TP 14367E

Tank-Car Thermal Protection Defect Assessment: Updated Thermal Modelling with Results of Fire Testing

SUMMARY REPORT

Prepared for

Transportation Development Centre
of
Transport Canada

by

A.M. Birk Engineering
Kingston, Ontario, Canada

March 2005

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This report reflects the views of the author and not necessarily those of the Transportation Development Centre of Transport Canada or the co-sponsoring organization.

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

Temperature Conversion

Temperature in ºC	Temperature in ºF
450	842
500	932
550	1022
600	1112
650	1202
700	1292
750	1382
816	1500

Stress Conversion

Stress in MPa	Stress in ksi
100	14.5
125	18.1
150	21.8
175	25.4
200	29.0
225	32.6
250	36.3
300	43.5

Une traduction de ce rapport est également disponible en français : «Évaluation des défauts de protection thermique de wagons-citernes : mise à jour du modèle thermique par des essais au feu – Rapport sommaire», TP 14367F.

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16. Abstract

This summary report gives an overview of the work done on the analysis of thermal protection defects on railway tank-cars carrying LPG (liquefied petroleum gas). The work included high temperature stress-rupture testing of tank-car steels, computer modelling of tank-cars with thermal protection defects in fires, and fire testing of 500 gal. (1890 L) tanks with simulated thermal protection defects.

The fire testing showed that even relatively small defects can result in tank rupture if the defect area is engulfed in a severe fire and is not wetted by liquid. The thermal modelling showed that the allowable defect size depends on the condition of the remaining thermal protection system. It is difficult to define an exact limit of allowable defect. Based on the data obtained and the analysis conducted, the critical defect size is around 1.2 m long along the tank-car axis by about 0.4 m wide. A defect this small can theoretically result in tank-car rupture if it is located in the tank car vapour space and if the tank-car is engulfed in fire. The total allowable defect area depends on the condition of the remaining thermal protection system. For the expected condition of tank car thermal protection systems, the allowable total area of defects is in the range of 1 to 9 percent of the tank surface area.

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16. Résumé

Ce rapport donne un aperçu des travaux d'analyse des défauts de protection thermique de wagons-citernes transportant des gaz de pétrole liquéfiés (GPL). Ces travaux ont comporté des essais de rupture par fluage à haute température d'aciers utilisés dans la fabrication des wagons-citernes, la modélisation informatique de cas d'exposition au feu de wagons-citernes présentant des défauts de protection thermique et des essais au feu de citernes de 500 gallons (1 890 L) dans lesquelles des défauts de protection thermique avaient été introduits.

Les essais au feu ont révélé que même des défauts de dimensions relativement faibles peuvent entraîner la rupture de la citerne si la zone défectueuse est soumise à un feu intense, sans être mouillée par la phase liquide. La modélisation thermique a montré que les dimensions admissibles d'un défaut dépendent de l'état du reste du système de protection thermique. Il est difficile de définir les limites exactes d'un défaut admissible. D'après les données recueillies et les analyses effectuées, les dimensions d'un défaut deviennent critiques autour de 1,2 m de longueur dans l'axe de la citerne sur environ 0,4 m de largeur. Un tel défaut peut théoriquement mener à la rupture du wagon-citerne s'il est situé dans l'espace vapeur de la citerne et si celle-ci est enveloppée par les flammes. L'étendue totale admissible des défauts dépend de l'état du reste du système de protection thermique. Selon ce que l'on sait de l'état des systèmes de protection thermique des wagons-citernes, la surface totale admissible des défauts serait de l'ordre de 1 p. 100 à 9 p. 100 de la surface de la citerne.

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Executive Summary

This summary report gives an overview of the work done on the analysis of thermal protection defects on railway tank-cars carrying liquefied petroleum gas. The work included high temperature stress-rupture testing of tank-car steels, computer modelling of tank-cars with thermal protection defects in fires, and fire testing of 500 gal. (1890 L) tanks with simulated thermal protection defects.

Thermal protection is used to protect dangerous goods tank-cars from accidental fire impingement. These tank-cars are designed so that they will not rupture for 100 minutes in a defined engulfing fire, or 30 minutes in a defined torching fire. One common system of thermal protection includes a 13 mm blanket of high temperature ceramic fibre thermal insulation covered with a 3 mm steel jacket. Recent inspections [1] have shown that some tank cars have significant defects in these thermal protection systems. This work was done to establish what level of defect is acceptable from a safety standpoint.

The fire testing [2] showed that even relatively small defects can result in tank rupture if the defect area is engulfed in a severe fire and not wetted by liquid. The thermal modelling [3] showed that the allowable defect size depends on the condition of the remaining thermal protection system, because this determines how fast the liquid level will drop in a fire impingement accident. A defect must be located in the vapour space for it to cause a tank rupture. This, of course, assumes the tank has no flaws, fatigue cracks, weld defects or corrosion.

It is difficult to define an exact limit of allowable defect. Based on the data obtained and the analysis conducted, the critical defect size is around 1.2 m long along the tank-car axis by about 0.4 m wide. Defect areas smaller than this will be cooled by the surrounding protected wall. Defects this critical size or larger can heat up sufficiently to result in tank rupture. The total allowable defect area depends on the condition of the remaining thermal protection system. For the expected condition of tank car thermal protection systems, the allowable total area of defects is in the range of about 1 to 9 percent of the tank surface area.

The following conclusions were made based on the fire testing of 500 gal. tanks with thermal protection defects and from computer modelling of 112J type tank-cars with defects.

i) Fire testing of 500 gal. propane tanks with simulated thermal protection defects showed that even small defects can lead to tank rupture.

ii) Based on fire tests of 500 gal. tanks with simulated thermal protection defects, it was determined that a thermal protection defect as small as 1.2 m long (along tank axis) by about 0.4 m wide is theoretically large enough to result in local wall thinning and stress rupture in a 112J type tank-car with a diameter of 3 m and a wall thickness of 16 mm. This assumes a hoop stress condition of about 190 MPa.

iii) A thermal protection defect is only a problem if it is located in the vapour space during a fire engulfment accident. This means the tank liquid level relative to the defect location is an important factor.

The following conclusions were made based on thermal modelling.

i) The IDA 2.1 code was reasonably validated against the 2004 fire testing of 500 gal. propane tanks (both baseline and with thermal protection defects).

ii) The IDA 2.1 code is in reasonable agreement with the RAX 201[4] fire test results of a full-scale unprotected railway tank-car.

iii) There are some differences between the IDA 2.1 model and the test results. IDA 2.1 tends to predict a more rapid increase in wall temperatures, which leads to failure prediction a few minutes earlier than observed in tests. This can partly be explained by how the fire is modelled. Real fires take some time to build up whereas in IDA the fire is on 100% at time = 0.

iv) The model appears to be reasonable and conservative in the prediction of tank failure.

The following conclusions were made based on the modelling of tank-cars with thermal protection defects. It was assumed that the critical thermal protection defect size is 1.2 m measured along the tank-car (112J) axis by 0.4 m wide as determined from the 2004 fire testing.

i) A critical thermal protection defect can lead to tank rupture if it is located in the tank-car vapour space during a fire engulfment accident.

ii) The failure of a tank-car with thermal protection defects depends not only on the size and location of the defects, but also on the quality of the remainder of the thermal protection system that is not defective (including all direct heat conduction links in the tank structure). The better thermally protected the tank is, the more capable it is of surviving with local thermal protection defects. This is because the overall thermal protection system determines how fast the liquid level will drop when the tank is exposed to fire.

iii) The total allowable defect area is very strongly affected by the area average thermal conduction properties (i.e., k/w where k = thermal conductivity and w = insulation thickness) of the tank thermal protection insulation during fire conditions. It is estimated that this value of thermal conductivity is in the range of 0.15 to 0.30 W/mK for high temperature ceramic blanket insulation under fire exposure conditions.

