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Analysis of a Propane Sphere BLEVE

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The events in March of 2011 in Japan have provided us with an example of what can happen when large LPG spheres are exposed to severe fire engulfment. This paper presents an approximate failure analysis of a sphere exposed to a severe fire engulfment scenario. It estimates the expected failure time of the sphere based on predicted wall temperatures and internal pressure buildup. The prediction of the pressurization rate is based on a two-zone, thermally stratified liquid model. It shows that the pressurization rate depends strongly on the initial fill level. At high fill levels, the sphere can pressurize much faster then would be expected if the liquid were well mixed and isothermal. This rapid pressurization can lead to early failure.
The analysis considered two fire heat flux conditions and shows how prediction of failure time can be affected by high temperature stress rupture. The analysis also considers various initial fill conditions to predict BLEVE hazards at failure. The results are in reasonable agreement with limited observations and data from the March 2011 incident in Japan.

Introduction

In March of 2011 a magnitude 9.0 earthquake and subsequent tsunami devastated the Tohoku area of Japan. This disaster included some of the largest BLEVE type failures of LPG spheres ever recorded, at the Chiba refinery near Tokyo (Koseki, 2011). Fireball diameters of greater than 200 m were recorded on video by helicopter based news cameras. This paper presents an analysis of a large propane sphere exposed to partial fire engulfment to give some idea of expected failure times and hazard potential.

Time to Failure for Spheres Exposed to Fire

The time to failure of a pressure vessel in a fire is driven by the fire heat flux, the fire exposure area, and the vessel fill level. The failure is caused by a combination of high internal pressure and wall degradation due to high wall temperatures. To get rapid pressurization the fire must impinge the liquid wetted wall. For high wall temperatures, the fire must impinge the vapour wetted wall well above the liquid level. These processes have been seen in many fire tests of pressure vessels exposed to fire - see for example (Townsend et al., 1974, Balke et al., 1999, Birk et al., 1997, Moodie et al., 1988, Droste and Schoen, 1988, Appleyard, 1980)). All of these tests involved cylinders of various L/D ratios. For spheres the process will be the same but there are some differences such as:

i) Scale – large cylinders may have diameters of 3-5 m and L/D ratios of 6 or greater, where large spheres may have diameters of 20 m or larger. Wall thicknesses on large spheres can exceed 70 mm. This means longer time scales for heating of the wall and lading (see for example (Birk, 1995)).
ii) Different volume to surface area ratio (ratio of total sphere volume to the thermal boundary layer volume) for sphere vs cylinder.
iii) Lower stress (sphere vs cylinder).

The different scale and volume to surface area ratio will affect how the vessel pressurizes when exposed to fire. The large wall thicknesses will affect the time it takes to heat the steel wall to dangerous temperatures.

Fire Conditions

From the limited available photographs it appears the sphere BLEVE in Japan in March 2011 was partially engulfed by a massive jetting liquid propane fire from a failed pipeline beside the spheres. The fraction of

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engulfment was estimated to be approximately 20 % based on the photographs posted on the internet. The engulfment appeared to cover part of the bottom and top of the sphere.

API 521 states that jet fires can have heat fluxes from 100-400 kW/m^2 and large unconfined pool fires can have heat fluxes of 100-250 kW/m^2. For the present analysis we will assume modest heat fluxes of 87 - 181 kW/m^2. API 521 recommends the following fire heating conditions for sizing PRVs for large spheres.

i) Fire heat input based on liquid wetted wall area A up to the equator of the sphere.
ii) Heat transfer to liquid $Q = 70.9\ A^{0.82}$ for bare steel without adequate drainage and no firefighting equipment where Q is in kW and A is in m^2.

For a 15.6 m diameter sphere (2000 m^3) we calculate a heat transfer rate to the liquid of 9325 kW based on this API 521 approach. We have also estimated the heat transfer as a function of sphere fill level based on the following assumptions:

i) Heat transfer to liquid based on liquid wetted area
ii) Average heat flux to liquid wall 150 kW/m^2

Table 1 gives a summary of this calculation. As can be seen in the table the estimated heat into the sphere liquid exceeded 9325 kW for all fill levels above 30%. If the PRVs were sized based on the API 521 formula it is possible the PRVs were undersized for the accident.

Predicting Time to Failure

To predict time to failure we need to predict the wall temperature in the vapour space and the sphere pressure. With these we can determine the stresses and material strength. The pressure will rise at a different rate than the wall temperature will. The failure will require high wall temperature and high pressure at the same time. The pressure will rise to the PRV set pressure and then the PRV will open. The PRV full flow capacity is reached at 120 % of the PRV set pressure. Here we have assumed a tank operating pressure of 2 MPa. This assumes the PRV has been properly sized for this fire condition.

