TP 14561E

Fire Testing and Computer Modelling of Rail Tank-Cars Engulfed in Fires: Literature Review

For

Transport Dangerous Goods and Transportation Development Centre
Transport Canada

By

A.M.Birk Engineering
Kingston, Ontario, Canada

March 2006

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This report reflects the views of the author and not necessarily the official views or policies of Transport Canada.

Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

Un sommaire français se trouve avant la table des matières.

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16. Abstract

This review covers the literature on fire effects on rail tank-cars carrying pressure liquefied gases such as LPG and anhydrous ammonia. The literature is categorized into the areas of computer modelling, fire testing, high temperature stress rupture, scale effects, thermal stratification and 2-phase swell, thermal protection system defects, and pressure relief valves.

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Cette recherche a porté sur la littérature concernant les effets du feu sur des wagons-citernes transportant des gaz liquéfiés sous pression, comme les GPL et l'ammoniac. Les documents sur ce sujet ont été classés dans les catégories suivantes : modélisation informatique, essais au feu, rupture par fluage à haute température, effets d'échelle, stratification thermique et expansion biphasique, défauts des systèmes de protection thermique, soupapes de sûreté.

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EXECUTIVE SUMMARY

This literature review contains important references relating to fire effects on pressure vessels. The specific pressure vessels of interest are rail tank-cars carrying pressure liquefied gases such as LPG and anhydrous ammonia. The literature identified is mainly from the U.S., Canada, the U.K., and Germany.

The references have been organized into the areas of computer modelling, fire testing, high temperature stress rupture, scale effects, thermal stratification and 2-phase swell, thermal protection system defects, and pressure relief valves (PRV).

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Cette recherche documentaire a recensé des documents de référence majeurs portant sur les effets du feu sur les appareils à pression, plus particulièrement sur le type particulier d'appareil à pression que constituent les wagons-citernes transportant des gaz liquéfiés sous pression, comme les GPL et l'ammoniac. Les documents de référence inventoriés émanent principalement des États-Unis, du Canada, du Royaume-Uni et de l'Allemagne.

Ces références ont été classées par domaine, soit la modélisation informatique, les essais au feu, la rupture par fluage à haute température, les effets d'échelle, la stratification thermique et l'expansion biphasique, les défauts des systèmes de protection thermique et les soupapes de sûreté.

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Introduction

This literature review contains a listing of some important references relating to fire effects on pressure vessels. The specific pressure vessels of interest are rail tank-cars carrying pressure liquefied gases such as LPG and anhydrous ammonia.

The references have been organized into the following areas:

i) computer modelling
ii) fire testing
iii) high temperature stress rupture
iv) scale effects
v) thermal stratification and 2-phase swell
vi) thermal protection system defects
vii) pressure relief valves (PRV)

The references identified are mainly from the US, Canada, UK and Germany. The list is located at the end of this report. The references cited are available in the public domain.

Not all of the references listed in the bibliography have been cited. References that are specifically cited appear in a separate reference section. These references can also be found in the bibliography.

Computer Modelling

There are several models for pressure vessels in fires, and specifically rail tank cars. These models have been developed in the U.S. [1,2], UK [3,4], Germany [5] and Canada [6,7]. Other applicable models exist.

It should be noted that there are commercial computer codes for simulating fluid flows (Fluent, CFX, etc) and structural analysis (ANSYS, ABAQAS, etc) that could be used to model tank-cars in fires. However, these would require substantial setup by experts and would require enormous computing resources to solve the problem. The improvements in modelling are unlikely to be worth the resources required. This may be an area requiring further study.

For example, a recent study was just completed by Battelle Memorial Labs and Thermdyne Technologies Ltd. using ABAQAS and Tank2004 to model the high temperature stress rupture of a propane tank exposed to fire. The stress and failure analysis part took ABAQAS 80 hours to run on a powerful work station. This model did not include any of the fluid and heat transfer processes – just the stress and failure (i.e. the transient pressure and wall temperatures of the tank were inputs to the ABAQAS model). The Tank2004 code by Thermdyne [8] did the entire analysis of the tank including stress and heat transfer in about 2 hours. The two codes were within a few minutes of predicting the same failure time. Unfortunately the sponsor of this study is not releasing the results for publication.

