Enhancement of chemical plant safety by the development of minimum safety distances for separation of Plants/Equipment handling flammable & toxic Liquid

Mr. Veeraj Rajendra Patil
Department of Chemical Engineering.
School of Engineering And Applied Sciences, University Of Mumbai (Kalyan Sub Center)
Mumbai, India

Dr. Satyajeet M. Deshmukh
Department of Chemical Engineering.
School of Engineering And Applied Sciences, University Of Mumbai (Kalyan Sub Center)
Mumbai, India

Abstract: -In chemical plant layout considerations, it is necessary to develop a simple and acceptable method of determining safety distance in the event of a fire scenario and toxic substance leakage. This working mechanism is method for calculating adequate safety distances for storage tanks containing highly flammable liquids based on appropriate radiation thermal and concentration fluxes for structures and people. The safety distance is defined in this document as the least separation between a hazard source and an object that will mitigate the effect of a likely foreseeable incident and prevent a minor incident from escalating into a larger incident. The primary goal is to establish appropriate separation distances between storage tanks and objects so that design engineers can create industry standards. The theoretical model used to determine acceptable safety distances with respect to tank diameter produces outcomes in the form of a parabolic curve, indicating that the value of safety distances increases with increasing tank diameter, reaches a maximum value, and then decreases. The program PHAST was used to simulate fires. The goal of this paper is to provide a relatively simple and user-friendly calculation tool that provides designers with a solid theoretical foundation on which they can base their designs if/when it is called into question by authority or when different flux values are stated by authorities.

Keyword:- Chemical Plant safety, Fire Safety, Flammable Liquid, Theoretical Model, PHAST Software.

I. Introduction

Given today's situation of housing being built close to industrial zones, we have witnessed numerous accidents resulting in injuries/deaths and property and asset damage. Fire is the most common type of accident encountered in chemical process industries (CPI) that deal with the production, transportation, and/or storage of flammable substances. According to a survey of accidents based primarily on major hazards incident data from both domestic and international sources, all accidents in CPI involve jet fire, flash fire, fireball, and pool fires. According to many previous accident reports, a dike fire or pool fire is the most common disaster form in the petrochemical industry, resulting in more deadly radiation and higher flame, which can have a serious impact on the surrounding personnel and equipment and can also lead the boiling liquid to a vapor explosion or vapor cloud explosion. The storage of flammable liquids and vapors in closed vessels can result in the vessel failing catastrophically during a fire. A sudden release of energy from a compressed vessel failure will cause damage from the pressure wave and the impact of missiles displaced by the explosion. In the case of a vessel containing flammable gas or liquid, the material's sudden ignition can result in a fireball that travels upward while burning. The associated flame radiation may cause additional damage. This encourages the development of inherently safe plant layout and industrial area layout, which will lead to the prevention of industrial hazards and thus reduce/avoid injuries, loss of life, and damage to property in the vicinity of the chemical industries. The main objective of this is to define a philosophy for determining appropriate separation distances, so that design engineers/governing authorities/regulating bodies can develop consistent standards for a safe Industrial Area. Limiting the complexity of current methods (based on dynamic simulations) in order to develop a simple and effective method for calculating appropriate safety distances for separation plants/equipment handling flammable and toxic substances. Many scholars have conducted a wide range of relevant studies since the 1960s. Planas-Cuchi [5] researched the flame structure based on a summary of previous experimental data and research results; Hamins [4]. However, due to a variety of constraints, conducting large-scale experiments directly is both difficult and costly. Many empirical and semi-empirical calculation models have been developed to describe the fire combustion process, heating characteristics, or related factors. This method is a simple software tool, and the results will be validated by comparing them to the results of dynamic simulation software (PHAST). The calculation method for determining minimum safety distances for storage tanks containing highly flammable liquids based on appropriate radiation thermal fluxes for structures and people is defined in this paper. The safety distance is the minimum distance between a hazard source and an object that will mitigate the effect of a likely foreseeable incident and prevent a minor incident from escalating into a larger incident.

II. Methodology

The calculation methodology of calculation includes following steps:

- Selection of fire scenario.
- Determination of acceptable values of thermal flux.
- Theoretical Model for estimation of safety distances.

2.1. Selection of fire scenario

The fire hazards in chemical plant tank yard surroundings can be classified into different scenarios as follows:

- Pool fire
- Flash fire
- Jet flame
- Fireball or Bleve

The most appropriate scenario in this case is the pool fire. Pool fires do not occur suddenly as it usually takes time between tank ignition and its subsequent collapse that eventually leads to pool fire. Considering Human safety as the first priority, there is sufficient time for evacuation while tank is burning and it is cooled down by monitors.

Considering this, the pool fire scenario is considered with the tank itself as the containment basin, instead of considering the dyked area as containment basin.

2.2. Determination of acceptable values for thermal flux

Buettner (1957) has collected a table of exposure times which will exceed the pain threshold. Buettners table (Table 1) [11] is presented below.