iv) A tank with 13 mm ceramic blanket thermal protection with an area average thermal conductivity of 0.15 W/mK (at fire conditions) can probably allow up to 8 to 9 percent of its surface to have thermal protection defects. This assumes there is at least one critical defect in the vapour space. This also assumes the pressure relief valve (PRV) has a flow capacity greater than about 5000 scfm at 110 percent of the pressure relief valve (PRV) set pressure (280.5 psig assumed here).

v) A tank with 13 mm ceramic blanket thermal protection with area average thermal conductivity of 0.20 W/mK (at fire conditions) can probably allow up to 4 percent of its surface to have thermal protection defects. This assumes there is at least one critical defect in the vapour space. This also assumes the PRV has a flow capacity greater than about 4000 scfm at 110 percent of the PRV set pressure (280.5 psig assumed here).

vi) A tank with 13 mm ceramic blanket thermal protection with area average thermal conductivity of 0.30 W/mK (at fire conditions) cannot allow any critical defects (i.e., longer than 1.2 m along tank axis by 0.4 m wide). This effective thermal conductivity is the maximum allowable for a 13 mm blanket that meets the original plate test standard for thermal protection systems. If a tank has this average thermal conductivity, then a 3500 scfm PRV is probably too small for that tank.

vii) If there are no defects larger than 1.2 m x 0.4 m, then a larger defect area may be acceptable, but this should be determined on a case-by-case basis by running the IDA 2.1 code for the specific tank. For this case, insulation samples should be taken so actual *k* values can be measured. At least 10 samples should be taken so that a truly representative average *k* can be determined.

viii) 112J type tank-cars equipped with small PRVs (approximately 3500 scfm) should not be allowed to have any defects unless the overall thermal protection properties can be defined.

The reader is reminded that this study did not consider the following:
i) end failures
ii) defective PRVs
iii) defects in primary shell
iv) corrosion
v) impact damage
vi) torching fires
vii) rolled tanks
viii) hard contact between jacket and tank shell

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4. Townsend W, Anderson CE, Zook J, Cowgill G, 1974, *Comparison of Thermally Coated and Uninsulated Rail Tank-Cars Filled with LPG Subjected to a Fire Environment,* FRA-OR&D 75-32, Federal Railroad Administration, U.S. Department of Transportation.

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Glossary

AFFTAC	Analysis of Fire Effects on Tank Cars
ASME	American Society of Mechanical Engineers
BLEVE	Boiling Liquid Expanding Vapour Explosion
FRA	Federal Railroad Administration (U.S.)
IDA	Insulation Defect Analyzer
IR	Infrared
PRV	Pressure Relief Valve

1.0 Introduction

This summary report gives an overview of the work conducted to assess the severity of thermal protection defects on tank-cars. The report includes results from computer modeling [1,2], stress-rupture testing [3] and fire testing [4].

1.1 Background

This project began when Transport Canada started looking for a reliable method of inspecting railway tank-cars for thermal protection system defects. Thermal protection systems are designed to protect dangerous goods tank-cars from accidental fire impingement. The systems are intended to stop a tank-car from rupturing for a period of 100 minutes when engulfed in a hydrocarbon pool fire and for 30 minutes when exposed to a torching fire (e.g., the burning relief valve flare from a nearby tank). The thermal protection system of direct interest in this report consisted of a 13 mm blanket of high temperature ceramic blanket insulation covered by a 3 mm steel jacket.

The work started with the development of a non-contact inspection method using a thermal imaging camera. This led to the report by Birk and Cunningham [5] that showed how infrared (IR) thermography could be used for this purpose. It also resulted in a small survey of tank-cars, in which it was found that some tank-cars can have significant thermal protection defects. This led to a follow-on contract to develop a way to assess the severity of thermal protection defects from a safety standpoint. This resulted in a second report by Birk and Cunningham [6], which suggested that defects do not have to be very large to become theoretically dangerous if the tank-car were engulfed in fire.

Since that time, the computer modelling has continued, but there has been a general lack of data to validate the modelling. In the summer of 2004, six 500 gal. ASME code propane tanks were fire tested with scaled thermal protection defects [4]. This data was used to validate the computer models [1] and the results are outlined in this summary report.

1.2 Objectives and Scope

The objective of this project was to develop a means of assessing the severity of thermal protection defects. The scope of this analysis was limited to considering engulfing pool fires. The case of a torching fire has not been included. This report does not attempt to calculate the probabilities of events, but rather attempts to predict the outcome if a tank-car with thermal protection defects is engulfed in a severe fire.

1.3 Summary

Thermal protection defects do not have to be very large to theoretically result in tank failure in an engulfing fire. Under the right conditions of fire contact and defect location, a defect about 1.2 m long (along the tank axis) by about 0.4 m wide could result in the formation of a small stress rupture in the wall of a 112J type tank-car. This requires the following to happen:

i) Defect is located near or at the tank top.
ii) Defect is engulfed in fire.
iii) Remaining tank-car thermal protection allows sufficient heat to enter the tank to lower the liquid level below the defect area.

The probability of this event has not been considered in this report. It should be noted that the length of 1.2 m happens, in most cases, to coincide with the width of the ceramic blanket roll used on tank-cars, and as a result is a common defect size.

2.0 Tank-Cars Exposed to Fire

When a tank-car is exposed to fire, the heat from the fire enters the tank shell. Where the shell is wetted by liquid in the tank, the heat is effectively removed from the wall and the wall in this area remains at a temperature close to that of the liquid. In the vapour space, the vapour does not effectively cool the wall and, as a result, the wall temperature rises rapidly. As the steel temperature rises above 400ºC, the steel begins to lose strength. Above 600ºC, the steel has lost much of its ambient temperature strength and time dependent creep damage is important. Even with the pressure relief valve (PRV) working properly, the tank wall will rupture within a few minutes when the wall temperature reaches about 620 - 640ºC.

An engulfing fire test of a full-scale non-thermally protected tank was conducted by Townsend et al. [7] and the tank failed violently in about 24 minutes. The government research lab BAM in Germany recently did a fire test of a 45 m^3 tank filled to 22 percent capacity with propane and it failed violently in 17 minutes [8]. These tanks failed with very similar conditions of pressure, stress and peak wall temperature. The tank materials were also very similar. These illustrate how quickly non-thermally protected tank-cars can fail in fires.

2.1 Thermal Protection

Thermal protection is used to slow the rate of heating from a fire. Thermal protection involves covering the tank-car with a thermal insulation material. This insulating layer slows the rate of heating, which delays the pressure rise, the wall temperature rise and the tank failure. The current thermal protection systems for 112J type tank-cars have been designed so that a tank can be expected to survive a credible hydrocarbon pool fire for 100 minutes or a jetting fire for 30 minutes.

The original design of the thermal protection systems was intended to keep the tank wall temperature below 427ºC [9] for 100 or 30 minutes, depending on the fire type. At this temperature, the tank is not expected to fail at all if the PRV is working to keep the tank pressure near the PRV set pressure.

The most common thermal protection system for LPG (liquefied petroleum gas) tank-cars involves a 13 mm thick blanket of high temperature ceramic fibre insulation. This is then covered with a 3 mm jacket of steel. This system reduces the fire heat flux by about a factor of ten [9]. Table 1 summarizes the thermal conductivity versus temperature of this type of ceramic blanket.

Table 1: Summary of Ceramic Fibre Insulation Properties
(Unifrax, tank-car insulation, 72 kg/m^3 density, new condition [7])

Temperature (°C)	Thermal Conductivity k (W/mK)	Comment
-20	0.03	
100	0.05	liquid wetted wall temperature in fire
300	0.09	
500	0.15	protected vapour space wall temperature in fire
650	0.20	
800	0.30	jacket temperature in engulfing fire

As can be seen from Table 1, the thermal conductivity increases as the temperature increases. The fire will quickly heat the jacket to near the fire temperature, so the thermal conductivity of the insulation near the jacket will be around 0.3 W/mK. On the wall side of the insulation, the insulation will take up the wall temperature. In the liquid wetted regions, this means the insulation will have a *k* around 0.05 W/mK. The net affect is an average *k* of about 0.17 W/mK in wall areas cooled by the liquid. In the vapour space the *k* is closer to 0.3 W/mK.

