AN APPLICATION OF FIRE SCIENCE TO AN INDUSTRIAL INCIDENT

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SYNOPSIS

The majority of petroleum refineries and petrochemical facilities store highly flammable liquids in open top floating roof tanks. Occasionally the floating roof loses buoyancy and sinks. This exposes an large pool of hydrocarbon product. If the vapour ignites, a full surface fire occurs which can escalate and involve adjacent tanks. Such an incident occurred in Singapore in October 1988. As a result, a number of studies and papers have been written on fire science matters associated with such events. This paper discusses the following three associated fire science topics namely; the electrostatic hazards of foam blanketing operations, fire escalation from radiation heat, and the extinguishment of large tank fires.

INTRODUCTION

The largest tank fire ever experienced in Singapore occurred on the 25th October 1988 at a petroleum refinery. The incident involved three open top floating roof naphtha tanks containing a total of 294,500 barrels of product.

The three naphtha tanks shared a common dike/bunded area. Each tank had a diameter of 41 metres with a shell height of 21 metres. The tanks were spaced at 21 metres apart.

One of the tanks was receiving sour straight run naphtha when the floating roof was found partially submerged. The Refinery Fire Service was applying foam through the tank's fixed foam pourers when ignition occurred resulting in an immediate full surface fire. Two hours later, an adjacent tank caught fire in the rim seal area and within a further 2 hours became totally involved. The third tank became fully involved 7 hours later.

The fire was successfully contained within the primary bund/dike by cooling adjacent exposed tankage and the naphtha tanks were allowed to burn out, pumping out as much product as possible. The fire took five days to burn out.

The incident was contained by the combined efforts of the refinery personnel, Singapore Fire Service, the Civil Defence Force, the Armed Forces, Civil Aviation Authority, Port of Singapore Authority fire tugs and the mutual aid partners.

No serious injuries were incurred during the incident.

The enquiry team set up to investigate the incident concluded hat the floating roof sank due to a combination of flooded roof pontoons, heavy local rainfall and a partially choked drain.

1. SOURCE OF IGNITION AND IMPLICATIONS ON PROCEDURES FOR DEALING WITH A SUNKEN OR JAMMED FLOATING ROOF

Evidence [1] suggests that sunken floating roofs are uncommon but can lead to full surface fires at a frequency of 3 x 10^{-5} per tank year. If the expected ignition of the contents from a sunken roof is 1 /40[1], then the frequency of a sunken roof is estimated at 1.2 x 10^{-3} per tank year (or once in 833 tank years).

If such an event occurs, it was previously accepted practice to cover the exposed surface of the volatile product with foam to minimise the probability of ignition.

The enquiry team into the Singapore tank fire concluded that the most likely cause of the ignition was a frictional spark due to mechanical failure of the support for the anti-rotational pole where it was attached to the rim of the tank shell as a consequence of the sinking of the tank roof. (See Appendix 1 for details of a floating roof tank). The enquiry team also commented that the risk of ignition would have been significantly reduced if the foam had been applied earlier and the tank levels had remained stationary.

However, a paper published at a Singapore conference[2] in 1993 suggests that such a foaming operation can create a source of ignition. This raises the question of whether to cover an exposed surface of the volatile product with foam or not. (Photograph #1)

Howells[2] lists a number of tank incidents ignited by electrostatic discharges as a result of the application and/or breakdown of foam. (Appendix II). The Dorn Effect Charging generated by the electrochemical separation of charge as water drains through low conductivity liquids (Appendix III) is well known in the chemical and petroleum industry. Howells[2] compared his experimental work with a theoretical expression for electrical field generation developed by Klinkernberg and van der Minne[2] and obtained a similar order of magnitude for the generation of an electric field.

As a result of his experimental work, BP drew up a set of guidelines for dealing with the problem of sunken floating roofs. (Appendix IV)

2. FIRE ESCALATION FROM A FULL SURFACE FIRE AND IMPLICATIONS ON TANK SPACING AND FIRE FIGHTING

A previous study[3] reported that 45% of large full surface fires escalate to involve neighbouring tanks.

