DESIGN FACTORS FOR LAYOUT AND SPACING OF STORAGE TANKS IN OIL AND GAS INSTALLATIONS USING THERMAL RADIATION MODELS

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ABSTRACT

Storage tanks facilities in chemical industries or any petroleum installations is increasing gradually where the violation of safety considerations with respect to layout and spacing between the tanks in a tank farm and other process facilities, occupied buildings will have a major impact. Tanks handling huge quantities of fuel oils like crude oil, gasoline etc.., have various standards and requirements for calculating the safe distances between storage tanks with specific considerations where providing these standards and codes will not be able to restrict the fire accidents from happening such as Pool fires/ Tank fires, Jet fires and leaks.

The main idea of this project is to provide an overview of safety considerations in layouts and spacing for storage tank facilities by determining the safe inter tank distances in case of pool fire/tank fire through thermal radiation models available in literature.

Keywords: *pool fire/Tank fire, layout, spacing, thermal radiation*

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Chapter 1

Introduction

1.1 General

Safety is number one priority in the chemical industry. Its importance is globally acknowledged specially due to recent significant chemical accidents, increases in public awareness and skyrocketing liability and accident costs. Among various chemical industrial sites, tank farms have been targets of more catastrophic events. A storage tank farm (sometimes called an oil depot, installation or oil terminal) is an industrial facility for the storage of oil and/or petrochemical products where these products are transported to the end users or further storage facilities. A tank farm typically includes tanks, either above ground or underground, and gantries for discharging products into the road tankers or other vehicles (such as barges) or pipelines. The major hazards in the storage tanks are fire, explosion, spill and toxic release. Among them, fire is the most common but explosion is particularly significant in terms of fatalities and loss. The below table reviewed 242 accidents in the storage tanks from 1960 to 2003 and found that fires and explosion together accounted for 85% of total cases. Oil spill and toxic gas/liquid release were the third and the fourth most frequent, respectively.

Table 1.1 shows the types and frequency of accidents in the storage tanks since 1960 to 2003.

TYPES AND FREQUENCY OF ACCIDENT IN THE STORAGE TANKS

Year	Fire	Explosion	Spill	Toxic gas Release
1960- 1969	8	8	0	0
1970-1979	26	5	5	0
1980-1989	31	16	3	2
1990-1999	59	22	2	1
2000-2003	21	10	8	10
Subtotal	145	61	18	13

Table 1.1 Frequency of accidents in storage tank facilities

The safety aspects apart from periodic maintenance are extremely important. The recent accident of Jaipur oil depot where twelve tankers containing 10^5 KL of diesel and gasoline caught fire, creating severe environmental pollution which shows the importance of proper layout with safe separation distance to prevent such hazardous accidents.

This project deals with various models available in literature to determine safe inter tank distance which provides an optimal layout for storage tanks and important Parameters used for explaining the project are explained in the definition section.

In this project a case study is presented to show the importance of layouts for storage tanks and spacing between them.

At the end of this of this report specific methodology is applied for calculating the thermal radiation in case of a pool fire and determined the safe inter tank distance.

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1.2 Aim of the Project

The aim of the project is to explain various design factors considered in layouts and spacing of storage tank facilities by using thermal radiation models.

1.3 Objective of the Project

The Objective of the project is to estimate the thermal radiations for pool fire/ tank fires by using Shokri Beyler's methodology available in literature by considering both wind free and in the presence of wind conditions.

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1.4 Definitions

- **Plot Plan**

A plot plan is an architecture, engineering, and/or landscape architecture plan drawing - diagram which shows the buildings, utility runs, and equipment layout, the position of roads, and other constructions of an existing or proposed project site at a defined scale

- **Tank Farm**

Tank Farm is an oil depot, a facility for storage of liquid petroleum products of petrochemicals

- **Bund wall**

It is a constructed retaining wall designed to prevent inundation or breaches from a known source. It is a secondary containment system commonly used to protect environments from spills where chemicals are stored.

- **Heat Flux**

Heat flux is defined as the amount of heat transferred per unit area per unit time from or to a surface. In a basic sense it is a derived quantity since it involves, in principle, two quantities viz. the amount of heat transfer per unit time and the area from/to which this heat transfer takes place.

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- **Heat of Combustion**

It is the energy released as heat when a compound undergoes complete combustion with oxygen under standard conditions. The chemical reaction is typically a hydrocarbon reacting with oxygen to form carbon dioxide, water and heat.

- **Vapor Pressure**

It is defined as the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phases (solid or liquid) at a given temperature in a closed system. The equilibrium vapor pressure is an indication of a liquid's evaporation rate.

- **Auto Ignition Temperature**

Auto-ignition temperature is the minimum temperature required to initiate self-sustained combustion in a substance without any apparent source of ignition (spark or flame). The substance may be solid, liquid or gaseous. Thus auto ignition is the ignition of a combustible material without initiation by any external agency like a spark or flame - when the material has been raised to the auto ignition temperature.

- **Jet Fire**

A jet or spray fire is a turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction or directions. Jet fires can arise from releases of gaseous, flashing liquid (two phase) and pure liquid inventories.

- **Tank Fire**

Oil is stored in floating roof tank. Leak in rim seal leading to accumulation of vapor is a source of fire. Lighting can be a source of ignition and can cause tank fire. Overflow from tank leading to spillage may cause vapor cloud formation, this can catch fire and it can flash back to the tank to cause tank fire.

- **Pool Fire**

A pool fire is a turbulent diffusion fire burning above a horizontal pool of vaporizing hydrocarbon fuel where the fuel has zero or low initial momentum.

- **BLEVE**

A boiling liquid expanding vapor explosion (BLEVE) is an explosion caused by the rupture of a vessel containing a pressurized liquid above its boiling point

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Chapter 2

Background

2.1 Case Study

The Buncefield oil storage and transfer depot is a tank farm in Hemel Hempstead, Hertfordshire, England, close to Junction 8 of the M1 motorway. In December 2005 there were three operating sites at the depot:

- Hertfordshire Oil Storage Ltd (HOSL), a joint venture between Total UK Ltd and Chevron Ltd and under the day-to-day management of Total UK Ltd. HOSL (the site) was divided into East and West sites:
- British Pipeline Agency Ltd (BPA), a joint venture between BP Oil and Shell Oil UK, though assets were owned by UK Oil Pipelines Ltd (UKOP). This tank farm was also in two parts, the north section and the main section which was located between HOSL East and West;
- BP Oil UK Ltd, at the southern end of the depot.
- On the night of Saturday 10 December 2005, Tank 912 at the Hertfordshire Oil Storage Limited (HOSL) part of the Buncefield oil storage depot was filling with petrol. The tank had two forms of level control: a gauge that enabled the employees to monitor the filling operation; and an independent high-level switch (IHLS) which was meant to close down operations automatically if the tank was overfilled. The first gauge stuck and the IHLS was inoperable – there was therefore no means to alert the control room staff that the tank was filling to dangerous levels. Eventually large quantities of petrol overflowed from the top of the tank. A vapour cloud formed which ignited causing a massive explosion and a fire that lasted five days.
- Having failed to contain the petrol, there was reliance on a bund retaining wall around the tank (secondary containment) and a system of drains and catchment areas (tertiary containment) to ensure that liquids could not be released to the environment. Both forms of containment failed. Pollutants from fuel and firefighting liquids leaked from the bund, flowed off site and entered the groundwater. These containment systems were inadequately designed and maintained.
- Failures of design and maintenance in both overfill protection systems and liquid containment systems were the technical causes of the initial explosion and the

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seepage of pollutants to the environment in its aftermath. However, underlying these immediate failings lay root causes based in broader management failings.

- The fire lasted five days and large quantities of water and firefighting foam were used to bring the blaze under control. Fuel, water and foam spilled from leaking bunds formed a large pool of liquid to the east of BPA Tank 12. Liquids subsequently flowed down Cherry Tree Lane, past the roundabout into Hogg End Lane and as far the M1 motorway bridge, several hundred metres away.
- The adjacent area contained a number of drains and soak ways that the site operators had not identified and liquids were able to penetrate into the soil beneath them. The pollutants in this liquid run off consisted of PFOS (perfluorooctane sulphonate) from the foam, and hydrocarbons such as benzene and xylene. These pollutants have entered the chalk stratum below the site which is an aquifer from which potable water is extracted. The contamination close to the site did not affect drinking water supplies but the long-term possibility of pollution remains. The Environment Agency has a monitoring programme to check on the level of pollutants in the aquifer.

Figure 2.1 Aerial view of the Buncefield depot before the incident

Figure 2.2 Aerial view of the Buncefield after the incident

- Figure 1 and Figure 2 shows that lots of these accidents had occurred and they are likely to continue unless the lessons from the past are correctly learnt with respect to layout and spacing and other safety concerns.

2.2 Design Approach Methodology

After studying the content in the above case study and also the literature review mentioned in the following chapter, design approach is then established. The scenario consists of major fire that is Tank fire/Pool fire.

The Incident heat flux is calculated while determining the flame height, pool size, view factors, heat release rate, and tilt angle in the view of no wind condition and in presence of wind by using shokri beyler co-relation which is available in literature.

Chapter 3
Literature Review

3.1 Literature survey

1. A. Sengupta, I. M. Mishra* (2011) Department of Chemical Engineering from Indian Institute of Technology Roorkee have modified the point source model by introducing the wind speed in the engineering layout of fuel tanks in tank farms.

Publication: "Engineering layout of fuel tanks in a tank farm". Journal of Loss Prevention in the Process Industries 24, 568-574, 2011 [1].

2. Moosa Haji Abbasi, Emad Benhelal, Arshad Ahmad (2014) determined the optimal layout for a storage tank contains different type of hydrocarbon fuels. A quantitative risk assessment is carried out on a selected tank farm in Jaipur, India, with particular attention given to both the consequence modeling and the overall risk assessment using PHAST Software.

Publication: “Designing an Optimal Safe Layout for a Fuel Storage Tanks Farm: Case Study of Jaipur Oil Depot” - International Journal of Chemical, Nuclear, Metallurgical and Materials Engineering Vol: 8 No: 2, 2014.

3. James I. Changa,* (2005) Department of safety, Health and Environmental Engineering Taiwan. This paper reviews 242 accidents of storage tanks that occurred in industrial facilities over last 40 years. Fishbone Diagram is applied to analyze the causes that lead to accidents. Corrective actions are also provided.