The *k* also depends on the blanket density. If the insulation is crushed, the *k* increases.

It should be noted that thermal protection only delays failure. If the fire were to last long enough, then eventually the tank would empty, the wall temperature would approach the fire temperature, and the tank could fail if still pressurized.

2.2 Thermal Protection Defects

Thermal protection defects may involve any of the following:

i) gaps between the blanket material.
ii) crushing of the insulation by the jacket.
iii) tearing and dropping of the blanket.

In many cases the defect appears as an area where no blanket is present. In this case there is just an air gap between the jacket and the wall. Air is a good insulator and the jacket acts as a thermal radiation shield. This reduces the heat flux from the fire by about half [10]. This is about five times worse in terms of heat flux from the fire than good thermal protection.

With just the jacket as fire protection, this will slow the fire heat flux and delay the onset of high wall temperatures. Earlier we noted that an unprotected 112J tank-car would fail in about 24 minutes [7]. This means we would expect a tank with 100 percent defect to fail in about 48 minutes. Fire tests and modelling support this estimate. This will be shown later in this report.

If the defect involves the steel jacket making direct and firm contact with the tank wall then there is no thermal protection in that area.

2.3 Tank Response with Thermal Protection Defects

The following will happen if a tank-car that has thermal protection defects is exposed to an engulfing fire.

i) Pressure will rise more rapidly (the PRV will pop sooner).
ii) Liquid level will drop more rapidly and expose more wall to the vapour space.
iii) Wall temperatures will rise more rapidly.
iv) Wall temperatures will reach higher values.
v) Tank will fail or empty earlier.

All of the above are relative to a tank that is properly thermally protected.

The following are needed for an otherwise safe tank-car with thermal protection defects to fail in a fire.

i) Defect must expose a significant part of the vapour space wall to strong heating by the fire.
ii) Defect must be large enough so that the surrounding protected wall does not protect the defective area by cooling it through the action of conduction heat transfer.
iii) Total heat entering the tank must be sufficient to lower the liquid level so that the defect in the vapour space can achieve high enough temperatures to initiate stress rupture.

2.4 Allowable Defects

The allowable level of thermal protection defects is a complex function of the following:

i) fire conditions
ii) tank wall material properties (stress rupture)
iii) tank design (tank D, tank L, wall thickness w)
iv) PRV performance (capacity, pop pressure, reclose pressure)
v) remaining thermal protection system (overall k/w [conductance per unit area] including direct conduction links in the tank structure)
vi) initial conditions (fill and temperature)

All tank-cars have some minor thermal protection system defects. It is very difficult to make a perfect system – there may be some gaps between blankets or perhaps the addition of the steel jacket caused some of the blankets to slip or to be crushed and/or torn. These may result in a fraction of one percent of the tank-car surface being defective. If the defects are small, they will not be important because the surrounding wall is protected and the defect area will not get very hot in a fire.

At some point, however, if the defects become large or if there are enough of them, they will compromise the safety of the tank-car if it were exposed to a severe fire. The question, then, is how big can the defects get before they become a real problem?

2.5 Pressure Relief Valves

PRVs are sized such that they can control the tank-car pressure in the event that it is engulfed in fire. The required size of the PRV depends on the rate of fire heating of the tank-car lading. If a tank-car is thermally protected, then theoretically the size of the PRV can be reduced. In recent years, the sizing of PRVs has allowed for the effect of thermal protection and, as a result, the allowable PRV size for thermally protected tank-cars has been reduced. For a 112J type tank-car with 13 mm of high-temperature ceramic thermal insulation, the PRV flow capacity can be reduced by a factor of about ten from the case of an unprotected tank-car. This typically means the flow rating can be reduced from about 16 to 1.6 m^3/s (35,000 to 3500 scfm) for a 112J type tank-car.

If a tank-car is equipped with a 3500 scfm PRV, then the issue of thermal protection defects becomes even more critical. If a PRV is sized assuming a thermally protected tank-car, then it could be undersized for a tank-car with significant defects.

This report considered 112J tank-cars with PRVs with capacities of 35,000 scfm. In other words, it has been assumed in this report that the tank-car failure is caused by excessive wall temperature, not excessive pressure. With a full-sized PRV, even a tank-car with a 100 percent thermal protection defect (i.e., steel jacket with air gap) will not have its pressure exceed about 110 percent of the PRV set pressure.

A very limited analysis was conducted with 3500 scfm PRVs on tank-cars with thermal protection defects. Preliminary analysis suggests that tank-cars with this size of PRV should not be allowed to have any thermal protection defects. Further analysis is needed.

2.6 Thermal Modelling

As already noted in section 2.4, the allowable level of thermal protection defects is a complex function of fire conditions, tank wall material properties, tank design, PRV performance, remaining thermal protection system, and initial conditions.

To account for all of these complexities, we have developed a computer model of a tank-car with thermal protection defects. This model is called the Insulation Defect Analyzer (IDA 2.1). Tank-car thermal models have been developed around the world and several good ones exist [11,12]. All of them have limitations. None of them is perfect and fully developed.

AFFTAC [13] is one example of a thermal model that is used by Transport Canada and the U.S. Federal Railroad Administration (FRA) for modelling tank-cars in fires. Birk recently conducted a review of this code [14] for the purposes of assessing the suitability of using AFFTAC to model thermal protection defects. He found that AFFTAC had several deficiencies when it comes to modelling thermal protection defects. As a result, a new code was developed based on methods similar to those used in AFFTAC and other well-known codes.

IDA 2.1 was developed specifically to account for thermal protection defects. It has recently been validated using fire test results from scale model tests of tanks with thermal protection defects [4].

IDA 2.1 is a pseudo three-dimensional code that allows for defects in any position. Figure 1 shows a graphic from IDA 2.1 showing a tank with simulated defects.

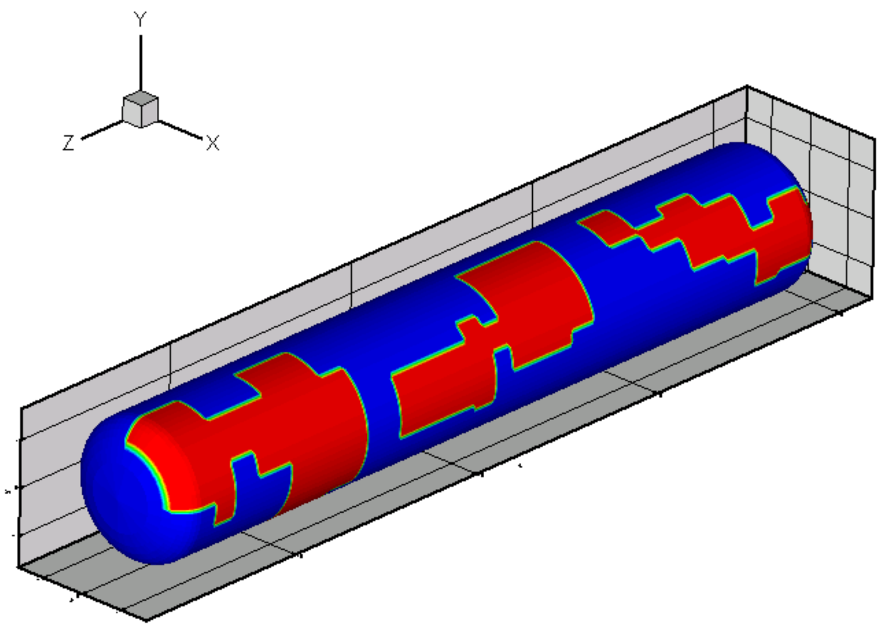


Figure 1: Graphic Showing 112J Type Tank-Car with Thermal Protection Defects (in red)

This code accounts for the main processes in a tank fire, including:

i) fire-to-tank heat transfer
ii) wall heat conduction, convection and radiation
iii) lading thermodynamic process
iv) PRV action
v) tank stress
vi) tank wall failure by high-temperature stress rupture

The failure of the tank-car is dominated by the wall temperature in the vapour space, the tank wall material properties at high temperature, and the tank pressure. The tank failure criteria and tank-car wall material properties are absolutely critical in predicting reasonable failure times.