The three tanks involved in the Singapore fire contained light naphtha with an initial boiling point of 36^{0}C. It took 2 hours for the adjacent tank to catch fire in the rim seal area and a further 2 hours to become totally involved. The third tank become totally involved within 7 hours of the full surface fire on the second tank.

The Singapore Oil and Petrochemical Industrials Technical and Safety Committee (OPITSC) representing twelve local companies: BP, Shell, Esso, Mobil, SPC, SRC, GATX, Paktank, Van Ommeren, Caltex, PCS and Oiltanking commissioned an independent consultant (DNV Technica) to undertake a fire study to determine the adequacy of existing codes on tank spacing.

2.1 Fire Modelling

The Consultant found that there was no readily available fire model which could be applied directly to the tank fire escalation problem.

The modelling was therefore developed in two parts:

- a heat source model to predict thermal radiation generated from a range of flammable liquid pool fires.

- a receptor tank model* to predict the temperature response of adjacent tanks holding a range of liquids of different floating roof designs and incorporating mitigatory measures such as water sprays.

The heat source model [4] was based on an elevated pool fire. The approach and model is publicly available using well known correlations for flame dimensions, flame tilt, surface thermal flux, view factors and atmospheric transmissivity. The model took into account the thermal radiation emission from a lower brightly emitting area of flame and an upper smoke obscured area of flame. The results compared favorably with data from large scale Japanese pool fire experiments and the Singapore naphtha tank fires.

The receptor model[4] was more novel and was derived from the UK Safety and Reliability Directorate ENGULF model[5][6]. It predicted the time temperature response of the adjacent storage tanks containing different products with different features such as water sprays and double deck roof design.

The model calculated temperature gradients in the tank at the facing shell, under the roof, in the bulk liquid, at the bottom and at the rear face of the tank.

The receptor model, unlike the source model is dynamic. The receptor tank is assumed to be at ambient temperature at the start of the incident. Temperature of the liquid behind the shell facing the fire and under the roof rises the fastest. The actual rate of rise of temperature depended upon whether the roof of the tank was a single deck or double deck design and if the tank was fitted with water sprays.

The fire was considered to have escalated to the adjacent downward tank when the layer of product next to the shell facing the flames or the product immediately beneath the roof reached its initial boiling point. This was considered to be well in advance of the bulk of the liquid reaching this temperature.

When the liquid at the shell facing the fire or under the roof reaches its initial boiling point, then large volumes of vapour would be formed and this will collect under the roof and in the seal area. These flammable vapours would then pass through the seal areas onto the roof and ignite from the hot smoke particles emitted by the adjacent tank's fire. In addition, if sufficient vapour is emitted from one side of the rim seal, this could tilt the roof sufficiently to cause it to sink.

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* This model is not available in the public domain.

2.2 Findings from Fire Modelling

In order to test the validity of the model, the Consultant used the Singapore tank fire data as the base case. Fortunately, considerable information including a video tape of the fire was made available to the Consultant.

The base case was therefore taken as a 50m diameter open floating roof naphtha tank affecting an adjacent tank of the same dimensions and design and containing the same material.

Details are as follows:

Naphtha tank dimensions:		50m dia x 18m height	
	Roof type	Pontoon (single deck)	
	Wind:	4 m/s towards adjacent tank	

Burning Rate: = $0.12\ kg/m^2/sec$
Flame length = 77 m
Flame tilt = 31^0 (from the vertical)
Surface emissivity of bright flame portion
(one third) = $139\ kW/m^2$
Surface emissivity of smokey portion
Average emissivity = $59\ kW/m^2$
Flame dragged diameter = 61 m

It was assumed that the wind was blowing towards the adjacent tank. Results from the base case were as follows:

Distance Between Tanks (D = Diameter of Tank)	Time to Escalation (Hours)
0.3 D	1.4
0.5 D	2.7
0.75 D	4.2
1.0 D	5.7
2.0 D	11.7

The above results have an important implication on fire fighting strategies. It clearly indicates that the closer the tanks are spaced, the less time the fire service/emergency response team has in mounting a successful extinguishment before escalation occurs. NFPA 11 “Standard for Low Expansion Foam” stipulates a minimum foam discharge time of 55 minutes for fixed foam discharge outlets and 65 minutes if foam monitors are used. This means if tanks containing light naphtha are spaced in accordance with NFPA 30 “Flammable and Combustible Liquids Code” in open top floating roof tanks, there is a requirement to commence immediate extinguishment under the above conditions.

