BUND EFFECTIVENESS IN PREVENTING ESCALATION OF TANK FARM FIRES

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Bunds in tank farms are usually effective in containing relatively small spillages. In certain circumstances, however, bulk storage tank contents can be released catastrophically and the bund may not be successful in retaining all of the released material. This paper reviews the incidents on the Major Hazard Incident Database (MHIDAS), where bund overtopping was known to be a contributory factor to the spread of the incident; the catastrophic failure frequency of bulk storage tanks; reasons why bunds fail to contain spilled materials; the spread of tank farm fires as a result of bund failure and the subsequent increase in individual risk.

Key Words: Bund, Overtopping, Tank Failure, Tank Farm Fire Frequency, Risk.

INTRODUCTION

Bunds are widely used in the process industries as a means of preventing spread of hazardous liquids following failure of the primary containment. UK Guidance on the construction of bunds (1)(2) gives recommendations for the volume of the bund to be equal to 110% of the volume of the storage tank (100% in USA) or, if there is more than 1 tank in the bund, then equal to 110% of the volume of the largest tank (100% in USA). Providing such bunds are properly constructed and maintained, they would be expected to contain most spillages from the primary containment.

However, it has been recognised that, in some circumstances, the bunding may not be effective in preventing the spread of hazardous material. Greenspan (3)(4), for example, showed experimentally that, in the event of a catastrophic failure of the primary storage, the momentum of the released liquid would cause it to "build-up" at the bund wall and a significant proportion would subsequently overtop the wall. The actual proportion overtopping was found to be primarily dependent on the relative height of the liquid in the tank to the height of the bund wall, with the angle of inclination of the bund wall having a smaller, secondary effect.

This paper reviews incidents of catastrophic failure of bulk storages of flammable, hazardous liquids and, from the incident descriptions, identifies reasons for the failure of bunds to contain the released materials. The particular case of spread of fire through tank farms has been studied and the contribution of bund overtopping to fire spread estimated.

Models for liquid pool spread, gas/vapour dispersion and pool fires have been used to calculate the hazardous consequences of bund overtopping. These estimations have been combined with the observations of Greenspan et al and estimated catastrophic failure frequencies for bulk storage tanks to predict the increase in individual risk as a result of bund overtopping.

CATASTROPHIC FAILURES OF BULK STORAGE TANKS

Examples of catastrophic failures of bulk storage tanks and subsequent bund overtopping, taken from the AEA Technology Consultancy Services databank, MHIDAS, are summarised in Table 1 (5)(6).

Table 1: Examples of Catastrophic Failures of Bulk Storage Tanks

Location	Date	Incident Description
Long Beach, USA	1969	Explosions in petrol storage tank during loading operations. Tank rocketed damaging bund and pipework. Fire spread to other tanks, one of which also rocketed.
Nashville, USA	1970	Roof drain piping of floating roof petrol tank froze and ruptured. Open discharge valve allowed petrol into bund and 2nd open valve allowed liquid into sewers. Explosions occurred when vapours entered treatment plant.
Moose Jaw, Canada	1980	Brittle fracture of 98,000 bbl crude oil tank released contents. Shell thrown in opposite direction breaching dyke wall. Resulting fire caused extensive damage over industrial area.
Tacoa, Venezuela	1982	Explosion and fire in fixed roof storage tank during gauging operation. Boil-over spread incident over large area, killing more than 150 people and igniting contents of second tank.
Milford Haven, UK	1983	Bulk storage tank contents ignited by hot particles from nearby flare stack. Tank boiled over after 12 hours causing fire over 4 acres. Second boil-over 2 hours later. Two other tanks involved in fire which took 36 hours to extinguish.
Thessalonika, Greece	1986	Sparks from welding torch ignited fuel spills in tank farm. Fire spread by grass and fuel spills, passing through pipe channels in bund. Ten out of 12 tanks involved in fire, with 1 boiling over.
Colon, Panama	1986	Storage tank ruptured spilling 240,000 bbl of light crude oil. Force of oil ruptured dyke allowing oil to flow into refinery area and drains.
Floreffe, USA	1988	40 year old re-assembled diesel oil tank suddenly ruptured and released contents. Estimated 1,000,000 US gall washed over 10 ft dyke into drainage system on adjacent property. Force of spurting oil moved tank 100 ft off its foundations
Brisbane, Australia	1988	Several thousand people evacuated when 1,200,000 gall petrol tank ruptured at fuel depot.

