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TNO report

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Heat Resistant Coatings and Pressure Relief Devices on Transport Tanks for Liquefied Gases; Investigation of uncertainties

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Executive summary

Introduction

During the meeting of the “ADR/RID Working Group on the Reduction of the Risk of a BLEVE” (hereafter referred to as the “Working Group”) in Berlin, 15-17 April 2013 the results of new bonfire test on transport tanks for liquefied gases performed by “Bundes Anstalt für Materialprüfung” (BAM) on request of Germany and France were discussed. The tested tanks had been thermally coated and/or had been fitted with a pressure relieve valve (PRV).

The Working group concluded that the application of a heat resistant coating on the outside of the tank wall is the only effective measure to delay the time to BLEVE of a fire engulfed 3 m^3 LPG tank, until at least 60 minutes after the start of a fire. When the heat resistant coating is combined with a Pressure Relieve Valve (PRV) an even longer period could be achieved. With respect to these conclusions the Working group discussed the several questions and uncertainties with respect to the experiments and the application of the heat resistant insulation on a full size transport tank.

These question could not be answered during the meeting of the Working group. Therefore the Dutch delegation commissioned TNO to perform the required research to answer the questions. The required research and results are presented in this report. Based on this research the following conclusions are summarised:

Questions

1. Are test conditions representative for a real road/rail tanker fire?

Based on the ADR/RID and CFR regulations and the performed bonfire tests a heat load of ± 110 kW/m^2 is a representative heat load for a pool fire. Also in literature typical heat loads of an engulfing pool fire are quoted in the order of 100 -140 kW/m^2. For a jet fire heat loads are 200 kW/m^2 or higher. Based on this research the heat load for full poolfire engulfment should be 100-110 kW/m^2.
BAM used a heat load of 75 kW/m^2 in their bonfire tests. This seems to be a somewhat low value. However it should be noticed that BAM used a very narrow array of gas burners instead of a liquid hydrocarbon pool fire. Flames from these gas burners around the tank do not drift so far away with the wind as the flames of a hydrocarbon pool fire do. So the effective heat transfer for gas burners is better than for a hydrocarbon pool fire.

For a tank wagon partial or full engulfment in a pool fire is a realistic scenario.
Full engulfment of a road tanker in a fire is possible during (un)loading or parked near a tank (vehicle) with flammable liquids. During transport it is an unlikely scenario. Only if the truck would become involved in an accident with another truck carrying a large volume of flammable liquid, this would be realistic. Exposure to fires of other vehicles on fire is a realistic scenario for road accidents. Such fire can also have high heat loads. Hence for a road tanker a test for the effectiveness of a coating with a heat load of 75 kW/ m^2 is realistic for the fires that can occur during parking and transport.

Partial exposure of a transport to a fire does not reduce the risk of a tank rupture.

The tank wall will locally heat up as fast as for full fire engulfment, due to low heat transfer to the gas phase in the tank. The consequences of such a tank rupture will be less severe than in case of full fire engulfment because of the lower temperature and pressure of the liquid in the tank at the moment of rupture. Because of the limited heat input and hence reduced pressure increase one could consider a higher acceptable temperature limit than for a pool fire. As a consequence a different test regime would be required.

The tank wall temperature and liquid temperature in a large transport tank engulfed in a fire will increase slower than in a small test tank of, say, 3 m^3. The wall temperature shows a slower increase because of the thicker tank wall. The pressure in a real transport tank will also have a slower increase than a 3 m^3 test tank because of the lower tank surface area / volume ratio. A bonfire test of a 3 m^3 tank is conservative for a transport tank with a larger volume.

2. What is the effect of a PRV?

With respect to the questions that were addressed in chapter 2 the following can be concluded:

- A PRV will reduce the pressure increase in a tank and may also decrease the temperature increase of the wall, resulting in a delay of time to failure.
- If gas is vented via the PRV the ignition will be several meters (10 m or so) from the PRV because of the high velocity of the vented gas. The ignited yet will not significantly contribute to the heat input on the tank.
- In case a tank is overturned liquid may be expelled from the PRV. This will add significantly to the heat load on the tanker but only for a short time, as the tank will be emptied much quicker than when gas is expelled from the tank. It is not expected that, for a coated tank, this temporary extra heat load will have serious consequences.
- Fitting an extra PRV, or a PRV with a larger capacity, will delay or even prevent a pressure increase to values above the PRV pressure settings, but will not prevent the temperature increase of the tank wall and hence the process of tank strength reduction. Ultimately this will lead to tank failure. Applying an extra PRV, or a PRV with a larger capacity is therefore an insufficient measure to prevent tank failure/BLEVE.
- PRV operation is influenced by a fire. The spring of the PRV is softened and sometimes PRV materials melted. However this can be considered as fail-safe failure, the PRV stay open and more gas is vented.
- For a tank with a thermal insulation a PRV will reduce the wall temperature by: (a) The venting of evaporated liquid heat input in the tank, (b) Improved heat transfer from the wall to the gas phase

3. What is the effect of a transport accident (overturning or collision) on coating performance?

TNO has collected the material properties of several heat resistant insulating materials (Molag, 2006a). It was concluded that only the intumescent epoxy coatings fulfilled all requirements for a heat resistant insulation under transport conditions. Other materials were not resistant to the vibrations during transport, or needed more thickness to protect the insulation against weather influences.

The manufacturers of intumescent epoxy coatings do not supply quantitative data on the impact resistance of the coating.

The heat insulation must follow the possible deformation of the steel tank in a transport accident. So the elasticity of the coating is important. The elasticity of the intumescent coatings is larger than the steel elasticity (Molag, 2006b). So the steel tank will show a rupture earlier than the coating.
The coating should also have a high shear stress and good adhesion to the tank wall to avoid tear off during an accident. Quantitative data on adhesion are not presented, only data showing their performance relative to other insulating materials

The accident performance of mineral wool blankets with a steel or polyester jacket is less than that of epoxy coatings. There have been a several rail and road accidents where the protecting jacket and insulating blankets were torn off.

4. How does the coating affect the life time performance of a tank?

Data on the durability of intumescent insulating coatings are not presented. However standardised UV exposure tests exist to determine if the coating can be guaranteed during the life-time of a road or rail tanker.
Further curing of the intumescent coating during the life time of the tanker that could lead to brittleness of the coating should also be investigated with a standardised curing test.

Corrosion at the interface between coating and metal is only possible if the coating has cracked during transport. This is not expected but can be controlled by visual inspection and during periodic testing of the tank. Ultrasound inspection will give additional information on possible corrosion on the metal coating interface.

ADR/RID regulations prescribe that periodic inspection should also be possible for tanks with a coating. Experience with coated tanks has shown that visual inspection of a tank with a intumescent coating is not different from inspection of uncoated tanks. Cracks in the paint or coating can be observed. Ultrasound testing of important parts of the tank (e.g. welds of tank supports on the sub frame) can give information on cracks.
The diameter of a tank will slightly increase during hydraulic pressure testing of the tank. The coating has enough elasticity to follow this increase in diameter.

Agreements regarding durability criteria like UV exposure, curing, elasticity etc. still need to be made.

5. What is the effect of the additional weight of the coating?

A heat resistant coating will reduce the pay load by 3% for a tank vehicle and 2 % for a rail wagon. The coating will lead to a lower centre of gravity. The sunroof on top of the tank disappears and the total weight of the tank, coating and load does not increase.

Tanks not equipped with a sunshield will not have the weight benefit of removal of the sunroof. However, an uncoated tanker without a sunshield will be allowed a lower payload than a coated tanker, which will reduce the loss of payload. For tanks without a sunroof the centre of gravity will not be affected.

6. Which tests should be performed on heat resistant coatings before implementation?

The following tests are proposed to demonstrate the fulfilment of the relevant requirements for heat resistant coatings:

- Water permeability test
- UV exposure test
- Curing test
- Adhesive test
- Standard elasticity modulus test
- Shear stress test
- Friction test
- 900 ˚C furnace plate test
- Mock-up furnace test
- 2-3 m^3 bonfire test
- Finite elements model calculation for full scale performance

Contents

1 Introduction

During the meeting of the “ADR/RID Working Group on the Reduction of the Risk of a BLEVE” (hereafter referred to as the “Working Group”) in Berlin, 15-17 April 2013 the results of new bonfire test on transport tanks for liquefied gases performed by “Bundes Anstalt für Materialprüfung” (BAM), on request of Germany and France, were discussed. The tested tanks had been thermally coated and/or had been fitted with a pressure relieve valve (PRV) (Ulrich, 2010), (Balke, 2012a), (Balke, 2012b)

The Working group, with the exception of AEGPL, concluded that the application of a heat resistant coating on the outside of the tank wall would be the only effective measure to delay the time to BLEVE of a fire engulfed 3 m^3 LPG tank, until at least 60 minutes after the start of a fire. When the heat resistant coating would be combined with a Pressure Relieve Valve (PRV) an even longer period could be achieved. With respect to these conclusions the Working group discussed the following questions and uncertainties (UNECE, 2013)]:

- Are the BAM bonfire test conditions representative for real accident situations?
- What are the advantages of a PRV (e.g. longer delay time) and what are the disadvantages (e.g. heat of a torch fire)?
- Are the conclusions still valid when extrapolated to a full size road of rail tanker?
- Is there a practical way to test whether a heat resistant coating can sufficiently delay a BLEVE without the need for a full size bonfire test?
- How does an accident affect the effectiveness of the heat resistant coating?
- Does the coating have an effect on corrosion? Does it impede inspection? How well can the coating resist vibrations?

These question could not be answered during the meeting of the Working Group. Therefore the Dutch delegation commissioned TNO to perform the required research to answer the questions. The required research and results are presented in this report.
In chapter 2 an overview of the research questions and research activities is given. In chapter 3 a description is given of transport tank properties and how a tank can rupture when exposed to a fire. In chapters 4 – 9 the various questions are addressed and in chapter 10 the conclusions of the study are presented.

2 Research questions and activities

Table 2.1 presents the open issues that will be addressed in this research. The questions have been grouped into six main questions:

1. Are test conditions representative for a real road/rail tanker fire?
2. What is the effect of a PRV?
3. What is the effect of a transport accident (overturning or collision) on coating performance?
4. How does the coating affect the life time performance of a tank?
5. What is the effect of the additional weight of the coating?
6. Which tests should be performed on heat resistant coatings before implementation?

The research activities are described in more detail in Table 2.1.On forehand identified sources (literature, software) are also indicated. Additional literature sources that were used are indicated in the chapters describing the study.

Table 2.1 Questions addressed in this research and foreseen activities

Question		**Research activities**
1	**Are test conditions representative for a real road/rail tanker fire?**	
1.1	Are BAM test fire conditions representative for a real scale tanker fire? Can the small scale test results be extrapolated to a real ADR/RID tank? What is the relevance of small scale test?	Perform literature search on fire conditions of a real tank fire. List assumptions including fire scenarios already included in ADR/RID/UN. Study assumptions in software packages to calculate heat radiation of hydrocarbon pool fires (Safety (DNV), FRED (Shell), Effects (TNO) and other literature). Perform a qualitative assessment on partial and full engulfment of a tanker in a fire and the influence of hot spots on tanker integrity.
2	**What is the effect of a PRV? (several types and sizes)**	
2.1	What is the positive influence of the time to BLEVE?	Assess bonfire experiments as described in literature.
2.2	What are possible negative consequences of a PRV?	Calculate additional heat input from a flare directed away from the tank, a flare on an adjacent tank (rail) and a flare impinging on the ground for an overturned tank. Assess consequences of additional stress in the tank wall around the PRV (assumption: PRV size in agreement with ADR/RID/UN and working conditions are not influenced by the fire).
2.3	What is the performance of a well-designed PRV (properly sized and made of stainless steel) on the time to BLEVE?	Determine the difference in the PRVs used in BAM tests and PRVs used on ADR/RID tankers by comparing the construction and material properties.
2.4	Will application of 2 or more PRVs have a better performance on the time to BLEVE?	Assess behaviour of 2 PRVs in fire conditions and determine additional reliability.