2.2.1 Effects of Other Parameters

Wind

Results from different wind speeds using the same tank data were as follows:

Distance Between Tanks (D = Diameter of Tank)	Time to Escalation (Hours)	
	Wind Speed 4m/sec	Low Wind Speed < 1m/sec
0.3 D	1.4	4.2
0.5 D	2.7	7.0
0.75 D	4.2	10.0
1.0 D	5.7	-
2.0 D	11.7	>24.0

Water Sprays

Results indicated that the application of water sprays to the shell of an open top floating roof tank may not be as beneficial as originally thought in the prevention of escalation. (See Photograph #2). This is because radiant heat can still enter the floating roof deck. It would be unwise to spray water onto the deck because of the possibility for it to sink should the drain not be designed to cater for the maximum flow.

Distance Between Tanks (D = Diameter of Tank)	Time to Escalation (Hours)		
	Base Case (No Water Sprays)	Water Sprays $2l/min/m^2$	Water Sprays No Wind
0.3 D	1.4	1.4	>24
0.5 D	2.7	2.7	>24
0.75 D	4.2	5.5	>24
1.0 D	5.7	9.5	>24
2.0 D	11.7	>24	>24

It can be seen that water sprays are more beneficial when the tanks are spaced further apart or in conditions of no wind because much less radiant heat enters the roof.

Double Deck Roof

Two types of roof were considered a single deck (See Appendix I for details) and a double deck. The advantage of a double deck is that it provides an insulating air space between the top skin and the bottom skin that is in contact with the liquid.

Results indicated that there was no change in the escalation times except a marginal improvement at close separations because the prominent mechanism for the heat transfer through the shell is unaltered.

Distance Between Tanks (D = Diameter of Tank)	Time to Escalation (Hours)	
	Base Case Single Deck	Double Deck Roof
0.3 D	1.4 D	1.7 D
0.5 D	2.7 D	2.7 D
0.75 D	4.2 D	4.2 D
1.0 D	5.7 D	5.7 D
2. 0 D	11.7 D	11.7 D

Double Deck Roof and Water Sprays

The results from having both water sprays for the shell and a double deck roof are as expected since both the roof and the shell are protected against radiant heat transfer.

Distance Between Tanks (D = Diameter of Tank)	Time to Escalation (Hours)	
	Base Case ▪No Water Spray ▪Single Deck	Water Sprays and Double Deck Roof
0.3 D	1.4 D	>24
0.5 D	2.7 D	>24
0.75 D	4.2 D	>24
1.0 D	5.7 D	>24
2. 0 D	11.7 D	>24

Effect of Heavier Fuel in Adjacent Tank

Kerosene has an initial boiling point above 140^{0}C. This means that it would take much longer to create an escalation event.

Distance Between Tanks (D = Diameter of Tank)	Time to Escalation (Hours)	
	Base Case	Adjacent
0.3 D	1.4 D	>24
0.5 D	2.7 D	>24
0.75 D	4.2 D	>24
1.0 D	5.7 D	>24
2. 0 D	11.7 D	>24

Effect of Tank Diameters

A selection of tank diameters were taken to reflect typical sizes for open top floating roof tanks. All the modelling was done for tanks of equal diameter for both the source tank on fire and the adjacent tank (receptor). It is normal practice to have the same product in similar size tanks in the same bund or dike area.

Distance Between Tanks (D = Diameter of Tank)	Time to Escalation (Hours)			
	Tank Diameter			
	(Base Case) 50M	30 M	75 M	150M
0.3 D	1.4	0.4	2.5	3.7
0.5 D	2.7	0.7	4.7	8.0
0.75 D	4.2	1.5	7.5	13.0
1.0 D	5.7	2.7	-	-
2. 0 D	11.7	5.5	>24	>24

The model indicated that increasing the tank diameter increased the time to a potential escalation.

Flame impingement would significantly reduce the time to a potential escalation for an adjacent tank. This would be particularly applicable to smaller tanks and reduced spacing e.g. 20 metres diameter with 10 metre spacing between tanks.

