Storage Tank Explosion Frequencies on FPSOs

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This paper presents a new estimate of the frequency of explosions in the oil storage tanks of floating production, storage and offloading (FPSO) vessels.

Although no such event has occurred to date, the fatal explosion in the pump room of the FPSO *Cidade de São Mateus* in Brazil shows that it could happen. Offshore operators need to assess the risks to design against them. Existing published estimates of the tank explosion frequencies are based on explosions on conventional trading tankers, some dating back to the 1970s and 80s, with judgemental adjustments for trends and for the unique features of FPSOs.

A new analysis of fires and explosions in cargo tanks of large oil tankers trading world-wide shows a significant reduction in accident frequency in recent decades, probably due to the progressive introduction of inert gas systems, segregated ballast tanks and double-hulls. These are now fitted to the entire fleet, but there have been so few accidents on modern vessels that it is now difficult to obtain robust results for these alone. Although the oil storage tanks on FPSOs are much like cargo tanks on trading tankers, there are many specific differences that may affect the frequencies. This paper proposes an approach to these issues, and presents new frequencies and confidence ranges appropriate for modern FPSOs.

Key words: Risk analysis; fire and explosion hazards; tank explosions; accident frequencies

Introduction

Floating production, storage and offloading (FPSO) vessels produce and process oil and temporarily store it in large tanks prior to offloading. Their oil storage tanks are like the cargo tanks on conventional trading tankers. While many trading tankers have suffered cargo tank explosions, there has never been an explosion in the oil storage tanks of an FPSO. Nevertheless, there is an undoubted potential for such an event. The fatal explosion in the pump room of the Brazilian FPSO *Cidade de São Mateus* in February 2015 highlights the potential for major accidents on this type of vessel.

Offshore operators need to assess the risks of such events to design against them. One of many inputs needed for an FPSO quantitative risk assessment (QRA) is the frequency of storage tank explosions (i.e. the annual likelihood on an individual FPSO).

The challenge of estimating the frequency of an event that has never happened is a common one in QRA. One approach is to build a fault-tree model of the causes of such events. This can take account of the specifics of an individual FPSO design, and can be quantified using incident data or expert judgement. However, the results of such a model can be very uncertain, and it is desirable to calibrate it against actual explosion frequencies.

Another approach, which gives a direct estimate of the average explosion frequency, is to use experience from a larger group of similar vessels. In the present case, the world-wide fleet of trading tankers is appropriate. There have been many explosions on such ships, in part because there are many more of them at sea. Because of the similarity in tank designs, the frequency of cargo tank explosions on trading tankers can be used to estimate the frequency of storage tank explosions on FPSOs. Adjustments can be made to account for any important differences.

Yet the frequency of explosions in the cargo tanks of trading tankers is also very uncertain. In the 1980s there were many such events, but tanker design and operation have improved since then. In recent years, there have been so few cargo tank explosions that it becomes difficult to estimate the frequency. Many QRAs are based on published estimates of the tank explosion frequencies on trading tankers dating back to the 1970s and 80s.

The process of estimating the frequency of storage tank explosions on a modern FPSO can therefore be split into two important aspects:

- Estimating the frequency of cargo tank explosions on modern trading tankers.
- Adjusting the frequency to estimate the frequency of storage tank explosions on FPSOs.

This paper considers these two aspects in turn, developing a new explosion frequency estimate for storage tank explosions on FPSOs.

Cargo Tank Fire/Explosion Frequency on Trading Tankers

Data Selection

This analysis has made use of data on large oil tankers, defined as those over 80,000 dwt[1], as these are comparable in size to FPSOs. There are roughly 2000 such ships in service around the world.

The IHS (2014) casualty database was used as the basis because this is the most comprehensive available data source. Casualties were selected for the period 1980-2013, in all reported locations world-wide. This includes events occurring at sea, in port, at anchor and in yards (construction, repair and scrapping). Although construction and scrapping could be

[1] Dwt refers to deadweight tonnage, approximately the cargo-carrying capacity of the vessel, measured in metric tonnes

excluded as not relevant for a QRA of normal operations, there were very few such events and they are included for completeness.