Inspection of incidents recorded on the MHIDAS database gave the following reasons for catastrophic releases from storage vessels:

(i) Brittle failure of primary containment - sometimes associated with rapid changes in ambient temperature;

(ii) Failure of tank seams due to fire attack;

(iii) Failure of the tank during the initial filling process;

(iv) Boil over of tank contents;

(v) Acts of vandalism or sabotage.

Additionally, the following reasons for failure of the bund to contain losses from the primary containment(s) were mentioned:

(a) Overtopping of bund by surge of liquid;

(b) Structural failure of bund due to impact of the stored liquid;

(c) Structural failure of bund due to impact by pieces of collapsing vessel;

(d) Fire fighting water retained, resulting in overfilling;

(e) Drain valves left open;

(f) "Holes" in the bund wall;

(g) Failure of 2 or more tanks in a common bund;

(h) "Rocketing" of tanks carrying associated burning liquid.

No instances of "spigot flow" (7) (ie, liquid flowing from a hole near the top of the tank having sufficient momentum to clear the bund) are recorded on the MHIDAS database, although incidents of spigot flow have been reported elsewhere (8).

COMPARISON OF GREENSPAN'S PREDICTIONS WITH HISTORICAL DATA

Reports of the incident at Floreffe, Pennsylvania in January 1988 gave sufficient details for a comparison with the theories/experimentation of Greenspan et al.

Following rupture of a oil storage tank (14.6 m tall and 18.3 m radius) approximately 3.5 million US gallons (13250 m^3) of the fuel were released (5). Part of this spillage was retained by the bunding surrounding the failed tank and some by the bunding of neighbouring tanks. The total containment system (3.05 m tall bunds) retained an estimated 2.5 million

US gallons and the remaining 1.0 million US gallons drained into a nearby waterway. From diagrams of the tank farm, the bund round the failed tank was estimated to have a volume of ½ to ¾ of that of the total containment system and it is therefore assumed that the primary bunding retained somewhere between 1 million and 2 million US gallons (3800 m^3 and 6400 m^3).

Now, volume of liquid in the tank = 13250 m^3,

$$\therefore \textit{height H of liquid in tank} = \frac{13250}{\Pi \times 18.3 \times 18.3} = 12.6m \tag{1}$$

$$\therefore \textit{ratio of } \frac{\textit{height of bund h}}{H} = \frac{3.05}{12.6} = 0.24 \tag{2}$$

None of the reports of the incident mentioned the angle of dyke inclination but from photographs it was estimated as 30°. For 30° angled bund walls ref (4) records that for h/H = 0.234 and for complete tank lift-off an overtopping fraction of 0.67 was observed. From the above, the actual fraction overflow at Floreffe was estimated as:

$$\textit{Minimum fraction overtopping bund} = \frac{13250 - 6400}{13250} = 0.40 \tag{3}$$

$$\textit{Maximum fraction overtopping primary bund} = \frac{13250 - 3800}{13250} = 0.71 \tag{4}$$

While this comparison is necessarily coarse and several gross assumptions have been made, the agreement between the predicted fraction to the upper limit of the estimated "observed" overtopping fraction gives confidence in applying the theoretical/small scale experimental work to large volume installations.

FREQUENCY OF CATASTROPHIC FAILURE OF BULK STORAGE TANKS

Non-Fire Failure

Estimated frequencies of catastrophic failure of bulk storage tanks from historical evidence and theoretical, fault tree calculations are summarised in Table 2. Although the number of actual failures is small, the historical records and the theoretical estimations indicate a generic failure rate for bulk storages of the order of $10^{-7} \rightarrow 10^{-6}$ per year.