2.3 General Conclusions

The following conclusions were drawn from the fire modelling of open top floating roof tanks and are particularly related to highly volatile products like naphtha.

- Water spray protection or a double deck roof on their own do not prevent escalation
- Water spray protection together with a double deck is very effective in minimizing escalation. (This was substantiated by a fire at Neste Oy refinery in Finland, March 1989 when a full surface fire on a 52m diameter open top floating roof tank containing iso-hexane did not escalate to involve an adjacent crude oil tank.)
- Escalation is very probable to adjacent tanks containing highly volatile products like naphtha if tanks are spaced in accordance with internationally accepted codes (e.g. NFPA 30) unless the original fire is extinguished or adjacent tanks are protected by water sprays and double decks.
- Lower volatility products provide a much greater time before potential escalation will occur.
- Large diameter tanks and increased separation between tanks delay the potential for escalation.

2.4 Impact on Singapore StorageTank Planning Requirements

As a result of the fire modelling, the Fire Safety Bureau (FSB) of the Singapore Civil Defence Force (Licensing Authority) required the increase spacing for NFPA Class I/II products including crude oil above that required by NFPA 30 (See Appendix V) unless the tanks were fitted with water sprays and double decks.

FSB Requirements in Singapore – 1994

Tank Diameter (D = Diameter of Tank)	Tank Spacing	
	With Fixed Water Sprays	With Fixed Water Sprays and Double Deck
10 – 45 M	0.75 D	0.3 D (Naphtha and Gasoline) 0.5 D (Crude Oil)
>45 M	1.0 D	0.5 D

3. EXTINGUISHMENT OF LARGE TANK FIRES

The least understood and potentially most important aspect if a full surface fire occurs in an open top floating roof tank is the probability for extinguishment. API 2021 (1991 Edition) "Fires in and Around Flammable and Combustible Liquid Atmospheric Tanks" considers a "controlled burnout" as an acceptable fire fighting strategy with recovery of as much of the tank's contents as practicable. Accepting a "controlled burnout" requires adequate protection of adjacent exposures.

It has also been recognised that a full surface fire on very large tanks (more than 45m in diameter) pose extraordinary logistical and co-ordination problems. There is little substantiated evidence that full surface fires above 40M diameter have been successfully extinguished.

3.1 Tank Fire Dynamics

There is little practical data and no modelling known by the authors to simulate the extinguishment of a fully involved tank fire.

Fuel type (lower volatility) and tank level impact the difficulty of extinguishment. The rate of foam application may have to be increased by 60% above NFPA recommended rates to reduce losses by evaporation and thermal updrafts.

When the foam finally reaches the surface of the liquid, it has to spread across the tank itself. The application of foam has to be undertaken sufficiently quickly with the tank shell cooled with water sprays since a tank shell exposed to fire will fail within 15/20 minutes by folding inwards like the effect seen when a candle burns down. If this occurs, pockets of fuel will form underneath the steelwork which may be impossible to reach with foam and hence a total extinguishment may never be achieved.

3.2 Fire Fighting Strategies

It has to be recognised that there are substantial gaps in the knowledge for attempting to extinguish a large tank fire both in terms of application rates and distance that foam can effectively travel across a burning liquid surface.

One report[1] considers NFPA 11 "Standard for Low Expansion Foam" which quotes 30M as the maximum flow over burning liquid to be conservative and considers 50m plus to be possible. However this has never been substantiated.

The OPITSC Atmospheric Tank Study[(2)(7)] considered that semi-fixed foam application systems would be required to successfully extinguish fires in the 45m-60m diameter range.

The Commissioner of the Singapore Civil Defence Force currently requires all sites in Singapore to have sufficient on-site resources to extinguish a full surface fire up to 80m in diameter. Tanks above 80m in diameter can be extinguished with the aid of resources from industry mutual aid partners.

A last note, although large tank fires are spectacular events, risk of fatalities and serious injury should be minimal if good fire pre-planning has been implemented.

