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Fire Testing of Total Containment Pressure Vessels

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Full engulfment fire tests have been conducted on total containment pressure vessels filled to 50% and 98 % capacity with water. The tests included an unprotected tank and tanks with two different levels of thermal protection. Total containment in this context means there was no pressure relief device.

The tests were conducted with 1/3rd linear scale rail tank cars similar to the DOT 111 tank cars used in North America. The 2.4 m^3 model tanks were subjected to 100 % engulfing fires fuelled by liquid propane. The fire heat flux was approximately 80 % by radiation and 20 % by convection with a total heat flux to a cool surface of approximately 100 kW/m^2.

The tanks were instrumented with wall and lading thermocouples and pressure transducers. The fire conditions were measured using directional flame thermometers (DFT).

In these tests the tank pressure increased rapidly suggesting strong liquid temperature stratification. Even at high fill levels of 98 % the tank wall temperature in the vapour space increased rapidly to dangerous levels.

The results from these tests will be used to validate computer models of the tank heating process.

1. Introduction

In North America certain hazardous materials are transported in rail tank cars that must be able to survive an engulfing liquid hydrocarbon pool fire for 100 minutes without rupture. To meet this requirement these tanks are normally equipped with pressure relief valves (PRV) and some form of thermal insulation or thermal protection (TP).

These tanks sometimes have non-accident releases (NAR) due to unwanted activation of, or leakage from the pressure relief valves (PRV). These NARs are a nuisance for Industry and for this reason, the industry now wants to remove the PRVs from certain tanks. This is known as total containment and is common practice in Europe. However, Europe does not have a 100 minute fire survival requirement.

This paper is about a series of fire tests of 1/3 rd linear scale US DOT 111 Tanks cars. The 2.4 m^3 vessels were subjected to fully engulfing fires generated by liquid propane fueled burners.

2. Fire Conditions

The fire system was developed specifically for this test program. The fire tests were conducted at the BAM test facilities near Berlin Germany. The fire fuel was liquid propane and it was distributed using an array of ground and elevated nozzles. The specified fire conditions were:

i) black body radiating temperature between 816 and 927 °C
ii) fire heat transfer to tank at least 80 % by radiation
iii) credible relative to the fire conditions used for the full scale fire test of a rail tank car from Anderson et al. (1974).

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Figure 1 View of simulated pool fire.

Details of the fire will be published in an upcoming US DOT FRA report. Figure 1 shows typical view of the fully engulfing fire. Table 1 shows some average fire properties from calibration tests using a water filled tank. Figure 2 shows the fire average performance relative to the full scale fire test of a rail tank car from Anderson et al. (1974).

Table 1 Results Summary (DFT = directional flame thermometer, which gives the approximate black body radiating temperature of the fire)

Test	DFT Temp Top Average Deg C	DFT Temp Side Average Deg C	DFT Temp Bottom Average Deg C	Average DFT Deg C	Average Heat Flux kW/m^2	Estimated Radiation Fraction
14027 Sept 3, 2014	909	877	886	887 SD 112	103	81 %
14028 Sept 4, 2014	914	885	868	888 SD = 78	108	77 %
14029 Sept 4, 2014	937	900	892	907 SD = 55	111	81 %
average	920	887	882	896	107	80 %

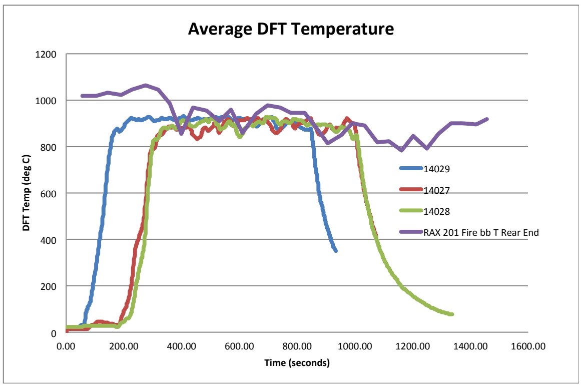

Figure 2 Average fire black body radiating temperature compared to full scale tank car fire test [1].

Figure 3: Bare Tank (no insulation or jacket) ready for test. *Figure 4: Insulated and Jacketed tank ready for test.*

3. Test Tanks

The test tanks were 1/3rd linear scale models of 111 type tank cars used in North America. The model tank details are as follows:

A414 Grad G steel (min tensile ultimate stress 515 MPa)
Total Volume = 2.4 m3
Wall Thickness = 3.1 mm
Outside Diameter = 91.5 mm
Length 3.6 m
elliptical heads

Further details of the tank can be found in Gonzalez et al. (2015). Figure 3 shows the bare tank mounted for a test. Figure 4 shows the jacketed tank mounted for a test. The model tank was hydrostatically tested to failure at 39.5 Barg. The volume expansion at failure was approximately 12 %.