Publication: “A study of storage tank accidents” - Journal of Loss Prevention in the Process Industries 19 (2006) 51–59

5. Gunnar Heskestad (1984) Factory Mutual Research Corporation, 1151 Boston-Providence Turnpike, Norwood, MA 02062 (U.S.A.). This paper presents a number of engineering relations drawn from the literature for calculating properties of fire plumes. Plume properties considered include flame heights, temperatures, velocities, concentrations of combustion products, and entrainment rates of air from the surroundings. In addition, a brief discussion is presented on the effect of fire growth to demonstrate the validity of the relations set forth.

Publication: “Engineering Relations for Fire Plumes” Fire Safety Journal, 7 (1984) 25 – 32

6. E. Ufuah and C. G. Bailey (2011) This Paper deals with the fundamental subject of fire research with problems involving hydrocarbon pool fires focuses on thermal radiation from the flame surface. The object is to establish the temperature and heat flux profiles, and assess the hazard consequences that may arise from these fire actions.

Publication: "Flame Radiation Characteristics of Open Hydrocarbon Pool Fires" - World Congress on Engineering 2011 Volume III WCE 2011, July 6 - 8, 2011, London, U.K.

3.2 Overview of Storage Tanks

Storage tanks had been widely used in many industrial established particularly in the processing plant such as oil refinery and petrochemical industry. They are used to store a multitude of different products. They come in a range of sizes from small to truly gigantic, product stored range from raw material to finished products, from gases to liquids, solid and mixture thereof. There are a wide variety of storage tanks and they can be constructed above ground, in ground and below ground. In shape, they can be in vertical cylindrical, horizontal cylindrical, spherical or rectangular form, but vertical cylindrical are the most usual used. In a vertical cylindrical storage tank, it is further broken down into various types, including the open top tank, fixed roof tank, external floating roof and internal floating roof tank. The type of storage tank used for specified product is principally determined by safety and environmental requirement.

Operation cost and cost effectiveness are the main factors in selecting the type of storage tank. Design and safety concern has come to a great concern as reported case of fires and explosion for the storage tank has been increasing over the years and these accident cause injuries and fatalities. Spills and tank fires not only causing environment pollution, there would also be severe financial consequences and significant impact on the future business due to the industry reputation.

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3.3 Classification of Storage Tanks

- Below figure illustrates the classification of storage tanks.

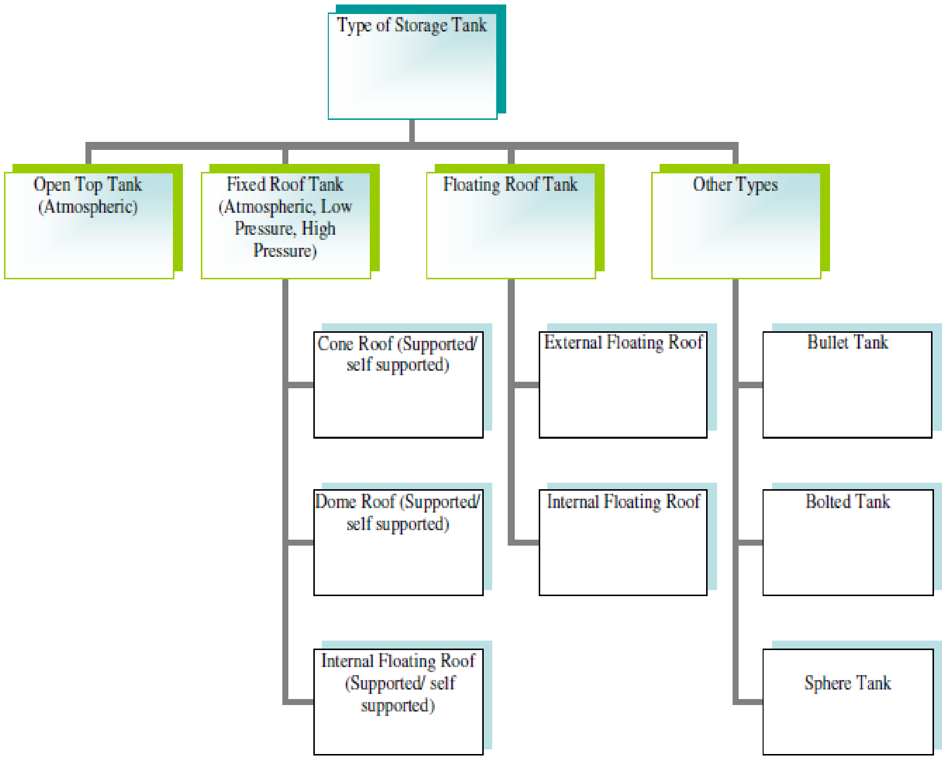

Figure 3.1 Types of storage tank

3.3.1 Open Top Tank

This type of tank has no roof. They shall not be used for petroleum product but may be used for fire water/ cooling water. The product is open to the atmosphere; hence it is an atmospheric tank.

3.3.2 Fixed Roof Tank

Fixed Roof Tanks can be divided into cone roof and dome roof types. They can be self-supported or rafter/ trusses supported depending on the size.

Fixed Roof are designed as

1. Atmospheric tank (free vent)
2. Low pressure tanks (approx. 20 mbar of internal pressure)
3. High pressure tanks (approx. 56 mbar of internal pressure)

3.3.3 Floating Roof Tank

Floating roof tanks is which the roof floats directly on top of the product.

There are 2 types of floating roof:

1. **Internal floating roof** is where the roof floats on the product in a fixed roof tank.
2. **External Floating roof** is where the roof floats on the product in an open tank and the roof is open to atmosphere.

Types of external floating roof consist of:

i. Single Deck Pontoon type
ii. Double deck
iii. Special buoy and radially reinforced roofs

3.4 Standards and Codes

The design and construction of the storage tanks are bounded and regulated by various codes and standards. List a few here, they are:

- American Standards API 650 (Welded Steel Tanks for Oil Storage)
- British Standards BS 2654 (Manufacture of Vertical Storage Tanks with Buttwelded Shells for the Petroleum Industry.
- Company standards such as shell (DEP) and Petronas (PTS)

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3.5 Floating Roof Storage Tank

3.5.1 History and Introduction

Floating roof tank was developed shortly after World War I by Chicago Bridge & Iron Company (CB & I). Evaporation of the product in fixed roof caused a great lost of money; this led to research to develop a roof that can float directly on the surface of product, reducing the evaporation losses.

3.5.2 Principle of Floating Storage Tank

- The floating roof is a circular steel structure provided with a built-in buoyancy which allowing it to sit/ float on top of the liquid product in a close or open top tank.
- The overall diameter of the roof is normally 400 mm smaller than the inside diameter of the tank, which has about 200 mm gap on each side between the roof and the inside tank wall. This is due to the limitation on the accuracy of dimension during construction for the large diameter tank. The gaps allow the floating roof to

rise and fall without binding on the tank wall. To protect the product inside the tank from evaporation to the atmosphere and contamination from the rain water through the gaps between the outer rim of the floating roof and the tank wall, the gaps will be closed or sealed up by mean of flexible sealing system.

- Due to environmental issue, selection of the roof seal is one of the major concerns in the floating roof tank design.
- In single deck roof which also called pontoon roof, the buoyancy is derived in the pontoon, an annular circular pontoon radially divided into liquid tight compartments. The center deck which is formed by membrane of thin steel plates are lap welded together and connected to the inner rim of the pontoons.
- Double deck roof (Figure 4) consists of upper and lower steel membranes separated by a series of circumferential bulkhead which is subdivided by radial bulkhead. The outer ring of the compartments is the main liquid tight buoyancy for the roof.
- Double deck roof is much heavier than single deck one, hence it is more rigid. The air gap between the upper and bottom plates of the deck has insulation effect which helps against the solar heat reaching the product during the hot climate and preventing heat loss of the product during cold climate.

3.5.3 Advantages of Floating Roof Tank

As the roof floats directly on the product, there is no vapor space and thus eliminating any possibility of flammable atmosphere. It reduces evaporation losses and hence reduction in air pollution. Vapor emission is only possible from the rim seal area and this would mainly depend on the type of seal selected and used. Despite of the advantages of the floating roof, to design and construct a floating roof tank will be much more complicated and costly than the fixed ones. In term of tank stability and design integrity, floating roof tank is never better than the fixed roof tank as there are still many unknown parameters and factors in designing the floating roof.

Chapter 4
Layout design of storage tanks

4.1 Design Philosophy

Following philosophy should be adopted in layout of an installation:

a) Risk Analysis / Assessment shall be carried out at the layout stage with an objective to arrive at any specific mitigation measures required for Hazards identified. Risk reduction / mitigation measures shall be given due credit. Risk assessment shall include unconfined Vapour cloud explosion (UVCE). The outcome shall guide in preparation of onsite off site emergency plan. Quantitative Risk Assessment (QRA) shall be done when ever major addition(s) in facilities or major changes in the surrounding areas, operating parameters, product grade takes place or once in every five years whichever is earlier.

b) Two road approaches from the highway / major road should be provided, one for normal movement and other for emergency exit. Both these approaches should be available for receipt of assistance in emergency.

c) Roads inside the hazardous area of Installation shall be restricted to vehicles required for operational, maintenance and safety/security reasons and allowed only with proper safety fittings and authorization from location in-charge/designated safety officer.

d) Alternative access shall be provided for each facility so that it can be approached for firefighting in the event of blockage on one route.

e) Road widths, gradient and turning radii at road junctions shall be designed to facilitate movement of the largest fire-fighting vehicle envisaged in the event of emergency.

f) Layout shall consider the space requirements for

- Maintenance and inspection of each equipment / facility.
- Future expansion for addition of facilities.

g) Vehicles with spark ignition engine shall not be allowed inside hazardous area. Vehicles with internal combustion engine (compression ignition) such as tank truck (fuelled by HSD) required to be permitted for business shall have PESO approved spark arrestor fitted on the vehicle.