REFERENCES

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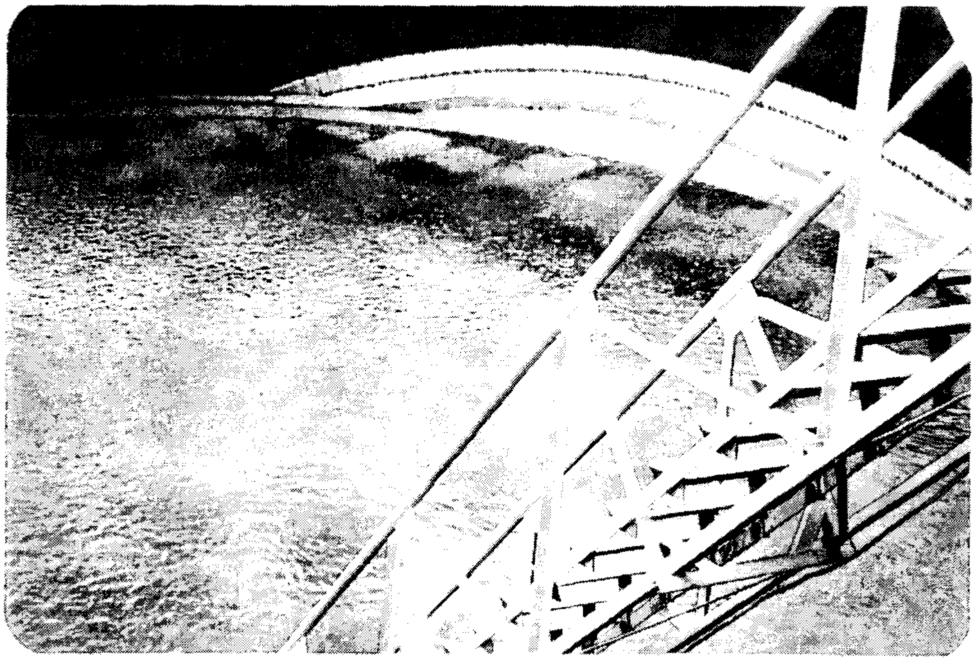
(5) Hunt DLM and Ramskill PK (1987) A description of ENGULF – a computer code to model the thermal response of a task engulfed in fire, UK Safety and Reliability Directorate R354.

(6) Ramskill PK (1988) A description of ENGULF computer codes – codes to model the thermal response of an LPG tank either fully or partially engulfed by fire. J Haz Mats, 20, p177-196.

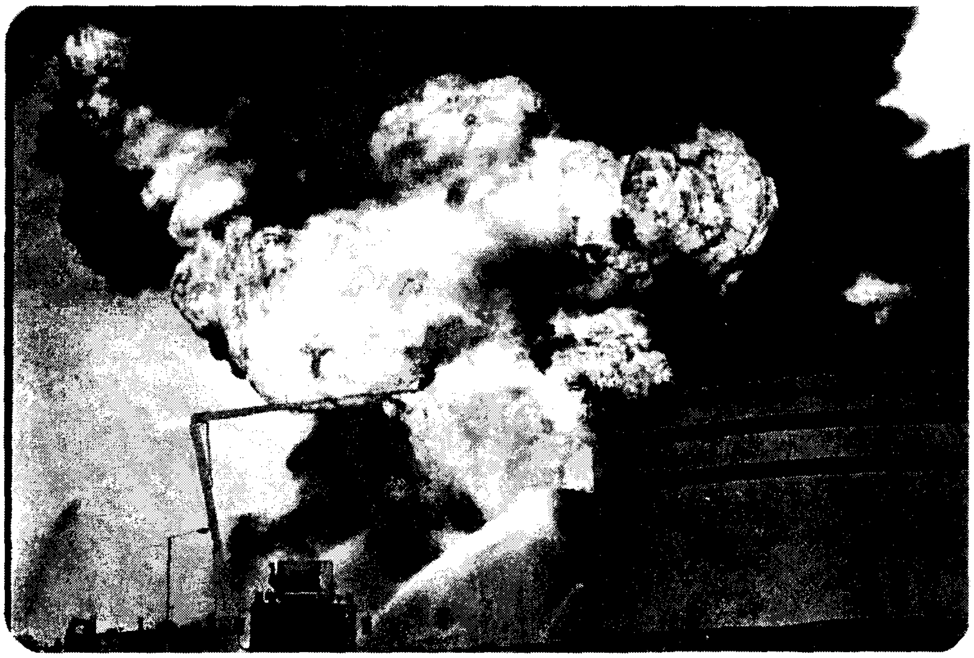
(7) Pitbaldo, R.M. Purdy, G., Bagster D.F., Lockwood, J.R., "Consequence Assessment of Atmospheric Storage Tank Fires" AIChE Process Plant Safety Symposium, Houston, Feb. 1992.