3	**What is the effect of a transport accident (overturning or collision) on coating performance? (several types and thickness)**	
3.1	What is the resistance of the coating to impact in case of overturning of a tank or a tank collision. What is the effect on the time to BLEVE?	Assess material properties of coating and expected impact forces.
3.2	What is the influence of a damaged coating on time to BLEVE due to overturning or collision	Perform a literature study on the consequences of hot spots in coatings.
4	**How does the coating affect the life time performance of a tank? (several types and thickness)**	
4.1	What is the influence of vibrations during transport and of degradation on coating performance?	Assess material properties of the coating (elasticity, ageing).
4.2	Is corrosion possible under the coating?	Assess material properties of the coating and application process.
4.3	Is the required ADR/RID inspection of coated tank with non-destructive test methods possible?	Assess inspection procedure and interview with testing authorities.
4.4	Is a life time manufactures warranty possible for coated tanks?	Interviews with tank and coating suppliers.
5	**What is the effect of the additional weight of the coating?**	
5.1	Does the coating change the centre of gravity of a tanker?	Calculate the centre of gravity of coated and non-coated tank.
5.2	What are the additional operational costs of a coated tank?	Calculate the operational coast (loss of pay-load, additional maintenance/inspection) for coated tanks.
6	**Which tests should be performed on heat resistant coatings?**	
6.1	Which tests should be performed on heat resistant coatings before implementation?	Propose testing procedure for heat resistant coatings (Bonfire tests, Finite Elements analyses)

Following a chapter on transport tank properties and failure (chapter 3) the research into these six subjects will be described in the chapters 4 - 9. This will be followed by the conclusions (chapter 10), that will be presented and discussed during the next meeting of the Working Group.

3 Transport tank properties and failure

3.1 ADR/RID Tank construction requirements

ADR/RID regulations ((ADR, 2013) (RID, 2013)) have several requirements to prevent that the tank will fail during operation. These are described in ADR chapter 6.8. (ADR, 2013). The tank wall must be strong enough to resist the pressure of the liquefied gas transported in the tank. The internal pressure (p_i) in a tank filled with liquefied gas is determined by the vapour pressure of the gas, that depends on:

- Physical properties of the substance in the tank i.e. substance and composition;
- Temperature of the tank.

At a temperature of around 20 °C for instance pure propane will have a vapour pressure of around 8 bar and butane of around 2 bar. The vapour pressure of LPG, which is a mixture of these components will be somewhere between these values depending on the composition[1]. During transport the temperature in the tank will vary depending on local temperature and solar radiation. For that reason ADR/RID 4.3.3.2.5 describes a test pressure for non-isolated tanks at 65 °C and for tanks with insulation or sun roof at 60 °C. The test pressures of some substances are presented in Table 3.1.

Table 3.1 Test pressure for insulated and non-insulated tanks

Substance	UN	Test pressure [MPa]		Maximum load
		Insulated tank	Non-insulated tank	[kg/l]
propane	1983	2.1	2.3	0.42
butane	1011	1	1	0.51
LPG mixture C	1965	2.5	2.7	0.42

In ADR/RID 4.3.3.1.1. it is indicated that the calculation pressure for the tank must be larger than or equal to the test pressure. In general manufacturers of LPG tank vehicles and tank wagons will fit a sun roof that will allow them to apply the test pressure for insulated tanks. Therefore a calculation pressure of 2.5 MPa is used for the construction. This allows for transport of all flammable liquefied gasses in such tanks. The maximum allowed working pressure (MAWP) in these tanks is 1.92 MPa (ADR/RID 6.8.2.1.14: calculation pressure must be at least 1.3 times the filling or discharge pressure).The tank shell must be able to withstand this pressure.

The minimum shell thickness e to withstand the test pressure is (ADR/RID 6.8.2.1.17):

$$e = \frac{P_T\, D}{2\, \sigma\, \lambda} \qquad (1)$$

P_T is the test pressure in MPa

D is the internal tank diameter in m

σ is the permissible stress in MPa as defined in ADR/RID 6.8.2.1.16:
$\sigma \leq 0.75\ Re$ or $\sigma \leq 0.5\ Rm$, *where:*

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[1] If ethane is present in the LPG the vapour pressure can be higher.

Re is the apparent yield strength for steels having a clearly defined yield point or guaranteed 0.2 % proof stress for steels with no clearly defined yield point (1% for austenitic steels);

Rm is the tensile strength

λ =1 if all beads have been subjected to non-destructive checks and, as far as possible, have been visually inspected on both sides. A weld test-peace shall be taken (ADR/RID 6.8.2.1.23).

In this investigation calculations will be done for a representative tank vehicle and a tank wagon. The dimensions and material properties of the tank shell are presented in Table 3.2.[2]

Table 3.2 Dimensions and properties of a representative tank vehicle and tank wagon

	Unit	**Tank vehicle**	**Tank wagon**
Volume	m^3	50	92
Internal diameter	m	2.3	2.65
Tank length	m	12	16,5
Tank surface	m^2	87	138
Shell thickness	m	0.0095	0.015
Test pressure	MPa	2.5	2.5
Shell stress	MPa	315	222
Applied Steel		P460NL2	P460NL2
$Re_{0,2}$ applied steel	MPa	460	460
$\sigma = 0.75\ Re_{0.2}$	MPa	345	345
Rm applied steel	MPa	630	630
$\sigma = 0.5\ Rm$	MPa	315	315

As can be seen in Table 3.2 the shell stress of the tanks is equal or less than the permissible stress σ. This is valid for normal operational temperatures (-40°C - +50°C).

3.2 ADR/RID Pressure Relieve Device

ADR/RID 6.8.3.2.9 indicates that tanks for transport of pressurised liquefied gases may be fitted with a spring loaded safety valve or pressure relief valve (PRV), opening at 0.9 – 1.0 times the test pressure. ADR/RID 6.7.3.8.1 states that the combined delivery capacity of the relief devices shall be sufficient that in the event of total fire engulfment , the pressure (including accumulation) inside the shell does not exceed 120% of the MAWP. The required capacity of the safety device(s) valve shall be calculated according ADR/RID 6.7.3.8.1.1.:

$$Q = 12.4 \frac{FA^{0.82}}{LC} \sqrt{\frac{ZT}{M}} \qquad (2)$$

where:

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[2] The construction details of the representative tanks are based on information supplied by Hobur and GATX. For the representative tanks λ = 1.

Q = minimum required rate of discharge in cubic metres of air per second (m^3/s) at standard conditions: 1 bar and 0 °C (273 K);

F = is a coefficient with the following value:
for non-insulated shells: $F = 1$;
for insulated shells: $F = U(649 - t)/13.6$ but in no case is less than 0.25 where:
U = thermal conductance of the insulation, in $kW.m^{-2}. K^{-1}$, at 38 °C;
t = actual temperature of the substance during filling (in °C); when
this temperature is unknown, let $t = 15$ °C;

The value of F given above for insulated shells may be taken provided that the insulation is in accordance with 6.7.2.12.2.4;

A = total external surface area of shell in m^2;

Z = the gas compressibility factor in the accumulating condition (when this factor is unknown, let Z=1.0);

T = absolute temperature in Kelvin (°C + 273) above the pressure-relief devices in the accumulating condition;

L = the latent heat of vaporization of the liquid, in kJ/kg, in the accumulating condition;

M = molecular mass of the discharged gas (g/mol);

C = a constant which is derived from one of the following formulae as a function of the ratio k of specific heats:

$$k = \frac{c_p}{c_v}$$

where:
c_p is the specific heat at constant pressure; and
c_v is the specific heat at constant volume.
When k > 1:

$$C = \sqrt{k\left(\frac{2}{K+1}\right)^{\frac{k+1}{k-1}}}$$

When $k = 1$ or k is unknown:

$$C = \frac{1}{\sqrt{e}}$$

where e is the mathematical constant 2.7183.

The idea behind this formula is, for a tank engulfed in a fire, that the heat transfer per second from the fire to the tank should be equal to the quantity of the substance in the tank that is evaporated and vented per second (equilibrium or accumulation condition). This will prevent that the pressure in the tank will increase to values above 120% of the Maximum Allowed Working Pressure (MAWP).
The physical properties and the temperature T in the formula should be taken in the accumulating condition (Ludwig, 2000). Table 3.3 presents the vent capacity in m^3 air calculated for the representative tanks with the formula.

Table 3.3 Dimensions and properties of a representative tank vehicle and tank wagon filled with propane

	Unit	Tank vehicle	Tank wagon
Volume	m^3	50	92
Max load propane	kg	21000	38640
Tank surface	m^2	87	138
Test pressure	MPa	2.5	2.5
MAWP	MPa	1.92	1.92
PRV set pressure	MPa	2.25	2.25
T propane at relieving pressure	°K	336	
L at 336 °K	kJ/kg	252	
Cp at 336 °K	kJ/kg.K	1.955	
Cv at 336 °K	kJ/kg.K	1,766	
K (Cp/Cv)	-	1,11	
C	-	0.63	
Z at 336 °K	-	0.66	
M (propane)	kg/kmol	44,09	
Q (air)	nm^3/s	6.67	9.97

3.3 Tank failure

There are several causes of a tank failure:

1) Construction failures
2) Accidental impact
3) Overloading
4) Exposure to a fire

The first two causes are not part of this investigation. Overloading and fire exposure will increase the internal pressure in the tank. The tank will fail if the internal pressure inside the tank (p_i) exceeds the strength of the tank wall (p_s), i.e. the pressure the tank can withstand. This is not possible at normal operation conditions; the pressure will be below the test pressure.

If the tank is overloaded the pressure could become larger than the test pressure. Several measures in the ADR/RID regulations prevent overloading of the tank. An overloaded tank with a PRV will not fail. An increase of liquid temperature in the tank by solar radiation or higher environmental temperature will increase the liquid volume. The PRV will vent the excess fluid if the volume of the expanded fluid exceeds the tank volume.

However when a tank filled with pressurised liquefied gas is exposed to a fire the following will occur:

1. The temperature of the liquefied gas will increase and as a result of this the saturated vapour pressure ($p_i(T)$) in the tank will increase;
2. The temperature of the tank shell will increase thus reducing the yield strength and tensile strength of the applied steel will decrease at temperatures above 300°C. This is particularly important for the part of the shell that is in contact with the gas phase (top part) of the tank. As there is

no cooling effect by the liquid in the lower part of the tank the temperature increase will be significant.

The tank shell will fail if:

$$p_i(T) > p_s(T) = \frac{R_m(T)e}{D} \tag{3}$$

When the internal pressure exceeds the tensile strength of the wall the tank can fail. A schematic view of the increase of pressure and decrease of tensile strength of a tank wall in contact with the gas phase when the tank is engulfed in a pool fire is shown schematically in Figure 3.1. Upon heating the internal pressure will increase (blue line). When the setpoint pressure of the pressure relieve valve ($P_{setpoint}$ in Figure 3.1) is reached the PRV will open and pressure will be released. The consequence is that the liquid will evaporate to replace the vented gas.
Due to this evaporation a lot of heat will be transferred out of the tank.
The temperature of the liquid in the tank will not further increase if the vent capacity of the safety valve is enough to release all heat input through the evaporated liquefied gas. If the vent capacity is too small the temperature will continue to rise, al be it at a slower rate, (see Figure 3.1).
The temperature of the top side of the tank shell that is not in contact with the liquid will increase because of the poor heat transfer from the top part of the tank wall that is in contact with the gas phase to the gas in the tank. Consequently the strength of tank shell will decrease rapidly (red line in Figure 3.1). Because of the heat release after opening of the valve, the temperature increase of the tank wall will slow down somewhat, as also shown Figure 3.1. The actual time dependence of pressure and strength of the tank shell will also be influenced by local circumstances like intensity of the fire, vessel condition, PRV behaviour etc. and will not be linear. For instance a PRV with a high capacity will open and close frequently which causes the pressure in the tank to oscillate between opening and closing pressures of the safety valve. This is not shown in the schematic drawing of Figure 3.1. Therefore actual times to failure for a vessel vary considerably (Abassi, 2007).