4.2 Layout Facilities

To prepare a layout, information should be collected on the all the applicable affecting aspects and not limiting to following

- Storage tanks, utility requirements.
- Product receipt / dispatch and mode of transport (rail, road and pipeline).
- Warehouses, storage areas for bitumen / asphalt, lube etc and other open storage areas like scrap yards and dumping ground.
- Chemicals / Toxic chemicals storage, Sludge, hazardous waste storage / disposal facilities etc.
- Service buildings, fire station and allied facilities.
- Site topography including elevation, slop, and drainage.
- Meteorological data.
- Approach roads for functional areas.
- Aviation considerations to and from adjacent facilities.
- Environmental considerations.
- Statutory requirements.

a) Petroleum storage tanks shall be located in dyked enclosures. Each dyke shall have roads all around for access for normal operation and maintenance as well as for emergency handling. Aggregate capacity (Combined safe capacity) of tanks located in one dyked enclosure shall not exceed following values

- 60,000 cum. for a group of fixed roof tanks.
- 120,000 cum. for a group of floating roof tanks

Fixed cum floating roof tanks shall be treated as fixed roof tanks. However in case these tanks are provided with windows opening on the shell and these windows will not get blocked in any case, then these should be considered as floating roof tanks. If a group of tanks contains both fixed and floating roof tanks, then it shall be treated as a group of fixed roof tanks for the purpose of above limits.

b) Dyked enclosure shall be able to contain the complete contents of the largest tank in the dyke in case of any emergency. A free board of 200 mm above the calculated liquid level or 10% of calculated dyke capacity whichever is higher shall be provided for fixing the height and capacity of the dyke. Enclosure capacity shall be calculated after deducting the following volumes

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- Volume of the tanks other than largest tank up to enclosure height without free board.
- Volume of all tank pads.
- Volumes of fire break walls.
- Volume of pipes/supports/steps etc.

The height of tank enclosure dyke (including free board) shall be at least 1.0 m and shall not be more than 2.0 m above average inside grade level. The dyke wall made up of earth, concrete or solid masonry shall be designed to withstand the hydrostatic load and shall be impervious. Earthen dyke wall shall have not less than 0.6 meter wide flat section on top for stability of the dyke wall. Dyke enclosure area (inside area of the dyke) shall be also impervious to prevent the ground water pollution.

c) The dyke and the enclosures will be inspected for cracks, visible damage etc. every six months (pre and post monsoons) and after every major repair in the tanks / dykes etc. so as to keep it impervious. Piping thru' dyke wall if any shall be properly sealed to make dyke impervious. The dyke area shall have proper slope outward of tank pad towards the inner periphery of the dyke enclosure to prevent reverse flow.

d) Earth-pits shall be provided outside of Dyke area and strips buried under the earth except at termination points from a shortest possible distance. The earthing lay out diagram of each facility shall be displayed near each facility for reference.

e) For excluded petroleum, the capacity of the dyked enclosure should be based on spill containment and not for containment on tank rupture. The minimum height of dyke wall in case of excluded petroleum shall be 600 mm.

f) Pump stations and piping manifold should be located outside dyke areas by the side of roads.

g) Horizontal above ground tanks mounted on pedestals shall meet separation distances and shall have dyked enclosure.

4.3 Grouping of Storage tanks

a) Grouping of tanks in a dyke: Storage tanks should be grouped in a dedicated dyke according to their respective classification of petroleum product.

b) In case, different class of products are stored in any combination of product classification, the following shall, be applicable.

- When classes A, B and/or C are stored together, all the provisions of class A shall be applicable.

- When class A & B are stored together, all the provisions of class A shall be applicable.
- When class B &C are stored together, all the provisions of class B shall be applicable.

c) Excluded petroleum shall be stored in a separate dyked enclosure and shall not be stored along with Class-A, Class-B or Class-C petroleum.

d) Tanks shall be arranged in maximum two rows so that each tank is approachable from the road surrounding the enclosure. This stipulation need not be applied to tanks storing excluded petroleum class.

e) Tanks having 50,000 cum capacity and above shall be laid in single row.

f) Tertiary containment: Provision shall be made for Tertiary containment. The objective of Tertiary containment is to prevent escape of spills due to failure of secondary containment for any reasons and will not allow such spill over to outside of the boundary of the installation that may lead to any damage to outside. All the drain openings shall be controlled through sluice gates. Efforts should be made to minimize such opening/s for drainage.

4.4 Fire walls inside dyke enclosure

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a) In a dyked enclosure where more than one tank is located, firewalls of minimum height 600mm shall be provided to prevent spills from one tank endangering any other tank in the same enclosure.

b) A group of small tanks each not exceeding 9 meters in diameter and in all not exceeding 5,000 cum in capacity shall be treated as one tank for the provision of firewall.

c) For excluded petroleum product storage, firewall of height not less than 300 mm shall be provided by limiting the number of tanks to 10 or the capacity of group of tanks to 5,000 cum whichever is lower.

4.5 General

a) The tank height shall not exceed one and half times the diameter of the tank or 20 m whichever is less.

b) All Piping from / to any tank including connected sprinkler / foam line shall comply the following:

i) Shall not pass through any other dyked enclosure.

ii) Shall run directly to outside of dyke to minimise piping within the enclosures.

iii) Shall not pass through other tank areas / fire walls.

Piping design inside tank dyke area should ensure easy accessibility for any operations in the tank farm. Elevated Catwalks above the height of the dyke wall shall be provided for safe access and exit in case of normal / emergency situations. The catwalks shall run at the same level and terminate directly outside the dyke.

c) No part of the dyked enclosure shall be below the level of surrounding ground within the hazardous area.

d) The minimum distance between a tank shell and the inside toe of the dyke wall shall not be less than half the height of the tank.

e) Properly laid out road shall be provided for easy access on all four sides of each dyke.

4.6 Protection of facilities

a) Properly laid out roads around various facilities shall be provided within the depot/terminal for smooth access of fire tenders etc. in case of emergency.

b) The boundary wall shall be constructed as per the directives of the Ministry of Home Affairs or any other Government directive. In any case the boundary wall shall be of minimum 3m height with V/U shaped barbed wire fencing on the wall with 600 mm diameter concertina coil on top.

c) There shall be a pedestrian patrolling track along the inside perimeter of the boundary wall for security patrolling. Security watchmen tower (if provided) shall have clear access.

d) The emergency gate shall be away from the main gate for evacuation of vehicles and personnel in emergency and shall always be kept available and free from obstruction.

e) CCTV shall be installed in depot/terminal locations covering entry/exit gate, periphery of installation and all critical operating areas which shall be monitored continuously. The CCTV monitoring station shall be provided in control room, Security cabin and in-charge room.

f) Proper sized TT parking area based on fleet size shall be provided with following facilities:

- Well laid out hydrant system with alternate double headed hydrant post and water or water cum foam monitors covering the parking area.

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- Segregation of parking area thru’ chain link fence/boundary wall
- Separate entry and exit gate with access control.
- Parking lane demarcation & quick evacuation in emergency.

g) Hydrocarbon (HC) detectors shall be installed near all potential leak sources of class “A” petroleum products e.g tank dykes, tank manifolds, pump house manifold. These detectors shall be placed in a way that entire possible source of leaks and collection of products is continuously detected and alarm is set at 20% of lower explosive limit of class A.

4.7. Separation distances

a) Minimum separation distances between various facilities described above shall be as per Table-1. The table shall be read in conjunction with the notes specified with the table.

b) The layout shall also take into account findings/recommendations Risk Analysis / Assessment study, which shall be carried out at all the stages of facility development process.

Separation Distances between tanks / offsite facilities

The following stipulations shall apply for the separation distances for above ground tanks storing petroleum products.

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c) For larger installation, minimum separation distances shall be as specified in Annexure- 1. The tables are applicable where total storage capacity for Class-A and Class-B petroleum products is more than 5000 cum or the diameter of Class-A or Class-B product tank is more than 9 meters.

d) For smaller installation, minimum separation distances shall be as specified in Annexure- 2. This table is applicable where total storage capacity of Class-A & Class-B is less than 5000 cum and diameter of any tank storing Class-A and Class-B petroleum product does not exceed 9 meters. Annexure- 3shall also be applicable for the installation storing only Class-C petroleum.

e) Excluded petroleum should be treated as Class-C petroleum for the purpose of separation distances and Annexure- 3 shall be applicable for their separation distances.

f) Separation distances between the nearest tanks located in separate dykes shall not be less than the diameter of the larger of the two tanks or 30 meters, whichever is more.

4.8 Thermal Radiation Model

4.8.1 Overview of Thermal Radiation

The three basic modes of heat transfer, namely conduction, convection and radiation, are involved in almost all fire scenarios. It is observed that one mode dominates at different stages of fire growth or in different locations. For example, conduction is of high importance when trying to determine the expected temperature of a structural element during a fire. It is radiation; however, that is the dominant mode of heat transfer for the spread of flames within compartments (Karlsson & Quintiere, 2000). It is the mechanism by which items at a distance from a fire are heated up, which can lead to ignition without direct flame contact. For these reasons, this thesis investigates thermal radiation only and is not concerned with convective or conductive heat transfer.

Thermal radiation is emitted from tiny soot particles which are present in nearly all diffusion flames (Drysdale, 1999). It is these soot particles which give the flame its characteristic yellow luminosity.

Emissive power and emissivity

The total emissive power of a flame is a function of temperature and wavelength, as described by Planck's Law, given in many radiation references such as Siegel and Howell (1992). Here, the emissive power is for an ideal radiator, known as a 'black body'. However, real surfaces are not ideal radiators and therefore have an emissive power, E, less than that for a black body. The fraction of radiation emitted in relation to the maximum possible emission from a surface is called the emissivity, (Karlsson & Quintiere, 2000). Therefore, a black body has an emissivity equal to unity.

The total radiation emitted, E, per unit area from a grey surface is given by Equation 4.1

$$E = £\sigma T_f^{\ 4} \tag{4.1}$$

Where is the emissivity, σ is the Stefan-Boltzmann constant (5.67 × 10-8 W/m2K4) and T_f represents the flame temperature (K). E can also be termed the emissive power of the flame.

Configuration factors

The above equation can be used to calculate the radiative heat loss from a surface.