Radiation Intensity kW/m^2(Btu/h*ft^2)	Time-to-pain threshold (s)
174 (550)	60
233 (740)	40
290 (920)	30
473 (1500)	16
694(2200)	9
946 (3000)	6
1167 (3700)	4
1987 (6300)	2

Table 1. Exposure times necessary to reach the pain threshold. [6]

According to research, Stoll and Greene (1958) [9] and Buettner (1957) [11], the pain threshold time and radiation intensity has clear connection. According to same research API Standard 521 states that the exposure time in an emergency case is in a range of 8 to 10 seconds before individual person will start to seek cover or decide to leave from area. In table 2 few different exposure cases are viewed (API521, 2007).As a basis of comparison, the intensity of solar radiation is in the range of 0, 79 kW/m^2 to 1, 04 kW/m^2 (250 Btu/h·ft^2 to 330 Btu/h·ft^2) depending on geographical location and time of year. Solar radiation can be a factor for some locations, but its effect added to radiation has only a minor impact on the acceptable exposure time. (API521, 2007).According to research and API standard 521 following values for acceptable thermal flux are established, see table 3. [7]

Permissible level kW/m^2	Condition
9,46 (3000)	Maximum radiant heat intensity atany location whereurgent emergency action by personnel is required. When personnel enter or work in an area with the potential for radiant heat intensity greater than 6.31 kW/m^2 (2000 Btu/h * ft^2), then radiation shielding and/or special protective apparel (e.g. a fire approach suit) should be considered. SAFETY PRECAUTION - It is important to recognize that personnel with appropriate clothing ^{a} cannot tolerate thermal radiation 6.31 kW/m^2 (2000 Btu/h * ft^2) for more than a few seconds.
6,31 (2000)	Maximum radiantheat intensity in areaswhere emergency actions lasting up to 30 s can be required by personnel without shielding but with appropriate clothing ^{a}.
4,73 (1500)	Maximum radiant heat intensity in areas where emergency actions lasting 2 min to 3 min can be required by personnel without shielding but with appropriate clothing ^{a}.
1,58 (500)	Maximum radiant heat intensity at any location where personnel with appropriate clothing ^{a}can be continuously exposed.
Appropriate clothing consists of hard hat, long-sleeved shirts with cuffs buttoned, work gloves, long-legged pants and work shoes. Appropriate clothing minimizes direct skin exposure to thermal radiation.	

Table 2. Permissible design levels for variety of surrounding conditions. [7]

Scenario	Personnel Safety Criteria	Structure Safety Criteria	Solar radiation magnitude
Pool fire in retention basin	4.73 kWm$^{2(1)}$	9.46 kWm$^{2(1)}$	1.04 kW/m2

Table 3.Acceptable thermal flux levels for personnel and structures. [7]

2.3. Theoretical Model for estimation of safety distances

Research field has several different methods to determine safety distances between sources of heat and object. Point Source Model (Modak, 1977) [7] was one of the best to determine safety distances. API Standard 521 / ISO23251 is using point source model when determining safety distances.

$$D = \sqrt{\frac{\tau \cdot F \cdot Q}{4\pi \cdot K}} \qquad (1)$$

Where, D is the minimum distance from the epicenter of the flame to the object being considered, meters (feet);
τ Is the fraction of the radiated heat transmitted through the atmosphere.
F is the fraction of heat radiated.
Q is the heat release (lower heating value), expressed in kW (Btu/h);
K is the radiant heat intensity, expressed in kW/m^2 (Btu/h·ft^2). [7]
Equation 1 is result of empirical study (Hajek & Ludwig, 1960)[10]. Equation 1 can be used to calculate minimum safety distance from a single radiant epicenter flame to an object. Equation 1 contains a parameter F, which is the

fraction of heat radiated from source to object. F parameter in above equation is taken as 0.35 and it is applicable for flares where efficient mixing of fuel + oxygen takes place so that there is no fuel rich zone that leads to smoke formation. Direct application of above equation to pool fires can produce much higher magnitudes than large pool fires generates in real case. Depending on the fuel and the size of the fire, up to 20 % of the fuel mass is converted to smoke particulate in the combustion process (Society of Fire Protection Engineers, 1999)[8]. This smoke shields much of the luminous flame region from the viewer, and it is this luminous flame region that is the source of most of the thermal radiation. This shielding effect is most pronounced for fires that are tens or hundreds of meters in diameter because of the decreased efficiency of combustion at these scales. Therefore, it is necessary to correct the *F* (i.e. the fraction of heat radiated) for large scale pool fire.

Modification of parameter F

Equation 2 is used to correct the F parameter for large scale pool fires. Values for $\chi_{r\,\max}$ and k in equation 2 are based on a curve fit to experimental data involving a range of different combustible liquids. (National Institute of Standards and Technology -NISTIR 6546) [11]

$$F = \chi_r = \chi_{r\,\max} \cdot e^{-kd} \qquad (2)$$

Where,

$\chi_{r\,\max}$ =0.35

K = 0.05 m^{-1}

D = Diameter of pool fire (equivalent diameter in case of non-circular pool).

Equation 2 includes only one variable; diameter of pool fire, and two constant values which are chosen based on experimental data.

Summarisation of results as function of fuel type and tank diameter

The results from the equation are tabularized and plotted as following functions:

- Tank Diameter v/s parameter F
- Tank Diameter v/s Acceptable Safety Distances (for personnel & structures)

These plots can be seen in figures 1 and 2.For following flammable substance:

- Heavy Fuel Oil (hence forth referred as HFO) (Refer Annexure-A)

Physical properties for HFO are viewed in table 4. These physical properties can be found from several different sources. Between different sources there might be small variation on values. Values presented in table 4 are from SFPE Handbook [8]. Equations 3 and 4 are presenting how duration of a pool fire can be calculated. Burning duration is basically produced of volume height and physical burning properties of a liquid.

Fuel	Heat of Combustion (kJ/kg)	Mass burning rate (kJ/m^2-sec)	Density (kg/m^3)
HFO	39700	0.0335	970

Table 4. Physical properties of fuel used.