The analysis covered events categorised as "fires/explosions". Available accident reports do not distinguish rigorously between fires and explosions, and hence it is difficult to separate them. Events occurring in tank spaces were identified from the details provided by IHS. This excluded events in the engine room, pump room, other equipment rooms, superstructure, transfer equipment or forecastle area, even if they subsequently escalated to affect cargo tanks. It included explosions in non-cargo tanks, since these were typically from leaks of cargo (or cargo vapour) into them.

Historical Average Frequency

In total 88 tank fires/explosions were identified. The exposed population of oil tankers over 80,000 dwt during 1980-2013 is estimated to be 40,097 ship-years, based on the IHS database. The overall frequency of tank fire/explosion is therefore estimated as 88/40097 = 2.2×10^{-3} per tanker year.

IHS categorises the severity of maritime casualties as follows:

- Total loss, in which the ship has ceased to exist, because it was either irrecoverable or broken up because of the casualty.
- Serious casualty, which includes casualties causing breakdown, structural damage that makes the ship unseaworthy, total loss or other damage or financial loss that IHS considers to be serious.
- Non-serious incidents, including any other reported incidents in which the condition of the ship suffers adversely.

Table 1 gives the breakdown of the fires/explosions into these categories. Out of the 88 events, 17 resulted in total loss of the ship and 31 others were considered serious.

Table 1. Cargo Tank Fire/Explosion Frequencies on Trading Tankers Over 80,000 dwt, 1980-2013

SEVERITY	EVENTS (1980-2013)	FREQUENCY (per tanker year)
Total losses (TL)	17	4.2E-04
Serious casualties (excluding TL)	31	7.7E-04
Serious casualties (including TL)	48	1.2E-03
Non-serious incidents	40	1.0E-03
All events	88	2.2E-03

Frequency Trend

Figure 1 shows the fire/explosion frequencies in each year. Although there are many random variations year-to-year, there have clearly been fewer accidents recently, and hence the average frequencies above may be pessimistic if applied to current operations. Figure 2 shows 5-year averages of the same data, which clarifies the trends. Almost all events are now serious casualties, since hardly any non-serious incidents have been reported since 1998 and there have been no total losses since 2001.