2.7 Stress Rupture

A critical part of the thermal model is the failure analysis.

When a tank-car fails in a fire, the failure can begin at a large flaw or it can take place due to high-temperature stress rupture. The flaw may be due to corrosion, a fatigue crack, or a bad weld. This study did not consider large flaws in the tank. Failure in this study has been based on high-temperature, ductile stress rupture.

When steel is heated to temperatures above 400ºC it begins to lose its tensile strength. The higher the temperature rises, the weaker the steel gets. Figure 2 shows the high-temperature stress rupture properties of new TC 128B tank-car steel. This data was recently generated as part of this project [3]. High-temperature stress rupture tests were conducted on steel samples from tank-cars involved in a recent derailment accident in Ontario, Canada. Figure 2 shows some of the results from this test program. This new data is much more detailed than previously available data for TC 128B from [15].

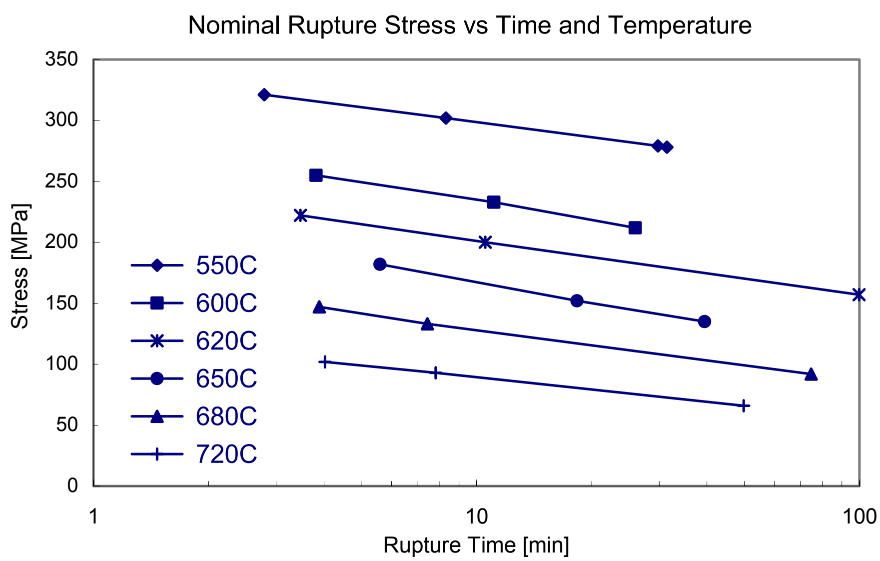


Figure 2: Stress Rupture Data for TC 128B Steel [3]

The data in Figure 2 is based on uniaxial tensile testing but experience shows that it can be used to estimate tank-car failure if the wall hoop stress and temperature are known. For example, a 112 J type tank-car with a diameter of 3 m, a wall thickness of 16 mm, and an internal pressure of 2 MPa will have a hoop stress of about 190 MPa. From Figure 2, we see the steel would rupture in about 3 minutes at 650ºC and in about 30 minutes at 620ºC.

This data has been used in this study to determine tank failure times.

2.8 Fire Tests

Computer models need to be validated with experimental data. For tank-cars with thermal protection defects, fire tests need to be conducted to generate this data. These tests provide data on critical tank and lading properties such as:

- i) tank pressure buildup
- ii) PRV action
- iii) wall temperatures in the tank vapour space and liquid space
- iv) time to empty or time to failure
- v) extent of failure

This report includes data from testing of 500 gal. tanks that were used to simulate full-scale tank-cars with thermal protection defects. These 500 gal. tanks have a diameter about 1/3, and a length about 1/6 that of a tank-car.

3.0 Fire Testing of 500-Gallon Propane Tanks

The tests were conducted in the summer of 2004 [4] using ASME code 500 gal. propane tanks. These tanks were outfitted with defects and then exposed to partial fire engulfment. Figures 3 and 4 show the tanks during the fire testing. The fire tests of 500 gal. tanks were conducted to see how defect size related to rupture size.

Figure 3: Test Tank Showing Jacketed Area (defect under jacket on other side of tank) [4]

Figure 4: ASME Code 500 gal. Test Tank with 25% Fire Engulfment (fire blackbody temperature 800-900ºC) [4]

These tanks were 25 percent engulfed in fire. The fire blackbody temperature was in the range of 800 to 900ºC, which is in the range of credible hydrocarbon pool fires. Three cases are presented here – a baseline test with an unprotected tank (no insulation or jacket) and then 15 percent (large defect) and 8 percent defect cases. The tanks were protected with new tank-car insulation (13 mm ceramic blanket) and this was covered with a 3 mm steel jacket in the area covered by fire.

Figures 5 and 6 show results from the fire tests of the 500 gal. tanks with simulated thermal protection defects [4].

Figure 5 shows how thermal protection affects the tank pressurization rate. The tank with the best thermal protection (8 percent defect) pressurized the slowest. Figure 6 shows how the wall temperatures rise in the defective areas. Note that the tanks failed where the plots end. None of the tanks with simulated defects failed catastrophically, but rather they failed with axial fissures of differing lengths. The smallest defect had the smallest rupture length.

As can be seen, the defective cases reach the same peak wall temperatures as the unprotected cases, but it takes longer to achieve these temperatures. It should be noted that the wall temperatures were affected by wind moving the fire. Where there is a sudden drop in the wall temperature, this means the wind decreased the fire heating. One needs to extrapolate in the graph to get the time to failure without wind effects. It can be seen that the tanks all failed when the wall temperature exceeded about 710ºC. If we consider the small defect case, the tank failed at 59 minutes. However, if the wind had not reduced the fire effect, it is very likely the tank would have failed at about 36 minutes.

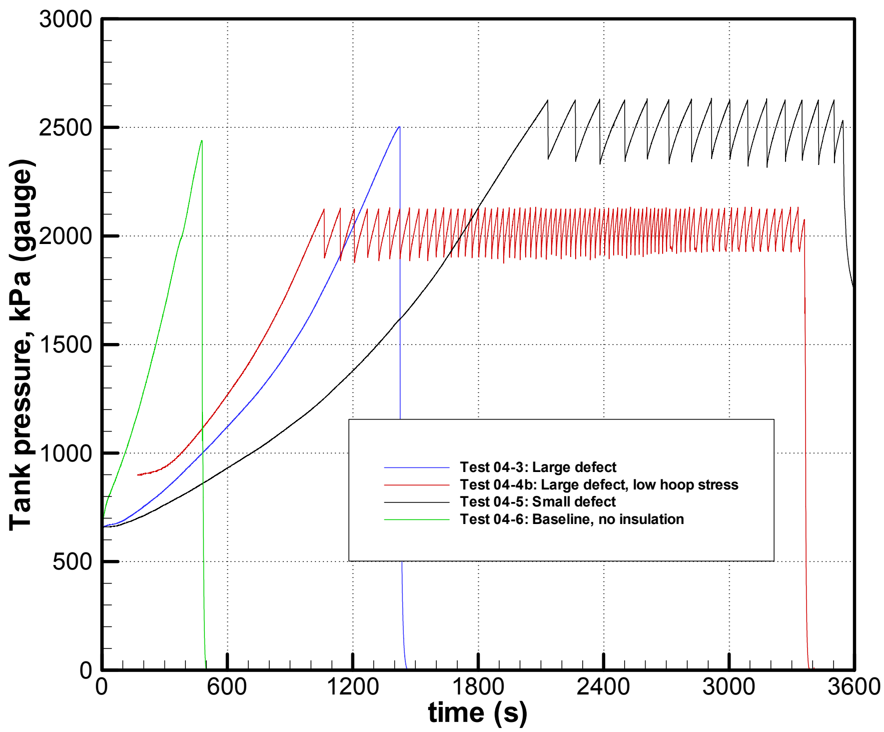
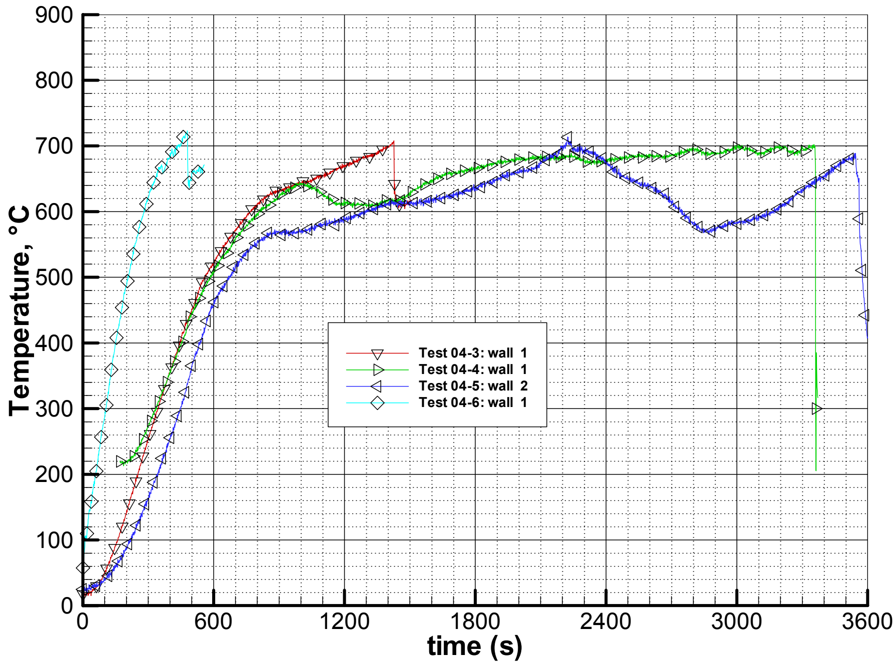