Table 2: Frequency of Catastrophic Failure of Bulk Storage Tanks (non-fire failure)

Frequency (per tank.year)	Reference	Type of Storage	Basis of Calculation	Comments
2×10^{-7}	(9)	General purpose liquid	2 tank failures in USA in period 1968-88. Tank population estimated at 600,000 over this 20 year period.	Tanks assumed to be thin-walled and non-pressurised
$< 2 \times 10^{-5}$	(10)	General purpose liquid	No major incident in estimated 150,000 tank years operation in UK in past 50 years. Quoted value is statistical upper limit on the actual failure rate (11)	As above.
$< 2 \times 10^{-5}$	(12)	Pressure vessels	Value of 2×10^{-5} derived from analysis of 300,000 vessel years in period 1962-76	Catastrophic failure defined as "destruction of vessel or component necessitating major repair, replacement or scrapping". Vessels considered were Class 1 pressure vessels mostly having full stress relief and 100% weld radiography.
1×10^{-6}	(13)	LNG inner aluminium, outer steel tank	Full details not given	Likelihood of failure of "serious fatigue failure" estimated as $<1 \times 10^{-5}$. Assumed that 1 in 10 probability of "serious fatigue failure" resulting in catastrophic failure of inner tank.
4.3×10^{-5}	(14)	Acrylonitrile atmospheric pressure vessel	Fault tree analysis	
$0.8 \rightarrow 2.0 \times 10^{-6}$	(15),(16)	LNG	Not given	Various designs and capacities considered
1×10^{-6}	(14)	LNG	Fault tree analysis	

Storage Tanks Subject to Fire Attack

Of the tank farm fires analysed in Ref (6), in every case where there was more than 1 tank in the bund the fire spread to involve other vessels. When the tank was in its own bund the probability of tank failure following fire attack was found to be approximately 0.5.

Frequencies of fires in bunds have been estimated as 1.2×10^{-4} per tank.year for highly flammable liquids and 1.2×10^{-5} per tank.year for flammable liquids (17). Combining these frequencies and probabilities gives the following tank fire failure rates:

i highly flammable liquid (18) in common bund = 1.2×10^{-4} per year

ii highly flammable liquid in own bund = 6.0×10^{-5} per year

iii flammable liquid (19) in common bund = 1.2×10^{-5} per year

iv flammable liquid in own bund = 6.0×10^{-6} per year

For shared bunds the fire and failure frequencies are multiplied by the number of tanks in the bund.

SPREAD OF TANK FARM FIRES AS A RESULT OF BUND FAILURE

The results of a search of the MHIDAS database to identify incidents involving release of flammable liquids from atmospheric storage vessels are summarised in Table 3. Table 3 includes analysis of vessels where the presence or absence of a bund was specifically mentioned. Inspection of Table 3 shows that:

- the majority (84%) of releases ignited although the proportion was slightly less for bunded vessels (61%). These values probably overestimate the actual probabilities since instances of fires are more likely to be reported to the database than examples of liquid releases;
- where the presence of a bund was specifically mentioned there was a probability of 0.4 that the bund was ineffective for one, or more, of the reasons mentioned above;
- the probability of fire spread to other vessels was significantly less for bunded vessels (39%) than for unbunded vessels (80%) even though the number of tanks in the bund was not taken into account in Table 3.

Table 3: Comparison Between All Atmospheric Storage Incidents and Incidents in Bunded Installations

		All Incidents	Bunded	Unbunded	Not Known
No of Incidents		376	51	5	320
Ignition		314 (84%)	31 (61%)	4 (80%)	278 (87%)
Reasons for Bund Failure	Overtopped	-	9 (18%)	-	-
	Breached	-	11 (22%)		
	Not Recorded	-	10 (19%)	-	-
Fire Spread to Other Vessels		174 (46%)	20 (39%)	4 (80%)	148 (46%)

The 51 recorded incidents where the presence of a bund was specifically mentioned were further investigated and the results are shown in Table 4, which analyses the results in terms of:

- incidents in tank farms where the tanks were individually bunded;
- incidents in tank farms where the tanks were in common bunds;
- incidents involving isolated tanks.

Table 4: Summary of Results for Bunded Installations

	Tank Farm		Isolated Tank	Unknown	Total
	Shared Bund	Single Tank in Bund			
No of Incidents	15	17	10	9	51
Ignition	13 (87%)	12 (71%)	5 (50%)	1	31 (61%)
Bund Fails to Retain Spilled Liquid	12 (80%)	7 (31%)	5 (50%)	6	30 (59%)
Other Vessel Involved	14 (93%)	6 (35%)	0	0	20 (39%)

Inspection of Table 4 shows that:

- the probability of ignition was greatest (0.87) for releases from tanks in common bunds;
- the probability of the bund failing to contain the release was greater for tanks in a shared bund (0.80) than single tanks (0.50) or singly bunded tanks (0.31).
- the spread of the incident to other tanks was significantly greater for tanks in common bunds than for tanks in single bunds.