All of the models cited in this report contain the following basic elements:

i) fire heat transfer
ii) tank wall, thermal insulation and jacket heat conduction
iii) liquid space heat transfer
iv) vapour space heat transfer
v) lading thermodynamic properties and process
vi) PRV flow
vii) Wall failure model

Most of these models have been validated at several scales. This means the model has been used to predict failure of full scale tank-cars, and probably 1/3rd and 1/5th linear scale tank-cars (i.e. 1/5th linear scale, or 1/125 volume scale). Some have been validated down to 33 lb propane cylinder scale (Tank2004, [8]).

Some of the models (e.g. Tank2004, [8]) account for more detailed processes in the tank such as:

i) PRV cycling (shows full pressure and stress range)
ii) 2-phase PRV flow (needed for high fill levels to account for proper mass loss)
iii) PRV spring softening at high temperatures (shows real world pressure reduction as PRV spring is heated)
iv) temperature sensitive pressure relief devices
v) liquid temperature stratification (needed to predict correct PRV first open time).
vi) 2-phase swell (needed for correct vapour space heat transfer and wall temperatures)
vii) tank roll and pitch
viii) thermal protection
ix) thermal protection defects
x) high temperature stress rupture (needed for long duration, reduced heating cases where failure may take up to 100 minutes).

Fire Testing

Fire testing has been conducted in several countries including the US, UK, Germany, and Canada. To the authors knowledge, full scale tests of rail tank-cars have only been conducted in the U.S. [9] and Germany [5].

Fire testing methods and test fire behaviour is very important in the outcome of a test. Fire scale is important because it affects the total heat flux from the fire to the tank. Wind effects can dramatically alter the fire geometry. Attempts to block or redirect the wind using walls or trenches or other structures just adds new wind effects.

The scale of the fire determines how much heat is transferred by convection and how much is transferred by thermal radiation. Tests have shown that a fire pan with liquid hydrocarbon fuel must have a diameter bigger than about 1 m for the fire to be dominated by thermal radiation. For this reason we should not try to model rail tank-cars with very small cylinders in very small fire pans.

Of course, the fire must be big enough to engulf the subject tank. Birk [10] did fire tests of 200 gallon ASME code automotive fuel tanks in pool fires using pans with a diameter of about 2.5 m. In this case the fire pan extended about 1.5 tank diameters beyond the dimensions of the tank. This means the fire was about 1 m thick all around the tank. This is probably the smallest scale that could still be used to model a tank-car in a luminous fire.

The scale of the fire determines how luminous the fire is and this is determined by the soot content in the flame. Large hydrocarbon fires are sooty and very luminous. For large scale tanks like rail tank-cars the heat transfer is about 90% by thermal radiation and 10% by convection. As the size (diameter) of the tank reduces, the heat flux by convection increases to a fraction more like 20 or 30% (see for example [11],[12]). This is not a problem as long as the total heat flux is comparable to the heat flux of interest. The total heat flux is the fire heat flux due to convection plus the heat flux due to thermal radiation. The ultimate goal is to achieve similar heat input to the lading and similar peak wall temperatures in the tank vapour space.

The current fire standard (i.e. engulfing fire with $T = 871^{o}C$ plus or minus 56 ^{o}C) for tank-cars was based on the RAX 201 fire test of an unprotected tank. Various researchers have shown that the fire temperature actually depends on what is in the fire. A large cool object is known to reduce the temperature of the fire [13]. If the object is thermally insulated from the fire then the fire will not be cooled to the same degree. Therefore the fire conditions observed in the RAX 201 test may not be the fire observed in fire tests of thermally protected tanks.

Fire test results from several scales have been used to develop and validate computer models of tanks in fires [5,10,14-21].

Stress Rupture

Many tank models assume the tank ruptures when the tank nominal hoop stress exceeds the wall material ultimate strength at the peak wall temperature. This is known as the maximum normal stress theory of failure. This failure model is not always accurate or conservative.

High temperature stress rupture is a widely known failure model for high temperature pressure components [22]. Our ability to use this analysis method for tank-cars is limited by a general lack of stress rupture data for pressure vessel steels that are not intended for high temperature service (i.e. TC 128B). Birk and Yoon [23] have recently generated high quality stress rupture data for TC 128B.

Scale Effects

Scaling issues are complex. Small tanks in fires behave differently than large tanks in fires. We need to understand the effects of scale so we can learn things about full scale tank-cars in fires by conducting fire tests with small tanks. This is the basis for reduced scale testing in industries such as aerospace, naval architecture, chemical and mechanical processing, and others.

When we do scale model testing we expect that we will need to adjust the results from the small scale tests so they apply to the large scale system. This requires analysis. Sometimes we use dimensional analysis [24], sometimes we solve the governing conservation equations (mass, momentum, energy, etc.) in computer models.