PHOTOGRAPH #1

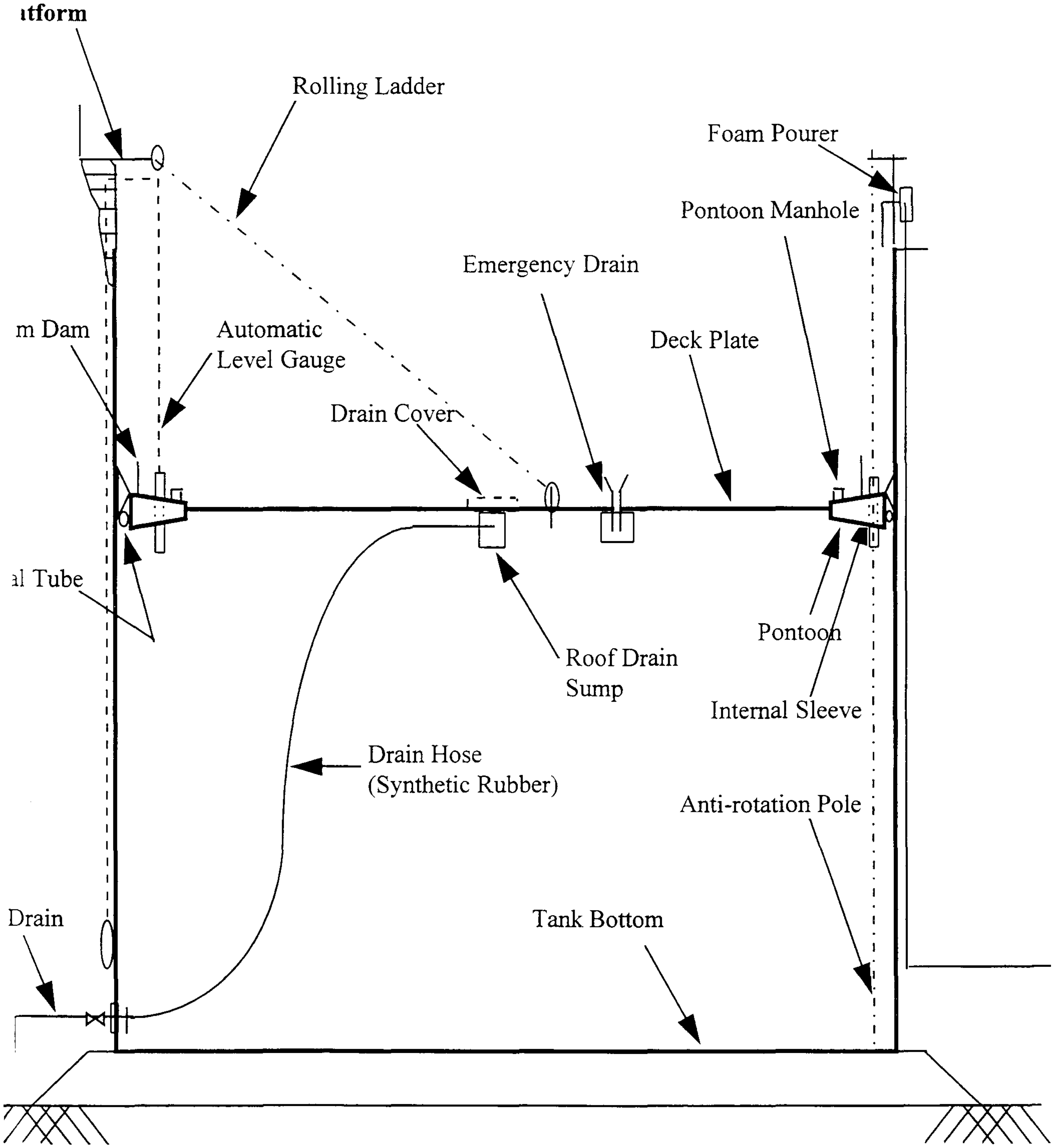


Submerged Floating Roof . To Foam or Not to Foam?