However, if one wishes to know the rate of heat transfer to a nearby object, the amount energy being radiated in that particular direction must be calculated. This can be done using Equation 4.2, which introduces the concept of a configuration factor.

$$q'' = F_{1-2}\sigma £ Tf^{4} \tag{4.2}$$

Where q" is the radiant heat flux (kW/m^2) and F_{12} is the configuration factor. This factor takes into account the geometrical relationship between the emitter and the receiver. Configuration factors (also known as shape or view factors) have a value between zero and one. For example, when the receiver is very close to the flame and oriented so that it is facing the fire, the configuration factor approaches one, as everything viewed by the receiver is the flame (Iqbal & Salley, 2004). Davis and Bagster (1989) explain that the configuration factor is dependent on three variables:

- The geometry of the emitter and receiver
- Whether the emitter and receiver can be 'viewed' by each other
- The direction of the exchange of thermal radiation

In this work, the configuration factor is determined for radiant energy exchange between a finite surface (the flame) and a differential element at some distance from the flame. The configuration factor is dependent on the dimensions of the finite surface and the distance and angle between the emitter and target. Usually an assumption is made whereby the flame is approximated as a simple shape such as a rectangle or cylinder, which enables calculation of the configuration factor using established equations. Assuming that the flame takes on the shape of a cylinder or rectangle is far from an exact reproduction of the observed geometry. However, due to the rapid fluctuation of the flame shape with time, calculating an accurate configuration factor from the fire to a target would be an extremely complicated and time intensive process.

4.8.2 General Approach to Thermal Radiation Modeling

Beyler (2002) describes the three major steps involved in estimating the thermal radiation field surrounding a fire:

1. Determine the geometric characteristics of the fire, including the burning rate and the physical dimensions of the fire. These dimensions are based on time-averaged values.
2. Characterise the radiative properties of the fire. This involves the

determination of the average emissive power of the flames.

3. Calculate the incident radiant heat flux at the target location. For this to be carried out, steps 1 and 2 must have been completed, as well as knowing the location, geometry and orientation of the receiver.

The radiation models described in the following section use these three steps to varying degrees of accuracy.

4.8.3 Shokri and Beyler Radiation Models

The primary aim of radiation modeling usually is to calculate safe separation distances between fire sources and potential targets that could be damaged or ignited by radiation from the fire. These models range in the level of detail and rigour and some are more suitable for certain applications than others. Some methods are most appropriate for crude initial hazard assessments, while others are capable of more accurate predictions, although more effort is required. The following sections outline a number of thermal radiation models that are available in the literature.

4.8.4 Shokri and Beyler Detailed correlation - Solid Flame Radiation Model with Target At and Above Ground Level in wind free condition

Shokri and Beyler (1989) developed a simple correlation based on experimental data from large-scale pool fire experiments. This method calculates the radiant heat flux at ground level as a function of the radial position of a vertical target. Note that the term ‘ground level’ is loosely used to represent the height of the base of the fire.

The basis of the model is to provide a simple yet realistic model of the flame. To achieve this, the flame is assumed to be a cylindrical, black-body, homogeneous radiator with an average emissive power. It is assumed that thermal radiation is emitted from the surface of the cylinder and that radiation from non-visible gases is negligible (Iqbal & Salley, 2004).

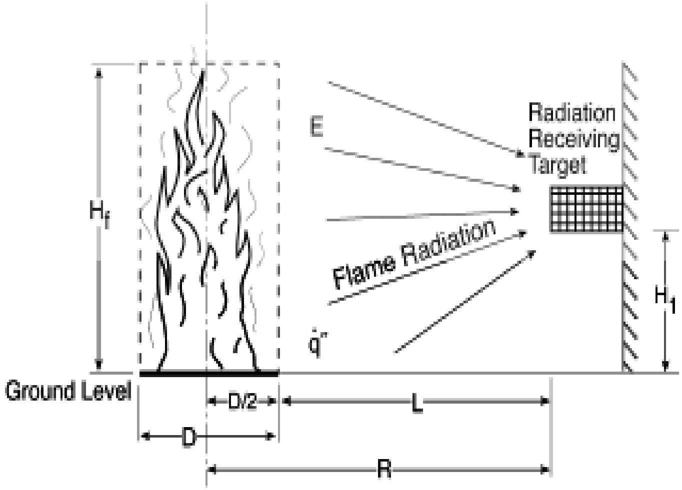

Figure 4.1 Solid Flame Radiation Model with No Wind and Target at Ground Level

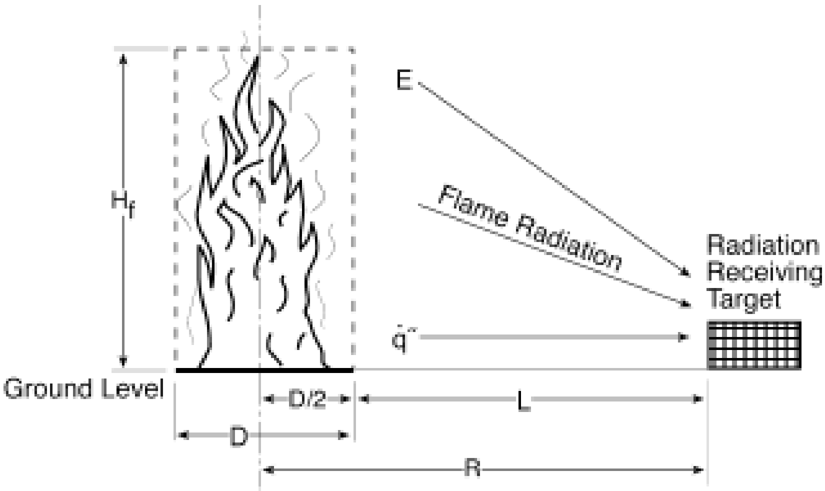

Figure 4.2 Solid Flame Radiation Model with No Wind and Target above Ground Level

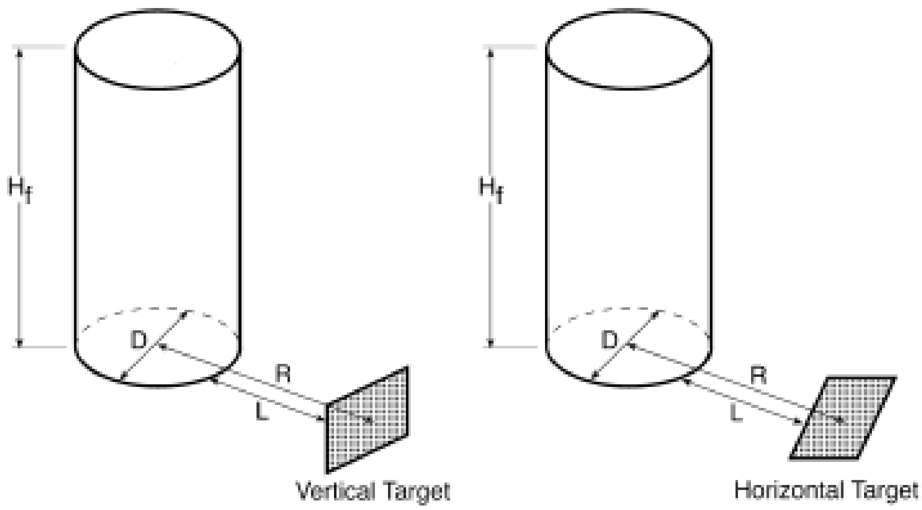

Figure 4.3 Cylindrical flame shape configuration factor geometry for vertical and horizontal targets at ground level with no wind (Beyler, 2002)

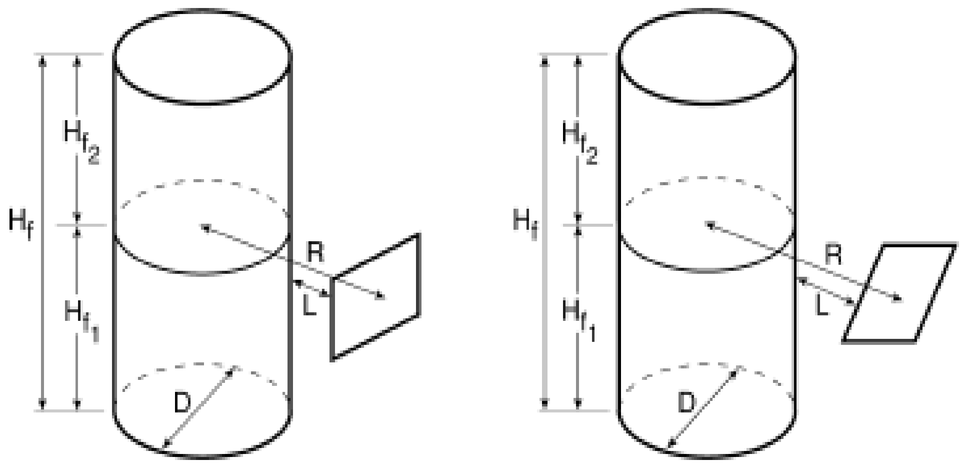

Figure 4.4 Cylindrical flame shape configuration factor geometry for vertical and horizontal targets above ground level with no wind (Beyler, 2002)

Like many fire radiation models, this method was developed using pool fire radiation data ground level (Beyler, 2002)

The incident radiative flux to a target outside the flame is given by Equation.

$$q'' = EF_{12} \quad (4.3)$$

where

q” is radiant heat flux (kW/m2)

E is emissive power (kW/m2)

F_{12} is radiation view (configuration) factor between the target and the flame (0 < F12 < 1)

The configuration factor is a function of the target location and the flame height and diameter. F_{12} always takes a value between zero and one, depending on these factors.