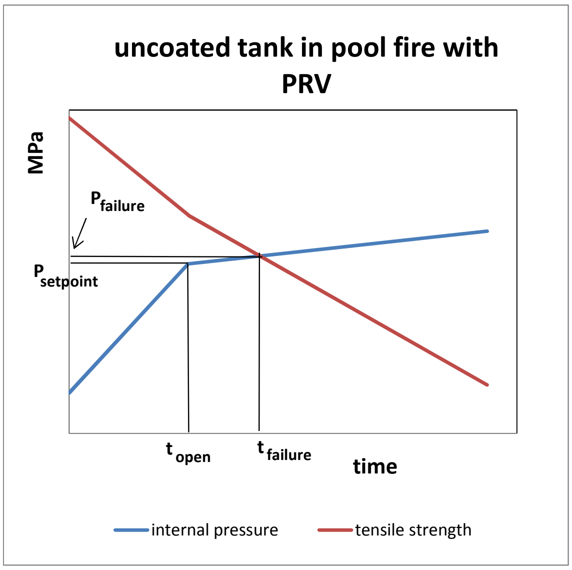
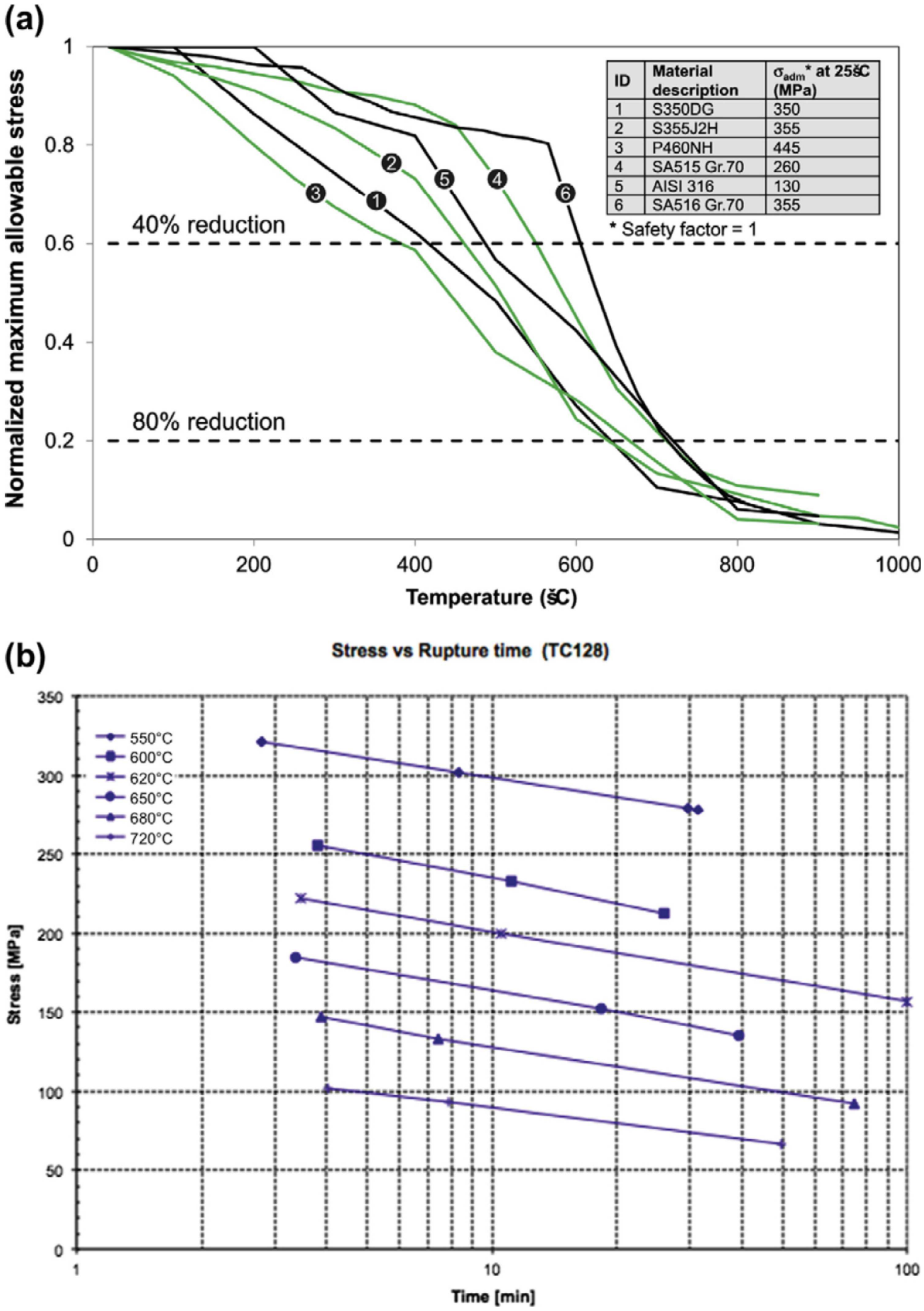


Figure 3.1 Schematic view of the increase of internal pressure and decrease of the strength of the tank wall in contact with the gas phase when an uncoated tank, equipped with a pressure release valve (PRV) is engulfed in a pool fire.

3.4 Shell strength at high temperature

Steel is applied for the shell of transport tanks for pressurised liquefied gases. The tensile strength and yield strength of steel decreases at higher temperatures. This is indicated in Figure 3.3. Figure 3.3 (a) shows that the allowable stress strongly decreases at temperatures above 300 ˚C. If the steel is exposed to high temperature for a longer period the admissible stress decreases. This is shown in Figure 3.3 (b).



ID	Material description	σ_{adm}* at 25šC (MPa)
1	S350DG	350
2	S355J2H	355
3	P460NH	445
4	SA515 Gr.70	260
5	AISI 316	130
6	SA516 Gr.70	355

Figure 3.2 Effect of temperature on the normalised maximum admissible stress of construction steels. (a) Normalised admissible stress: $\sigma_{adm\,(T)}/\sigma_{adm\,(25°C)}$ (b) high temperature stress rupture data for TC-128 Tank Car Steel (Landucci, 2013).

3.5 Thermal insulation

Thermal insulation of the shell will reduce the heat transfer from a fire to the tank shell. The consequence is that the liquid temperature and internal pressure will increase at a slower rate than without insulation. Also the increase of the shell temperature is slower, with the consequence that the shell strength decreases at a slower rate (Figure 3.3).
Therefore both the time to open for the PRV and the time to failure will be longer for an insulated tank than a tank without thermal insulation. The time to failure will further increase if the thermal insulation of the shell is combined with a PRV. The evaporation of the gas that is vented will slow down the increase of the liquid temperature and the saturated vapour pressure. This is also indicated in Figure 3.3.

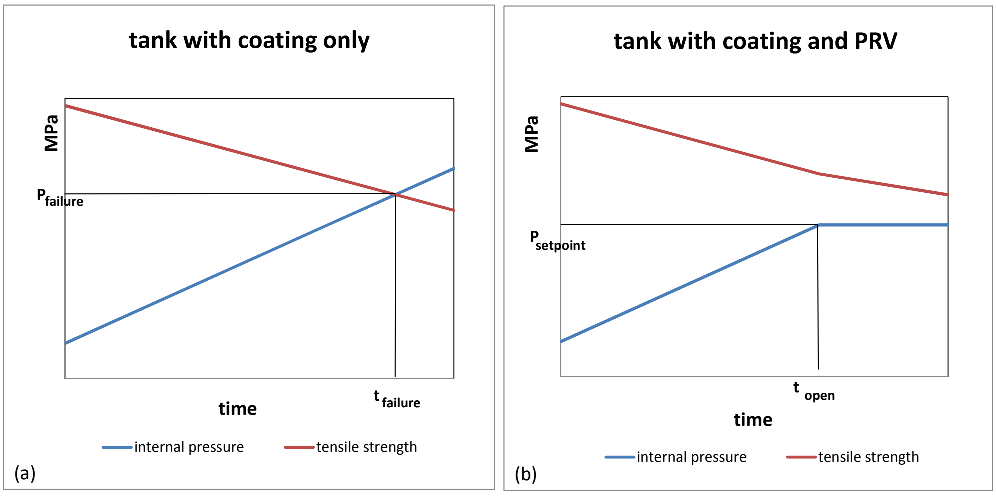


Figure 3.3 Schematic view of the increase of internal pressure and decrease of tensile strength of the tank wall in contact with the gas phase when a tank is engulfed in a pool fire: (a) tank with thermal coating only; (b) tank with thermal coating and PRV.

3.6 Consequences of a tank shell failure

The heat transfer of fire to a pressurised liquefied gas tank can lead to a failure of the tank wall, especially the top (gas) side of the tank is endangered. It may result in an instantaneous rupture of the shell, although in some cases the result was only a small crack in the shell (Balke, 2012b).
A small crack in the tank shell will result in a jet release of the pressurised liquefied gas, without explosion effects. A jet of a flammable gas will cause a long flare that could hit people or buildings.

An instantaneous rupture of the tank shell will cause an extremely fast evaporation of the liquid in the tank. The general accepted theory is that a Boiling Liquid Expanding Vapour Explosion (BLEVE) will be the result if the temperature of the pressurised liquid is above its super heat limit temperature (T_{slt}) of 53 ˚C (Reid, 1979). A BLEVE results in a physical explosion and fire ball. Parts of the ruptured tank will be propelled over large distances. In (Abassi, 2007) it is described that some authors claim that a BLEVE also can occur below T_{slt}.

Smaller explosion effects will occur if the tank ruptures after all the liquid in the tank is evaporation.

4 Representative test conditions for a real fire

A bonfire test of a tank should be representative for a full scale Class 2 transport tank exposed to a fire. Two conditions determine if the bonfire test is representative:

- The heat input during the bonfire test must be representative for a transport tank exposed to a real fire;
- Full fire engulfment of the tank in a bonfire test should be representative for (partial) exposure of a transport tank in real fire.

In a bonfire test a tank is completely engulfed in a fire. These fire conditions have been defined to represent exposure to a hydrocarbon pool fire. Exposure of wagons filled with liquefied gas to pool fires can occur during combined rail transport of such wagons filled with pressurised liquefied gas and wagons filled with flammable liquids. A rail accident could cause leakage of the flammable liquid leading to a liquid pool. Upon ignition, a nearby wagon with pressurised liquefied gas could be engulfed in a pool fire. Such accidents have been reported during rail transport and on shunting yards (Molag, 2008). For road transport this is a less likely accident scenario. The inventory of the diesel tank (600 - maximum 1499 litre) of the truck is not large enough to cause a large burning liquid pool that completely engulfs the tank. However this scenario is possible on a parking where both tank vehicles with flammable liquids and liquefied flammable gasses are parked, as illustrated by the explosion of a tank vehicle in Harthausen (D) on 28 September 2013 (SWR, 2013). During transport, exposure of tank vehicles to a fire of the diesel from the fuel tank or tyres, or exposure to fire of another nearby vehicle loaded with combustible materials (wood, plastic etc.) is a more likely scenario. Both fire scenarios are evaluated in this chapter. At the end of this chapter conclusions are drawn with respect to representative fire conditions.

4.1 Heat input from a hydrocarbon pool fire

The heat load applied to the outside of the (test) tank is one of the most important parameters determining the rate (°C/s) at which the temperature of the tank and its contents (and hence the pressure) increases. The most important question is what is a representative heat load from a pool fire. Several sources have been investigated:

- Regulations
- Fire tests
- Risk assessment software

4.1.1 Regulations

The following regulations have been identified and investigated:

- ADR/RID regulations
- CFR regulations
- IAEA regulations

ADR/RID

There are a few regulations in ADR/RID ((ADR, 2013), (RID, 2013)) that refer directly or indirectly to the fire case. In ADR/RID 6.7.2.2.1 it is stated that portable tanks with aluminium shells should be able to withstand a heat load of 110 kW/m^2 for 30 minutes.

The formula (2) to determine the flow capacity of a safety valve for fire engulfment of a transport tank in ADR/RID 6.7.3.8.1.1. (see §3.2) is based on heat radiation levels derived from pool fire tests in the USA in the forties of the previous century. Based on these test a heat flux of 109 kW/m^2 has been used in the formula (Ludwig, 2000). This heat flux is adapted for the size of the tank to a net heat input by introducing the factor f.

$$f = H'/H = 1.534 \times A^{0.18} \tag{4}$$

where:

f correction factor for heat input to the tank
H' net heat input to the tank (kW/m^2)
H heat flux from the fire (kW/m^2)
A surface area of tank (m^2)

Table 4.1 presents the net heat input for the representative tanks. It shows that the net heat input in the tank assumed in the formula to calculate the vent capacity for the PRV in the ADR/RID regulations is less than 1/3rd of the heat flux of 109 kW/m^2.

Table 4.1 Representative tank vehicle and tank wagon heat input for a heat flux of 109 kW/m^2

	Dimension	Tank vehicle	Tank wagon
Tank volume	m^3	50	92
Tank surface	m^2	87	138
Net heat input	kW/m^2	31.8	29.3
Heat flux of the fire	kW/m^2	109	109

CFR

In the appendix B of §179.18 Thermal protection systems of the US Code of Federal regulations – Title 49 (CFR, 2011) the criteria for a pool fire and torch fire are defined. The temperature curve for the fire is defined. An engulfing pool fire must have a temperature of 871 °C ± 55.6 °C. A torch fire must have a flame temperature of 1204 °C ± 37,8 °C. The flare velocity must be 64.4 km/h ± 16 km/h. Heat fluxes are not defined.

IAEA regulations

Ulrich describes the IAEA test conditions for a thermal test for containers intended for carriage of radioactive materials based on § 728 of the IAEA regulations (safety series No 8). The container must be completely engulfed in a fire with a temperature of 800 °C for 30 minutes. This represents a net heat transfer into the tank of 75 kW/m^2 (Ulrich, 2010). It is noticed that larger tanks will be less exposed to the flames. It is proposed to apply the same correction f as in ADR/RID formula (2).

4.1.2 *Fire tests*

In the period 1974 – 2006 14 bonfire experiments have been performed by Townsend, Droste, Moodie, Persaud, Birk, Faucher, Molag, Balke well documented in scientific journals. Landucci et.al. present an overview of these experiments and an analysis of the experimental data (Landucci, 2013).
The conclusion of the authors is that the typical heat load of an engulfing pool fire is in the order of 100 -140 kW/m^2. For a jet fire heat loads are 200 kW/m^2 or higher.