For tests at different scales to apply to each other, we need to ensure that the testing is dynamically similar. This requires the following:

i) geometry similarity (object shape is the same)
ii) kinematic similarity (motion, flow directions are the same)
iii) dynamic similarity (force ratios are the same, i.e. buoyancy, viscous, stress, etc.)

In most cases of scale model testing there is a model scale at which the results from the testing are no longer dynamically similar to the full scale system. If you make the model too small you start to introduce large errors. The physics may change if the model gets too small. For example, consider the case of a liquid hydrocarbon pool fire. We know from testing that when these kinds of fires are larger than about 1 m in diameter they are dominated by thermal radiation. Fires smaller than this are affected by convection. Very small fires are dominated by convection. If you want to model a 10 m diameter fire you should not do it with a 0.1 m diameter fire because the physics have changed. You should not go smaller than about 1 m if you want to model a 10 m diameter fire. A better model would be a 3 m fire. The best model would be a 10 m fire, which would basically be the real thing.

We apply this same approach to modelling tank-cars in fires. We know that if we go too small we will not get results that are representative of full scale tank-cars. The question then is – how small can we go? We know that the smaller we go, the less expensive the test. However, if we go too small the results do not apply to the full scale system because the physics may change. Examples of where the physics may change in the tank-car if the scale is too small are:

i) free and forced convection in the vapour space
ii) 2-phase flow pattern in liquid space (swell)
iii) Boundary layer effects in liquid and vapour space
iv) PRV behaviour

Examples where the physics should not change significantly include:

i) heat conduction
ii) stress
iii) material failure

As noted earlier, we can account for many of the changes with our computer models. For example, we can account for the changes in convective heat transfer.

The response of a rail tank-car filled 95% with propane to a 100% engulfing fire exposure depends on the fire properties and the tank shape and size and orientation. We will assume here we are considering long horizontal cylinders like railway tank-cars.

All of the processes are affected by the scale of the tank including:

i) Fire heat transfer
ii) Wall heat conduction and convection
iii) Liquid thermodynamics (P vs T, temperature stratification, two phase swell, etc).
iv) PRV performance
v) Wall rupture

The following discussion of this has been extracted from Transport Canada Report TP 14366E dated March 2005.

Discussion of Scale Effects

Let us begin by considering two tanks, a full sized 112J tank-car and a reduced scale tank where the following is true for both tanks:

i) same shape meaning same length to diameter (L/D) ratio and same end types
ii) wall thickness scaled to give same hoop stress at same pressure
iii) same wall material (i.e. same ultimate tensile strength UTS, density, thermal conductivity, specific heat, etc)
iv) PRV size based on tank surface area and fire heat flux so that pressure does not exceed 120% of PRV set pressure during fire exposure.
v) same PRV pressure setting

Let us put these two tanks in fires that have the same heat flux (kW/m^2). The pool fire standard for tank-car thermal protection requires a fire in the range of 816 to 927 ^{o}C effective blackbody temperature. This has been determined to be the fire environment seen by the RAX 201 test of a full scale tank-car [9].

Let us also consider that the tanks start off with the same fill level and initial temperature.

The question is – will the small scale tank behave the same as the full scale tank? What will be different? Can we account for this in some way?

From the above the tanks only differ in tank diameter, tank length and wall thickness. All of these would be related to the full scale tank by a single scale factor λ. For example, we may choose to test with a tank 1/3rd the diameter of the full scale tank. This means the tank length, diameter and wall thickness are all 1/3rd that of the full scale tank. In this case the volume would be 1/27th that of the full scale tank.

Tank failure in a fire is dictated by the following:

i) wall temperature in the vapour space
ii) tank stress in heated area
iii) wall material properties at the elevated temperature

We have already said the tank will be scaled to have the same material and stress.

The wall temperature rise rate depends on:

i) fire heat flux
ii) wall thickness, density, thermal conductivity and specific heat
iii) convection in vapour space
iv) radiation in vapour space

We know the fire must be large and luminous for the heat transfer to be dominated by thermal radiation [25]. We know from fire testing [13] that large massive cool objects actually cool the fire and reduce the heat flux. However, if a tank is thermally protected this effect does not apply since the cool object is insulated from the fire. We also know from testing that the small scale tank will see less heating by radiation and more heating due to convection [11]. Therefore, we expect the heat flux to be similar for the two different scales but probably a little higher (worse) for the small scale (i.e. small scale is slightly conservative). This is good since we will err on the safe side. We should take care that our error is not too large.