Pool Size

Once sustained combustion is achieved, liquid fires quickly reach steady-state burning with a near constant mass-burning rate. As such, the heat release rate for the fire becomes a function of the liquid surface area exposed to air. A liquid fuel spill may either be confined or unconfined. A confined spill is limited by physical boundaries (e.g., a diked area) and results in a pool of liquid with a depth that is greater than would be obtained if the fuel spilled unconfined. An unconfined spill will tend to have thin fuel depths (typically less than 5 mm), which will result in slower burning rates of the fuel. For non-circular fires, an effective diameter can be calculated using Equation 4.4

The spill area, as for a confined pool fire is defined by the physical boundaries and can be expressed as

$$A_{dike} = \Pi D^2/4$$

$$D = \sqrt{(4A_{dik}e/\pi)} \quad (4.4)$$

where

A_{dike} - Surface Area of the Pool fire (m^2)

D - Pool fire Diameter (m)

S.No	View Factors	Formula – Horizontal View & Vertical View
1	$F_{1\to2,H}$ =	$(B-1/S)/\pi(B^2-1)^{1/2} \tan^{-1}((B+1)(S-1)/(B-1)(S+1))^{1/2}-(A-1/S)/(\pi(A^2-1)^{1/2}) \tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
2	$F_{1\to2,V}$ =	$1/(\pi S) \tan^{-1}(h/(S^2-1)^{1/2})-(h/\pi S) \tan^{-1}((S-1)/(S+1))^{1/2} + Ah / \pi S(A^2-1)^{1/2} \tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
3	A =	$(h^2+S^2+1)/2S$
4	B =	$(1+S^2)/2S$
5	S =	2R/D
6	h =	$2H_f/D$
7	$F_{1\to2,max}$ =	$\sqrt{(F^2_{1\to2,H} + F^2_{1\to2,V})}$

Table 4.3 Configuration View Factors calculation - 1

Where

L = the distance between the center of the cylinder (flame) to the target (m)

H = the height of the cylinder (flame) (m)

D = the cylinder (flame) diameter (m)

Using the flame height and diameter, the configuration factors for horizontal and vertical ($F_{12,V}$, F_{12H}) targets can be calculated using the Table 4.3

- For targets above the ground, two cylinders should be used to represent the flame. In such instances, one cylinder represents the flame below the height of the target, while the other represents the flame above the height of the target (See Figure 4.3). Thus, the following expressions are used to estimate the configuration factor (or view factor) under wind-free conditions for targets above ground level

S.No	View Factor	Formula –Vertical View
1	$F_{1\text{->}2,V1}$ =	$1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2})-(h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_1h_1/\pi S(A_1^2-1)^{1/2}$ $\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$
2	$F_{1\text{->}2,V2}$ =	$1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2})-(h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_2h_2/\pi S(A_2^2-1)^{1/2}$ $\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$
3	A_1 =	$(h_1^2+S^2+1)/2S$
4	A_2 =	$(h_2^2+S^2+1)/2S$
5	B =	(1+S2)/2S
6	S =	2R/D
7	h_1=	2Hf1/D
8	h_2=	2Hf2/D
9	$F_{1\text{->}2,V}$ =	$F_{1\text{->}2,V1} + F_{1\text{->}2,V2}$

Table 4.4 Configuration View Factors calculation -2

Where

$F_{1\text{->}2,\,V}$ = total vertical view factor

L = the distance between the center of the cylinder (flame) to the target (m)

H_f = the height of the cylinder (flame) (m)

D = the cylinder (flame) diameter (m)

Alternatively, Beyler (1999) provides for targets above the ground, two cylinders should be used to represent the flame. In such instances, one cylinder represents the flame below the height of the target, while the other represents the flame above the height of the target (See Figure 4.4). Thus, the following expressions are used to estimate the configuration factor (or view factor) under wind-free conditions for targets above ground level yielding two configuration factors, $F_{12,V1}$ and $F_{12,V2}$ see table 4.4.

Flame Height

When determining flame height, an assumption that the flame is a solid gray emitter with a well-defined cylindrical shape is made for ease of calculation. The cylinder may be straight or tilted as a result of wind

Flame height of the pool fire is then determined using the following correlation (Heskestad, 1995)

$$H = 0.23Q^{2/5} - 1.02\ D \qquad (4.5)$$

Where

Hf = flame height (m)

Q* = heat release rate of the fire (kW)

D = diameter of the burning area (m)

4.8.5 Shokri and Beyler Detailed correlation - Solid Flame Radiation model with Target At and Above Ground Level in Presence of Wind

The solid flame radiation model the turbulent flame is approximated by a cylinder. Under wind-free conditions, the cylinder is vertical, in the presence of wind, the flame may not remain vertical and thermal radiation to the surrounding objects will change in the presence of a significant wind. The flame actually follows a curved path and makes an angle of tilt or an angle of deflection approximate to its curved path. Figures 8 and 9 describe the flame configuration in presence of wind velocity (uw) for target at and above ground level.

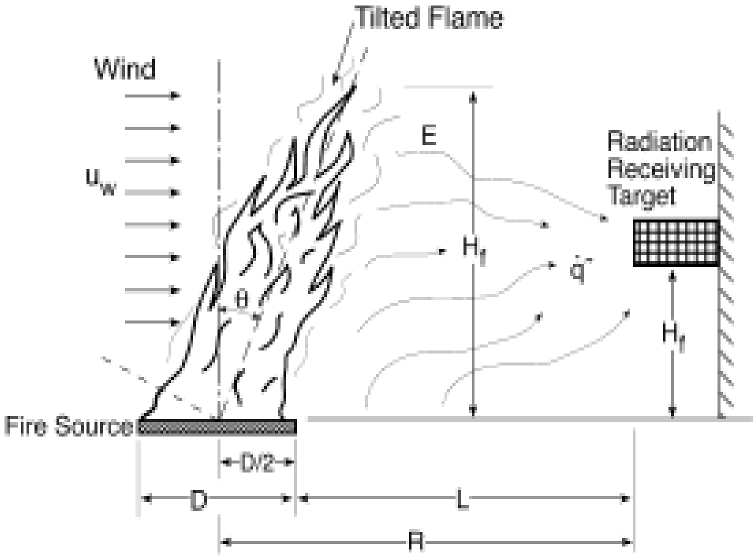

Figure 4.5 Solid Flame Radiation Model in Presence of Wind and Target above Ground Level

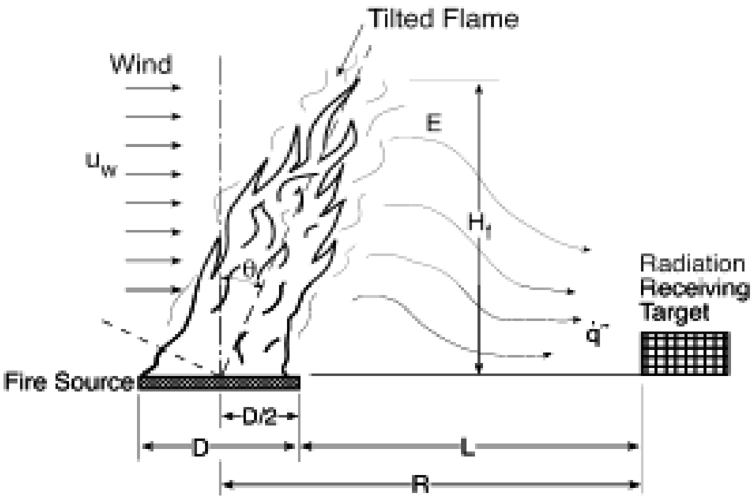

Figure 4.6 Solid Flame Radiation Model in Presence of Wind and Target at Ground Level

For horizontal and vertical target orientations at ground level in presence of wind, the expression for estimating the configuration factors is expressed by the following equations (Beyler, 2002)

S.No	View Factors	Formula – Horizontal View & Vertical View
1	$F_{1\text{->}2,H}$ =	$(a^2 + (b + 1)^2 - 2 (b + 1 + ab \text{ Sin } \theta)/(AB)^{0.5} \tan^{-1} (A/B)^{0.5}/((b - 1)/(b + 1))^{0.5} + \text{Sin } \theta /(C)0.5 (\tan^{-1} ((ab - (b^2 - 1)\text{Sin } \theta)/ (b^2 - 1) (C)^{0.5}) + \tan^{-1} ((b^2 - 1) \text{ Sin } \theta /(b^2-1)^{0.5} (C)^{0.5})$
2	$F_{1\text{->}2,V}$ =	$(a \text{ Cos } \theta /(b - a \text{ Sin } \theta)) (a^2 + (b + 1)^2 - 2b (1 + a \text{ Sin } \theta))/ (AB)^{0.5} (\tan^{-1} (A/B)^{0.5} ((b - 1)/(b + 1))^{0.5} + \text{Cos } \theta /(C)^{0.5} ((\tan^{-1} (ab - (b^2-1) \text{ Sin } \theta)/((b^2 - 1) (C)^{0.5} + \tan^{-1} (b^2-1) \text{ Sin } \theta /(b^2 - 1)^{0.5} (C)^{0.5})) - (a \text{ Cos } \theta)/(b - a \text{ Sin } \theta) (\tan^{-1} (b - 1/b + 1)$
3	a =	H_f/r
4	b=	R/r
5	A =	$a^2 + (b +1)^2 - 2a (b + 1) \sin \theta$
6	B =	$a^2 + (b - 1)^2 - 2a (b - 1) \sin \theta$
7	C =	$1 + (b^2 - 1) \text{Cos}^2 \theta$
8	$F_{1\text{->}2,max}$ =	$\sqrt{}(F^2_{1\text{->}2,H} + F^2_{1\text{->}2,V})$

Table 4.5 Configuration View Factors calculation – 3

Where

$F_{1\text{->}2,}$ H	= horizontal view factor
F1->2, V	= vertical view factor
F1->2, max	= maximum view factor
R	= distance from center of the pool fire to edge of the target (m)
H_f	= height of the pool fire flame (m)
r	= pool fire radius (m)
ϴ	= flame tilt or angle of deflection (radians)

For targets above the ground in presence of wind, two cylinders must be used to represent the flame. In such instances, one cylinder represents the flame below the height of the target, while the other represents the flame above the height of the target. The following expressions are used to estimate the configuration or view factor in presence of wind for targets above ground level