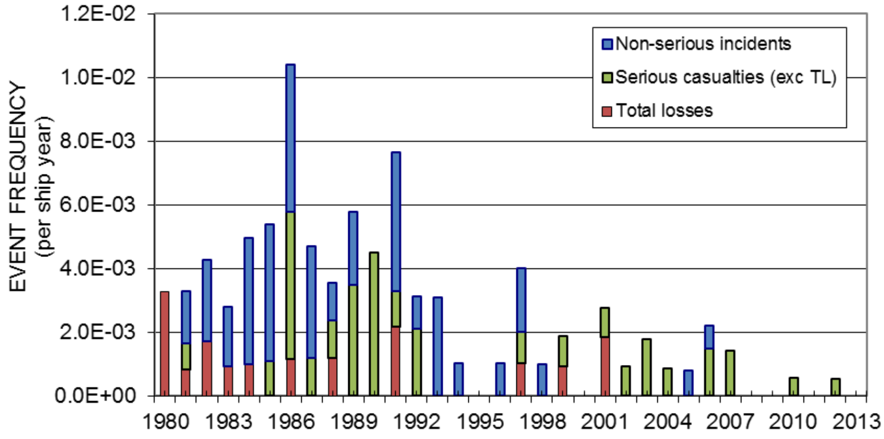

Figure 1. Annual Tank Fire/Explosion Frequencies

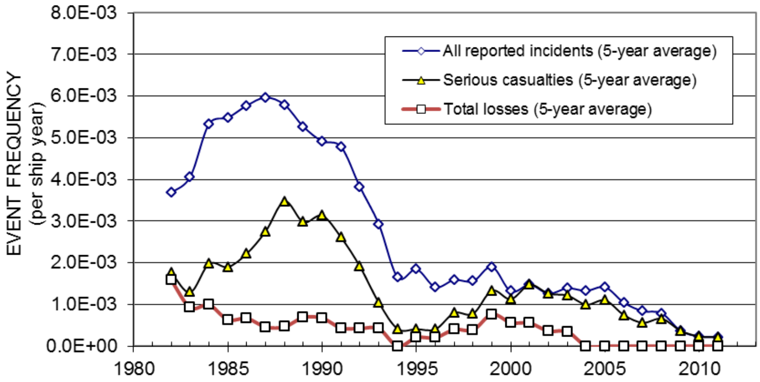

Figure 2. Smoothed Trend in Tank Fire/Explosion Frequencies

To interpret the trends, it is necessary to take account of some important changes in tanker design during this period. The requirements affected different sizes of vessel, and mainly covered new-built tankers not the existing fleet. The following summary is approximate:

- Inert gas systems (IGS) were first required in 1974 for tankers over 100,000 GT[2] in the USA; international requirements for new tankers over 20,000 dwt were introduced in 1982; and these were extended to existing tankers in 1985.
- Segregated ballast tank (SBT) requirements, which reduced the need for tank cleaning, were introduced for new tankers over 20,000 dwt in 1983, and existing tankers were phased out by 2010.
- Double-hull requirements were introduced in 1993 for new tankers over 5000 dwt, and were extended to existing tankers in 2005, although some single-hull tankers with protectively-located tanks continued in service until 2010. This phase-out also had the effect of reducing the average age of the tanker fleet.

The reduction in frequency since the mid-1980s is probably due to the progressive introduction of these changes.

Although the introduction of double-hull tankers appears to coincide with the largest reduction in explosion frequency, it is not certain why this reduction occurred. Double hulls are mainly intended to prevent oil spills, and may help prevent tank explosions originating from these, but they do not affect the main causes of tank explosions. Furthermore, they introduce explosion hazards in the double-hull spaces. It is possible that the explanation is not related to the double-hull as such, but to the fact that double-hull requirements were met by new-building rather than retrofits. At present, most double-hull tankers are relatively new, and newer tankers tend to experience fewer accidents than older ones.

Therefore, although the trend shows steady improvement over the last decade, it may be optimistic to expect the frequency to continue reducing. As the double-hull fleet ages, it is possible that the frequency will begin to increase. Positive trends have reversed before, notably in the late-1990s. Therefore, no extrapolation of the trend is attempted.

Frequency for Modern Tankers

The recent safety improvements mean that it is now very difficult to estimate the frequency of tank explosions on modern trading tankers. Ideally, only the period since 2010 would be used, since this eliminates single-hull tankers. However, there have been so few accidents since then that it is not yet possible to obtain robust results from this period alone. Any result would be sensitive to the period chosen.

Another approach, which gives more stable results, is to estimate the frequency on double-hull tankers. Based on the hull design categorisation by IHS, combined with other sources of information on vessels that were converted, there were 7 double-hull and 2 double-sided vessels among the 88 tank fires/explosions. This is 10% of the fire/explosion events. Of these 9 events, 8 were serious casualties (and none were total losses), which is 17% of the total serious casualties. The exposed population of double-hull oil tankers over 80,000 dwt has been estimated from the IHS fleet database as 20,491 ship-years, which is 51% of the total exposure during 1980-2013, but has been 100% of the fleet since 2010.

The values above imply a frequency for serious casualties due to tank fires/explosions on double-hull tankers of 8/20,491 = 3.9×10^{-4} per tanker year. Consideration of alternative approaches indicates an uncertainty range of approximately a factor of 2 higher or lower.