Equation 3 is used for calculation of Burning Duration of pool fire (SFPE Handbook of Fire Protection Engineering, 1995) [8]

tb = V / A n (3)

Where,tb = burning duration of pool fire (sec) considered, expressed in meters

V = volume of liquid (m^3)

A = Surface Area of pool

n = regression rate (m/sec)

Equation 4 is used for calculation of regression rate (SFPE Handbook of Fire Protection Engineering, 1995) [13]

n = m"/r (4)

Where,n = regression rate (m/sec)

m" = mass burning rate of fuel (kg/m^2-sec)

r = liquid fuel density (kg/m^3)

III. RESULTS

3.1. Parameter F

The results show that the values for parameter F (the fraction of heat radiated) drops exponentially with increase of tank diameter. Table 5 shows variance of parameter F with respect to different standard tank diameters. Values presented in table 5 are calculated with equation 2, where maximum radiated heat is assumed to be 0.35 as mentioned above

Sr. No.	Diameter of Tank (m)	Volume of Tank (m^3)	F (Fraction of heat radiated)
1	3	35	0.301
2	4.5	50	0.279
3	4.5	80	0.279
4	4.5	100	0.279
5	6.8	150	0.249
6	6.8	200	0.249
7	6.8	300	0.249
8	9	500	0.223
9	10.5	700	0.207
10	11.5	1000	0.197
11	12.6	1500	0.186
12	14.5	2000	0.107
13	16.2	2500	0.156
14	17.8	3000	0.144
15	19.2	4000	0.134
16	21.5	5000	0.119
17	26.5	7500	0.093
18	30.3	10000	0.077
19	38	20000	0.052
20	45	30000	0.037

Table 5.Variance of Fraction F with respect to different standard tank diameters used in plants.

It can be seen that the corrected value of parameter F varies from 0.077 to 0.301. Values of equation 2 are plotted in figure 1.

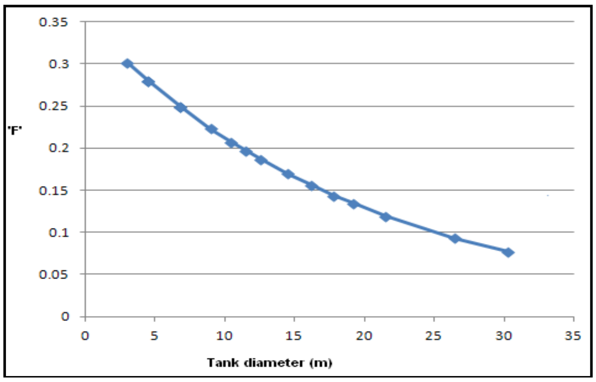


Figure 1.Variance of Fraction F with respect to different standard tank diameters of storage tanks

As already noticed; dense smoke is one reason why this parameter F is decreasing in a function of tank diameter, viewed in figure 1.

3.2. Safety distances

Main goal of this research was to calculate and produce a simple method to determine acceptable safety distances for personnel and structures. Acceptable safety distances are calculated for different fuels and for variety of tank sizes. In figure 2 typical curve for acceptable safety distances are viewed. As can be seen from figure 2, plotted results reveals that equation has two portions; ascending and descending.From table 6 can be seen that acceptable safety distance is reaching its maximum value around tank diameter of 22 m and decreases with further increase in tank diameter. This parabolic behavior of curve is due to the exponential decrease in parameter F with respect to increase in tank diameter.

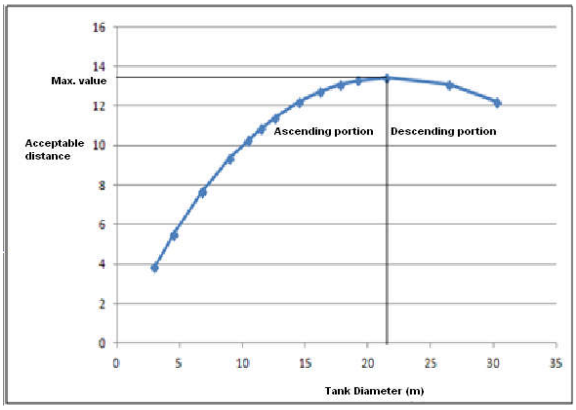


Figure 2.Acceptable safety distances for buildings with respect to different HFO standard tank diameters

Table 6 shows the actual computed acceptable safety distances for standard tanks diameters for different fuels. Safety distanced viewed in table 6 are divided to people and buildings, respectively.

Tank Volume (m^3)	Tank Diameter (m)	Safety Distance for Radiation Intensity (m) (Measured from outside Diameter of tank)	
		HFO	
		4.739.46 kW/m^2	9.46 kW/m^2
35	3	6.5	3.8
50	4.5	9.3	5.4
80	4.5	9.3	5.4
100	4.5	9.3	5.4
150	6.8	13.1	7.5
200	6.8	13.1	7.5
300	6.8	13.1	7.5
500	9	16.1	9.2
700	10.5	17.9	10.1
1000	11.5	19.0	10.6
1500	12.6	20.1	11.2
2000	14.5	21.7	11.9
2500	16.2	22.9	12.4
3000	17.8	23.8	12.8
4000	19.2	24.5	13.0
5000	21.5	25.3	13.1
7500	26.5	26.0	12.7*
10000	30.3	25.6*	11.8*
20000	38	23.2*	9.0*
30000	45	19.4*	5.3*

Table 6.Computed Values of acceptable safety distances for different standard tank diameters