S.No	View Factors	Formula –Vertical View
1	$F_{1\text{->}2,V1}$ =	$(a_1 \, Cos\theta/(b - a_1 \, Sin\theta)) \, (a_1^2 + (b + 1)^2 - 2b \, (1 + a_1 \, Sin\theta))/ (A_1B_1)^{0.5} \, (tan^{-1} \, (A_1/B_1)^{0.5} \, ((b - 1)/(b + 1))^{0.5} + Cos\theta/(C)^{0.5} \, ((tan^{-1} \, (a_1b - (b^2-1) \, Sin\theta)/((b^2 - 1) \, (C)^{0.5} + tan^{-1} \, (b^2-1) \, Sin\theta/(b^2 - 1)^{0.5} \, (C)^{0.5})) - (a_1 \, Cos\theta)/(b - a_1 \, Sin\theta) \, (tan^{-1} \, (b - 1/b + 1)$
2	$F_{1\text{->}2,V2}$ =	$(a_2 \, Cos\theta/(b - a_2 \, Sin\theta)) \, (a_2^2 + (b + 1)^2 - 2b \, (1 + a_2 \, Sin\theta))/ (A_2B_2)^{0.5} \, (tan^{-1} \, (A_2/B_2)^{0.5} \, ((b - 1)/(b + 1))^{0.5} + Cos\theta/(C)^{0.5} \, ((tan^{-1} \, (a_2b - (b^2-1) \, Sin\theta)/((b^2 - 1) \, (C)^{0.5} + tan^{-1} \, (b^2-1) \, Sin\theta/(b^2 - 1)^{0.5} \, (C)^{0.5})) - (a_2 \, Cos\theta)/(b - a_2 \, Sin\theta) \, (tan^{-1} \, (b - 1/b + 1)$
3	A_1 =	$a_1^2 + (b +1)^2 - 2a_1 \, (b + 1) \, sin\theta$
4	A_2 =	$a_2^2 + (b +1)^2 - 2a_2 \, (b + 1) \, sin\theta$
5	B_1 =	$a_1^2 + (b - 1)^2 - 2a_1 \, (b - 1) \, sin\theta$
6	B_2 =	$a_2^2 + (b - 1)^2 - 2a_2 \, (b - 1) \, sin\theta$
7	C =	$1 + (b^2 - 1) \, Cos^2\theta$
8	a_1 =	$2H_{f1}/r = 2H_1/r$
9	a_2 =	$2H_{f2}/r = 2 \, (H_f - H_{f1})/r$
10	b =	R/r
11	$F_{1\text{->}2,V}$ =	$F_{1\text{->}2,V1} + F_{1\text{->}2,V2}$

Table 4.6 – View Factor Calculation – 4

Where

F1->2, V = total vertical view factor in presence of wind

R = distance from center of the pool fire to edge of the target (m)

Hf = height of the pool fire flame (m)

R = pool fire radius (m)

Ө = flame tilt or angle of deflection (radians)

In presence of wind, the expression for estimating flame height is expressed by the following correlation, based on the experimental data (Thomas, 1962)

$$H = H_f = 55 \, D \, (m''/\rho a \, (\sqrt{g} \, D))^{0.67} \, (u^*)^{-0.21} \quad (4.6)$$

Where

D = diameter of pool fire (m)

m" = mass burning rate of fuel (kg/m2-sec)

ρ_a = ambient air density (kg/m3)

g = gravitational acceleration (m/sec2)

u* = non-dimensional wind velocity

The non-dimensional wind velocity is given by

$$\mathbf{U^*} = \frac{\boldsymbol{Uw}}{\sqrt[3]{\frac{\boldsymbol{g\,\dot{m}''D}}{\boldsymbol{\rho v}}}} \tag{4.7}$$

Where:

u* = non- dimensional wind velocity

u_w = wind speed or wind velocity (m/sec)

g = gravitational acceleration (m/sec2)

m" = mass burning rate of fuel (kg/m2-sec)

D = diameter of pool fire (m)

ρ = density of ambient air (kg/m3)

Heat Release Rate (Q*)

Fire development is generally characterized in terms of heat release rate (HRR) vs. time. Thus, determining the HRR (or burning rate) is an essential aspect of a fire hazard analysis (FHA). The average burning rates for many products and materials have been experimentally determined in free-burning tests. For many materials, the burning rate is reported per horizontal burning area in units of kg/m -sec. If the area of 2 the fuel and the effective heat of combustion are known, the above equation becomes

$$Q = m''\Delta H_{c,eff}\,(1-e^{-kb\,D})\,A_{dike} \tag{4.8}$$

Where

m"= burning or mass loss rate per unit area per unit time (kg/m^2-sec)

A_{dike} = horizontal burning area of the fuel (m^2)

kβ= empirical constant (m^{-1})

D = diameter of burning area (m)

BURNING RATES OF VARIOUS FUELS			
Fuel	Mass Burning Rate	Heat of Combustion	Empirical Constant
	m" (kg/m^2-sec)	$\Delta H_{c,eff}$ (kJ/kg)	kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26.*			

Table 4.7 Large Pool Fire Burning Rate Data

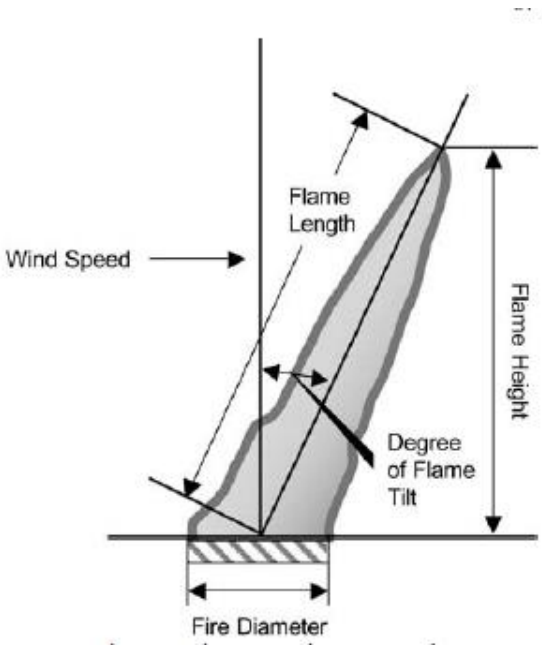

Figure 4.7 Flame Inclinations due to Wind (SFPE, 2002)

The correlation relating to angle of tilt or angle of deflection (q), of the flame from the vertical is expressed by the following equations based on the American Gas Association (AGA) data

$$\cos\Theta = 1 \text{ for } U^* \leq 1$$

$$\cos\Theta = \frac{1}{\sqrt{U*}} \text{ for } U^* > 1$$

Where

Θ = angle of tilt or angle of deflection (radians)

u* = non- dimensional wind velocity

Once a mass-burning rate of the fire is established, the duration of the fire (burn time) can be calculated as

$$t_b = m_f/m"A = V\rho/m"A \qquad (4.9)$$

Where

t_b is burn time (s)

m_f is mass of fuel spilled or contained in the pool (kg)

V is volume of fuel (m^3)

m ″ is mass burning rate per unit area (kg/m^2 s)

A is fire area (m^2)

ρ is density (kg/m^3)

Storage tanks can be treated as a confined pool fire. For confined pools that have a significant level of material, Table – II shows the burning rate in inches per hour for a variety of materials. When first ignited, the fire spreads rapidly across the full extent of the hydrocarbon pool and proceeds to consume the liquid at a characteristic burning rate (Spouge, 1999).

Shokri and Beyler (1989) explain it is important to note that the ‘effective’ emissive power of the flame is defined only in terms of a homogeneous flame radiation model. Rather than being the local emissive power measured at a specific point in space, it is more of an averaged emissive power over the whole flame. As the model was developed for pool fire scenarios, an expression for the ‘effective’ emissive power was formed in terms of the effectiv pool diameter.

It is expressed as

$$E = 58(10^{-0.00823D}) \tag{4.10}$$

E may be expressed in terms of the diameter (D) of the fire

Shokri and Beyler (1989) observed that the major uncertainty with their model is in the definition of the emissive power and not in the view factor model. In fact, it was found that for pool fires the cylindrical approximation of the flame is highly accurate at predicting view factors over a wide range of conditions. This model assumes that the fire is circular or nearly circular in shape. Comparison with experimental data suggests that the performance of the method is better at heat fluxes greater than 5 kW/m^2 at the target (Beyler, 1999).

Therefore, the main limitation to the model is that it should only be used when the radiant heat flux to the target exceeds 5 kW/m^2. Again, a safety factor of two should be used for design purposes (Shokri & Beyler, 1989).

4.9 Pool Fire/ Tank Fire Hazard Analysis

Pool fires begin with the release of a flammable material from process equipment or storage. If the material is liquid, stored at a temperature below its normal boiling point, the liquid will collect in a pool. The geometry of the pool will be dictated by the surroundings. If the liquid is stored under pressure above its normal boiling point, then a fraction of the liquid will flash into vapor, with the un flashed liquid remaining to form a pool in the vicinity of the release. To determine the impact of a pool fire on adjacent equipment, a series of calculations are required as shown in Figure 4.8

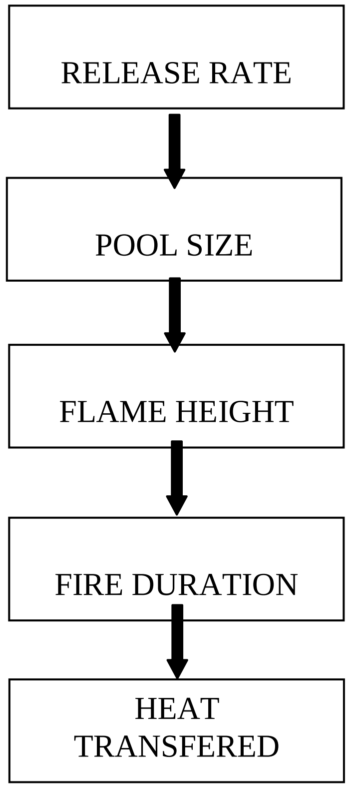

Figure 4.8 Evaluation Process for Pool Fire

4.9.1 Flame Radiation to External Targets

Several methods have been described for prediction of radiation from pool fires (SFPE, 1999). The primary methods are based on correlations developed from experimental data. Shokri and Beyler correlated experimental data of flame radiation to external targets in terms of an average effective emissive power of the flame (Shokri and Beyler, 1989). The flame is assumed to be a cylindrical, black body radiator with an average emissive power, diameter (D), and height (Hf), see Figure 4. 9

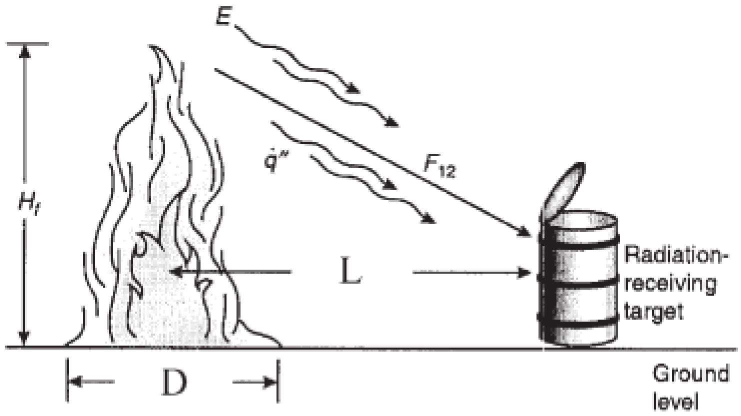

Figure 4.9 Shokri and Beyler Representation

Utilizing the Shokri and Beyler method to estimate the incident flux on a target involves the following steps:

1. Calculate the heat release rate of the fire, Q.
2. Determine the diameter and flame height of the fire (if the fire is noncircular, use the effective diameter). The flame height is calculated using Equation (9).
3. Determine the view (configuration) factor.
4. Calculate the emissive power of the flame using Equation (7).
5. Calculate the incident heat flux to the target using Equation (3).