Tank Explosion Frequency

The data above refers to the frequency of serious casualties due to fires/explosions. An FPSO QRA typically needs to know the frequency of explosions. Fires that develop no blast overpressure are not of interest, whereas explosions that are vented without causing serious damage should be included. Available casualty reports do not distinguish reliably between fires,

[2] GT refers to gross tonnage, which is a measure of the enclosed volume of the vessel, typically approximately equal to dwt/2.

explosions and events involving both fires and explosions. However, based on the event descriptions in the IHS database, the total number of explosions (50) is similar to the number of serious casualties (48). Hence the frequency of serious casualties due to fire/explosion provides a reasonable estimate of the total frequency of explosions.

Application to FPSOs

Comparison of FPSOs and Trading Tankers

Oil storage tanks on FPSOs are much like cargo tanks on trading tankers. Although some FPSOs are new-built vessels, others are in fact converted trading tankers, sometimes single-hull tankers that have been taken out of service due to recent double-hull requirements.

Key differences that might affect the risks of tank explosions are:

- New-build FPSOs typically have more, smaller tanks than trading tankers of the same size, because the weight of topside process equipment reduces stability in the flooded condition, requiring smaller compartments to meet the damage stability requirements. A previous analysis (OGP 2010) assumed the explosion probability varies with the number of tanks, but also assumed that FPSOs would have fewer, larger tanks. Comparing an FPSO with 6 tanks to a typical trading tanker with 12 tanks, it reduced the explosion frequency by 50%. However, there is no evidence that the frequency varies with the number of tanks and not the tank size. More tanks imply more pipework for leaks, but most explosions are due to maintenance and tank cleaning, which would relate more to the area of tank surface than the number of tanks.

- New-build FPSOs may have cofferdams between tanks, whereas trading tankers rarely do. This enables better detection of leaks between tanks, but introduces new explosion hazards if detection is unsuccessful. Available causal data suggests that leaks contribute a small proportion of the causes of serious casualties on trading tankers, so a reduction in this component may not be very significant. The major benefit of reducing escalation probabilities is outside the scope of the present analysis.

- Converted FPSOs may have single-hulls, whereas trading tankers all now have double-hulls. Double-hulls are mainly intended to prevent oil spills, but frequency data suggests that single-hull FPSOs would have a much higher explosion frequency.

- FPSOs are continuously loading, whereas trading tankers load intermittently in port. This might increase the frequency of explosions due to loading, although this contributes only a small proportion of the causes of serious casualties on trading tankers, so an increase in this component may not be very significant. Normally only one FPSO tank is being loaded at once, so the total number of tank hours being loaded may be more similar.

- FPSOs load and discharge at sea, whereas trading tankers do so in port. In rough weather this might make leaks more likely. However, weather contributes only a small proportion of the causes of serious casualties on trading tankers, so an increase in this component may not be very significant.

- FPSOs operate at one location, whereas trading tankers typically load and discharge in different ports. This allows for more consistent safety management on FPSOs, which may reduce explosion frequencies. On the other hand, it reduces the ability to avoid severe weather, which may make leaks more likely as above.

- New-build FPSOs are typically designed for service at the intended location, whereas trading tankers are designed for generic ocean climates (based on North Atlantic wave conditions). This may significantly affect explosion risks at the end of the vessel's service life, but it depends on the inspection and maintenance regime, and is difficult to predict in advance. There is no obvious reason why it should result in different average explosion frequencies.

- Converted FPSOs may be based on older hull structures, whereas current trading tankers are relatively new structures due to the recent double-hull requirements. In general, accident frequencies vary strongly with vessel age, and the explosion frequency may therefore be higher on a relatively old vessel. However, this depends on the inspection and maintenance regime, which may be sufficient to compensate for the increased hazard. The current trading tanker explosion frequency, based on double-hull vessels, may be appropriate for new-build FPSOs, whereas the older values, based on a mix including single-hull vessels, may be more appropriate for converted FPSOs.

- FPSOs typically have process equipment on the decks above the storage tanks. This may increase the sources of leaks in this area, and the ignition probability for any leaks from the tanks. It also increases the escalation potential for any tank explosion, but this is outside the scope of the present analysis. The increased number of structural attachments increases the potential for fatigue cracking.