Table 1 : Estimated Heat Transfer to Liquid as a function of fill level (assuming exposure is 20% and fire heat flux is 150 kW/m^2).

Fill Level	Heat In (kW) 20% exposure fire Q = 150 kW/m^2	Heat In (kW) API 521 for PRV sizing
0.1	6,720	
0.2	8,291	
0.3	9,484	
0.4	10,529	
0.5	11,515	9,325
0.6	12,501	
0.7	13,546	
0.8	14,739	

Peak Wall Temperature vs Time

The prediction of the vapour space wall temperature depends on the fill level and on the fire conditions. We have assumed the following:

i) fire heat flux of 87 or 181 kW/m^2 to a cool surface (i.e. 871 and 1100 ^{o}C black body fire)
ii) sphere liquid fill 50%
iii) surface emissivity = 0.9
iv) wall thickness 52 mm
v) internal convection coefficient 10 W/m^2 K
vi) internal wall sees hot vapour space wall and cool liquid surface

With these assumptions we predict wall temperature rise rates as shown in Figure 1.

Tank Pressure vs Time

Predicting the tank pressure rise rate is complicated by the fact of liquid temperature stratification with high fill levels. This stratification causes the pressure to rise much more rapidly than it would if the liquid was isothermal (Birk and Cunningham, 1996). Here we have used a simplified liquid stratification model. The following assumptions have been used.

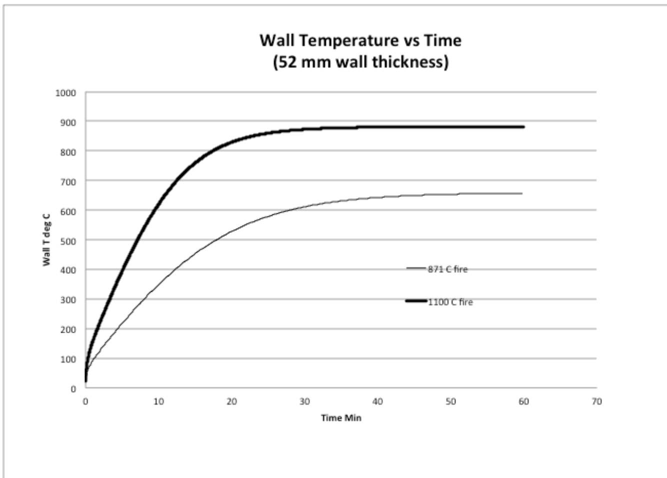

Figure 1: Predicted Vapour Space Wall Temperature for a Sphere

i) Lading is divided into two zones.
   a. Saturated zone includes the liquid boundary layer heated by the fire exposed wall and the vapour space.
   b. Subcooled zone is the remaining liquid in the core
ii) The liquid boundary layer thickness is a constant fraction of the tank diameter
iii) All the fire heat goes into the boundary layer where the liquid wetted wall is exposed to fire. This heat input increases the internal energy of the heated boundary liquid and vapour space
iv) The core liquid has no heat input and therefore it remains at the initial temperature
v) The 2 zones are heated at constant total volume which is equal to the vessel volume

The heat that enters the liquid boundary generates the vapour that pressurizes the vessel. In reality some heat does mix into the core liquid by free convection, but this is relatively small when the PRV is closed (Birk, 1983). The mixing between the boundary layer and core increases after the PRV opens because boiling causes strong buoyancy driven convection currents (Birk and Cunningham, 1996). The model used here is only appropriate for the time the PRV is closed.

Figure 2 shows the predicted time to reach 2 MPa for a North American Rail Tank car (125 m^3). This vessel measures 3 m in diameter and approximately 18 m in length. The plot shows the time to reach 2 MPa for a range of fill levels and fire exposure fractions (exposure = fraction of liquid wetted wall covered by fire = 0.1, 0.2, 0.5 and 0.7) for the case where the liquid is stratified assuming the boundary layer is 0.075 of the tank diameter. Two curves are also shown assuming the liquid is isothermal for two fire exposure conditions of 0.1 and 0.7. We have included two data points from two full scale fire tests of rail tanks cars. The first is from (Townsend et al., 1974) and involved an unprotected 125 m^3 rail tank car fill to 95% full with propane. The second is from (Balke et al., 1999) and involved a 45 m^3 rail tank filled to 22% with liquid propane. Further details can be found in Table 2. As can be seen both models do a reasonable job of predicting the pressurization rate for the low fill level tank. This is because at low fills the boundary layer is most of the liquid volume. However at high fill levels the unheated core liquid is the largest fraction of the liquid volume and therefore stratification must be considered when calculating the pressurization rate.