Here we again note that both tanks are made of steel with similar density, thermal conductivity and specific heat. Surface emissivities should also similar [26] for similarly aged tanks. Any difference can be accounted for in computer models.

The convection and radiation in the vapour space depends on the liquid level and on the action of the PRV. The shape of the vapour space is important. For horizontal round cylinders the shape of the vapour space is similar for different scales for similar fill levels. Smaller tanks will have higher convective heat transfer coefficients in the vapour space which will reduce the wall temperature slightly. The small tanks will have higher fire convection effects as well which will tend to increase the wall temperature [11]. As a result we do expect a small difference in wall temperature from small to large scale but it will not be large. This difference can be accounted for in computer models.

At high wall temperatures and low liquid fill levels, thermal radiation heat transfer will dominate in the vapour space.

For radiation heat transfer the vapour space shape is very important and we just noted that this will be the same for the different scales, provided the fill is the same. We must be sure the surface emissivities are the same between scales. Emissivity does not vary with scale but depends on materials and surface properties which are the same between the scales considered here. We expect some difference between new and old tanks (i.e. oxidation affects surface emissivity for bare metals).

The boiling heat transfer effects will change slightly with scale since the vapour bubbles will be the same for both large and small tank (both have propane) [27] . In both cases the ratio of the bubble diameter to the tank diameter is very small. This will affect the bubble terminal rise velocity only slightly and therefore liquid swell only slightly. It is important to consider liquid swell when trying to predict mass flows through the PRV. Two phase swell can result in 2-phase flow in the PRV and this can make the liquid level drop faster. This then affects wall temperatures and failure time.

The rate of increase of the wall temperature in the vapour space is determined by the heat in from the fire, the heat out by convection and radiation on the inside (backside) and the tank wall heat capacity. In mathematical terms this can be written (see for example Holman [28]).

$$\frac{dT_w}{dt} = \frac{(q_{fire} - q_{back})A}{\rho c A w} \propto \frac{1}{w} \text{ (i.e. α means proportional to)} \qquad (1)$$

Where,

T_w = wall temperature
t = time
w = wall thickness.
ρ = density of wall material
c = wall specific heat
A = wall area exposed to heating
q = heat flux

The above shows the temperature rise rate depends on the wall thickness if the heat flux is similar. The thicker the wall the slower it heats up. Therefore we know the smaller tank will heat up faster and fail faster. This will scale with the wall thickness, which also happens to scale with the tank diameter (w proportional to D for same hoop stress). This has been seen in numerous tests of small scale tanks [5,10,14-16,18,20,21].

The tank stress depends on:

i) tank pressure P
ii) wall thickness w

iii) tank diameter D
iv) tank L/D
v) end types
vi) heating pattern (fill level, fire contact area, etc.)

The nominal hoop stress = PD/2w. For tanks of similar shape with the same w/D and L/D ratio the stress field will be the same for the same heating pattern.

Stress rupture data [22] provides time to failure as a function of nominal tensile stress and sample temperature under constant load conditions. The size of the sample is not a strong factor. This is the basis of tensile testing. Therefore a 7.1 mm wall should behave the same as a 16 mm wall as far as stress rupture is concerned provided the stress is the same and there are no large defects in the steel. Therefore the time to failure for a given stress and temperature should be the same for the different scales.

The size of the failure or rupture will depend on the wall thickness. Therefore we would expect the failure length to scale with the wall thickness. For the assumed tanks this means the failure length scales linearly with tank diameter.

The tank pressurization depends on:

i) fire heat flux
ii) PRV setting and capacity
iii) tank fill

Tanks with higher fills pressurize faster because of the small vapour space and large surface area of liquid wetted wall [20].

For the same fill level, the tank initial pressurization rate depends on the temperature rise rate in the liquid boundary layer. The liquid boundary layer is the liquid near the tank wall. The heat from the fire passes through the wall and enters this liquid layer near the wall. This warm liquid then rises to the liquid surface. The rate of temperature rise of the boundary layer is determined by the ratio of heated surface area covered by liquid to the heated liquid boundary layer volume. It is the heating of the liquid boundary layer that determines the pressure in the tank. The boundary layer volume is determined by the wetted surface area and the boundary layer thickness δ. Or in equation form:

$$\frac{dT_{bl}}{dt} = \frac{qA_w}{\rho c V_{bl}} = \frac{q\pi DL}{\rho c \pi DL\delta} \propto \frac{1}{\delta} \tag{2}$$

The boundary layer thickness δ is a weak function of the tank diameter – it is probably related to $D^{1/4}$ (based on the laminar thin conduction layer model for free convection in an enclosure, see Rohsenow et al, [29]). In other words, if you test with a 1/3rd scale tank you expect the smaller tank boundary layer to heat up about 31% faster than a full scale tank. For a near full tank this means the difference between the PRV popping in 2 minutes for the full scale tank [9] vs 1.5 minutes for a tank with 1/3rd the diameter. There is a difference but it is not very significant. Test experience suggests the difference is even smaller than stated above and is lost in the fire variability. Once again, we can account for this in a computer model.