The reported average flame temperatures of the pool fires in these tests are 800 °C or higher.

In (Cowley, 1992) it is stated that it is very difficult to calculate or measure the heat transfer to objects engulfed in a flame. In this document a range for the total heat flux in heavy hydrocarbon pool fires is given of 100 and 160 kW/m^2. In (Birk, 2000) a maximum heat flux of 130 kW/m^2 is quoted for kerosene, diesel oil, gasoline and jet fuel JP4. In (Roberts, 2004) a range of 50-150 kW/m^2 is given for open pool fires. In this reference a value of 75 kW/m^2 is quoted for a kerosene pool fire based on the Shell HEATUP model.

4.1.3 Risk assessment software

In the various models that are used in external safety risk assessments, like TNO's EFFECTS, DNV's Phast or Shell's FRED, the heat load within a fire is not relevant for external safety and is not calculated. The basis for most of the models used in these software packages is the Yellow Book (TNO, 1997). Only heat radiated by the flames to the surroundings is relevant and is calculated from the Surface Emissive Power (SEP) of the flames. This value highly depends on how much of the flames is covered with soot, which reduces the radiation intensity. Clear flames of gasoline for instance will have a SEP of about 130 kW/m^2. This means that the heat load within the fire will be ≥ 130 kW/m^2.

4.1.4 BAM bonfire tests

BAM has performed several bonfire tests of LPG tanks (BAM, 2008), (Ulrich, 2010), (Balke, 2012a), (Balke, 2012b). Although a 'real' pool fire with a hydrocarbon like diesel or heating oil would seem the most appropriate choice there are a number of drawbacks associated with this choice, as also indicated in the BAM reports (Balke, 2012a), (Balke, 2012b). Therefore BAM uses propane burners to generate the required heat input. This has the following advantages over a pool fire:

- Much less environmental pollution (hardly smoke, no risk on soil and groundwater contamination);
- Much more control over the fire/test conditions:
  - heat load can be controlled;
  - in critical conditions the test can be stopped;
  - no soot, so the test can be (visually) observed better;
  - quicker turnaround as no cleaning up of waste after the test is required.

BAM adheres to the IAEA conditions stating that a heat load of 75 kW/m^2 should be applied to the tank surface (BAM, 2008).

4.1.5 Conclusion

Based on the ADR/RID and CFR regulations and the performed bonfire tests a heat load of ± 110 kW/m^2 is a representative heat load for a pool fire. Also in literature typical heat loads of an engulfing pool fire are quoted in the order of 100 -140 kW/m^2. For a jet fire heat loads are 200 kW/m^2 or higher.
BAM used a heat load of 75 kW/m^2 in their bonfire tests. This seems to be a somewhat low value. However it should be noticed that BAM used a very narrow array of gas burners instead of a liquid hydrocarbon pool fire. Flames from these gas burners around the tank do not drift so far away with the wind as the flames of a

hydrocarbon pool fire do. So the effective heat transfer for gas burners is better than for a hydrocarbon pool fire.

4.2 Fire size

Important for a bonfire test is that the bonfire should be representative for fires that can occur during road and rail transport.

4.2.1 Road

A road accident with a tanker is unlikely to result in exposure to a full size pool fire. A full pool fire engulfment of an LPG road tanker is possible when a LPG road tanker is parked near tank vehicles with flammable liquids. Such accident have been reported in the recent past in Port La Nouvelle (IMPEL, 2010) and Harthausen (SWR, 2013).

The most likely scenario would be a fire of the diesel (say 600 l) and the tires of the truck. Assuming a pool thickness of 5 mm a spill of a 600 l diesel tank would result in a pool area of 120 m^2; a 1 cm thick pool would mean an area of 60 m^2. With both areas a full engulfment of a road tanker would be possible. However the fire duration would be only 1 or 2 minutes respectively, not enough to cause a BLEVE of an LPG tanker. The pool fire could set fire to the tyres though. These however, would only heat up a small part of the tank. The mudguards between the wheels and the tank might protect the tank against the fires, if constructed out of incombustible materials.

A more likely cause for a BLEVE of an LPG tank vehicle would be involvement in an accident with a number of (passenger) cars, or collision with another truck carrying combustible goods, say wooden furniture. The total heat load of a passenger car is generally around 5 MW, and for a truck with wooden goods about 100 MW (PIARC, 2013). As generally the burning material will also be of organic origin, the heat of the flames is likely to be comparable with a pool fire. Heymes et. al. have investigated the heat load and impact of wildland fires on LPG tanks (Heymes, 2013a).They consider a Surface Emissive Power (SEP) of 90 kW/m^2 for a wildland fire. The actual heat load on the tank is then equal to SEP multiplied by the atmospheric transmission coefficient multiplied by the viewfactor. This results in a heat load of 24 kW/ m^2 of a tank at 50 m distance from a very strong crown fire (height 40m, length 100m). For a tank vehicle exposed to a nearby other truck on fire the separation distance will only be a few meters, but the fire will be smaller. In another study investigated Heymes the heat load of a remote wall fire of 3 m by 8 m on a 2.3 m^3 LPG tank (Heymes, 2013b) located ± 2 m from the wall fire. Such a wall fire is representative of a truck on fire. The surface emissive power of this wall fire was 70 kW/m^2. The average measured heat flux at the tank wall was 43 kW/m^2 .

Full engulfment of a road tanker in a fire is possible during (un)loading and parked next to a vehicle with flammable liquids. During transport it is an unlikely scenario. Only if the truck would become involved in an accident with another truck carrying a large volume of flammable liquid, this would be realistic. Exposure to fires of other vehicles on fire is a realistic scenario for road accidents. Such fire can also have high heat loads. Hence for a road tanker a test of the effectiveness of a coating with a heat load of 75 kW/ m^2 is realistic for the fires that can occur during parking and transport.

4.2.2 *Rail*

A pool fire causing heat-up of a train wagon with liquefied gases is a very feasible scenario and considered in most risk analyses, as a train consists of many rail cars. If in case of an accident a wagon with flammable liquids fails a pool fire could occur. Pool sizes of about 600 m^2 have been reported resulting from instantaneous release of the total contents of train wagon with liquid (SAVE, 1989). A pool fire of such dimensions (say a circle with a diameter of 27 m) can easily engulf one or more train wagons (with a projected surface area of about 15 x 3 m) for 100 %. If these wagons contain a liquefied gas there is a risk of a BLEVE. Hence a full engulfment test is an appropriate method to test the effectiveness of a thermal coating on a rail car.

4.2.3 *Conclusions*

For a tank wagon partial or full engulfment in a pool fire is a realistic scenario. Full engulfment of a road tanker in a fire is possible during (un)loading or parked near a vehicle with flammable liquids. During transport it is an unlikely scenario. Only if the truck would become involved in an accident which another truck carrying a large volume of flammable liquid, this would be realistic. Exposure to fires of other vehicles on fire is a realistic scenario for road accidents. Such fire can also have high heat loads. Hence for a road tanker a test for the effectiveness of a coating with a heat load of 75 kW/ m^2 is realistic for the fires that can occur during parking and transport.

4.3 Partial engulfment / hot spots

Partial exposure is important in the following cases:

1. A small fire;
2. In case a part of the coatings is damaged, e.g. in an accident;
3. In case of a torch fire. This is of particular importance for rail transport. A torch from a rail wagon (e.g. ignited gas escaping from a hole after an accident or from the PRV) may impinge on a neighbouring wagon.

4.3.1 *Small fire*

If only a small area of the tank is exposed to a fire the heat input in the tank will be much less. Hence the time at which a critical temperature of the liquid and the shell would be reached will be longer. However this does not mean that the risk of a tank failure is lower with partial fire engulfment. Partial exposure would be heating up the liquid in the tank at a slower rate. The saturated vapour pressure in the tank will rise slower. Birk describes the response of 25% engulfing fire of a 2.3 m^3 tank with PRV (Birk, 2006). Opening of the PRV results in evaporation of the liquid. This evaporation process and the venting of vapour will increase the circulation in the liquid and in the gas phase. Due to this circulation the heat transfer in the gas phase will be better, resulting in lower gas wall temperature. In a partial engulfment the PRV will open at a later moment due to slower increase of the liquid temperature and vapour pressure. The area of the tank shell that is exposed will have a higher temperature for a longer time than a fully engulfed tank with PRV.

4.3.2 *Jet-fire*

This scenario is relevant for rail transport, less for road transport. A jet fire of a flare of a venting PRV or resulting from other damaged equipment or a shell puncture of a LPG wagon can affect a nearby rail wagon. During road transport it is unlikely that the flare of a PRV will be directed to the tank. The effect of a jet fire on the part of the wall in contact with the gas phase on a rail wagon is shown in Figure 4.1. As the heat flux of a jet is higher than a pool fire the wall at the exposed area will heat up faster than in case of a pool fire. Hence the strength of the tank shell will decrease strongly on the spot where the jet hits the shell. As the total energy input is much less than in a pool fire, the pressure in the tank will barely increase. The result will be a tank rupture at a lower pressure than for engulfment in a pool fire.

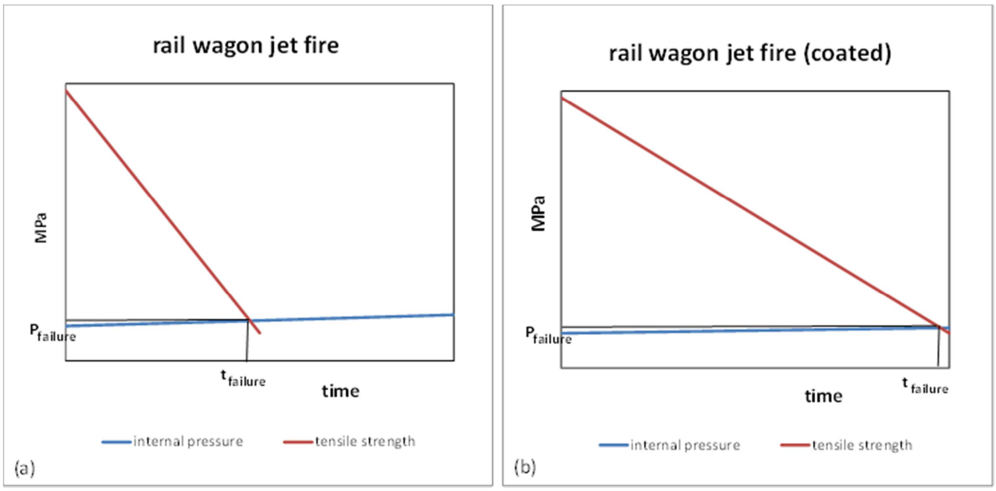


Figure 4.1 Schematic view of the increase of pressure and decrease of tensile strength of the tank wall in contact with the gas phase when a rail wagon (no PRV) is exposed to a jet fire: (a) no coating; (b) with coating.

4.3.3 Damaged heat insulation

Partial exposure of the tank shell with thermal coating in a fire is also possible if the insulation is damaged due to an accident. The effect of a damaged insulation of a road tanker is shown in Figure 4.2. Assuming that insulation on the tank wall in contact with the gas phase is damaged, the strength of the tank at the location of the damage would be lost at the same rate as if no insulation were present. The heat input in the tank will be somewhat higher than with an intact insulation, so the PRV will open a little earlier. The time to failure will depend on the size of the damaged area (see further on).

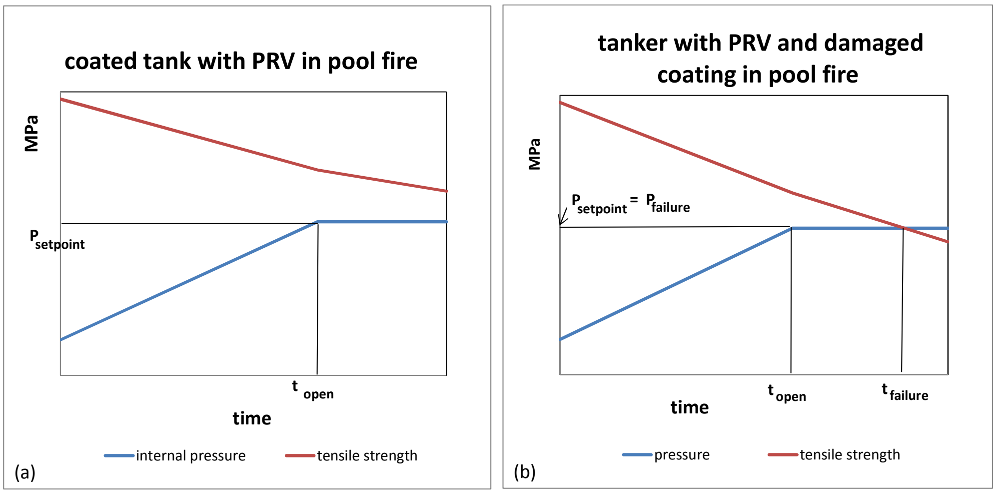


Figure 4.2 Schematic view of the increase of pressure and decrease of tensile strength of the tank wall in contact with the gas phase when a road tanker is engulfed in a pool fire: (a) fully intact coating; (b) damaged coating.