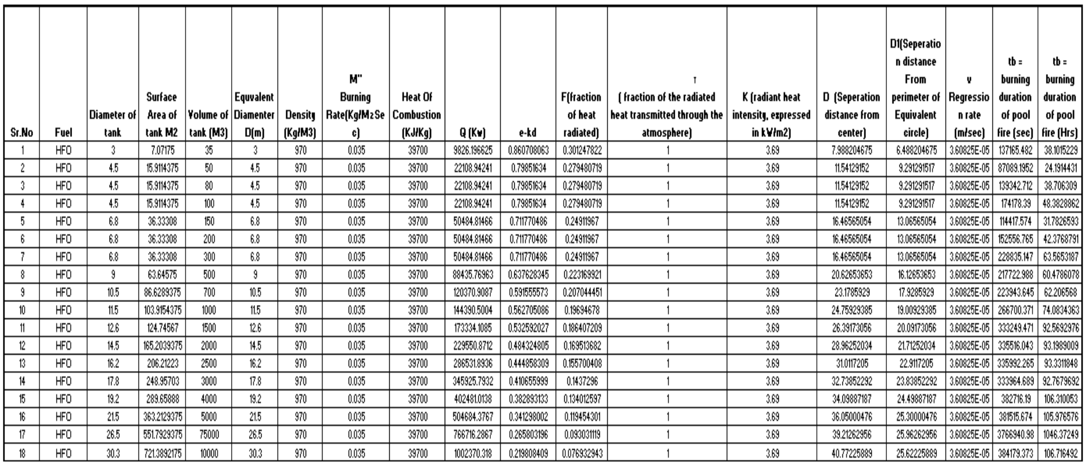
Tank diameters that correspond to the ascending portion of the tank diameter vs. safety distance plot are taken as applicable. For tank diameters that correspond to the descending portion (* marked) of the tank diameter vs. safety distance plot, the highest value on curve is assumed to be applicable. Using this principle the table 7 is corrected for the decreasing values.

Tank Volume (m^3)	Tank Diameter (m)	Safety Distance for Radiation Intensity (m) (Measured from outside Diameter of tank)	
		HFO	
		4.739.46 kW/m^2	9.46 kW/m^2
35	3	6.5	3.8
50	4.5	9.3	5.4
80	4.5	9.3	5.4
100	4.5	9.3	5.4
150	6.8	13.1	7.5
200	6.8	13.1	7.5
300	6.8	13.1	7.5
500	9	16.1	9.2
700	10.5	17.9	10.1
1000	11.5	19.0	10.6
1500	12.6	20.1	11.2
2000	14.5	21.7	11.9
2500	16.2	22.9	12.4
3000	17.8	23.8	12.8
4000	19.2	24.5	13.0
5000	21.5	25.3	13.1
7500	26.5	26.0	13.1
10000	30.3	26.0	13.1
20000	38	26.0	13.1
30000	45	26.0	13.1

Table 7.Corrected Values of acceptable safety distances for different standard tank diameters

IV. Calculation excel worksheet

Based on the above mentioned calculation philosophy excel worksheet are produced to help calculation. In figure 3 can be seen the layout of HFO worksheet. Own worksheets for different flammable substances can be produced in similar way by entering respective physical chemical properties



Sr.No	Fuel	Diameter of tank	Surface Area of tank M2	Volume of tank (M3)	Equvalent Diamenter D(m)	Density (Kg/M3)	M'' Burning Rate(Kg/M2Sec)	Heat Of Combustion (KJ/Kg)	Q (Kw)	e-kd	F(fraction of heat radiated)	τ (fraction of the radiated heat transmitted through the atmosphere)	K (radiant heat intensity, expressed in kW/m2)	D (Seperation distance from center)	D1(Seperation distance From perimeter of Equivalent circle)	v Regression rate (m/sec)	tb = burning duration of pool fire (sec)	tb = burning duration of pool fire (Hrs)
1	HFO	3	7.07175	35	3	970	0.035	39700	9826.196625	0.860708063	0.301247822	1	3.69	7.988204675	6.488204675	3.60825E-05	137165.482	38.1015229
2	HFO	4.5	15.9114375	50	4.5	970	0.035	39700	22108.94241	0.79851634	0.279480719	1	3.69	11.54129152	9.291291517	3.60825E-05	87089.1952	24.1914431
3	HFO	4.5	15.9114375	80	4.5	970	0.035	39700	22108.94241	0.79851634	0.279480719	1	3.69	11.54129152	9.291291517	3.60825E-05	139342.712	38.706309
4	HFO	4.5	15.9114375	100	4.5	970	0.035	39700	22108.94241	0.79851634	0.279480719	1	3.69	11.54129152	9.291291517	3.60825E-05	174178.39	48.3828862
5	HFO	6.8	36.33308	150	6.8	970	0.035	39700	50484.81466	0.711770486	0.24911967	1	3.69	16.46565054	13.06565054	3.60825E-05	114417.574	31.7826593
6	HFO	6.8	36.33308	200	6.8	970	0.035	39700	50484.81466	0.711770486	0.24911967	1	3.69	16.46565054	13.06565054	3.60825E-05	152556.765	42.3768791
7	HFO	6.8	36.33308	300	6.8	970	0.035	39700	50484.81466	0.711770486	0.24911967	1	3.69	16.46565054	13.06565054	3.60825E-05	228835.147	63.5653187
8	HFO	9	63.64575	500	9	970	0.035	39700	88435.76963	0.637628345	0.223169921	1	3.69	20.62653653	16.12653653	3.60825E-05	217722.988	60.4786078
9	HFO	10.5	86.6289375	700	10.5	970	0.035	39700	120370.9087	0.591555573	0.207044451	1	3.69	23.1785929	17.9285929	3.60825E-05	223943.645	62.206568
10	HFO	11.5	103.9154375	1000	11.5	970	0.035	39700	144390.5004	0.562705086	0.19694678	1	3.69	24.75929385	19.00929385	3.60825E-05	266700.371	74.0834363
11	HFO	12.6	124.74567	1500	12.6	970	0.035	39700	173334.1085	0.532592027	0.186407209	1	3.69	26.39173056	20.09173056	3.60825E-05	333249.471	92.5692976
12	HFO	14.5	165.2039375	2000	14.5	970	0.035	39700	229550.8712	0.484324805	0.169513682	1	3.69	28.96252034	21.71252034	3.60825E-05	335516.043	93.1989009
13	HFO	16.2	206.21223	2500	16.2	970	0.035	39700	286531.8936	0.444858309	0.155700408	1	3.69	31.0117205	22.9117205	3.60825E-05	335992.265	93.3311848
14	HFO	17.8	248.95703	3000	17.8	970	0.035	39700	345925.7932	0.410655999	0.1437296	1	3.69	32.73852292	23.83852292	3.60825E-05	333964.689	92.7679692
15	HFO	19.2	289.65888	4000	19.2	970	0.035	39700	402481.0138	0.382893133	0.134012597	1	3.69	34.09887187	24.49887187	3.60825E-05	382716.19	106.310053
16	HFO	21.5	363.2129375	5000	21.5	970	0.035	39700	504684.3767	0.341298002	0.119454301	1	3.69	36.05000476	25.30000476	3.60825E-05	381515.674	105.976576
17	HFO	26.5	551.7929375	75000	26.5	970	0.035	39700	766716.2867	0.265803196	0.093031119	1	3.69	39.21262956	25.96262956	3.60825E-05	3766940.98	1046.37249
18	HFO	30.3	721.3892175	10000	30.3	970	0.035	39700	1002370.318	0.219808409	0.076932943	1	3.69	40.77225889	25.62225889	3.60825E-05	384179.373	106.716492