The rate of heating of the bulk liquid depends on the heated surface area and the liquid volume. In mathematical terms this is:

$$\frac{dT_{bulk}}{dt} = \frac{qA_w}{\rho c V_{liq}} = \frac{4q\pi DL}{\rho c \pi D^2 L} \propto \frac{1}{D} \tag{3}$$

As the tank diameter gets bigger it takes longer to heat up the bulk liquid. Once again we have seen this in numerous tests [5,9,10,14,16-18,20,21].

The final pressure is determined by the PRV setting and the PRV capacity. If the PRV is properly sized the pressure will be limited to about 120% of the PRV setting. In most cases the tank fails some time after the pressure has reached the PRV set pressure. In large unprotected tanks the pressure will be at the PRV set pressure before the wall heats up to failure conditions. For example, with RAX 201 the PRV opened in 2 minutes and the tank failed in 24 minutes. With a 500 gallon propane tank the PRV opens in about 1.5 minutes, and the tank fails in about 10 minutes. It is possible that in very small tanks the wall will reach dangerous temperatures before the PRV is activated. This means the very small tanks behave differently than large tanks (as noted earlier). Don't test with tanks that are too small.

In thermally protected tanks both the tank pressure and wall temperature are delayed. However, if there are thermal protection defects the wall temperature may reach dangerous levels in the defect area before the PRV is activated. We need a computer model to consider all the possibilities.

If we consider tanks of similar shape (same L/D ratio) in similar fires, with similar material UTS, and similar stress (i.e. wall thickness scaled by D) then we can say the following:

i) the rate of wall temperature rise depends on D – the bigger the D the longer it takes to heat the wall.
ii) the rate of initial pressurization depends on fill, and only weakly on D.
iii) the rate of bulk heating of the liquid depends on D
iv) the failure time depends only on wall T assuming the tank is at the PRV set pressure (since stress and material are the same) and this depends on initial fill and D.

In other words, failure time scales with tank D if all other factors are fixed. How does it vary with D? For severe heating the failure time is almost linear with D. This means if you double the diameter the failure time doubles. We expect failure of an unprotected 112J type tank to take about 24 minutes (based on RAX 201). If we test with a 1/3 rd scale tank under similar conditions we expect it to fail in about 8 minutes. For less intense heating the failure time is dictated by stress rupture considerations.

Discussion of Scaling of Critical Defect Size

Let us consider a square defect with side dimensions S x S. Consider the plate with thickness w under the defect. From a conduction heat transfer standpoint the defect heat transfer depends on the thermal properties of the steel and the plate dimensions S and w.

Consider the case of the same fire heat flux (i.e. same fire blackbody T). The rate of temperature rise of the plate is a function of the (heat input)/(plate mass) which relates to $S^2/(S^2w)$ or just 1/w. Since the tank wall w depends on the tank D we can say that the defect temperature rise rate depends on the tank D. The larger the tank, the slower the defect heats up.

The temperature gradients in the defect area also depend on S and w. If you have the same S/w ratio then you get the same temperature distribution over the defect area. This assumes the backside heat transfer is the same. The backside (or inside surface) heat transfer on the wall is due to convection and radiation. This is not exactly true for small and large scale but it is close.

The local stress field in the bulging steel plate is a function of the heated length S and the heated area width B and wall thickness w [30]).The wall bulges because the wall has been weakened by the high temperatures in that area of the wall. The weakened area of the wall deforms plastically under the pressure forces from within, and this causes the bulging shape. The bulge geometry will be similar as long as the temperature and stress field are similar and this will be true if the ratio S/w and S/B are the same. Therefore we must scale the critical defect length for failure based on the wall thickness. In other words the critical defect length for the 112J tank car = (w for tank-car)/(w for small scale tank) x critical defect length for the small scale tank.