The effect of the size of the damaged area of the insulation has been investigated by Birk et. al. (see Figure 4.3) (Birk, 2003). They investigated the effect of various defect sizes on the temperature increase of a tank wall. The experimental apparatus used for the fire tests consisted of a quarter section tank-car model with a 16 mm thick steel wall, heated by nine propane utility burners. Thermal protection consisted of a 13 mm ceramic blanket of insulation covered by a 3 mm steel jacket. It was shown that if defects were larger than 40 cm x 40 cm the temperature increase (at the hottest spot) was about the same as the case where no ceramic blanket but only the steel jacket was present. They recommended that a thermal protection defect with average defect dimension of 40 cm or greater should be considered a very significant defect.

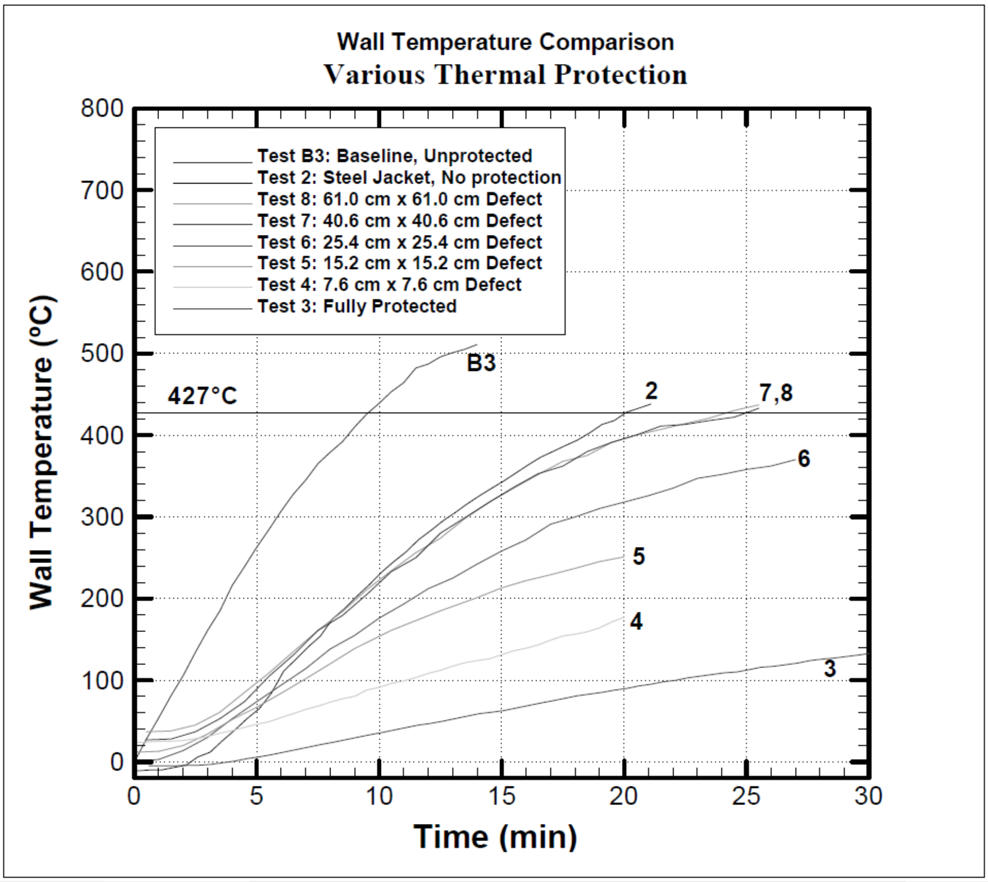


Figure 4.3 Wall Temperature versus Time for Various Defect Sizes (Birk, 2003).

One should consider however that this configuration may not be applicable to the European situation. Also, in case of an accident the steel shell may be exposed directly to a fire (i.e. there is no steel jacket). The results reported in (Birk, 2003) show that if no steel jacket is present the temperature increase is about twice as fast as the situation with a steel jacket and no ceramic blanket. Also, a defect in the ceramic blanket of about 8 cm x 8 cm (under the steel jacket) doubled the temperature increase compared to an intact blanket. From this it cannot be concluded which defect sizes are acceptable. However it would seem that if an unprotected shell area of only a few cm^2 would be subjected to the heat of a (pool) fire this could quickly result in very hot (and weak) spots. To determine the effect of damage on the effectiveness of thermal coatings specific tests would be required.

4.3.4 *Conclusion partial fire exposure*

Partial exposure of a tank to a pool fire can lead to rupture of the tank. The coating experiments show that an exposure of a relatively small area of the tank shell to the fire can lead to rupture of the shell. This scenario is also possible for torch fire exposure of a tank wagon.

To test the effectiveness of a thermal coating against partial fire exposure of a torch or jet fire the 75 kW/m^2 heat load would certainly be on the low side. Values in the range 50 - 300 kW/m^2 are reported for propane at release rates of up to 22 kg/s (Cowley, 1992) (a typical release rate for a PRV would be about 11 kg/s). Because of the limited heat input and hence reduced pressure increase one could consider a higher acceptable temperature limit than for a pool fire, which would require a different test regime.

4.4 Tank size in relation to heat input

Bonfire experiments are most often carried out with smaller tanks than those actually used for the transport of gases liquefied under pressure, i.e. test tanks have a thinner wall and a smaller diameter and length. Test tanks are typically around 3 m^3, whereas transport tanks have volumes of 60 m^3 (road tanker) and 110 m^3 (rail tanker).
The energy (heat) input in the tank will be absorbed by the tank and its contents and will lead to a temperature increase. The input is proportional to the total *surface area* of the tank exposed to the flames. However, the temperature increase will be proportional to the *volume* of the tank. As the surface area is proportional to r^2 and the volume to r^3 a larger tank will have a larger volume to surface area and will therefore show a slower increase in temperature. This is illustrated in Figure 4.4 and Figure 4.5, in which the results of a bonfire test carried out by TNO on a 3 m^3 thermally coated tank are extrapolated to a 60 m^3 road tanker using numerical modelling methods (Molag, 2006b).

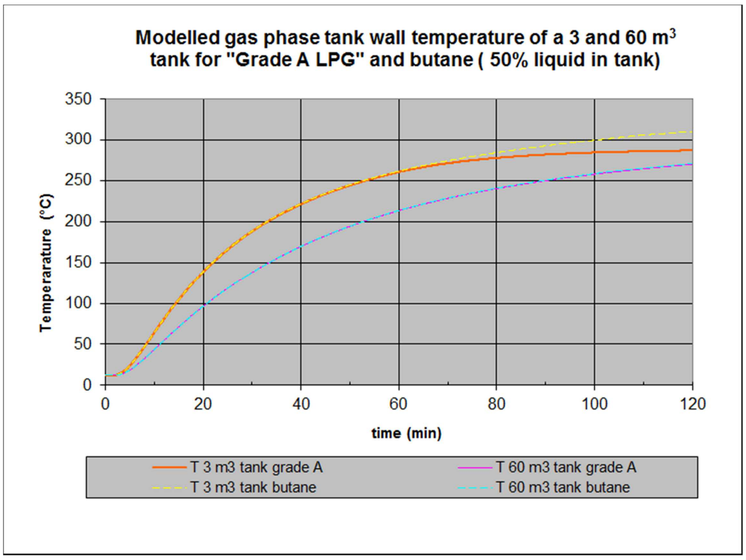


Figure 4.4 Modelled temperature of tank wall in contact with the gas phase of a 3 and 60 m^3 tank for “Grade A LPG” and butane filled for 50% with liquid product. Grade A LPG is a mixture of 73% propane and 27 % butane. Tank dimensions: 3m^3 tank: 1.25 m diameter; length 2.6 m; 60 m^3 tank: diameter 2.6 m, length 12 m; both 10 mm thermal coating.

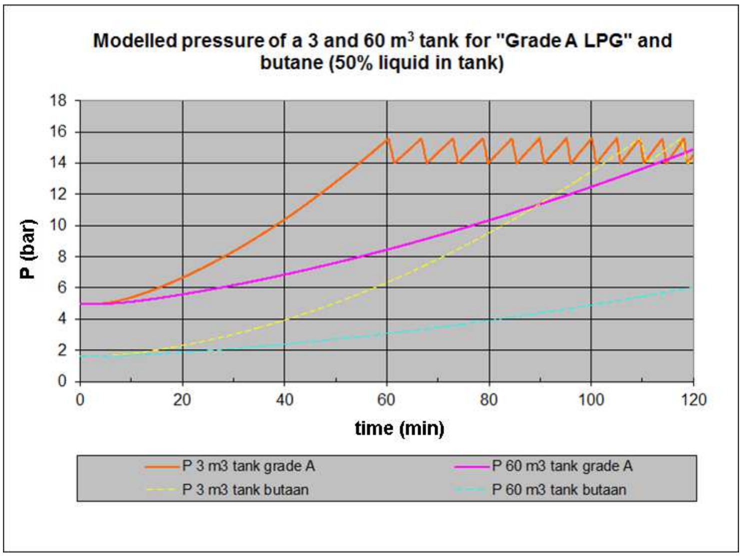


Figure 4.5 Modelled pressure of a 3 and 60 m^3 tank (with 10 mm coating) for “Grade A LPG” and butane filled for 50% with liquid product. Further specifications as in Figure 4.4.

This can also be illustrated with data from Birk et al. (Birk, 1995), shown in Figure 4.6, Figure 4.7 and Figure 4.8. In Figure 4.6 it is shown that pressure increase will be slower for larger tanks.

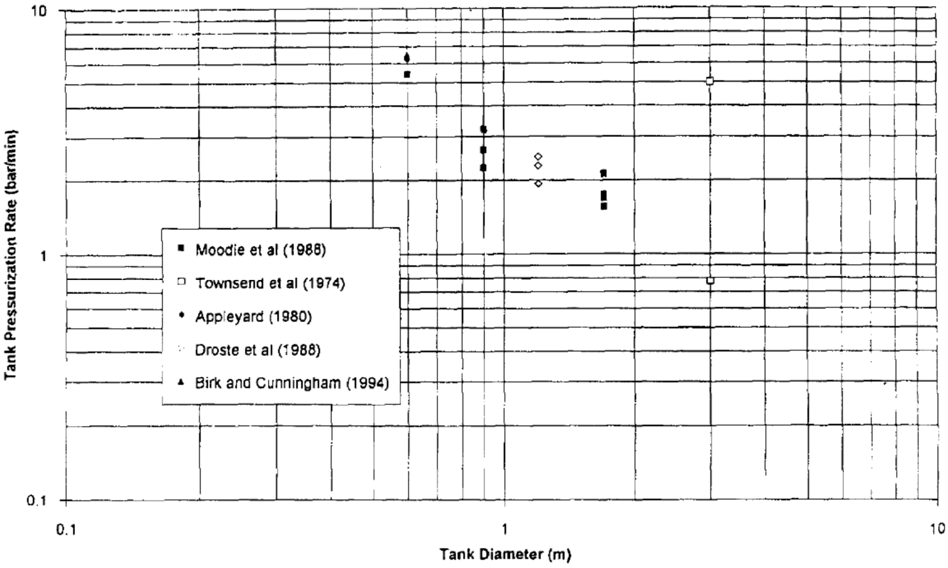


Figure 4.6 Tank pressurization rates for various tank diameters (Birk, 1995)

Figure 4.7 shows that the wall temperature increase will be slower for thicker tank walls. As larger tanks have thicker walls this also means that the wall temperature increase in larger tanks, and hence wall strength degradation will be slower.

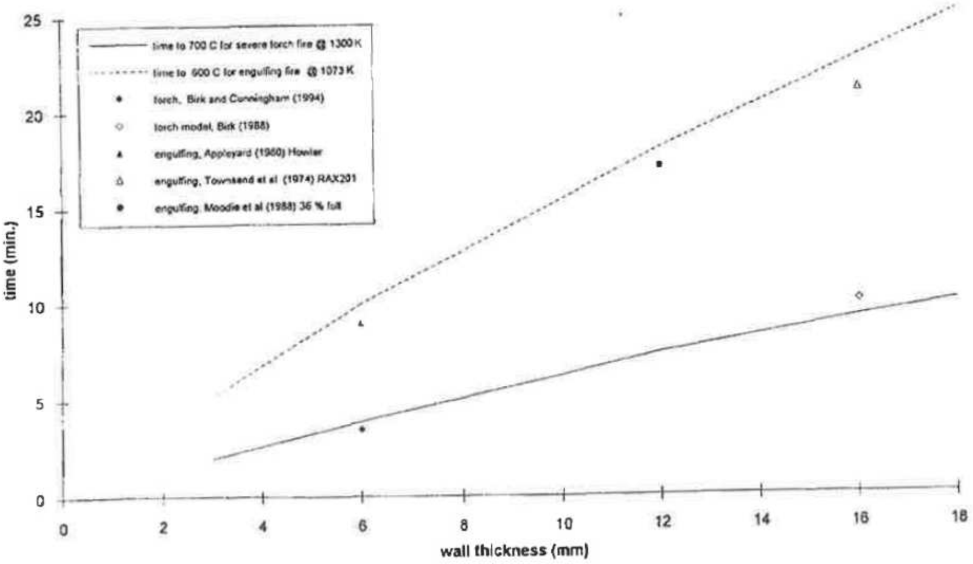


Figure 4.7 Predicted times for heated wall to reach 700 °C as a function of wall thickness (Birk, 1995).