4.9.2 Application of Pool Fire/Tank Fire

Based upon the above calculations the following details can be estimated:

Fire Impact to Personnel, Structures, and Equipment Impact to Personnel

When there is a line-of-sight between a person and the flame, the main impact is thermal radiation. The primary potential effects of thermal radiation are:

- Burns to exposed skin.
- Ignition or melting of clothing.

Burns are classified in increasing degrees of severity:

- First degree—superficial burns giving a red, dry skin (similar to mild sunburn).
- Second degree—burns more than 0.1 mm deep, affecting the epidermis and forming blisters.
- Third degree—burns more than 2 mm deep, affecting the dermis and nerve endings, resulting in a dry skin that has no feeling (major blistering).

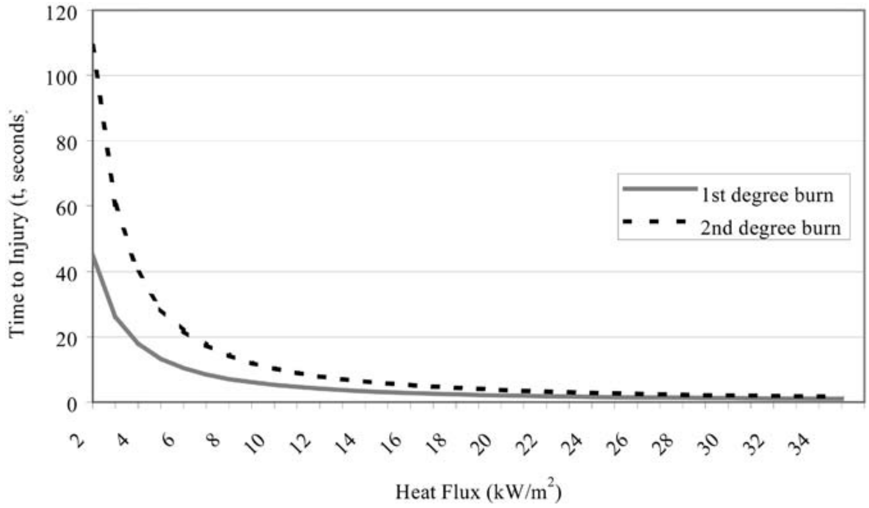

Figure 4.10 Prediction of First- and Second-Degree Burns

Incident Flux (kW/m^2)	Impact
37.5	100 % lethality in 1 minute (Barry,2002)
25	1% lethality in 10 seconds (Barry, 2002)
15.8	100% lethality in 1 minute, significant injury in 10 seconds (Barry,2002)
12.5	1% lethality in 1 minute; first degree burns in 10 seconds (Barry,2002)
6.3	Emergency actions lasting a minute can be performed by personnel without shielding but with appropriate clothing (API RP 521)
4.7	Emergency actions lasting a minute can be performed by personnel without shielding, but with appropriate clothing (API RP 521)

Table 4.8 Estimated Effects of Heat on Personnel

4.9.3 Thermal and Non-thermal Impact on Electrical and Electronic Equipment

A heat flux of 25 kW/m2 has been published as a general rule-of-thumb for damage to process equipment. Clearly, this excludes electrical and electronic equipment, which may fail to operate at much lower heat fluxes and resulting temperatures. For example, data on the thermal impact of fire on electrical and electronic equipment have been summarized for U.S. Navy applications. The following limits were derived from a literature evaluation:

- 50°C (122°F) for faults in operating electronic equipment.
- 150°C (302°F) for permanent damage to non-operating equipment.
- 250°C (482°F) for failure of standard Polyvinyl Chloride (PVC) cable.

Impact on the Environment

Impact on the environment may result from both unwanted fires, improper control of fire effluent or improper use of suppression system agents. Environmental considerations impact decisions on whether to provide protection for a hazard, and whether this protection should be provided automatically or manually

Chapter 5
Results and Discussions

5.1 Implementation of Shokri Beylers Methodology

In this scenario Tank fire/ Pool Fire calculations are carried out assuming that the liquid is released by overfilling and got ignited by some source of ignition say spark from engine start up.

The considerations taken are

Tank Diameter : ID - 30 m

Tank Capacity : 7870 m^3

Type : Floating roof tank

❖ **Pool Fire/Tank Fire Scenario- 1**

Scenario : Tank Fire at ground level under wind free condition

Liquid : Kerosene

Properties

Boiling point : 150-300°C

Relative vapour density (air = 1) : 4.5

Flash point : 37-65°C

Auto-ignition temperature : 220°C

Model : Shokri Beyler Solid Frame Radiation Model- I

S.No	Description	Value	Unit
1	Mass Burning Rate	0.039	Kg/Cm^2 – Sec
2	Effective Heat of Combustion of Fuel (ΔHc,eff)	43200	kJ/kg
-3	Empirical Constant (kβ)	3.5	m^{-1}
4	Vapor Density (ρv)	4.5	Kg/m^3
5	Fuel Area or Dike Area (A_{dike})	706.2	m^2
6	Distance between Fire and Target (L)	20	M

Table 5.1 Input Parameters for Pool fire/Tank Fire Scenario Calculation -1

i. Pool Size

$A_{dike} = \Pi D^2/4$

$D = \sqrt{(4A_{dike}/\Pi)}$

$= 30.0$ m

ii. Flame height

$H = 0.23Q^{2/5} - 1.02\,D$

$= 32.7$ m

iii. Heat Release Rate

$Q = m''\Delta H_{c,eff}(1 - e^{-kbD})\,A_{dike}$

$= 1189575.2$ kW

iv. Duration of Burning Fuels

$t_b = m_f/m''A = V\rho/m''A$

$t_b = 259365.6$ Seconds ~ 3 Days

v. Incident radiative heat flux to a target outside the flame is given by Equation.

$$q'' = EF_{12}$$

- Emissive Power

$E = 58(10^{-0.00823D}) = 32.86\ (kW/m^2)$

- Configuration View Factors

$F_{12}, max\ (no\text{-}wind) = \sqrt{(F^2_{12}, H + F^2_{12}, V)}$

✓ The below mentioned tables gives the equations to calculate the view factors.

$F_{12}, H = 0.096$

$F_{12}, V = 0.195$

$F_{12}, max\ (no\text{-}wind) = \sqrt{(F_{12}, H + F_{12}, V)} = 0.218$

- Incident Heat flux

$q'' = EF_{12} = 7.15\ kW/m^2$

As per the design factor given by shokri beyler (1989) multiply the equation with a value of two to the final value.

$$\mathbf{q'' = EF_{12} = 14.3\ kW/m^2}$$

❖ **Pool Fire/Tank Fire Scenario- 2**

Scenario **:** Tank Fire Above ground level under wind free condition

Liquid **:** Kerosene

Properties

Boiling point : 150-300°C

Relative vapour density (air = 1) : 4.5

Flash point : 37-65°C

Auto-ignition temperature : 220°C

Model **:** Shokri Beyler Solid Frame Radiation Model- II

S.No	Description	Value	Unit
1	Mass Burning Rate	0.039	Kg/Cm^2 – Sec
2	Effective Heat of Combustion of Fuel (ΔHc,eff)	43200	kJ/kg
3	Empirical Constant (kβ)	3.5	m^{-1}
4	Vapor Density (ρv)	4.5	Kg/m^3
5	Fuel Area or Dike Area (A_{dike})	706.2	m^2
6	Distance between Fire and Target (L)	20	M
7	Vertical Distance of Target from Ground (H1 = Hf1)	13	M

Table 5.2 Input Parameters for Pool fire/Tank Fire Scenario Calculation - 2

i. Pool Size

$A_{dike} = \Pi D^2/4$

$D = \sqrt{(4A_{dike}/\Pi)}$

$= 30.0$ m

ii. Flame height

$H = 0.23Q^{2/5} - 1.02\,D$

$= 32.691$ m

iii. Heat Release Rate

$Q = m''\Delta H_{c,eff}\,(1 - e^{-kbD})\,A_{dike}$

$= 1189575.2$ kW

iv. Duration of Burning Fuels

$t_b = m_f/m''A = V\rho/m''A$

t_b = 259365.6 Seconds ~ 3 Days

v. Incident radiative heat flux to a target outside the flame is given by Equation.

$$q'' = EF_{12}$$

- Emissive Power

$E = 58(10^{-0.00823D})$

$E = 32.86$ (kW/m^2)

- Configuration View Factors

$F_{12}, V = F_{12}, V1 + F_{12}, V2$

✓ The below mentioned tables gives the equations to calculate the view factors.