4. Instruments

The tanks were instrumented with i) two pressure transducers, ii) 29 internal lading thermocouples in vertical arrays , iii) 11 wall temperature, iv) 11 jacket temperatures, v) 10 directional flame thermometers. Details of locations can be found in Gonzalez et al (2015).

5. Tests Conducted

The results from four tests are presented in this paper. They include:

i) bare tank (no insulation or jacket) 98 % filled with water.
ii) tank with jacket only, 98 % filled with water.
iii) tank with insulation and jacket, 98 % filled with water.
iv) tank with I and J, 50 % filled with water.

The jacket was made from 3 mm steel and was held 102 mm away from the vessel primary shell. The jacket was structurally isolated from the main pressure vessel so that the hot jacket could expand freely from the cool water filled tank. For the system with no insulation the space between the tank and the jacket was filled with ambient air. Openings in the jacket were filled with insulation so that fire could not enter the jacket space. The jacket alone was expected to act as a radiation shield and this was expected to reduce the fire heat flux to a cool surface by about 50 %.

For the insulated and jacketed tank the 102 mm space was filled with a low temperature (rated for 250 ^{o}C) fibre glass type insulation. This low temperature insulation was expected to degrade at high temperature and lose most of its insulating value. If the insulation degrades 100 % then the results should be similar to the jacket only case.

6. Test Results

The following test results are shown here:

i) tank pressure vs time (Figure 5)
ii) peak wall temperature at top of tank vs time (Figure 6)
iii) sample of wall temperatures vs time (Figure 7)

As can be seen in Figure 5 the jacket and jacket plus insulation delayed the pressurization of the tank for a considerable period of time. The different fill level does not seem to affect the pressurization very strongly. In Figure 6 we see that the jacket and insulation also reduced the peak wall temperatures measured from the tank top. We also see that the lower fill case (50 %) experienced higher peak wall temperatures. The insulation significantly delayed the expected failure of the test vessel. However, even with protection and high fill level, damaging high wall temperatures are possible.

The tanks all pressurized rapidly due to temperature stratification in the water and heating of the air in the vapour space. Even with a fill level of 98 % the non liquid wetted wall temperatures increased rapidly. This is a clear indication that the 98 % filled tanks never went full of liquid. This was probably because of plastic deformation taking place before the tank went shell full, and this expanded the size of the vapour space.

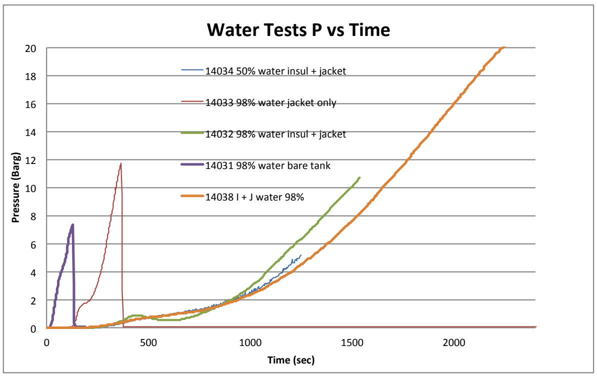

Figure 5 Measured tank pressure vs time in fire

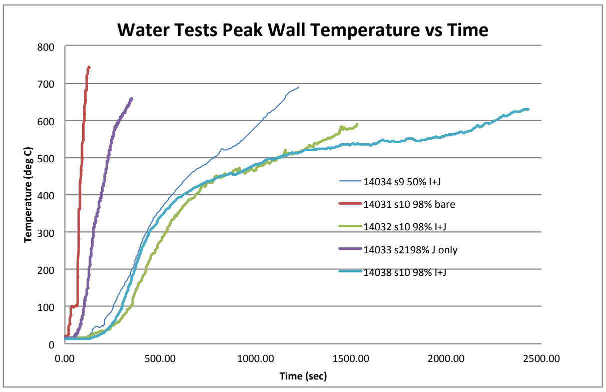

Figure 6 Maximum measured wall temperature at top of tank vs time.

The measured wall temperature lower down in the tank showed clearly that the liquid boundary layer was much warmer than the core liquid. The core liquid was well below 100 ^{o}C (i.e. Barg = 0) while other areas of the wall were well above 200 ^{o}C suggesting a warm boundary layer generating a stratified layer that generates pressure in the vessel.

The test results are summarized in Table 2. In this test series tank failure was defined as the following:

i) rupture of the vessel, or

ii) when the tank hoop stress exceeded the tank material ultimate stress at the measured peak wall temperature.

Figure 7 shows the measured wall temperatures in test 5 (98 % fill, water, Insul + Jacket). The peak wall temperatures are at the top of the tank and in the small vapour space. These top wall temperatures rise rapidly to dangerous levels (> 500^{o}C). The data also shows intermittent boiling lower down (but near the top of the liquid) in the liquid filled part of the tank. Sudden changes in wall temperature suggest subcooled boiling in the boundary layer. When the water boils the wall temperature drops due to a sudden increase in heat transfer coefficient. When the boiling is suppressed by a drop in the wall superheat, the temperature increases rapidly due to the drop in the heat transfer coefficient. At the bottom of the tank the wall temperatures stay well below 100 ^{o}C (i.e. Barg < 0).