From Figure 4.8 it can be seen that time to failure will increase with tank diameter.

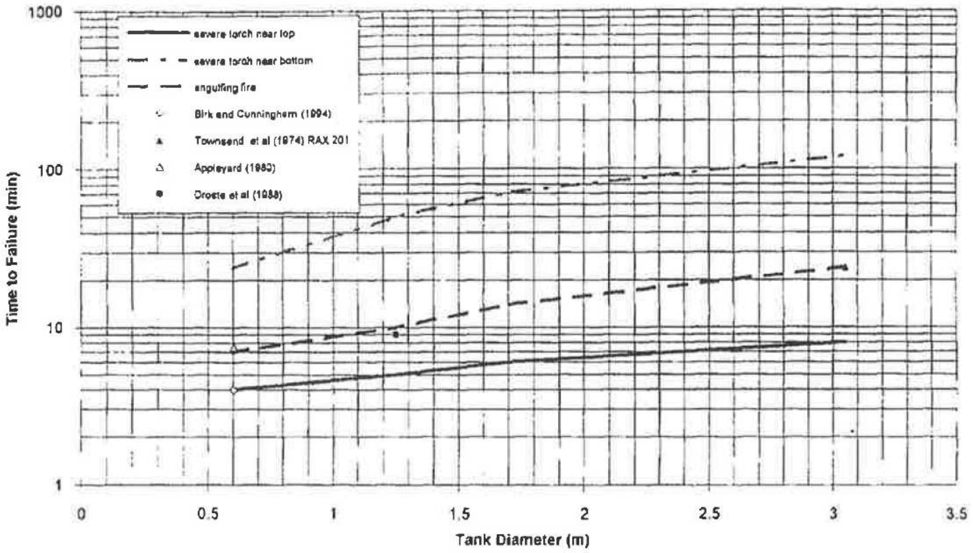


Figure 4.8 Approximate time to failure as a function of tank diameter, when the tanks are exposed to different levels of fire impingement (Birk, 1995).

The combined effects are also schematically illustrated in Figure 4.9. In the smaller tank the internal pressure and wall temperature will increase at a higher rate, resulting in a faster pressure increase and a more rapid loss of wall strength. This results in a shorter time to failure.

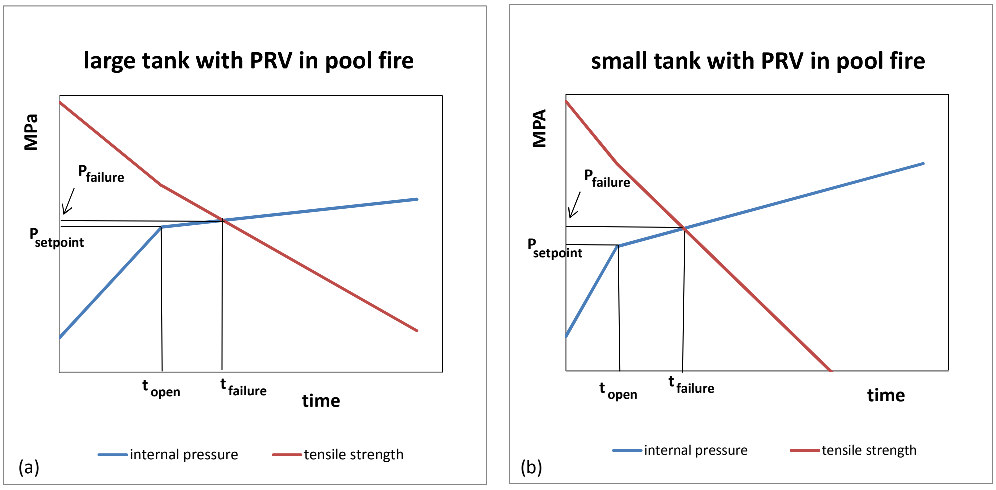


Figure 4.9 Schematic view of the increase of pressure and decrease of tensile strength of an uncoated tank wall in contact with the gas phase when a 60 m^3 road tanker (a) or 3 m^3 tank (b) is engulfed in a pool fire. Presence of a PRV is assumed for both tanks.

Conclusion

The tank wall temperature and liquid temperature in a large transport tank engulfed in a fire will increase slower than in a small test tank of, say, 3 m^3. The wall temperature shows a slower increase because of the thicker tank wall. The pressure in a real transport tank will also have a slower increase than a 3 m^3 test tank because of the lower tank surface area / volume ratio. A bonfire test of a 3 m^3 tank is conservative for a transport tank with a larger volume.

4.5 Conclusions test conditions

Based on the ADR/RID and CFR regulations and the performed bonfire tests a heat load of ± 110 kW/m^2 is a representative heat load for a pool fire. Also in literature typical heat loads of an engulfing pool fire are quoted in the order of 100 -140 kW/m^2. For a jet fire heat loads are 200 kW/m^2 or higher. Based on this research the heat load for full poolfire engulfment should be 100-110 kW/m^2.
BAM used a heat load of 75 kW/m^2 in their bonfire tests. This seems to be a somewhat low value. However it should be noticed that BAM used a very narrow array of gas burners instead of a liquid hydrocarbon pool fire. Flames from these gas burners around the tank do not drift so far away with the wind as the flames of a hydrocarbon pool fire do. So the effective heat transfer for gas burners is better than for a hydrocarbon pool fire.

For a tank wagon partial or full engulfment in a pool fire is a realistic scenario.
Full engulfment of a road tanker in a fire is possible during (un)loading and parked near to tank vehicle with flammable liquids. During transport it is an unlikely scenario. Only if the truck would become involved in an accident with another truck carrying a large volume of flammable liquid, this would be realistic. Exposure to fires of other vehicles on fire is a realistic scenario for road accidents. Such fire can also have high heat loads. Hence for a road tanker a test for the effectiveness of a coating with a heat load of 75 kW/ m^2 is realistic for the fires that can occur during parking and transport.

Partial exposure of a transport to a fire does not reduce the risk of a tank rupture. The tank wall will locally heat up as fast as for full fire engulfment, due to low heat transfer to the gas phase in the tank.
The consequences of such a tank rupture will be less severe than in case of full fire engulfment because of the lower temperature and pressure of the liquid in the tank at the moment of rupture. Because of the limited heat input and hence reduced pressure increase one could consider a higher acceptable temperature limit than for a pool fire. As a consequence a different test regime would be required.

The tank wall temperature and liquid temperature in a large transport tank engulfed in a fire will increase slower than in a small test tank of, say, 3 m^3. The wall temperature shows a slower increase because of the thicker tank wall. The pressure in a real transport tank will also have a slower increase than a 3 m^3 test tank because of the lower tank surface area / volume ratio. A bonfire test of a 3 m^3 tank is conservative for a transport tank with a larger volume.

5 Effect of Pressure Relief Valve

5.1 ADR/RID requirements for pressure relief valves

Tanks for the transport of pressurised liquefied gases may be fitted with a spring loaded Pressure Relieve Valve (PRV) (see chapter 3.2). The requirements concerning the relief capacity of pressure relief devices are given in Annex A chapter 6.7 of the ADR/RID regulations (see chapter 3.2). Requirements with respect to the construction and construction material of the safety valves are not prescribed by ADR/RID regulations. Also there are no requirements for the safety valve at temperatures above the normal operating temperatures of the tank. This means that there are no specific requirements for the safety valves for a tank under the condition of fire engulfment. For tank vehicles stainless steel as well as brass safety valves are used.

5.2 Positive effects

It will be obvious that the most important beneficial effect of a PRV is the release of gas and hence pressure. The pressure will remain at the set point of the PRV if the release capacity is lower than the evaporation rate of the liquefied pressurised gas in the tank. The pressure in the tank will further increase if the evaporation rate is higher than the vent capacity. The pressure will not increase as long as the net heat input is ≤ ±30 kW/m^2 (see Table 5.1). This net heat input is calculated according the ADR/RID regulation 6.7.2.12.2.1 (Ludwig, 2000). Compared to the heat loads described in section 4.1.2 it is rather low for a completely fire engulfed tank.

Table 5.1 Vent capacity of PRV of a representative tank vehicle and tank wagon for a heat flux of the engulfing fire of 109 kW/m^2

	Unit	**Tank vehicle**	**Tank wagon**
Tank volume	m^3	50	92
Max load propane	kg	21000	38640
Net heat input (see Table 2.1)	kW/m^2	31.8	29.3
PRV set pressure	MPa	2.25	
T propane at relieving pressure	K	336	
Heat of evaporation at 336K	kJ/kg	252	
Q propane relieved	kg/s	11	16.1
Time to heat liquid mass and tank from 288 till 336 K	min	±15	± 20
Time to relieve max load	min	32	40
Total heat up and vent time	min	47	60

The pressure in the tank with a PRV is illustrated in Figure 5.1b. When the PRV opens the internal pressure increase will slow down (as shown in Figure 5.1b). If the vent capacity is high enough there may even be no further pressure increase. The venting of propane will also have a temperature reducing effect on the liquid in the tank and on the tank wall in contact with the gas (see e.g. (Molag, 2006b) (Ulrich, 2010), (Balke, 2012b)). Hence the reduction in tensile strength will also slow down.

In total this means that the time to failure will be delayed (compare Figure 5.1a with Figure 5.1b). In some cases a BLEVE will even be avoided because all LPG has been vented before the steel wall temperature exceeds the critical value when the strength of the steel becomes insufficient to withstand the internal pressure.
However this avoidance of a BLEVE will only be the case if the liquid in the tank has completely evaporated. Table 5.1 gives a vent duration of 32 min (tank vehicle) and 40 minutes (tank wagon). The time to heat the tank shell and the liquid content from 288 K to 336 K takes 15 min (tank vehicle) and 30 min (tank wagon) for a heat input of 30 kW/m^2. Total heat up time and vent time is 47 minutes for a representative tank vehicle and 60 minutes for a tank wagon. A BLEVE will be avoided if the ultimate strength within these exposure times does not decrease below the critical shell stress.
At the moment all liquid has evaporated the tank is still filled with vapour at the vent pressure. Continuation of the wall heating by the fire will then result in a tank rupture with a pressure wave.
The time needed to vent all evaporated LPG can be shorter if a larger PRV is installed. A PRV with twice the capacity will half the vent time. However the heat-up time of liquid and tank will remain the same. It is doubtful if a reduction of the time to 31 minutes (tank vehicle) or 40 minutes (tank wagon) is enough to avoid a BLEVE. BLEVEs in the accidents and bonfire test have occurred within these fire exposure times.
For a coated tank the PRV has a positive effect on the time to BLEVE (illustrated in Figure 5.1c and Figure 5.1d). The heat input is then much lower, so a standard PRV, once opened, will be able to vent off all incoming energy. Also, without a PRV thermal stratification in the liquid and gas phase will occur. Gas phase tank wall temperatures will become higher due to the bad heat transfer in the gas phase. The relieve of gas via the PRV will induce mixing of liquid and gas and improve the heat transfer from the shell to the gas phase.

5.3 Effect of PRV and thermal coating on time to BLEVE

The effect on the time to failure of a road tanker equipped with either a PRV or a thermal coating as well as a combination of both is shown in Figure 5.1 and compared with the situation without protection. When no thermal coating but only a PRV is present the heat input will not be reduced. Heat and pressure are only dissipated because of the venting of gas. This will generally not be enough to prevent the pressure from further increasing (see also 5.2) and tank failure will only be delayed for some time (see Figure 5.1b). If only a thermal coating is present heat input will be delayed, but again, time to failure may be reduced insufficiently (see Figure 5.1c).
If both PRV and coating are present (Figure 5.1d) the heat input may be sufficiently reduced to enable the PRV to vent off enough gas to prevent a pressure increase, and to delay a failure long enough for emergency services to take adequate measures (see also §3.5).
The effect of 2 PRVs (or a larger PRV, see before) is shown in Figure 5.1e. Two PRVs will vent off more gas than only one, and the cooling effect (also on the tank wall) will be higher. However, the temperature of the tank shell will continue to increase and hence tank shell strength will continue to decrease.
Even if the PRVs are capable of maintaining the internal pressure at the setpoint value (as shown in Figure 5.1e) a tank failure can still occur before the tank is empty.