$F_{12}, V1 = 0.132$

$F_{12}, V2 = 0.166$

$F_{12}, V = F_{12}, V1 + F_{12}, V2 = 0.298$

Table 4 – View Factor Calculation – 2

- Incident Heat flux

$q'' = EF_{12}$ = = 9.79 kW/m^2

As per the design factor given by shokri beyler (1989) multiply the equation with a value of two to the final value.

$$\boldsymbol{q'' = EF_{12} = 19.6 \text{ kW/m}^2}$$

❖ **Pool Fire/ Tank Fire Scenario 3**

Scenario **:** Tank Fire at ground level in presence of wind condition

Liquid **:** Kerosene

Properties

Boiling point : 150-300°C

Relative vapour density (air = 1) : 4.5

Flash point : 37-65°C

Auto-ignition temperature : 220°C

Model **:** Shokri Beyler Solid Frame Radiation Model - I

S.No	Description	Value	Unit
1	Mass Burning Rate	0.039	Kg/Cm^2 – Sec
2	Effective Heat of Combustion of Fuel (ΔHc,eff)	43200	kJ/kg
-3	Empirical Constant (kβ)	3.5	m^{-1}
4	Vapor Density (ρv)	4.5	Kg/m^3
5	Fuel Area or Dike Area (A_{dike})	706.2	m^2
6	Distance between Fire and Target (L)	20	m
7	Wind Speed or Velocity ($U_{w)}$	5	m/sec
8	Ambient Air Temperature	25-30	^{0}C
9	Gravitational Acceleration	9.81	m/sec^2
10	Ambient Air density (ρ_a)	1.18	Kg/m3

Table 5.3 Input Parameters for Pool fire/Tank Fire Scenario Calculation -3

i. Pool Size

$A_{dike} = \Pi D^2/4$

$D = \sqrt{(4A_{dike}/\Pi)}$

$= 30.0$ m

ii. Pool Fire Flame height – (Thomas Method)

$H = H_f = 55\ D\ (m''/\rho a\ (\sqrt{g}\ D))^{0.67}\ (u^*)^{-0.21}$

$= 20.79$ m

iii. Heat Release Rate

$Q = m''\Delta H_{c,eff} (1 - e^{-kbD})\ A_{dike}$

$= 1189575.12$ kW

iv. Duration of Burning Fuels

$t_b = m_f/m''A \quad = V\rho/m''A$

$t_b = 259365.6$ Seconds ~ 3 Days

v. Non Dimensional wind velocity Calculation

$$\mathbf{U^*} \quad = \frac{\boldsymbol{Uw}}{\sqrt[3]{\frac{\boldsymbol{g\,\dot{m}''D}}{\boldsymbol{\rho v}}}}$$

Where *u** is the non- dimensional wind velocity given by

U* = 2.383 m

vi. Tilt angle of Flame

$\mathbf{cos\Theta} = 1$ for $U^* \leq 1$

$\mathbf{cos\Theta} = \frac{1}{\sqrt{U^*}}$ for $U^* > 1$

As U* is greater than one consider second condition i.e,

$\mathrm{Cos}\boldsymbol{\Theta} = \frac{1}{\sqrt{U^*}}$

$\boldsymbol{\Theta} = \cos^{-1} \left(\frac{1}{\sqrt{U^*}}\right)$

$\boldsymbol{\Theta} = 0.866$ rad $= 49.\ 63^0$

vii. Incident radiative heat flux to a target outside the flame is given by Equation.

$$q'' = EF_{12}$$

- Emissive Power

$E = 58(10^{-0.00823D})$

$E = 32.86\ (kW/m^2)$

- Configuration View Factors

` F_{12}, V = F_{12}, V1 + F_{12}, V2

✓ The below mentioned tables gives the equations to calculate the view factors.

F_{12}, H = 0.391

$F_{12}, V = 0.428$

$F_{12}, max = \sqrt{(F^2{}_{12}, H + F^2{}_{12}, V)} = 0.579$

- Incident Heat flux

$q'' = EF_{12} = 19.03$ kW/m^2

As per the design factor given by shokri beyler (1989) multiply the equation with a value of two to the final value.

$$\boldsymbol{q'' = EF_{12} = 38.06\ \mathrm{kW/m^2}}$$

❖ **Pool Fire/Tank Fire Scenario 4**

Scenario **:** Tank Fire Above ground level in presence of wind condition

Liquid **:** Kerosene

Properties

Boiling point : 150-300°C

Relative vapour density (air = 1) : 4.5

Flash point : 37-65°C

Auto-ignition temperature : 220°C

Model **:** Shokri Beyler Solid Frame Radiation Model - II

S.No	Description	Value	Unit
1	Mass Burning Rate	0.039	Kg/Cm^2 – Sec
2	Effective Heat of Combustion of Fuel (ΔHc,eff)	43200	kJ/kg
-3	Empirical Constant (kβ)	3.5	m^{-1}
4	Vapor Density (ρv)	4.5	Kg/m^3
5	Fuel Area or Dike Area (A_{dike})	706.2	m^2
6	Distance between Fire and Target (L)	20	m
7	Vertical Distance of Target from Ground (H1 = Hf1)	13	m
8	Wind Speed or Velocity (U_{w})	5	m/sec
9	Ambient Air Temperature	25-30	^0C
10	Gravitational Acceleration	9.81	m/sec^2
11	Ambient Air density (ρ_a)	1.18	Kg/m3

Table 5.4 Input Parameters for Pool fire/Tank Fire Scenario Calculation -4

i. Pool Size

$A_{dike} = \Pi D^2/4$

$D = \sqrt{(4A_{dike}/\Pi)}$

$= 30.0$ m

ii. Pool Fire Flame height

$H = H_f = 55\ D\ (m''/\rho a\ (\sqrt{g}\ D))^{0.67}\ (u^*)^{-0.21}$

$= 20.79$ m

iii. Heat Release Rate

$Q = m''\Delta H_{c,eff}\ (1 - e^{-kbD})\ A_{dike}$

$= 1189575.12$ kW

iv. Duration of Burning Fuels

$t_b = m_f/m''A \quad = V\rho/m''A$

$t_b = 259365.6$ Seconds ~ 3 Days

v. Non Dimensional wind velocity Calculation

$$\mathbf{U^*} = \frac{\boldsymbol{Uw}}{\sqrt[3]{\frac{\boldsymbol{g\,\dot{m}''D}}{\boldsymbol{\rho v}}}}$$

Where *u** is the non- dimensional wind velocity given by

$U^* = 2.383$ m

vi. Tilt angle of Flame

$\mathbf{cos\Theta} = 1$ for $U^* \leq 1$

$\mathbf{cos\Theta} = \frac{1}{\sqrt{U^*}}$ for $U^* > 1$

As U* is greater than one consider second condition i.e,

$\text{Cos}\boldsymbol{\Theta} = \frac{\mathbf{1}}{\sqrt{\boldsymbol{U^*}}}$

$\boldsymbol{\Theta} = \cos^{-1}\left(\frac{\mathbf{1}}{\sqrt{\boldsymbol{U^*}}}\right)$

$\boldsymbol{\Theta} = 0.866$ rad $= 49.\ 63^0$

vii. Incident radiative heat flux to a target outside the flame is given by Equation.

$$q'' = EF12$$

- Emissive Power

$E = 58(10^{-0.00823D}) = 32.86\ (kW/m^2)$

- Configuration View Factors

$F_{12}, V = F_{12}, V1 + F_{12}, V2$

✓ The below mentioned tables gives the equations to calculate the view factors.

$F_{12}, V_1 = 0.356$

$F_{12}, V_2 = 0.4031$

$F_{12}, V = F_{12}, V_1 + F_{12}, V_2 = 0.759$

- Incident Heat flux

$q" = EF_{12} = 25 \text{ kW/m}^2$

As per the design factor given by shokri beyler (1989) multiply the equation with a value of two to the final value.

$$\boldsymbol{q" = EF_{12} = 50 \text{ kW/m}^2}$$

➢ Calculating minimum separation distance using OISD 118

S.No	Item	Between floating Roof Tanks Class A & B	Between fixed Roof Tanks Class A & B	Between Class C Petroleum Storage tanks
1	All tanks with Diameter upto 50 meters	(D+d) / 4 Min 10 m	(D+d) / 4 Min 10 m	(D+d) / 6 Min 6 m
2	Tanks with Diameter exceeding 50 meters.	(D+d) / 4	(D+d) / 3	(D+d) / 4

Table 5.5 Separation Distances between Storage Tanks within a Dyke

(**Table 5 as Per OISD 118**)

a) All distances are in meters.
b) D & d stands for diameter of larger and smaller tanks.
c) In Table –7, Distances given are shell to shell in the same dyke.
d) For different combination of storage tanks, the stringent of the applicable formulae shall be considered for minimum separation distance.
e) The distance of storage tanks from boundary wall is applicable for;

(i) Floating roof tanks having protection for exposure

(ii) Tanks with weak roof-to-shell joint having approved foam or inerting system and the tank diameter not exceeding 50 meters

- A key safety consideration for tank farm siting, spacing, and location is the separation of non-compatible materials by the use of an internal bund or dike wall within the tank farm. Providing bund or dike checks the flow of the spilled oil to the neighbouring areas.
- Thus in case of fire engulfing the tank farm, the fire is confined to its origin. The bunds, however, need to be designed to have sufficient strength to withstand the pressure that may be created in the event of an oil spillage and the capacity to store the spilled liquid.
- Using this method the heat flux at various distances between a tank on fire and the adjacent (target) tank is calculated.
- The distance at which the heat flux becomes equal to 4.732 kW/m2 (1500 BTU/h/ft2) (Daniel, Crowl, & Louvar, 2002; Lees, 1995; SFPE Handbook of Fire Protection Engineering, 1995) is considered to be the safe inter-tank distance. No material is expected to ignite with a heat flux lower than 4.732 kW/m^2.
- So, as the above calculations the distance at which the heat flux reached 4.732 kW/m^2 ~ 5 kW/m^2 is 50 meters, but as per regulatory stand the minimum distance between the storage tanks is given as below.

✓ All tank diameters up to diameter 50 meters for floating roof storage tank containing class A & B petroleum products the formula is given as

$$(D+d) / 4 = (30+30)/4$$

$$= 15 \text{ m (minimum separation distance)}$$

Where – D - Largest tank diameter

d - Small tank diameter

S.No	Model	Condition	Wind Condition	Distance from the fire to target (meter)	Heat Flux (Kw/m^2)
1	Shokri Beyler Solid Radiation Model –I	Target at Ground Level	No	20	14.3
2	Shokri Beyler Solid Radiation Model –II	Target Above Ground Level	No	20	19.58
3	Shokri Beyler Solid Radiation Model –I	Target at Ground Level	Yes (5 m/s)	20	38.06
4	Shokri Beyler Solid Radiation Model –II	Target Above Ground Level	Yes (5 m/s)	20	40.26

Table 5.6 Heat flux comparision for solid frame radiation models

➢ As the aim of the project states the design factors of layout and spacing various factors were explained in chapter 4.

Chapter 6

Conclusion

The Pool fire/ Tank fire hazard analysis is done for storage tanks in an oil and gas installation and stated various design factors in terms of layout and spacing between two storage tanks. In terms of safety the thermal radiation appeared to be **4.732 kW/m^2 ~ 5 kW/m^2** which the distance between the fire source and the neighbouring tank is **45 meters**, but as per OISD 118 Standards table 5 the minimum distance between the storage tanks is calculated and obtained a distance of **15m** which was taken in the plot plan of an oil and gas installation. As mentioned the distance of 15 m will have an impact on personnel as well as other process facilities hence in case of space constraint extra fire protection measures should be taken to reduce the major accident scenario.

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