Figure 5: Tank Pressurization vs. Time (500 gal. ASME code tank with various levels of thermal protection, tank 25% engulfed in fire) [4]



Wall temperature vs. time.

Figure 6: Measured Peak Wall Temperature in Defect vs. Time (500 gal. ASME code tank with various levels of thermal protection, tank 25% engulfed in fire) [4]

The data in Figure 6 illustrate that thermal protection defects do allow dangerous wall temperatures to be established and that tanks will fail if a defect is large enough and the fire is severe enough.

3.1 Critical Defect Size

Heat transfer modelling [6] and fire testing [16] have shown that the critical defect size, from the standpoint of heat transfer, for a 16 mm thick plate is about 0.4 m x 0.4 m. At this size the centre of the defect area is not significantly cooled by the surrounding protected and cool metal. In other words, the centre of this plate will heat up as if it were not surrounded by protected material. This is shown in Figure 7 from [16].

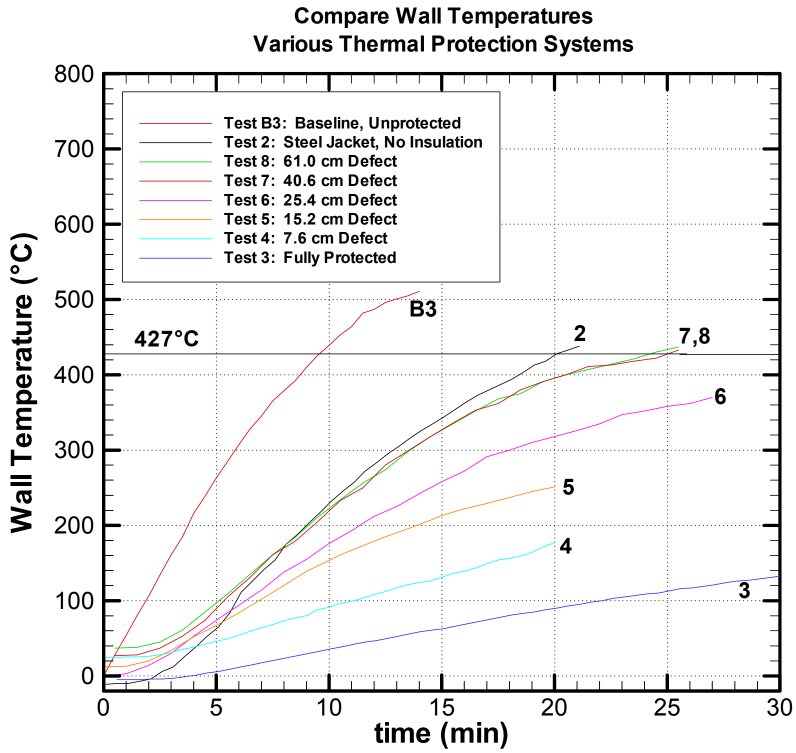


Figure 7: Measured Peak Temperatures Under Thermal Protection Defects (16 mm plate) Heated by Engulfing Fire (effective blackbody T = 840ºC) [16]

As can be seen from Figure 7, a defect 0.4 m square (test 7) is about the same as a 100 percent defect case (test 2).

For a defect to fail under stress, the defect must be larger than the size quoted in Figure 7 so that enough material in the defect reaches a high temperature to result in a stress rupture failure. This is not easy to predict without very detailed material properties and detailed modelling (e.g., 3D elastic-plastic-creep analysis using finite element analysis). Therefore, fire testing was used.

The thermal protection defects were located under the centre of the jacketed area shown in Figures 3 and 4. The jacketed area was then engulfed in a hydrocarbon fire with an effective blackbody temperature of approximately 800-900ºC. It should be noted that these tests were designed to give similar conditions to a tank-car, specifically:

i) similar fire heat flux
ii) similar stress
iii) similar material properties

The 500 gal. tanks were expected to fail about three times faster than the full-scale tanks. Further details of why this is can be found in [4].

The length of the resulting ruptures depended on the length (along the tank axis) of the thermal protection defect. Figure 8 shows how the rupture length varied with the thermal protection defect length. If we linearly extrapolate this data to zero rupture length (pin hole) then the resulting thermal protection defect length is about 0.55 m for the 500 gal. tank. This was for a 7.1 mm thick wall. If we scale this size based on the plate thickness, then the defect must be about 1.2 m long for a 112J tank-car with a 16 mm thick wall.

Therefore, theoretically, a defect only needs to be about 1.2 m long (along tank axis) by about 0.4 m wide to result in a small fissure on a 112J type tank-car. As it turns out, the blanket width of typical thermal insulation rolls is 1.2 m. Such a failure would probably not result in a catastrophic failure of the tank – but it could. The small fissure would probably act like an additional pressure relief device. However, small cracks can propagate to completely open the tank if the conditions are right. It is difficult to predict this with certainty and therefore any rupture should be considered unacceptable.

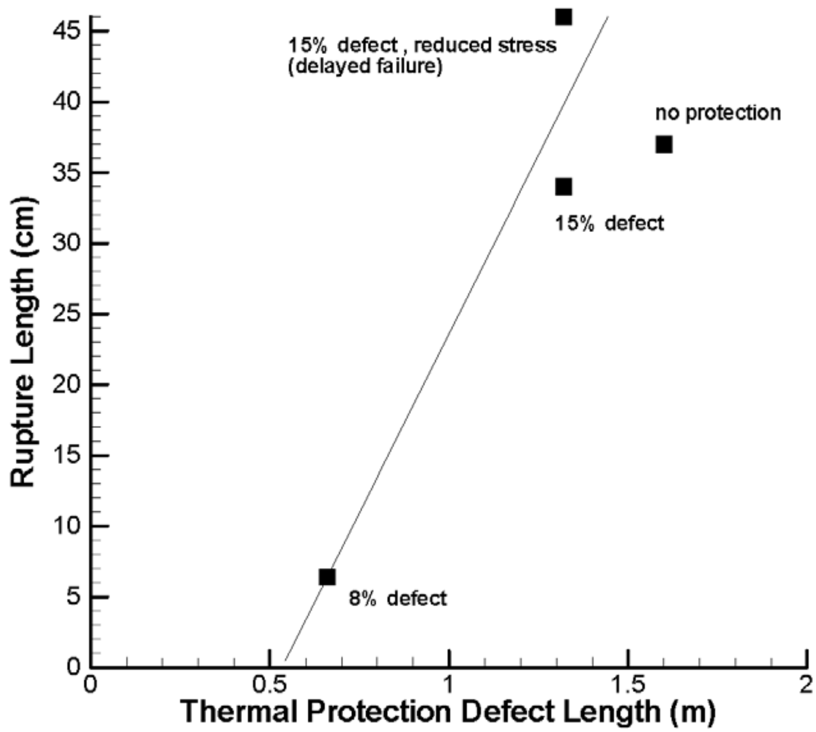


Figure 8: Rupture Length vs. Thermal Protection Defect Length (500 gal. tank, D = 0.96 m, 7.1 mm wall, SA 455 steel, fire heated length about 1.6 m, data from [4])