Using the values shown in Table 3.3 with two PRVs it may still take more than 15 minutes to empty the tank, which may be insufficient to prevent a tank failure.

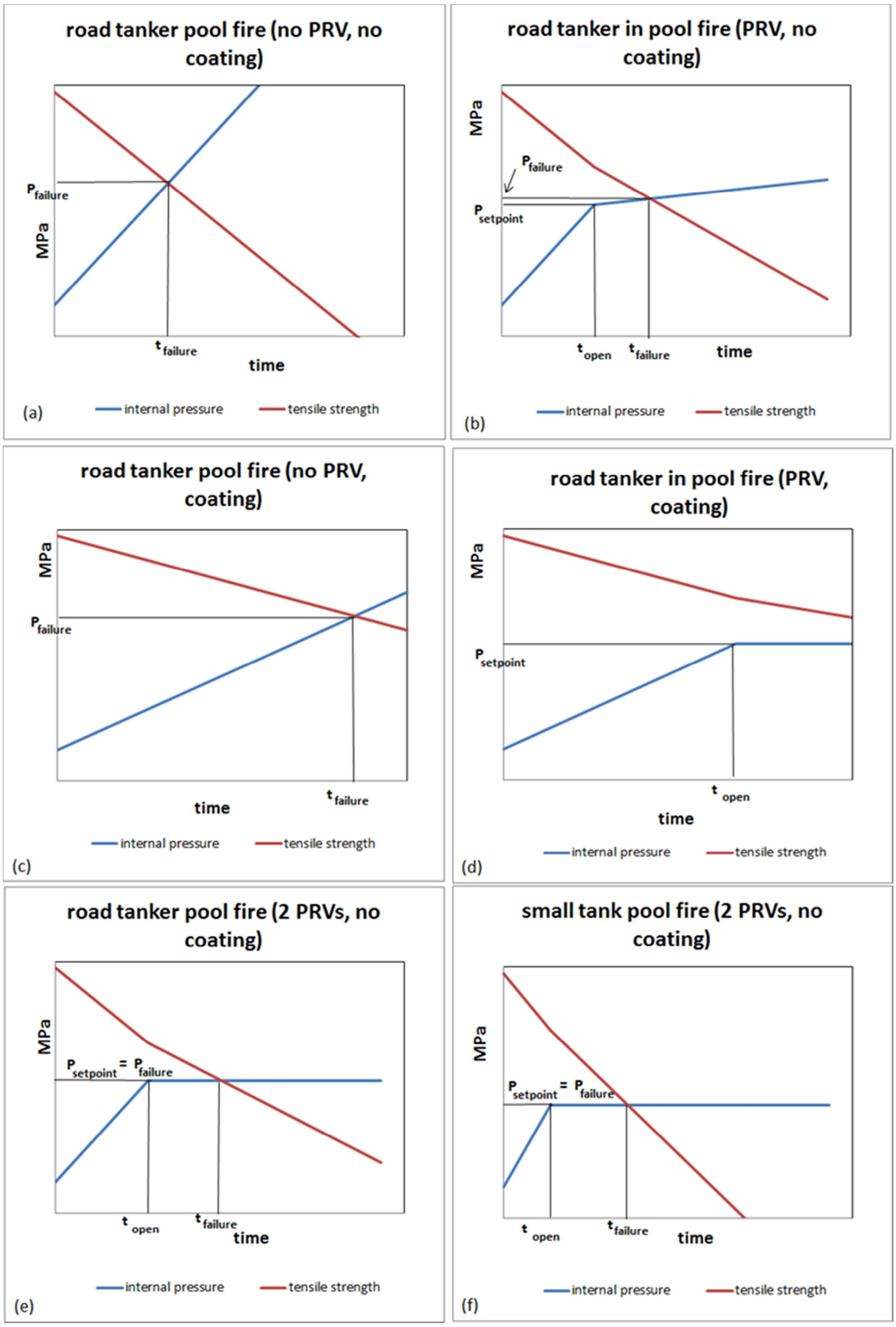


Figure 5.1 Schematic view of internal pressure and tensile strength on a tank wall in contact with the gas phase for a road tanker (a-e) and a small test tank (f) when the tank is engulfed in a pool fire:
(a) unprotected tank; (b) PRV only; (c) coating only; (d) coating and PRV; (e) 2 PRVs no coating; (f) small tank with 2 PRVs, no coating.

Also for a small test tank a second (or a larger) PRV may have sufficient capacity to maintain the internal pressure at the set value (or around this value, as opening and closing pressure are not identical) (as shown in Figure 5.1(f)). Nonetheless a failure may still occur, as the increasing wall temperature may reduce the strength of the tank to a value unable to withstand the set pressure. In BAM test nr 09080 (BAM, 2008), aimed at testing the effect of a larger PRV, such a failure at the setpoint pressure of the PRV occurred. The effects are also schematically illustrated in Figure 5.1f.

Rail wagons are in general not equipped with a PRV. The effect of a coating only on the pressure increase and tensile strength decrease is shown in Figure 5.2. As outlined in §4.2 the (larger) rail wagon will heat up slower than the road tanker. Hence a coating only will also further increase the time to failure. However, if this delay is sufficient for the emergency services to take adequate measures cannot be predicted on forehand.

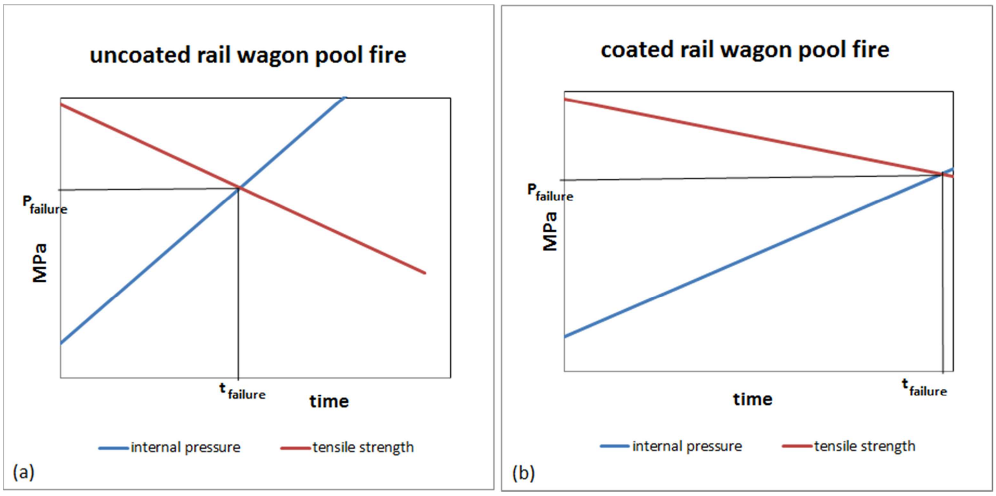


Figure 5.2 Schematic view of internal pressure and tensile strength on a tank wall in contact with the gas phase for a rail wagon (no PRV) when the tank is engulfed in a pool fire: (a) unprotected tank; (b) tank with thermal coating.

5.4 Negative effects PRV

5.4.1 Extra heat input

The escaping gas from an opened PRV will be ignited immediately in the fire and a torch or jet fire will be the result. As outlined earlier around 11 kg/s will escape form an opened PRV on a road tanker. At a pressure of 2.25 MPa this will result in a jet with a length of approximately 30 meters (for propane). Because of the high exit velocity and the fact that the pure gas has to mix with air prior to ignition the base of the flame will be at a distance of about 10 m from the exit point. As the flame will also be directed away from the tank, the additional heat input will be very low: max 1 kW/m^2 on a very small area directly under the flame. This value is negligible compared to the heat input of the flames (more than 75 kW/m^2 over the complete area of the tank). Only if the torch would be impinge ont another vehicle or object extra heat input could be expected. How much would depend on local circumstances.

In case the tank is overturned the PRV will be in contact with the liquid phase in the tank. At 2.25 MPa this will result in a flow of about 75 kg liquid propane per second (TNO, 2013), which will ignite in the flames of the pool fire. The heat from this will probably be much more than from the engulfing fire. A pool fire will burn at a rate of approximately 0.055 kg/s per m^2 pool area (TNO, 1997). For large pool of, say, 600 m^2 this means about 33 kg/s. It will depend on the local situation how much of the extra heat of the liquid flare will be dissipated by the tank, in particular the part of the wall in contact with the gas phase. The heat input will certainly increase, although not by a factor of 3, as oxygen supply, as well as tank wall area will be limiting factors. Nonetheless, during the first minutes after opening of the PRV the heat input is expected to be significantly higher. Also, as liquid rather than gas is expelled from the tank, pressure reduction will be limited. Hence the probability of failure during this period will increase. However, because of the high flow of 75 kg/s it would only take only about 6 min for the tank to empty completely. After this time the tank is empty and the risk on a BLEVE is averted.
It can be concluded that normal venting of gas via the PRV will not cause an additional heat input on the tank. However if the tank has turned over additional heat input is possible if liquid is released via the PRV. For a non-isolated tank this will cause an earlier BLEVE. An isolated tank can resist this additional heat input because the tank contents will be released much faster.

5.4.2 Stress around PRV

Near a venting PRV there will be higher temperatures gradients compared to other parts of the shell. Also, because of the layout there will be sharper bends around the PRV. This can cause additional stress and one would expect these locations to be more susceptible to failure. However in the bonfire tests of tanks with a PRV performed by Birk, BAM and TNO it is not noticed that tank ruptures had a significantly higher probability of originating near the PRV.

5.4.3 PRV behaviour in fire conditions

As written in section 5.1there are no specific requirements for PRVs under fire conditions in the ADR/RID regulations. The following behaviour has been noticed in bonfire:

- Hot venting vapours and high ambient temperatures heat the PRV itself causing ‘spring softening’; the opening pressure will decrease and the cycle will shift to lower pressures (15-20 bars versus 20-25 bar) (evidenced in (Balke, 2012a) test 11073)
- After first opening valve won’t close anymore (because of heat) (Ulrich, 2010)

This PRV behaviour in fire conditions will cause a venting of the PRV at a lower pressure and, in some cases, the PRV will not close anymore. This behaviour can be considered as fail save: more liquefied gas will be vented at a lower pressure than the PRV set point and for a longer period. If a BLEVE will occur the burst pressure will be lower and the fire ball smaller due to lower amount of remaining liquid in the tank.

5.5 Conclusions

With respect to the questions that were addressed in chapter 2 the following can be concluded:

- A PRV will reduce the pressure increase in a tank and may also decrease the temperature increase of the wall, resulting in a delay of time to failure.
- If gas is vented via the PRV the ignition will be several meters (10 m or so) from the PRV because of the high velocity of the vented gas. The ignited yet will not significantly contribute to the heat input on the tank.
- In case a tank is overturned liquid may be expelled from the PRV. This will add significantly to the heat load on the tanker but only for a short time, as the tank will be emptied much quicker than when gas is expelled from the tank. It is not expected that, for a coated tank, this temporary extra heat load will have serious consequences.
- Fitting an extra PRV, or a PRV with a larger capacity, will delay or even prevent a pressure increase to values above the PRV pressure settings, but will not prevent the temperature increase of the tank wall and hence the process of tank strength reduction. Ultimately this will lead to tank failure. Applying an extra PRV, or a PRV with a larger capacity is therefore an insufficient measure to prevent tank failure/BLEVE.
- PRV operation is influenced by a fire. The spring of the PRV is softened and sometimes PRV materials melted. However this can be considered as fail-safe failure, the PRV stay open and more gas is vented.
- For a tank with a thermal insulation a PRV will reduce the wall temperature by: (a) The venting of evaporated liquid heat input in the tank, (b) Improved heat transfer from the wall to the gas phase.

6 Transport accidents

Tanks with a heat resistant coating can be involved in a transport accident like a collision and overturning. The most important question is whether the coating will survive such an accident. If it is damaged by the accident the heat insulating properties could (partly) disappear. The consequences of a defect in the thermal coating have been discussed in § 4.3.3.

TNO has collected the material properties of several heat resistant insulating materials (Molag, 2006a). It was concluded that only the intumescent epoxy coatings fulfilled all requirements for a heat resistant insulation under transport conditions. Materials like Pyrocrete (a cement based insulating material) were not resistant to the vibrations during transport. Other materials like mineral wool blankets give enough thermal insulation, but needed more thickness than intumescent coatings or a (metal or polyester) jacket to protect the insulation against weather influences.