INCREASE IN INDIVIDUAL RISK LEVELS FOLLOWING BUND OVERTOPPING

Individual risk levels were estimated for bunded and unbunded releases based on the current Health and Safety Executive definitions of dangerous dose summarised in Table 5 (20). Estimates were made of the increase in hazard range and individual risk following catastrophic failure of a 12000 m^3 heptane storage tank with a fill height of 15 m (chosen to model spillage from a "typical" petrol storage tank).

Assumptions

In order to simplify the calculations, the following assumptions were made:

1. A catastrophic failure rate of atmospheric storage tanks of 1×10^{-6} per year;
2. A bund height of 2 m and an equivalent bund radius of 46 m;
3. Ignition probability of 0.3 (as given for large releases in ref (21));
4. Given ignition, then probabilities of immediate (1 minute) and delayed (at time of maximum pool vaporisation rate) ignition of 0.3 and 0.7 respectively (22);
5. A probability of 1 of death or severe injury for people within the envelope of an ignited gas cloud;
6. A probability of confinement (thereby leading to blast overpressures) of 0.5 (broadly deduced from a study of ref (23));
7. Relative probabilities of Pasquill weather conditions D5 and F2 of 0.8 and 0.2 respectively (as used in ref (21)).

Table 5: Definition of Dangerous Dose (20)

Hazard	Dangerous Dose
Pool Fire	1000 thermal dose units (1 thermal dose unit = $1(kW)^{4/3}$.sec, which has been interpreted as equivalent to exposure to a thermal flux of 19 kW/m^2 for 20 seconds)
Flash Fire	Extent of vapour cloud above LFL
Vapour Cloud Explosion	140 mbar (2 psi) overpressure

Consequence Modelling

Consequences were assessed using software tools available in AEA Technology, that is:

A. Pool size (radius) and mass evaporation rate from the pool were calculated as a function of time using the AEA computer code "GASP" (24). In order to represent events in which liquid overtops the bund, a two-stage approximation was used:

i for the material retained within the bund a mass evaporation rate, (m_r), of a pool equivalent to the bund radius was estimated;

ii for the material overtopping the bund, the mass evaporation rate (m_o), was estimated by using the bund radius as input for the GASP program.

The total mass evaporation rate was obtained by summing the two contributions.

B The radiant heat intensities at various distances from a pool fire of given radius were estimated using the AEA code PFIRE2 (25).

C The sizes and shapes of unignited vapour clouds as they drifted downwind were estimated using the AEA/HSE computer code DRIFT (26). Flash fires were assumed to be possible in gas clouds of concentration greater than the lower flammable limit of the material being investigated (10).

D The overpressures from vapour cloud explosions were calculated using the AEA technology code EXPEL1 (27), assuming:

i partial confinement;

ii a "low" ignition strength;

iii cloud volumes of "distance to LFL" x "width to LFL" x "height to

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i partial confinement;

ii a "low" ignition strength;

iii cloud volumes of "distance to LFL" x "width to LFL" x "height to

LFL" as predicted by the DRIFT computer runs;

iv one third of cloud contributes to the VCE (based on the confinement expected of a typical tank storage layout).

Results

From the graphs presented in Greenspan's papers (3)(4), shown in Figure 1, it was estimated that following a catastrophic failure of the tank/bund configuration studied, 63% percent of the tank's contents would overtop the bund.

On this basis, the results of the hazard range and individual risk estimations against distance from the storage facility are summarised in Tables 6 and 7.

Table 6: Hazard Ranges following Release of 12000 m^3 Heptane

		Release Contained by Bund	**63% Release Overtopping Bund**
Pool Radius (m) 1 minute after Release		46	164
Maximum Pool Radius (m)		46	500
Distance to LFL (m) from Edge of Pool	D5 Weather	15	170
	F2 Weather	62	1600
Plume Width (m)	D5 Weather	95	1020
	F2 Weather	114	2200
Plume Height (m)	D5 Weather	0.3	1.71
	F2 Weather	0.4	1.6
Distance (m) to Dangerous Thermal Dose (Immediate Ignition)	D5 Weather	72	250
	F2 Weather	92	190
Distance (m) to Dangerous Thermal Dose (Delayed Ignition)	D5 Weather	72	580
	F2 Weather	92	540
Distance (m) to Dangerous Overpressure Dose	D5 Weather	10	95
	F2 Weather	20	250