Figure 3.Calculation Excel worksheet for HFO.

4.1. Verification& Validation

The results of theoretical model discussed and presented in above was verified using computer program called DNV PHAST, used version was 7.01. DNV PHAST is a highly recommended computer program use vastly for simulation of different fire and hazard scenarios. Program and its results are considered credible and acceptableworldwide across the industry. Purpose of these simulations was to provide data, separation distances, from similar cases as was calculated with developed excel sheet and then execute comparison between these two calculations (excel sheet and PHAST simulation). Simulation parameters, tank sizes and simulation results are discussed in following sections; in the end also, short conclusion is provided.

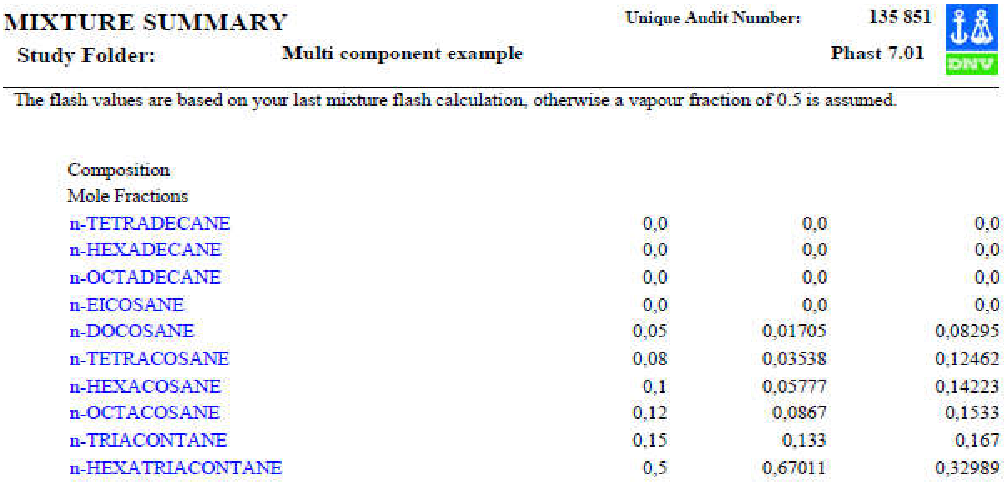
4.2. Factors considered for simulations

Following factors (User defined inputs) were considered in simulation:

Fire Scenario: Pool fire with tank as containment basin.

- Ambient temperature: 30^0 C.
- Ambient wind speed :10 m/sec
- Ambient humidity: 50%
- Fuel : Heavy gas oil

Heavy gasoil was chosen as fuel in simulations due to its properties were closest to HFO which was used in excel sheet calculations. Composition of heavy gasoil is shown in figure 4, other user defined simulation parameters which are viewed in above were chosen to correspond normal conditions in typical power plant locations. The physical properties of Heavy gasoil mixture are shown in figure 5.