The manufacturers of intumescent epoxy coatings do not supply quantitative data on the impact resistance of the coating. Only a notched impact energy of 0.7 – 0.9 J/cm is presented. However this not a good criterion to determine the impact of a transport accident on the coating. The heat insulation must follow the possible deformation of the steel tank in a transport accident. So the elasticity of the coating is important. The elasticity of the intumescent coatings is larger than the steel elasticity (Molag, 2006b). So the steel tank will show a rupture earlier than the coating.
It is possible that the tank will slide on the road after it is overturned in a transport accident. Coatings with a high shear stress give a better protection during such accidents. It is also possibility that the coating will be torn off in a transport accident. The coating should have a high adhesion to the tank wall to avoid this. Quantitative data on adhesion are not presented, only data showing their performance relative to other insulating materials.

The accident performance of mineral wool blankets with a steel or polyester jacket is less than that of epoxy coatings. There have been a several rail and road accidents where the protecting jacket and insulating blankets were torn off.

7 Life time performance

7.1 Durability of the coating

Data on the durability of intumescent insulating coatings on tanks are not presented in literature. However standardised UV exposure tests exist to determine if the coating can be guaranteed during the life-time of a road or rail tanker.
Further curing of the intumescent coating during the life time of the tanker that could lead to brittleness of the coating should also be investigated with a standardised curing test.

7.2 Corrosion

The coating itself cannot corrode. However corrosion might be possible on the interface between coating and metal. This is only possible if the coating has cracked during transport. This is not expected but can be controlled by visual inspection and during periodic testing of the tank. Ultrasound inspection will give additional information on possible corrosion on the metal coating interface.

7.3 Inspection

ADR/RID regulations prescribe that periodic inspection should also be possible for tanks with a coating. Experience with coated tanks has shown that visual inspection of a tank with a intumescent coating is not different from inspection of uncoated tanks. Cracks in the paint or coating can be observed. Ultrasound testing of important parts of the tank (e.g. welds of tank supports on the sub frame) can give information on cracks.
The diameter of a tank will slightly increase during hydraulic pressure testing of the tank. The coating has enough elasticity to follow this increase in diameter. However this must be proven by the manufacturer with an standard elasticity test of the cured coating.

7.4 Life time warranty

Up to now suppliers of epoxy coatings do not give a life time guarantee for a transport tank. Agreements regarding durability criteria like UV exposure, curing, elasticity etc. still need to be made.

8 Weight of the coating

The additional weight of the heat insulating coating has influence on the pay-load of a transport tank and on the centre of gravity.

Pay-load
A thermal coating is applied with a thickness of 1 cm over the total area of 50 m^3 tank vehicle. For a surface area of 87 m^2 this leads to a total volume of 0.87 m^3. The density of Chartek 7 is 1000 kg/m^3. Hence 870 kg of coating material is applied.

A sunshield is not necessary for a tank with a thermal coating. After subtraction of the weight of the sunshield (300 kg) the net weight increase of the tank is about 570 kg. In order not to exceed the maximum weight of the road tanker the payload of LPG will have to be reduced by this amount. On a maximum of 21000 kg this is nearly 3%. So at maximum there will be an increase in the number of transports by 3%. For a 92 m^3 rail wagon the weight of the coating is 1100 kg, the weight of the sunshield 400 kg. The loss of pay-load is approximately 700 kg or less than 2 %.

Tanks not equipped with a sunshield will not have the weight benefit of removal of the sunroof. However, an uncoated tanker without a sunshield will be allowed a lower payload than a coated tanker, which will reduce the loss of payload.

Centre of gravity
The height of the centre of gravity above the road affects the probability of overturning. However, the risk of overturning is reduced by Electronic Stability Control of the vehicle nowadays.
The coating will lead to a lower centre of gravity. The sunroof on top of the tank disappears and the total weight of the tank, coating and load does not increase. For tanks without a sunroof the centre of gravity will not be affected.

9 Test procedure for heat resistant coatings

The relevant requirements for heat resistant coating can be summarized as follows. The coating:

- should not affect the integrity of the tank by corrosion
- should have sufficient integrity during transport accidents
- should perform over the life time of a transport tank
- should protect the tank against a BLEVE for a period of 60 – 90 minutes when the tank is exposed to fire.

A proposal for the tests that should be performed to demonstrate the fulfilment of these requirements is shown in Table 9.1

Table 9.1 Proposed tests for heat resistant insulating materials to demonstrate adequacy for use on transport tanks for liquefied gases

Requirement	Test	Remarks
No tank corrosion		
No water permeability of the coating	Water permeability test	
No brittleness by ageing	UV exposure test Curing test	
Transport accident resistance		
High bond strength against tear-off	Adhesive test to be developed	1)
Elasticity larger or equal tank shell	Standard elasticity modulus test	
Tear – off heat protection	Shear stress test Friction test	
Life time performance		
Ageing	UV exposure test Curing test	
Heat insulation to delay BLEVE 60-90 minutes		
Sufficient insulation	900 ˚C furnace plate test	2)
Integrity insulation under fire conditions	Mock-up furnace test	3)
Demonstration 60-90 minutes protection	2-3 m^3 bonfire test	4)
Demonstration 60-90 minutes protection for full scale tank	Final elements model calculation	5)

Remarks:

1) The bond strength could be determined in a sandwich tensile test. Two metal plates with the a layer (same thickness as proposed for the protection) in between could be placed in a tensile tester and the tensile force could be increased until the sandwich breaks open. The force required to tear it open can be determined and also the location of the rupture: on the interface metal/coating or in the coating itself.
2) Several plate tests to determine the heat insulating properties over 60 – 90 minutes are described in literature (Birk, Landucci etc.)
3) The thermo-mechanical behaviour of a heat insulation on a full size tank (diameter 2 – 3 m) is different from the situation where it is attached to a small plate. Cracks in the insulation on a full size tank can cause the insulation to fall from the tank.
4) Bonfire test with 2,5 – 3 m^3 LPG tank, filling 50%, heat radiation ≥ 75 kW/m^2.

5) If the bonfire test is passed it should be demonstrated with a validated final elements model that the heat insulation is capable to protect a *full size* tank during 60 – 90 minutes against a BLEVE. Final element models have already been developed ((Landucci, 2013), (Manu, 2008). However these final element models still need to be validated against a full scale experiment.

10 Conclusions

The following conclusions with reference to the questions raised in chapter 2 are presented:

1. **Are test conditions representative for a real road/rail tanker fire?**

Based on the ADR/RID and CFR regulations and the performed bonfire tests a heat load of ± 110 kW/m^2 is a representative heat load for a pool fire. Also in literature typical heat loads of an engulfing pool fire are quoted in the order of 100 -140 kW/m2. For a jet fire heat loads are 200 kW/m^2 or higher. Based on this research the heat load for full poolfire engulfment should be 100-110 kW/m^2.
BAM used a heat load of 75 kW/m^2 in their bonfire tests. This seems to be a somewhat low value. However it should be noticed that BAM used a very narrow array of gas burners instead of a liquid hydrocarbon pool fire. Flames from these gas burners around the tank do not drift so far away with the wind as the flames of a hydrocarbon pool fire do. So the effective heat transfer for gas burners is better than for a hydrocarbon pool fire.

For a tank wagon partial or full engulfment in a pool fire is a realistic scenario.
Full engulfment of a road tanker in a fire is possible during (un)loading and parked nearby a tank (vehicle) with flammable liquids. During transport it is an unlikely scenario. Only if the truck would become involved in an accident with another truck carrying a large volume of flammable liquid, this would be realistic. Exposure to fires of other vehicles on fire is a realistic scenario for road accidents. Such fire can also have high heat loads. Hence for a road tanker a test for the effectiveness of a coating with a heat load of 75 kW/m^2 is realistic for the fires that can occur during parking and transport.

Partial exposure of a transport to a fire does not reduce the risk of a tank rupture. The tank wall will locally heat up as fast as for full fire engulfment, due to low heat transfer to the gas phase in the tank. The consequences of such a tank rupture will be less severe than in case of full fire engulfment because of the lower temperature and pressure of the liquid in the tank at the moment of rupture. Because of the limited heat input and hence reduced pressure increase one could consider a higher acceptable temperature limit than for a pool fire. As a consequence a different test regime would be required.

The tank wall temperature and liquid temperature in a large transport tank engulfed in a fire will increase slower than in a small test tank of, say, 3 m^3. The wall temperature shows a slower increase because of the thicker tank wall. The pressure in a real transport tank will also have a slower increase than a 3 m^3 test tank because of the lower tank surface area / volume ratio. A bonfire test of a 3 m^3 tank is conservative for a transport tank with a larger volume.

2. **What is the effect of a PRV?**

With respect to the questions that were addressed in chapter 2 the following can be concluded:

- A PRV will reduce the pressure increase in a tank and may also decrease the temperature increase of the wall, resulting in a delay of time to failure.

- If gas is vented via the PRV the ignition will be several meters (10 m or so) from the PRV because of the high velocity of the vented gas. The ignited yet will not significantly contribute to the heat input on the tank.
- In case a tank is overturned liquid may be expelled from the PRV. This will add significantly to the heat load on the tanker but only for a short time, as the tank will be emptied much quicker than when gas is expelled from the tank. It is not expected that, for a coated tank, this temporary extra heat load will have serious consequences.
- Fitting an extra PRV, or a PRV with a larger capacity, will delay or even prevent a pressure increase to values above the PRV pressure settings, but will not prevent the temperature increase of the tank wall and hence the process of tank strength reduction. Ultimately this will lead to tank failure. Applying an extra PRV, or a PRV with a larger capacity is therefore an insufficient measure to prevent tank failure/BLEVE.
- PRV operation is influenced by a fire. The spring of the PRV is softened and sometimes PRV materials melted. However this can be considered as fail-safe failure, the PRV stay open and more gas is vented.
- For a tank with a thermal insulation a PRV will reduce the wall temperature by: (a) The venting of evaporated liquid heat input in the tank, (b) Improved heat transfer from the wall to the gas phase

3. What is the effect of a transport accident (overturning or collision) on coating performance?

TNO has collected the material properties of several heat resistant insulating materials (Molag, 2006a). It was concluded that only the intumescent epoxy coatings fulfilled all requirements for a heat resistant insulation under transport conditions. Other materials were not resistant to the vibrations during transport, or needed more thickness to protect the insulation against weather influences.

The manufacturers of intumescent epoxy coatings do not supply quantitative data on the impact resistance of the coating. The heat insulation must follow the possible deformation of the steel tank in a transport accident. So the elasticity of the coating is important. The elasticity of the intumescent coatings is larger than the steel elasticity (Molag, 2006b). So the steel tank will show a rupture earlier than the coating.
The coating should also have a high shear stress and good adhesion to the tank wall to avoid tear off during an accident. Quantitative data on adhesion are not presented, only data showing their performance relative to other insulating materials

The accident performance of mineral wool blankets with a steel or polyester jacket is less than that of epoxy coatings. There have been a several rail and road accidents where the protecting jacket and insulating blankets were torn off.

4. How does the coating affect the life time performance of a tank?

Data on the durability of intumescent insulating coatings are not presented. However standardised UV exposure tests exist to determine if the coating can be guaranteed during the life-time of a road or rail tanker.
Further curing of the intumescent coating during the life time of the tanker that could lead to brittleness of the coating should also be investigated with a standardised curing test.

Corrosion at the interface between coating and metal is only possible if the coating has cracked during transport. This is not expected but can be controlled by visual inspection and during periodic testing of the tank. Ultrasound inspection will give additional information on possible corrosion on the metal coating interface.

ADR/RID regulations prescribe that periodic inspection should also be possible for tanks with a coating. Experience with coated tanks has shown that visual inspection of a tank with a intumescent coating is not different from inspection of uncoated tanks. Cracks in the paint or coating can be observed. Ultrasound testing of important parts of the tank (e.g. welds of tank supports on the sub frame) can give information on cracks.
The diameter of a tank will slightly increase during hydraulic pressure testing of the tank. The coating has enough elasticity to follow this increase in diameter.

Agreements regarding durability criteria like UV exposure, curing, elasticity etc. still need to be made.

5. What is the effect of the additional weight of the coating?

A heat resistant coating will reduce the pay load by 3% for a tank vehicle and 2 % for a rail wagon. The coating will lead to a lower centre of gravity. The sunroof on top of the tank disappears and the total weight of the tank, coating and load does not increase.

Tanks not equipped with a sunshield will not have the weight benefit of removal of the sunroof. However, an uncoated tanker without a sunshield will be allowed a lower payload than a coated tanker, which will reduce the loss of payload. For tanks without a sunroof the centre of gravity will not be affected.

6. Which tests should be performed on heat resistant coatings before implementation?

The following tests are proposed to demonstrate the fulfilment of the relevant requirements for heat resistant coatings:

- Water permeability test
- UV exposure test
- Curing test
- Adhesive test
- Standard elasticity modulus test
- Shear stress test
- Friction test
- 900 ˚C furnace plate test
- Mock-up furnace test
- 2-3 m^3 bonfire test
- Finite elements model calculation for full scale performance

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