Table 7: Estimated Individual Risk following Catastrophic Failure of 12000 m^3 Heptane Storage Tank

Hazard	Risk (per year) at Distance (m) from Storage Tank						
	Contents Retained by Bund		Bund Overtopped				
	40	100	40	100	200	400	1000
Flash Fire	1.0×10^{-7}	0	1.0×10^{-7}	1.0×10^{-7}	1.0×10^{-7}	1.0×10^{-7}	4.8×10^{-8}
Pool Fire	9.0×10^{-8}	0	9.0×10^{-8}	9.0×10^{-8}	7.2×10^{-8}	0	0
VCE	1.1×10^{-7}	0	1.1×10^{-7}	1.1×10^{-7}	1.1×10^{-7}	1.1×10^{-7}	0
TOTAL	3.0×10^{-7}	0	3.0×10^{-7}	3.0×10^{-7}	2.8×10^{-7}	2.1×10^{-7}	4.8×10^{-8}

Inspection of Table 7 shows that, as would be expected, close to the storage facility there is no difference in the estimated Individual Risk regardless of whether or not the bund is overtopped. However, in the case were the bund retains the spill of liquid the risk fall off very quickly with distance from the storage facility, whereas for the case where the bund is overtopped the risk levels fall off much more slowly.

Additionally, inspection of Tables 6 and 7 shows that, although the vapour cloud produces a larger hazard range through a flash fire than a VCE, the angle of entrapment reduces the numerical risk of the flash fire. This means that at intermediate distances (100 m → 400 m) the effects are similar but at further distances only the flash fire contribution to the overall risk remains.

CONCLUSIONS

1 Based on the experimental of Greenspan et al (3)(4) and the investigation of incidents recorded on the MHIDAS database (although information is not available as to when the installations involved in incidents recorded on the MHIDAS database were constructed), it is likely that some of the currently used bunding systems would not prevent spread of an incident following catastrophic failure of a storage tank.

2 Common causes of releases from bunds are due to overtopping, damage to the bund by the vessel as it collapses, or the integrity of the bund being compromised by open valves, poor state of repair or holes made for operational reasons (getting equipment in or out of the bund).

3 Escalation of historical incidents was of greatest probability for tank farm storage tanks in common bunds, followed by tank farm storage tanks in single bunds, followed by single tanks.

4 For individuals close to, or within the bund, of a storage tank the exposed risk is not

significantly altered by the effectiveness of the bund. For individuals further from the storage the estimated risk is significantly increased if bund failure is taken into account.

5 Although the risk levels estimated in the example shown in the text of the paper is below the HSE proposed "trivial" level of IR = 1 x 10^{-6} per year at the lower end of the ALARP (as low as reasonably practicable) region (21), this a reflection of the frequency of the initiating event (a tank catastrophic failure rate of 1 x 10^{-6}). In the case of tank farms with several dozen tanks, the risk within at least the nearer parts of the hazard range would enter the ALARP region on the basis of the increased number of tanks. Additionally, and perhaps more importantly, the total risk for large tank farms would be expected to be increased by possible escalation between tanks.

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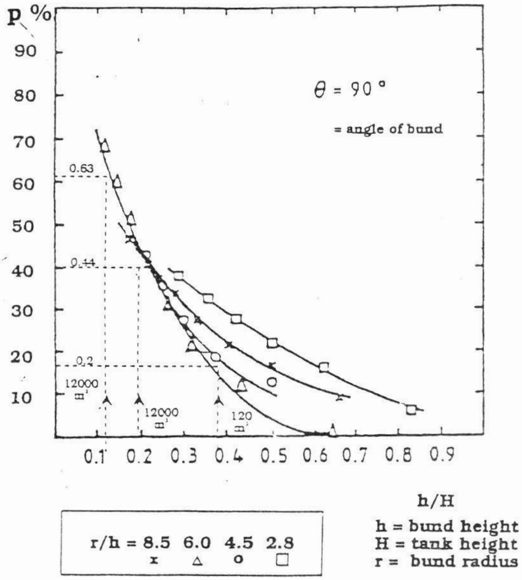

Figure 1. Overtopping Percentage p against h/H (from References 3,4)