MIXTURE SUMMARY

Study Folder: Multi component example

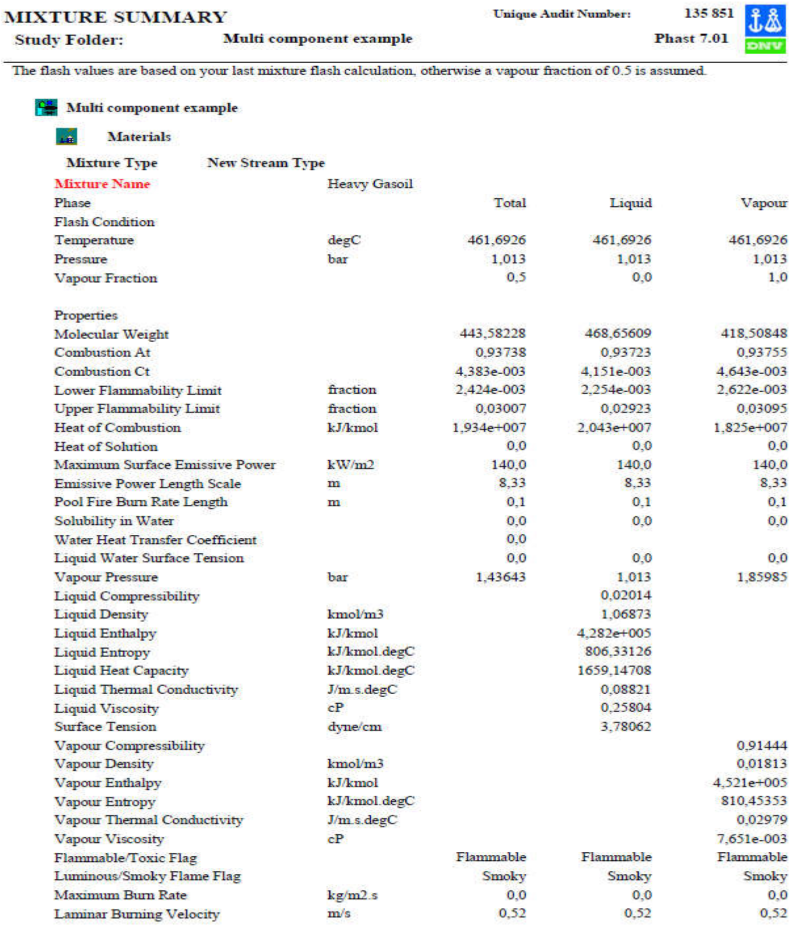
Unique Audit Number: 135 851

Phast 7.01

The flash values are based on your last mixture flash calculation, otherwise a vapour fraction of 0.5 is assumed.

Composition Mole Fractions			
n-TETRADECANE	0,0	0,0	0,0
n-HEXADECANE	0,0	0,0	0,0
n-OCTADECANE	0,0	0,0	0,0
n-EICOSANE	0,0	0,0	0,0
n-DOCOSANE	0,05	0,01705	0,08295
n-TETRACOSANE	0,08	0,03538	0,12462
n-HEXACOSANE	0,1	0,05777	0,14223
n-OCTACOSANE	0,12	0,0867	0,1533
n-TRIACONTANE	0,15	0,133	0,167
n-HEXATRIACONTANE	0,5	0,67011	0,32989

Figure 4. Composition of Heavy gas oil used for simulation.



MIXTURE SUMMARY

Study Folder: Multi component example

Unique Audit Number: 135 851

Phast 7.01

The flash values are based on your last mixture flash calculation, otherwise a vapour fraction of 0.5 is assumed.

Multi component example

Materials

Mixture Type New Stream Type

Mixture Name	Heavy Gasoil			
Phase		Total	Liquid	Vapour
Flash Condition				
Temperature	degC	461,6926	461,6926	461,6926
Pressure	bar	1,013	1,013	1,013
Vapour Fraction		0,5	0,0	1,0
Properties				
Molecular Weight		443,58228	468,65609	418,50848
Combustion At		0,93738	0,93723	0,93755
Combustion Ct		4,383e-003	4,151e-003	4,643e-003
Lower Flammability Limit	fraction	2,424e-003	2,254e-003	2,622e-003
Upper Flammability Limit	fraction	0,03007	0,02923	0,03095
Heat of Combustion	kJ/kmol	1,934e+007	2,043e+007	1,825e+007
Heat of Solution		0,0	0,0	0,0
Maximum Surface Emissive Power	kW/m2	140,0	140,0	140,0
Emissive Power Length Scale	m	8,33	8,33	8,33
Pool Fire Burn Rate Length	m	0,1	0,1	0,1
Solubility in Water		0,0	0,0	0,0
Water Heat Transfer Coefficient		0,0		
Liquid Water Surface Tension		0,0	0,0	0,0
Vapour Pressure	bar	1,43643	1,013	1,85985
Liquid Compressibility			0,02014	
Liquid Density	kmol/m3		1,06873	
Liquid Enthalpy	kJ/kmol		4,282e+005	
Liquid Entropy	kJ/kmol.degC		806,33126	
Liquid Heat Capacity	kJ/kmol.degC		1659,14708	
Liquid Thermal Conductivity	J/m.s.degC		0,08821	
Liquid Viscosity	cP		0,25804	
Surface Tension	dyne/cm		3,78062	
Vapour Compressibility				0,91444
Vapour Density	kmol/m3			0,01813
Vapour Enthalpy	kJ/kmol			4,521e+005
Vapour Entropy	kJ/kmol.degC			810,45353
Vapour Thermal Conductivity	J/m.s.degC			0,02979
Vapour Viscosity	cP			7,651e-003
Flammable/Toxic Flag		Flammable	Flammable	Flammable
Luminous/Smoky Flame Flag		Smoky	Smoky	Smoky
Maximum Burn Rate	kg/m2.s	0,0	0,0	0,0
Laminar Burning Velocity	m/s	0,52	0,52	0,52

Figure 5.Physical properties of Heavy fuel oil (From PHAST database).

4.3. Standard tanks considered for simulations

The considered simulation scenario was full fuel tank on fire under the weather conditions as considered in 4.1. Different standard tanks that are used in power plant installations were used to define pool fire sizes. Different tanks that were used for simulations are shown in Table 8.

Sr. No.	Tank Volume (m^3)	Tank Diameter (m)
1	35	3.0
2	200	6.8
3	500	9
4	1000	11.5
5	2500	16.2
6	4000	19.2
7	10000	30.3
8	50000	45

Table 8.The Standard tanks used for simulations.