- FPSO tanks require tank cleaning for inspection and repair and to prevent accumulation of deposits, resulting in a few tanks being washed on every unloading cycle, whereas trading tankers require tank cleaning for any change of cargo type. Depending on the number of offloading cycles, this may result in an FPSO carrying out tank washing more frequently. This is expected to increase the likelihood of explosions due to tank cleaning on an FPSO. Tank cleaning contributes substantially to the causes of serious casualties on trading tankers, so an increase in this component may be significant.

- FPSO tanks are normally inspected and repaired if necessary at sea during the annual shut-down, and very rarely taken to port, whereas trading tankers normally visit repair yards for inspection and repair. This may make repairs more difficult, but it also allows closer management control on FPSOs. Repairs contribute substantially to the causes of serious casualties on trading tankers, so if the annual shut-down is excluded by the scope of the study there will be a significant reduction in the frequency.
- FPSOs are normally maintained under the operator's own asset integrity programme, whereas trading tankers are subject to classification society requirements. However, third party verification of operator's maintenance is equivalent to classification requirements, and FPSOs are subject to classification society requirements while sailing to and from station, so the difference may not be very large.
- FPSO risk assessments normally refer to the operational part of the life-cycle. Events during construction and scrapping should therefore be excluded from the analysis. These contribute only a small proportion of the causes of serious casualties on trading tankers, so this is a small change.

Overall, there are no strong reasons to make a major change in the explosion frequency from trading tankers, unless the FPSO is a converted single-hull tanker, or if the annual shut-down is excluded from the scope. Some factors suggest an increase whereas others suggest a reduction. Estimates of the changes are mainly small, and less than the uncertainty in the original estimate. Therefore, it is proposed to use the trading tanker frequency directly.

Selected Frequency for FPSOs

The selected frequency of storage tank explosions on new-build FPSOs is therefore taken as 3.9×10^{-4} per FPSO year, based on the serious casualty value for double-hull trading tankers. This implies an explosion on average every 2600 FPSO-years. Cumulative experience with FPSOs to date is less than this, so the frequency is consistent with the absence of explosions to date.

The trading tanker data suggests that almost half of serious casualties occur during repair and tank cleaning. If the scope of the FPSO study excludes these operations, which are mainly associated with the annual shut-down, then this would justify making a further reduction in the frequencies by a factor of 2.

Comparison with Previous Analyses

Previous analyses of this issue included the following:

- Thompson & Prentice (1990) estimated a cargo tank fire/explosion frequency of 4.4×10^{-4} per tanker year. This was based only on experience with trading tankers in port, which is less onerous than loading and offloading FPSOs at sea. Nevertheless, the frequency is close to the present estimate.
- CMPT (1999) estimated a cargo tank fire/explosion frequency of 2.2×10^{-3} per tanker year. This was based on experience with trading tankers during 1972-86, which is now excessively old.
- The International Association of Oil & Gas Producers (OGP 2010) estimated a storage tank explosion frequency of 8.8×10^{-4} per FPSO year. This used the same old data as CMPT, combined with an assumption that FPSOs had half as many tanks as trading tankers.

The current estimate is lower than the latter two analyses, due to the use of more recent data. Fortuitously, it is consistent with the older source, although it is considered more justifiable. The OGP value could be appropriate for a sensitivity test, being approximately a factor of 2 higher.

Conclusions

This paper estimates the average storage tank explosion frequency as 3.9×10^{-4} per FPSO year, based on world-wide experience with double-hull trading tankers over 80,000 dwt during 1980-2013. Consideration of alternative approaches indicates an uncertainty range of approximately a factor of 2 higher or lower. This is a generic average value suitable for typical new-build FPSOs. Converted FPSOs may experience much higher frequencies. Approximately half the frequency arises from tank cleaning and repairs during annual shut-down. Studies of individual FPSOs may be able to reflect their unique features and any differences from modern trading tankers.

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