 4. also shows the dynamic ttf of vulnerable tanks from the beginning of initial fire calculated using the concept of critical thermal dose [5].

Table 4. Dynamic ttf of storage tanks since the start of primary fire

Tank Name	Critical Thermal Dose D_{th}	Time to Failure (ttf) using direct summative method (min)	Dynamic Time to Failure using critical thermal dose (min)
T1	18964.6	11.42	23.77
T2	17836.26	0	0
T3	18964.6	14.6	18.12
T4	17979.5	12.22	2.48
T5	17979.5	11.22	17.97
T6	17979.5	10.29	12.5
T7	19122	6.67	21.81
T8	19122	8.76	19.8

In the direct summative method, the summation of the overall thermal radiation incident on the vulnerable storage tank is directly utilized for the calculation of time to failure by also considering the incident heat radiation preheating the tank. Dynamic time to failure is calculated utilizing the critical thermal dose as a function of overall thermal radiation incident on the vulnerable storage tank at each time interval. From the dynamic time to failure of T3 and T5 which are failed by the synergistic effects of T2, T4 and T6, it is identified that T5 fails before T3. Thus, in order to calculate the time to failure of T1, which is failed by the synergistic effects of T2, T3, T4 and T6, the preheating by T5 is also considered in the overall heat radiation. This reduced the time to failure of T1 from 13.42 min to 11.42 min.

The dynamic failure probabilities of each storage tank are calculated using the improved probit equations (1) and (2) by considering their dynamic time to failure obtained using (7). The dynamic failure probabilities of each storage tank through domino effects once the primary tank T2 catches fire are tabulated in Table 5.

Table 5. Dynamic failure probabilities of storage tanks

Tank Name	**Dynamic Failure Probabilities**
T1	0.054
T2	Primary Tank
T3	0.134
T4	0.995
T5	0.137
T6	0.337
T7	0.0735
T8	0.054

From Tables 4 and 5, it is evident that higher the dynamic ttf, lower is the dynamic failure probability. Comparatively, higher failure probability implies higher possibility to fail.

4. Conclusions

Dynamic time to failure of each vulnerable storage tank accounts for the effect of time dependent variation in the heat radiation received from multiple fires in storage tanks which fail and catch fire at different times. The concept of critical thermal dose and synergistic effects are utilised to calculate dynamic ttf. The time-dependent estimation of ttf is more realistic as it maximizes synergistic effects during a multiple fire scenario. The estimation of dynamic time to failure can be utilised to calculate dynamic failure probabilities of storage tanks during multiple fire domino effects. It is evident from this case study that higher the dynamic time to failure of a vulnerable equipment, lower is its dynamic failure probability. Higher the failure probability of a vulnerable equipment, higher is its possibility to fail. Preheating of storage tanks by heat radiation below their threshold limits significantly reduces their time to failure.

From the analysis of heat radiation intensity in Table 3, it is concluded that T2, T4, T5 and T6 are critical storage tanks. Since T4 and T6 impact more than one storage tank at a time, these two tanks are considered as the most critical storage tanks that needs to be isolated first. From Table 4, it is observed that dynamic ttf using the concept of critical thermal dose comparatively provided more realistic time dependent cumulative failure time. From the dynamic ttf, the sequential order of failure of storage tanks is identified as T2, T4, T6, T5, T3, T8, T7 and T1. The dynamic time to failure and dynamic failure probabilities of storage tanks helps to implement a more realistic scheduling of emergency shutdown, accident mitigation and protection activities during multiple fire domino effects through real-time health, safety and environmental management.

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