The critical defect length would be the defect length required for fire induced rupture to take place within a specified length of time. For a full scale tank-car this time would be 100 minutes for a fully engulfing fire. If we use a 1/3rd linear scale model then the time allowed would be about 33 minutes (i.e. we have scaled by the diameter). A more accurate time scaling would be determined using a suitable computer model that accounts for the processes in more detail.

Non Ideal Scaling

Perfect scaling is usually not achieved in real world testing. Scale model tests usually have some scaling differences with the 112J tank-car. These can include:

i) material UTS
ii) tank L/D ratio
iii) tank t/D ratio

iv) hemi heads vs elliptical heads
v) nominal PRV pressure setting and flow capacity
vi) tank initial fill

The fire conditions were also probably not exact.

Material UTS can be accounted for in the stress rupture analysis. The different PRV set pressure is also accounted for in any hoop stress calculation. The tank w/D ratio is also accounted for in the stress analysis.

The PRV flow capacity is determined by the tank surface area and the assumed fire conditions. We need to make sure the PRV is not undersized. A properly sized PRV will not allow the pressure to exceed 120% of the PRV setting.

The different tank ends mean the stress will be different near and in the ends. We are not interested in end failures in this study and therefore end type is not important.

The different L/D means the cylinder stress field will be more affected by the ends. However, in the middle of the tank these end effects will be small. So this means we do not need exactly the same L/D. A tank-car has an L/D of about 6. We should not test with L/D less than about three.

For heat transfer the L/D is important because for the same defect length ratio S/w the defect will take up a smaller fraction of the total tank surface area on a tank with larger L/D. This means the defect will see more cool wall and this should reduce the wall T in the defect slightly. Again, this can be accounted for in a good thermal model.

The tank fill is important. Tank cars can be filled to 95% or more. Normal propane storage tanks are usually filled to about 80%. A tank-car is more likely to go liquid full and this can delay failure. The full scale propane railway tank test by BAM in Germany [5] showed a 22% full tank would fail in about 17 minutes when engulfed in fire. The full scale test RAX 201 [9] with a 94% fill failed in 24 minutes in an engulfing fire. Both failed at about the same vapour space wall temperature and tank pressure. The RAX 201 tank failed when it was about 40-50% full. The extra initial fill (95% vs 22%) in the RAX 201 test delayed failure by 7 min. This difference is significant, but not huge.

The above arguments show that some adjustments need to be done to compensate for non perfect scaling. We make these adjustments with our computer thermal model of the tank. If our model is properly validated and if it accounts properly for the important physics of the problem, our model predictions will be reasonable. The Tank2004 thermal model of a propane tank has accurately predicted failure times of 33 lb propane cylinders, 400 lb propane cylinders, 200 gallon ASME code tanks, 500 gallon ASME code tanks and 33,000 gallon railway tank-cars.

We do not expect the model predictions to be perfect or exact. There will always be some uncertainty in our analysis and therefore we should try to be conservative in our estimates.

Thermal Stratification and Two-Phase Swell

Thermal stratification has been observed in most fire tests of propane tanks [5,7,9,10,14,16-21,31,32]. Thermal stratification is due to the way heat enters the liquid from the heated wall. The heat is not instantly distributed uniformly throughout the liquid. In horizontal tanks the heat from the wall enters the liquid near the wall (in the boundary layer) and this warm and less dense liquid rises to the liquid top where it remains due to buoyancy. This warm layer of liquid drives the pressure in the tank. In other words, thermal stratification is very important in being able to predict the tank pressure rise.

Two phase swell is a phenomenon that takes place when the PRV opens to release vapour. When this happens vapour bubbles form in the liquid at the wall and this makes the liquid level rise suddenly due to added volume of the bubbles (i.e. two-phase swell). This is in addition to the normal liquid expansion due to temperature rise. This swell affects wall temperatures in the vapour space when the tank is near full. This swell can cause 2-phase fluid to enter the PRV.

Thermal Protection Defects

To our knowledge detailed analysis of thermal protection system defects for rail tank-cars has only taken place in Canada under sponsorship by Transport Canada. Several reports have been published.

PRV Performance

The performance of pressure relief valves is dictated by various performance standards. However, very little data is available on how PRVs actually perform under fire impingement conditions.

Several types of PRV behaviour has been observed in smaller tank PRVs. It is expected these same behaviours can been seen in full scale tank car PRVs. Examples are:

i) cycling vs continuous flow
ii) sticking or sitting partially open
iii) spring softening at elevated temperatures

All of the above affects how the tank and lading will respond to fire impingement. Models can include all of these effects if we want to study how important they are.

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