Figure 9 shows a picture of a ruptured 500 gal. tank with a thermal protection defect. This tank had a defect about 1.3 m along the tank axis. This thermal protection defect would scale to about 3 m in length on a 112J tank-car. The failure length would scale to about 0.8 m on a tank-car.

The critical fissure length to result in a tank-car catastrophic failure is determined by the Folias bulge parameter (see Birk et al. [17]). If this is used, then the critical failure length to result in a tank complete opening (BLEVE) upon failure would be about 2.2 - 3 m in length. This would translate to a thermal protection defect length on a 112J tank-car of about 3 - 3.8 m.

Figure 9: Ruptured Tank with 15 percent Thermal Protection Defect [4]

Table 2 gives a summary of the 500 gal. test results along with estimates for the full-scale 112J tank-car.

Table 2: Summary of Observed Failures of 500 Gallon Tank and Predicted Scaled Conditions for 112J Type Tank-Car

Result	500 gal. Tank (from testing) 7.1 mm wall		112J Type Tank-Car 16 mm wall (data below is scaled based on wall thickness from results for 500 gal. tank)	
	small defect L = 0.65 m[1] 8% of tank surface area	large defect L = 1.3 m 15% area	small defect L = 1.5 m 4% area	large defect L = 3 m 8% area
Time to failure	36 min est.[2]	24 min	108 min	72 min
Rupture size	6 cm	34 cm	14 cm	77 cm

[1] *L = defect length along tank axis*

[2] *For the 8% defect on the 500 gal. tank, the failure time was actually 59 minutes, but this included about 23 minutes of poor fire contact. It is believed that 36 minutes is a more realistic failure time.*

3.2 Scaling of Test Results

Is it appropriate to use results from a 500 gal. tank fire test to predict the outcome of a 33,000 gal. tank-car in a fire? Yes – but we must be careful. We cannot apply the results directly because of the different tank sizes, wall thicknesses, material properties, fill conditions, etc. We must scale the results using appropriate physical laws.

It is true that scaling results properly is very important and that is why we develop detailed computer models of the various physical processes. We do not take the small-scale results directly, but we use them to validate a detailed model. If the model accounts properly for the physics (i.e., conservation of mass, conservation of energy, thermodynamic properties of lading, etc.), then we should be able to predict full-scale performance from partial-scale testing.

Tanks in fires have been studied in detail since the early 1970s (see for example [7, 8, 9, 18-21]. Numerous small-scale tests have been conducted ranging in size from a few litres to many thousands of litres. Few large-scale tests have been conducted, but there have been enough of them to show that the same processes are observed in small- and large-scale tests. We are very confident that results from 500 gal. tanks can be scaled to full-sized tanks. A more detailed discussion of the scaling process can be found in [4], [22] and [23].

At some point it will probably be necessary to conduct full-scale tests to finally prove the point of scale effects.

4.0 Thermal Modelling Results

The fire tests carried out with the 500 gal. tanks are not perfect models of the 112J type tank-car. For example, the initial fill levels were not the same. The 500 gal. tanks were filled to about 70 – 80 percent, while tank-cars may be filled to higher levels. We know the liquid level is important because it helps to cool the vapour space wall and therefore we must correct for this difference in initial fill levels.

To correct for this, we need a detailed thermal model of a tank-car in a fire, like IDA 2.1. Further details of this model can be found in [1].

4.1 Validation

The IDA 2.1 model was validated based on a fire test of an unprotected full-scale tank [7] and the 500 gal. tank tests. A summary of this validation is given in Table 3.

Table 3: Summary of Thermal Model Results

Result	RAX 201 full-scale 112J tank-car		500 gal. tank no thermal protection		500 gal. tank 15% defect		500 gal. tank 8% defect	
	test	model	test	model	test	model	test	model
PRV first pop (min)	2	2	8-9	6	25	21	35	31
Time to fail (min)	24	20	8	7	24	21	36	31
Fill at fail (%)	50	55	75	75	71	70	74	72
Peak wall T at fail (ºC)	640	645	720	730	720	730	690	710

As can be seen in Table 3, the IDA 2.1 program predicts the first PRV pop and failure early by a few minutes. This may be partly due to the test fire taking time to reach full intensity (this is not modelled in IDA 2.1). Nevertheless, Table 3 demonstrates good validation for several cases. The model is slightly conservative in predicting time to failure.

4.2 Tank-Car Simulations

Now we use the IDA 2.1 model to simulate a 112J type tank-car with thermal protection defects.

Tank-car failure prediction is based on the latest high-temperature stress rupture data for new TC 128B steel. Table 4 gives a brief summary of the assumed conditions for the model runs.

Table 4: Summary of Main Variables

	Assumed	Comment
Fire	816ºC Blackbody No convection 100% engulfing at time = 0	Minimum fire case – actual conditions are 871ºC plus or minus 56ºC (i.e. fire T not conservative)
Material properties	TC 128 B UTS 620 MPa As tested by Birk and Yoon [3]	Minimum for TC 128B is 550 MPa (i.e. assumed material properties not conservative)
Tank design	D = 3 m, L = 18 m, wall thickness = 16 mm	
PRV	35,000 or 3500 scfm at 110% of Pset Pset = 1.93 MPa (280.5 psig) Pop assumed at 110% of Pset, reclose at 100%	
Remaining k/w	w = 13 mm Overall average k = 0.15, 0.175, 0.20, 0.3 W/mK	High temperature ceramic. Maximum *k* acceptable for plate test standard is 0.295 W/mK [13]
Initial conditions	T = 20ºC Fill = 94%	

The only variable that we do not know with a reasonable level of certainty is the overall effective conductance per unit area k/w (where *k* = thermal conductivity W/mK and *w* = wall thickness in metres). This is a very important variable since it can determine how quickly the liquid level drops to expose any defects located at the top of the tank. If the k/w is very good (low), then it is the total defect area that drives the rate of liquid lading loss through the PRV. If k/w is not so good (high), then it is this conductance that determines how fast the liquid level will drop and then you only need one critical defect near the tank top to have failure.

The simulations considered the following:

i) 13 mm of insulation with range of insulation thermal conductivities *k* (W/mK)
ii) one large defect* (1% tank area) in vapour space
iii) many defects, including one critical defect (1.2 m x 0.4 m) in the vapour space

Tables 5 and 6 summarize the results.

** A large defect is one that is larger than the critical defect (1.2 m along tank axis by 0.4 m wide).*

Table 5: Summary of Tank Condition for One Large Defect (112J tank-car, propane, defect at top, 2 m long along tank axis by 0.75 m wide, about 1% of tank surface, tank initial fill 94%, tank initial temperature = 20ºC, fire T = 816ºC, PRV capacity = 35,000 scfm)

Insulation conductivity	Pressure at 100 min	Fill at failure or 100 min	Failure time	Comment
k = 0.3 W/mK	2 MPa PRV cycling	0.50	82 min	max allowable *k* to meet plate test standard
k = 0.2	2 MPa PRV cycling	0.96	no fail in 100 min	may be typical of "as new" system
k = 0.1 or less	1.5 MPa PRV passing liquid when shell full	>99% shell full	no fail in 100 min	probably not typical of real systems

From Table 5 we see that the failure of the tank depends very much on the condition of the remaining thermal protection. If the rest of the tank is well protected, then the tank should survive if it only has one large defect in the vapour space. However, if the remaining insulation is not so good, then a large vapour space will form as the liquid drops and the one large defect will get very hot and could result in tank rupture.