Table 2: Full Scale Rail Tank Car Fire Tests, Observed Pressurization Times

Tank	Volume (m^3)	Initial Fill	Failure Pressure (MPa)	Time to PRV activation	Time to Failure	Peak Wall T (^oC)
RAX 201	125	95%	2.5	2 min	24 min	650
BAM 1999	45	22	2.5	14 min	17	650

This same model was used for the 2,000 m^3 sphere. The model was changed to account for the different shapes of the tank. The results are shown in Figure 3. If we consider the case of a 50 % full sphere 20 % exposed to an engulfing 87 kW/m^2 fire the stratified model predicts the PRV will be activated after about 50 min.

Failure Prediction

With a pressure of 2 MPa the hoop stress and von Mises stress for the assumed sphere (D = 15.6 m, wall thickness 52 mm) was approximately 150 MPa. With this level of stress it is possible to determine the time to failure for various vapour space wall temperatures. Figure 4 shows example high temperature stress rupture data (Birk and Yoon, 2006) for TC 128 tank car steel for the temperature range from 550 – 720 ^oC. This data was obtained for constant temperature and load tests.

The time to failure for the actual sphere is determined by the accumulated stress rupture damage as the wall is heated and stressed. Here we will use a simplified approach using Figure 4. The time to failure is approximated by the time it takes to reach the peak wall temperature or peak pressure, plus the time for stress rupture failure at that temperature/pressure combination.

Table 3 gives a summary of the failure times taken from Figure 4. For the case with the 871 ^oC fire we expect to see wall temperatures of about 650 ^oC in about 50 min. We do not expect failure at that time because the stress is low. However, we expect high temperature stress rupture after about 17 minutes at that condition of wall temperature and stress. This suggests a tank failure time of around 67 minutes. For the 1,100 ^oC fire the wall reaches very high temperatures (700 ^oC) in around 12 min. The PRV is estimated to activate at around 10 minutes. These conditions combine to give an estimated failure time of 12 min. This is summarized in Table 4

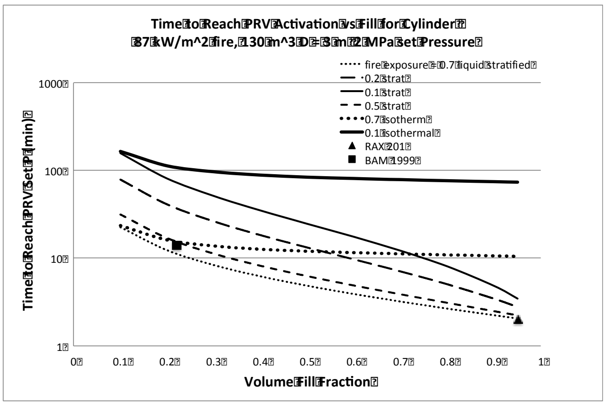

Figure 2: Predicted Time to PRV Activation for a Cylindrical Rail Tank Car.

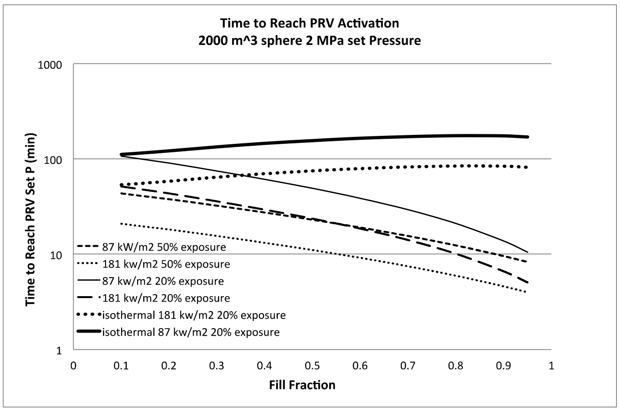

Figure 3: Predicted Time to PRV Activation for Sphere

The actual failure time from news reports was of the order of 60 minutes for the sphere BLEVE in Japan. This is in line with the estimate for the 871^o C fire case.

Sphere BLEVE Hazards

The hazards from the sphere BLEVE depend on the fill level and the pressure and lading temperature at failure. Here we have assumed failure at 2 MPa with saturated conditions. The results are summarized in Table 5.