PHOTOGRAPH #2



Full Surface Fire – Protecting Adjacent Tankage With Water Sprays



Typical Design Features For A Single Deck Open Top Floating Roof Tank

Year	Country	Product	Tank Diameter	Time to Ignition
1968	CARIBBEAN	HEXANE	34m	4-5 secs
1978	US	NAPHTHA	?	?
1985	US	AVGAS	40m	2 mins
1988	SINGAPORE	NAPHTHA	41m	8 mins
1988	FINLAND	i-HEXANE	52m	2-3 secs
1991	UK	NAPHTHA	15m	2-3 secs
1991	US(?)	NAPHTHA	39m	2-3 secs

Tank fires that may have been ignited by electrostatic discharge related to foam.

CONDUCTIVITY OF REFINED PRODUCTS TAKEN FROM API 2003

Liquid	Conductivity (picosiemens per meter)	Resistivity (ohm-centimeter)	Half-Value (seconds)
Highly purified HCs	0.01	10^{16}	1500
Light distillates	0.01 – 10	10^{16} - 10^{13}	1500 x 1.5
Black oils	1000 – 100,000	10^{11} – 10^{9}	0.015 – 0.00015
Distilled Water	100,000,000	10^{6}	4 x 10^{-6}

Except for mists, electrostatic accumulation is not significant when conductivity of liquid exceeds 50 picosiemens per meter and the fluid is handled in metal containers.

APPENDIX IV

ACTIONS TO BE TAKEN IMMEDIATELY IN THE EVENT OF A SUNKEN OPEN TOP FLOATING ROOF

1. Stop all movement in and out of the tank.

2. Determine the extent of the hazardous environment using gas measuring instruments. Remove/prevent any sources of ignition in this area and prohibit access by personnel.

3. Set up the resources as stipulated in the pre-fire plan in readiness in case of a fully involved surface fire. (Pre-fire plans must be rehearsed with simulated wet drills to make sure that they are workable at times of emergencies)

4. Do not foam* unless :

- It is necessary to protect personnel from fire or flash burns if ignition were to occur during the restoration of the floating roof or removal of the product from the tank

- The tank contains crude oil (no static discharge risk)

***Note :** Because of the potential for a static discharge ignition during the application of foam, the following information is provided for guidance based on recent initial research on this matter.

A) When the decision is taken to apply a foam blanket then : -

i) Wherever possible utilise fixed foam pourers to apply the foam gently down the inside surface of the tank.

ii) Once the foam has been applied, a total surface covering should be maintained at all times until the product has been removed.

iii) Foam applied by handliness or monitors must be applied onto the inside surface of the tank and allowed to slide gently down the inside of the tank wall onto the surface of the fuel.

In no circumstances, should the foam / water mix be applied directly onto the surface of the unignited fuel as this could be the prime cause of fire caused by electrostatic generation.

iv) Wherever possible the use of portable foam inductors which induce foam compound into the delivery hose using the venturi principle should be avoided. Foam production should be by means of fire pumps having built-in inductors or round the pump proportioners.

vii) If portable inductors are the only type available, full foam throughput should be established with the water jet initially directed away from the tank. Only then should be foam be applied to the tank as noted in (iii) above.

viii) Following application of foam onto a tank fire, which appears to have been successfully extinguished, vigilance should be maintained until the remaining product has been removed. There remains a possibility that the foam blanket in breaking down through a depth of product may cause an electrostatic charge to be generated sufficient to cause reignition of any vapours present. A minimum of two to three meters (6-9 feet) product depth is required before this is a problem.

However :

B. Because of the high conductivity of crude oils, there is no risk of ignition foam static discharge during foaming operations on crude oil tanks.

C. Spill and bund fires will not be ignited by this aspect of static generation unless depth of product is greater than 6-9 feet.

Pre-Fire Plans

Detailed pre-fire planning and training with simulated wet drills is the best known way to validate the probability of successful extinguishment.