4.4. Simulation results

Simulation results are expressed as values of heat flux and relative distance from the centre of fire. Simulation results are viewed in table 9, but for clarification one set of results is interpreted as graphical representation, see figure 6 and figure 7. The graphs are viewing following comparisons:

- Distance Vs Flux
- Pool fire contours in three levels of radiation

4.4.1. Distance Vs Flux

In this form of output, the results are expressed as a graph of Distance in meter from flame centre (in this case tank centre) versus the respective intensity of radiations (expressed in kW/m^2) at that location. It is to be noted that the distances mentioned are for the downwind direction from flame centre, as the distances are less in other directions relative to wind. Figure 6 shows an example of graph for distance versus heat flux, for tank of diameter 3 m.

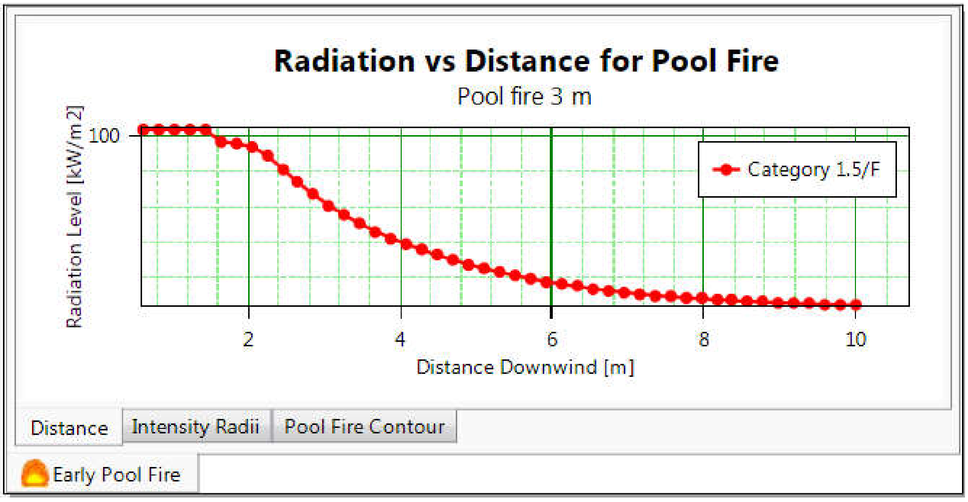


Figure 6 Distance Vs Radiation flux graph (From PHAST).

4.4.2. Pool fire contour

The results are expressed in the form of Distance in meter from flame centre (in this case, tank centre) for specific pre-defined values of heat flux. For PHAST program, the pre-defined values for heat flux are standardised to three different levels; $4kW/m^2$,$12.5kW/m^2$& $37.5kW/m^2$.This gives a rise to contours around the pool fire flame centre for each flux level. Figure 7 shows an example of radiation contours for tank of diameter of 3 m.

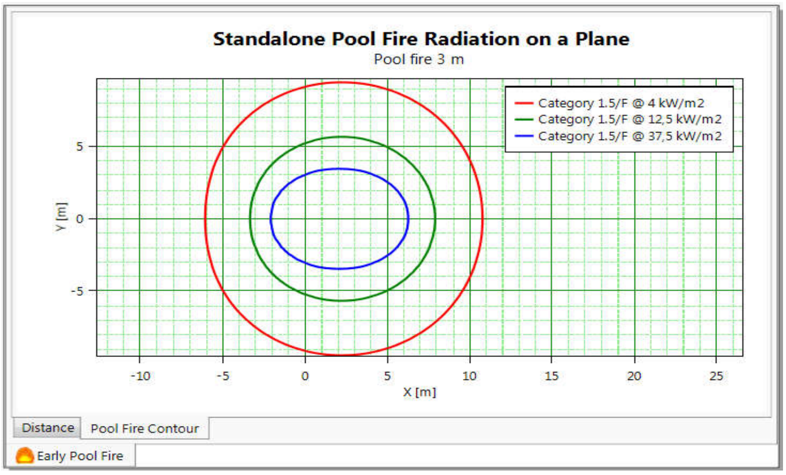


Figure 7Radiation contour for tank of diameter 3 m (From PHAST).

The tank centre is taken as origin (X=0, Y=0) on a plane coordinate system. It is to be noted that the wind direction is taken to be in the positive direction of X-axis. The different level of radiation flux form different elliptical contours around the pool fire centre.

V. COMPARISON OF RESULTS

The results of simulation were compared to those obtained from calculation excel worksheet. The physical properties of heavy gas oil that was obtained from PHAST were used and the calculations were made for three standard flux levels that are used in PHAST program. The results of simulations and calculation excel worksheet were compared and tabulated. Table 9 shows the comparison of results.

Sr. No	Diameter of Tank	Volume of Tank	Distance in meter for different flux level								
			4 kW/m^2			12.5 kW/m^2			37.5 kW/m^2		
			Cal	PHAST	Diffuse	Cal	PHAST	Diffuse	Excel	PHAST	Diffuse
1	3	35	8.0	7.10	1.0	4.5	4.76	-0.2	2.6	3.17	-0.5
2	6.8	200	16.6	12.12	4.5	9.4	7.80	1.6	5.4	3.90	1.5
3	9	500	20.8	13.85	6.9	11.7	9.10	2.6	6.8	4.33	2.5
4	11.5	1000	24.9	16.45	8.5	14.1	11.2	2.8	8.1	7.79	0.3
5	16.2	2500	31.2	20.35	10.9	17.7	13.8	3.8	10.2	8.66	1.5
6	19.2	4000	34.3	21.21	13.1	19.4	14.7	4.7	11.2	7.80	3.4
7	30.3	10000	41.0	28.86	12.2	23.2	18.4	4.8	13.4	11.54	1.9
8	45	50000	42.2	35.36	6.8	32.3	26.0	6.3	18.6	18.86	-0.2

Table 9.Comparison of results between calculations excels worksheets and PHAST simulations.