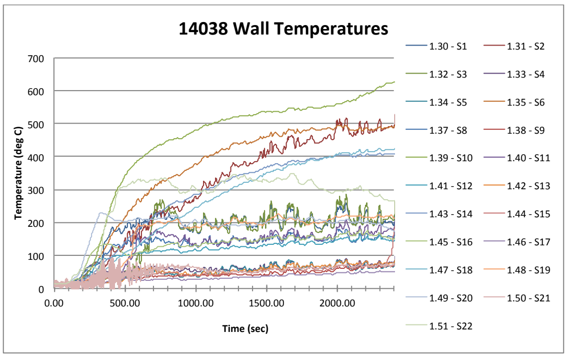

Figure 7 Measured tank wall temperatures at various positions around tank.

Table 1 Summary of Water Tests

	Test 0 14031	Test 1b 14033	Test 5 14038	Test 2 14034
Tank Condition	Bare Tank 98% Full water	Jacket Only 98% Full water	Insulation and Jacket 98% full water	Insulation and Jacket 50% full water
Test End Time	126 sec 2.1 minutes	361 6	2440 40.7	1250 21
Time to 5 Barg	95 sec	282	1200	1250
P at End	7.3 Barg	11.5	21	5
Time to 500 ^{o}C Wall T	89 sec	222	1070	750
T wall at Test End	755 deg C	669	622	700
Test Result	Rupture	Rupture	test terminated at indicated failure	test terminated before failure

7. Analysis

Pre-test analysis identified the following key processes that were expected to affect the outcomes of the tests.

i) for high fill cases, the tank was expected go shell full of water due to liquid thermal expansion. This was expected to strongly affect wall temperature at the tank top
ii) liquid temperature stratification and its effects on pressurization rates
iii) plastic deformation (volume expansion) before tank rupture
iv) boiling in the liquid and swell of the liquid level
v) liquid temperature stratification will remain longer with no PRV (i.e. PRV activation causes boiling and adds convective mixing in tank).

Before these tests were conducted an analysis was performed and the following outcomes were expected.

i) *for the 98 % fill case,* the tank would go shell full and the top wall wetting would keep the peak wall temperatures well below levels that would cause major reductions in the wall ultimate strength. Once shell full, the tank pressure would rise rapidly to the pressure necessary for wall yielding. The tank would rupture after a volume expansion of around 12 % (based on the hydrostatic pressure test result).
ii) *for the 50 % fill case*, the tank pressure would rise slowly but the peak wall temperature at the tank top would rise rapidly (due to poor cooling by the vapour). The tank would rupture when the hoop stress (conservative) or the von Mises stress (0.866 x hoop stress) exceeded the tank material ultimate strength for the measured peak vapour space wall temperatures.

A major question in this test program was -- how quickly will the tank pressurize due to liquid temperature stratification?

Several models exist around the world that are used to predict the behavior of pressure vessels exposed to accidental fires (see for example Johnson 1988, Ramskill 1988, Beynon et al. 1988, and Venart 1986). Most of these models assume the liquid and vapour temperatures are uniform during the heating process. It is well documented (Birk and Cunningham 1996, and Hadjisophocleous et al. 1990). that this is not the case. Liquid temperature stratification takes place and this has a significant effect on the pressurization rate.

Let us for now assume the liquid heats up with a uniform temperature. Table 3 gives a summary of the expected time for the 98 % fill tank to reach 5 Barg with the different heating rates expected in this test. These calculations neglect the effect of heating the small air space on the tank pressurization. Note that when the tank goes shell full we expect the tank pressure to rise rapidly to cause tank yielding

Table 3 Estimated (assuming uniform water temperatures) and Observed pressurization rates for water filled tanks.

Test Condition	Approximate Heat Flux to Cool Tank Shell	Time to Shell full of Liquid	Time to 5 Barg with no temperature stratification and no shell full	Measured Time to 5 Barg from Test
bare tank 98% full with water	100 kW/m^2	7 minutes	20 minutes	< 2 min
Tank with only jacket, 98% full with water	50 kW/m^2	14	40 minutes	4 min
tank with jacket and insulation 98% full with water	25 kW/m^2	28	80	22 min
tank with J and I 50% full of water	25	no shell full	87	21 min

8. Conclusions

The tests showed that even with a liquid fill level of 98 % it was still possible to achieve very high wall temperatures at the top of the tank leading to tank plastic deformation at relatively low pressures. It was also shown that the tank pressurizes rapidly due to the formation of a liquid boundary layer and hot stratified layer in the liquid.

This data suggests that computer models that assume uniform liquid temperature during accidental fire heating of pressure vessels are not conservative because they will not predict the correct tank pressure and stress vs time profile. It also suggests that models that predict full wall wetting at high fill levels will not be conservative when predicting wall temperatures.

Acknowledgments

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