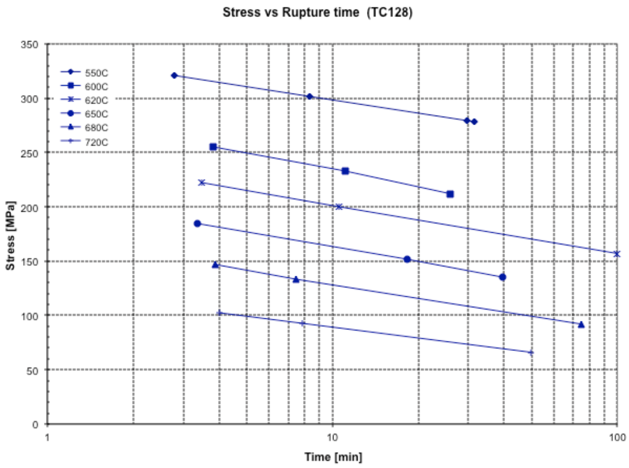

Figure 4: High Temperature Stress Rupture Data for TC 128 Pressure Vessel Steel.

Table 3: Summary of time to Temperature and Time for Stress Rupture.

Wall Temperature and stress rupture time at 150 MPa stress	**Time for Wall to Reach Temperature with 871 •C fire**	**Time for Wall to Reach Temperature with 1100 ºC fire**
550 ^{o}C SR fail time, no fail	22 min	8 min
600 SR fail > 200 min	28	10
650 SR fail at 17 min	50	11
700 SR fail at 1 min	temperature not achieved	12

Table 4 : Summary of Failure Times for 2,000 m^3 sphere, 50 % full, 20 % exposed to engulfing fire (D = 15.6 m, 52 mm wall thickness, 2 MPa pressure, TC 128 steel)

	Fire 87 kW/m^2	**Fire 181 kW/m^2**
Wall T reaches	650 ºC in 50 min	700 ºC in 12 min
P reaches 2 MPa	50 min	10 min
Failure Time based on Ult stress	failure not indicated	12 min
Failure Time based on Stress Rupture	failure after 17 min of stress rupture – total time 67 min	12

Fire Ball and Blast Overpressure

The fireball size and duration can be estimated from very simple correlations (see for example (Birk, 1996)). The following have been used here. $D = 6m^{0.333}$ and $t = 0.075D$, where m = propane mass in kg, D = fireball diameter in m and t = duration in seconds. One video showing a sphere BLEVE from Tokyo was available on the internet and was reviewed. The fireball duration was approximately 26 s. This suggests a propane mass of approximately 250,000 kg. If this was a 2,000 m^3 sphere is suggests it was about 15% full of liquid at failure. At this fill level we would expect a fireball diameter of about 350 m.

The blast overpressure produced by a BLEVE is still a subject of active research. Some data suggests that the shock produced by a BLEVE is due to the energy in the vapour space. The liquid phase change process may be too slow to produce a shock. Data from small scale experiments have supported this (Baker et al., 1983). In this analysis the blast was predicted using the methods described in (Birk et al., 2007). From the following Table 5 it is clear that the fireball hazard reaches further than the BLEVE overpressure.

Table 5: Summary of Calculated Hazards for 2,000 m^3 Sphere BLEVE containing saturated propane (failure pressure = 2 MPa).

Fill	**mass kg**	**vapour Energy kJ**	**total energy kJ**	**Distance to 300 mbar from vapour energy**	**Distance to 300 mbar from total energy**	**Fireball D (m)**	**Fireball Time (s)**
0.05	137.E3	12.0E6	14.9E6	66.8	71.9	307.9	23.1
0.1	175.E3	11.E6	17.2E6	65.6	75.4	334	25.05
0.2	250.E3	10.E6	21.8E6	63.1	81.5	376.5	28.24
0.3	326.E3	8.8E+06	26.4E6	60.4	86.9	411.2	30.84
0.4	402.E3	7.6E+06	30.9E6	57.3	91.7	440.8	33.06
0.5	477.E3	6.3E+06	35.5E6	54.0	96.0	466.8	35.01
0.6	553.E3	5.0E+06	40.1E6	50.1	99.9	490.3	36.77
0.7	628.E3	3.8E+06	44.7E6	45.5	103.6	511.7	38.37
0.8	704.E3	2.5E+06	49.3E6	39.8	107.0	531.4	39.85

Conclusions

A failure analysis has been presented for a 2,000 m^3 propane sphere. Two fire conditions were considered, one very severe (i.e. 1,100^o ºC fire) and another more modest (871 ^{o}C). The estimated failure time for the extreme fire was of the order of 12 min. The estimated failure time for the more modest fire was 67 min. The actual failure time for the sphere BLEVE in Japan is believed to be of the order of one hour.

The sphere fill level for the Tokyo BLEVE was estimated to be about 15 % based on the fireball duration of 26 s. This would correlate with a fireball of about 350 m diameter. We have no data to show that the correlations used for fireball size and duration apply to this scale of BLEVE.

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