Table 6 summarizes the allowable extent of defects for the case where the rest of the tank is thermally protected with insulation with an average k = 0.2 W/mK.

Table 6: Summary of Tank Condition for Many Defects Including at Least One Large Defect at the Top of the Vapour Space (112J tank-car, propane, 13 mm insulation, assumed insulation k = 0.2 W/mK, tank initial fill 94%, tank initial temperature = 20ºC, fire T = 816ºC, PRV capacity = 35,000 scfm)

Percentage of Tank Surface Covered with Defect	Pressure at 100 min	Fill at failure or 100 min	Failure time	Comment
1%	1.5 MPa PRV passing liquid while shell full	> 99%	> 100 min does not fail	pass
2%	2 MPa PRV cycling	> 99%	> 100 min does not fail	pass
4%	2 MPa PRV cycling	79%	96 min	limit of allowable defect?
8%	2 MPa PRV cycling	79%	89 min	fail
12%	2 MPa PRV cycling	75%	85 min	fail

As can be seen from Table 6, it only takes about 4 percent of the surface to be defective of insulation for the tank to fail within the 100 minute time frame when k = 0.2 W/mK. This requires that there be at least one large defect near the top of the tank.

A set of simulations was preformed for a range of defect areas and k values. These are summarized in Figure10. As can be seen from the figure, the allowable defect depends strongly on the effective conductance of the overall thermal protection system. We do not have any good data for this from the existing tank-car fleet. Testing is necessary to establish this.

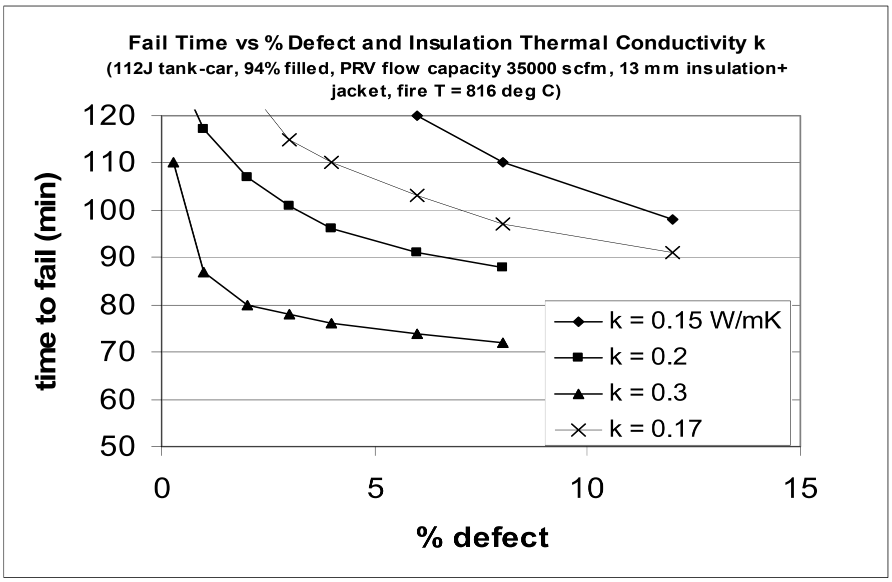


Figure 10: Predicted Time to Failure vs. % Defect and Overall Effective Thermal Conductivity of Thermal Protection System (assumes 13 mm ceramic blanket)

5.0 Discussion

The following sections provide some additional discussion.

5.1 IDA 2.1 and AFFTAC

IDA 2.1 generates results that are different than AFFTAC. The results from IDA 2.1 are conservative, but reasonable based on comparison with fire test data.

The following are the most significant differences between IDA 2.1 and AFFTAC.

i) IDA 2.1 is a partially 3D model so it can model local thermal protection defects anywhere on the tank.
ii) The IDA code predicts that the tank will pressurize faster due to liquid temperature gradients (liquid is warmer near the walls and liquid surface).
iii) The PRV cycles open and closed due to the pop action of the valve and this allows the tank pressure (and stress) to rise and fall like it would with a real valve cycling between its pop and reclose pressure.
iv) The vapour space wall heats up faster as the liquid level drops because convection and radiation parameters in the vapour space are more conservative.
v) The tank is less likely to go shell full in a fire situation because the PRV pops earlier due to saturation pressure (see item ii) and because the PRV entrains liquid as the liquid approaches the PRV inlet.
vi) Failure is predicted using high-temperature stress rupture data.

All of these add up to give a code that is more realistic in the prediction of time to failure.

5.2 IDA 2.1 Validation

The results generated by IDA 2.1 appear to be reasonable when compared to well-established benchmarks such as the RAX 201 fire test of a non-thermally protected tank-car [7]. We also have validation based on fire testing of a 500 gal. tank with simulated thermal protection defects. This suggests the code has the ability to predict performance over a range of realistic scales and defect conditions.

In all cases, the IDA 2.1 code predicted tank failure early by a few minutes compared to test results. In most cases, the IDA code predicts high wall temperatures earlier than observed in tests and this is what causes the early prediction of failure. This difference in predicted wall temperature is most likely due to the fire buildup time in the tests. It is also known from fire testing [24] that large cool objects in fires actually cool the fire and reduce the heat flux. As the large object heats up, the cooling effect is reduced and the fire gets hotter. This is not accounted for in IDA 2.1.

All in all, we consider the predictions by IDA to be reasonable and conservative.

5.3 Location of Defect

If there is no large defect near the top of the tank (i.e., in the vapour space), then the failure will be delayed until the liquid level drops down to the defect area. We must consider the fact that tanks can roll over in accidents and defects on the tank side can become defects on the tank top when it is rolled over on its side.

It should also be noted that a tank rolled on its side will empty more quickly through the PRV, because the PRV will be submerged in liquid. This means the liquid level will drop more rapidly, exposing more wall to a vapour space. We have not considered rolled tanks in this work.

5.4 PRV Capacity

The modelled cases all included full-sized PRVs with flow capacities of around 35,000 scfm. As noted in section 2.5, defects are more critical on tanks with small PRVs (3500 scfm as allowed for thermally protected LPG tanks by the Association of American Railroads PRV sizing equations) because the defects could lead to pressure buildup.

Simulations with IDA 2.1 were attempted for the case of a tank-car (same tank, fill, fire, initial conditions, etc.) with a PRV flow capacity of 3500 scfm. The first case was for 0 percent defect (i.e., no defects in thermal protection) with k = 0.30 W/mK. This simulation failed to run for the 100 minute fire duration. At 80 minutes the program terminated due to internal errors. At the 80 minute time, the tank was shell full at 3.3 MPa pressure (570 psig). We are uncertain whether the shell-full model (liquid and two-phase PRV flow) is working properly since we have no validation data for this case. The model result suggests that the 3500 scfm PRV may not be appropriate for the assumed heating conditions and thermal protection thermal conductivity. Based on this outcome, we would recommend that no defects are acceptable for the 3500 scfm PRV case until further analysis is conducted.

The RAX 201 tank-car was equipped with a 34,900 scfm PRV. During the fire test, the pressure reached 360 psig (128 percent of set). This probably means the PRV was slightly undersized for that test condition. If the tank had been covered with steel jacket with an air gap, the heat flux would have been reduced by about 50 percent, which means the PRV could be reduced to about 17,450 scfm. If the tank had been fully thermally protected, the heat flux would have been reduced by about 90 percent, so the PRV could be around 3500 scfm. This assumes that the thermal insulation is in like-new condition and has an average thermal conductivity of about 0.15 W/mK in the area covering the liquid wetted wall. This applies for ceramic fibre insulation at an average temperature of about 440ºC (i.e., tank wall T = 80ºC and jacket T = 800ºC).