As shown in the table 9, for each tank size, the values for distances of three standard flux levels were determined with calculation (recorded under the column Excel in Table 9) and by PHAST simulation (recorded under the column PHAST in Table 9). The arithmetic difference between values of calculation excels worksheet and corresponding PHAST simulation were determined (recorded under the column Diff. in Table 9). The values in the Diff column serve as indicator for the deviation between these two methods. The positive values indicate that the values obtained from excel worksheet are of higher magnitude than those of PHAST simulations, while negative values indicate that the values obtained from excel worksheet are of lower magnitude than those of PHAST simulations.The Table 9 shows that the values of Difference column are positive (with few exceptions for flux value of 37.5 kW/m^2, but such a high value of flux is not under consideration when safety distances are to be determined, for example acceptable value for persons was 4.73 kW/m^2 and for buildings 9.46 kW/m^2). This means that the values of distances predicted by excel worksheet are higher magnitude than those of PHAST simulations. Further, it can be noticed that the deviation values are high for the lower values of flux, ranging from 1 to 13.1 meter for flux level of 4 kW/m^2, the deviation values between the two methods decrease as flux values increases.

VI. CONCLUSION& FUTURE SCOPE

The theoretical model used of determining the acceptable safety distances with respect to tank diameter give results in form of parabolic curve, i.e. the value of safety distances increase with increase in tank diameter, reach a maximum value and then decrease. The decreasing portion of safety distance curve is basically due to properties of smoke. When the source of heat is assumed to be in the middle of tank and all the smoke what is produced is then around the heat source blocking the radiation. Wind direction and magnitude is not taken into account in presented calculation philosophy. If that is needed, it would be best to use simulations, where direction and magnitude can be changed easily.The excel worksheets are useful particularly when the site area has area limitations and when some different values of thermal flux are stated by local regulation/client and if simulation tools like PHAST are not available. The results of produced calculation method were verified with fire simulations. Fire simulations were done with program PHAST. Later, those values from excel worksheet and simulations were compared. Comparison results shows that the values of separation distance obtained from simulations are of smaller magnitude than those obtained from calculation excel worksheet. This proves the fact that combustion efficiency is reduced in pool fire scenario and further justifies the application of correction factor F used in calculations. The smaller values predicted by PHAST simulation can be mainly due to PHAST uses complex mathematical models in prediction, consideration of effects of wind, humidity and ambient temperature on the fire dynamics and consideration of effects of smoke on combustion efficiency.Considering the nature of engineering projects, it is not practically feasible to use simulations for project specific cases, considering economical and schedule implications. This leads to need of having relatively simple and user-friendly calculation tool. The calculation excel worksheet developed can serve the purpose, with the excess values predicted by this calculation method considered as safety factor against variation in wind condition and variation of ambient temperature and humidity. The results of calculation excel worksheet can therefore be used for determining the safety separation distances. This gives the designers a firm theoretical backing on which their design can be based, if/when under question by customer/judicial authority or when different flux values are stated by customer/judicial authority.

REFERENCES

1. Abbasi, T., & Abbasi, S. A. (2007a). Accidental risk of superheated liquids and a framework for predicting the superheat limit. Journal of Loss Prevention in the Process Industries, 20, 165-181.
2. Abbasi, T., Pasman, H. J., & Abbasi, S. A. (2010). A scheme for the classification of explosions in the chemical process industry. Journal of Hazardous Materials, 174, 270-280.
3. Zhang Miao et al. / Procedia Engineering 84 (2014) 565 – 577 577
4. S. Vasanth, S.M. Tauseef, Tasneem Abbasi, and S.A. Abbasi (2014). Multiple pool fires: Occurrence, simulation, modeling and management Journal of Loss Prevention in the Process Industries, 29, 103-121.
5. A. Hamins, Flame Extinction by Sodium Bicarbonate Powder in a Cup Burner, Proc. Combust. Inst. 27 (2), 2857ದ2864 (1998).
6. E. Planas-Cuchi and J. Casal, Flame Tempreture Distribution in a Poll-Fire, J. Hazard. Mater. 62 (3), 231ದ241 (1998).
7. Radiation from large pool fires. Publication of National Institute of Standards and Technology 6546.
8. ANSI/API STANDARD 521. 2007. Pressure-relieving and Depressuring Systems, Fifth Edition.
9. Society of Fire Protection Engineers. 1999. Engineering Guide for AssessingFlame Radiation to External Targets from Pool Fires. Bethesda, Maryland.
10. Stoll, A. M. and Greene, L. C. 1958. The Production of Burns by Thermal Radiation of Medium Intensity, Paper Number 58-A-219. American Society of Mechanical Engineers, New York.
11. Hajek, J. D. and Ludwig, E. E. 1960. How to Design Safe Flare Stacks, Part 1, Petro/Chem Engineer. Volume 32, Number 6; Part 2, Petro/Chem Engineer, Volume 32, Number /.
12. Buettner, J. K. J. 1957. Heat Transfer and Safe Exposure Time for Man in Extreme Thermal Environment, Paper Number 57-SA-20,
13. Modak, A. T. 1977. Thermal radiation from pool fires. Combustion and Flame
14. SFPE Handbook, chapter Burning Rates. National Fire Protection Association, Quincy, Massachusetts, 2nd edition, 199
15. Fleury, Rob. 2010. Evaluation of Thermal Radiation Models for Fire Spread Between Objects. Master thesis of Fire Engineering degree, in University of Canterbury, Chrisrchurch, New Zealand.

16. Thermal radiation from large pool fires by Mcgrattan, Kevin, B., Baum, Howard, R. and Hamins, Anthony. 2000, Publication of National Institute of Standards and Technology- 6546.