If a tank-car has thermal protection defects in the liquid space, then the required size of the PRV would scale linearly with the size of defect in the liquid space between these two values. For example, a tank with 10 percent defect in the liquid space would need a PRV of the following capacity:

$$scfm_{10\%defect} = 0.10(17450) + (1-0.1)(3500) = 4900scfm \quad (1)$$

These values are approximate and further analysis is required.

5.5 Effect of Fill Level

A tank-car with thermal protection defects can fail if the defect area reaches dangerous temperatures. This can only happen if the liquid level drops below the area with the defect. The question is, how far must the level drop below this defect area for it to reach dangerous wall temperatures?

The RAX 201 tank started with a fill of about 95 percent and failed when its fill level dropped to around 50 percent. The fire tests by Birk et al. [4] of 500 gal. tanks with thermal protection defects showed tanks could fail with fill levels as high as 80 percent when the thermal protection defect was at the tank top. Birk et al. [4] also did tests with 500 gal. tanks filled with water and found that a tank filled to 50 percent with water would have peak wall temperatures about 50ºC hotter than a tank filled to 80 percent with water. This is due to the expected cooling effect of the liquid.

With IDA 2.1, dangerous wall temperatures can be achieved at the top of the tank in defect areas when the fill level drops below about 80 percent. This is a conservative analysis.

5.6 Insulation Properties

It is not just the defective area that determines the performance of the thermal protection system. The properties of the intact thermal protection system also affect the system's response. If the overall thermal conductance (kA/w where A = overall surface area) of the system is large, then the liquid level will drop more quickly in a fire situation, exposing more vapour space wall to severe heating. In this case, you only need one critical defect in the vapour space for failure. This report considered three cases of thermal conductivity k: 0.15, 0.2 and 0.3 W/mK. There is insufficient information to specify which one is most common; therefore, to be safe, the highest value of k (0.3 W/mK) should be used. With this case, you only need one critical defect at the tank-car top for theoretical failure within 100 minutes of exposure to an engulfing fire.

6.0 Conclusions

The following conclusions were made based on the fire testing of 500 gal. propane tanks with simulated thermal protection defects and from computer modelling of 112J type tank-cars with defects.

i) Fire testing of 500 gal. propane tanks with simulated thermal protection defects showed that even small defects can lead to tank rupture.
ii) Based on fire tests of 500 gal. tanks with simulated thermal protection defects, it was determined that a thermal protection defect as small as 1.2 m long (along tank axis) by about 0.4 m wide is theoretically large enough to result in local wall thinning and stress rupture in a 112J type tank-car with a diameter of 3 m and a wall thickness of 16 mm. This assumes a hoop stress condition of about 190 MPa.
iii) A thermal protection defect is only a problem if it is located in the vapour pace during a fire engulfment accident. This means the tank liquid level relative to the defect location is an important factor.

The following conclusions were made based on thermal modelling.

i) The IDA 2.1 code has been reasonably validated against the 2004 fire testing of 500 gal. propane tanks (both baseline and with thermal protection defects).
ii) The IDA 2.1 code is in reasonable agreement with the RAX 201 [4] fire test results of a full-scale unprotected railway tank-car.
iii) There are some differences between the IDA 2.1 model and test results. IDA 2.1 tends to predict a more rapid increase in wall temperatures and this leads to failure prediction a few minutes earlier than observed in tests. This can be partly explained by how the fire is modelled. Real fires take some time to build up whereas in IDA the fire is on 100 percent at time = 0.
iv) The model appears to be reasonable and conservative in the prediction of tank failure.

Because of the complexity of the problem being analyzed, it is virtually impossible to fully validate a computer model like IDA 2.1 for all possible conditions. Therefore, IDA 2.1 and its results should be used with caution.

The following conclusions were made based on the modelling of tank-cars with thermal protection defects. It was assumed that the critical thermal protection defect size is 1.2 m measured along the tank-car (112J) axis by 0.4 m wide as determined from the fire testing conducted by Birk et al. [4].

i) A critical thermal protection defect can lead to tank rupture if it is located in the tank-car vapour space during a fire engulfment accident.
ii) The failure of a tank-car with thermal protection defects depends not only on the size and location of defects, but also on the quality of the remainder of the

thermal protection system that is not defective (including all direct heat conduction links in the tank structure). The better thermally protected the tank-car is, the more capable it is of surviving with local thermal protection defects. This is because the overall thermal protection system determines how fast the liquid level will drop when the tank-car is exposed to fire.

iii) The total allowable defect area is very strongly affected by the area average thermal conduction properties (i.e., k/w where *k* = thermal conductivity and *w* = insulation thickness) of the tank thermal protection insulation during fire conditions. It is estimated that this value of thermal conductivity k is in the range of 0.15 to 0.3 W/mK for high-temperature ceramic blanket insulation under fire exposure conditions.

iv) A tank with 13 mm ceramic blanket thermal protection with an area average thermal conductivity of 0.15 W/mK (at fire conditions) can probably allow up to 8-9 percent of its surface to be defective of thermal protection. This assumes that there is at least one critical defect in the vapour space. This also assumes that the PRV has a flow capacity greater than about 5000 scfm at 110 percent of the PRV set pressure (280.5 psig assumed here).

v) A tank with 13 mm ceramic blanket thermal protection with area average thermal conductivity of 0.20 W/mK (at fire conditions) can probably allow up to 4 percent of its surface to be defective of thermal protection. This assumes that there is at least one critical defect in the vapour space. This also assumes that the PRV has a flow capacity greater than about 4000 scfm at 110 percent of the PRV set pressure (280.5 psig assumed here).

vi) A tank with 13 mm ceramic blanket thermal protection with area average thermal conductivity of 0.30 W/mK (at fire conditions) cannot allow any critical defects (i.e., longer than 1.2 m along tank axis by 0.4 m wide). This effective thermal conductivity is the maximum allowable for a 13 mm blanket that meets the original plate test standard for thermal protection systems. If a tank has this average thermal conductivity, then a 3500 scfm PRV is probably too small for that tank.

vii) If there are no defects larger than 1.2 m x 0.4 m, then more defect area may be acceptable, but this should be determined on a case-by-case basis by running the IDA 2.1 code for the specific tank. For this case, insulation samples should be taken so actual *k* values can be measured. At least 10 samples should be taken so that a truly representative average *k* can be determined.

viii) 112J type tank-cars equipped with small PRVs (approximately 3500 scfm) should not be allowed to have any defects unless the overall thermal protection properties can be defined.

The reader is reminded that this study did not consider the following:

i) end failures
ii) defective PRVs
iii) defects in primary shell
iv) corrosion
v) impact damage

vi) torching fires
vii) rolled tanks
viii) hard contact between the jacket and tank shell

7.0 Recommendations

The results described in this report depend very strongly on the details of the heat transfer in the vapour space when the tank is at high fill levels. We have almost no data to validate these models in any detailed way.

The following work is needed based on the analysis presented in this report:

i) Conduct fire tests of tanks at high fill levels, including those with thermal protection defects.
ii) Measure typical thermal conductivity *k* valves for as-installed insulation in tank-car thermal protection systems. This must be measured under temperature conditions that are expected in fire accidents.
iii) Determine how often there is direct contact between the tank jacket and primary wall.
iv) Determine the behaviour of PRVs during shell-full conditions (i.e., how they open and close, flow capacity of liquid and 2-phase, etc.).
v) Measure typical surface emissivities for the inside wall of old and new tanks.
vi) Measure or obtain reflection characteristics of propane liquid surface.
vii) Investigate the current PRV sizing formula for thermally protected tanks. Simulations suggest that current sizing requirements may not be conservative.

The IDA 2.1 code continues to evolve. The following tasks are suggested for ongoing work:

i) Improve 2 and 3 node thermal models.
ii) Improve vapour space radiation model.
iii) Include 2 node vapour space model for cases where late PRV action is expected.
iv) Validate shell-full model assumptions (PRV flow, 2-phase swell, etc).
v) Include other commodities in the code.
vi) Improve user interface.

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