An Inspection Tool for Tank Car Thermal Protection System

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Abstract

Regulations require thermal protection on tank cars in compressed gas service. Investigation indicated occurrences of thermal protection deterioration.

To quantify the reliability of thermal protection systems to prevent incidence of catastrophic tank car ruptures in accidents, Transport Canada has undertaken a number of thermal protection studies. They include developing an inspection technique for detecting and quantifying defects; conducting propane tank fire tests and tank car steel high temperature stress-rupture tests; and modeling tanks with various defects to establish critical defect shapes, sizes and conditions.

The studies identified infrared cameras as a useful inspection tool for inspectors to evaluate thermal protection system on in-service tank cars. The behavior of the tank and lading from bare to fully thermally protected tank, as well thermally protected tanks with various defects were simulated in a computer model and validated with data from the propane tank fire tests and the high temperature stress-rupture tests. This provides a base for establishing thermal protection defect assessment criteria for inspectors to determine the compliance of thermal protection systems. Furthermore, it provides a guideline to which tank car facilities could follow in the thermal protection inspection during tank car qualification.

Introduction

As a result of a series of accidental catastrophic tank car ruptures in the 1960-70's involving certain un-insulated pressure tank cars, the U S Department of Transportation, under docket HM144, initiated a retrofit program to improve class 112 and 114 pressure tank cars used to transport flammable gases. Among other requirements, thermal protection was required on liquid petroleum gases and anhydrous ammonia tank cars to protect them from accidental fire impingement. Similar regulations were adopted in Canada.

The current thermal protection system requirement is published in Par. 15.8 of the National Standard of Canada CAN/CGSB-43.147-2005. It requires that thermal protection systems applied to class 112 and 114 rail tank cars be capable of prevent the release of any dangerous goods, except through the safety relief device, when the tank cars are exposed to a pool of fire for 100 minutes and a torch fire for 30 minutes. Compliance is verified by either testing or thermal analysis as specified in the standard. Thermal protection systems are inspected every 10 years as part of the tank car qualification.

Two types of thermal protection, a spray-on and a jacketed system, were used in the HM144 retrofit program. Of all class 112 and 114 tank cars, approximately 800 were retrofitted with spray-on systems while the remaining were retrofitted with the jacketed system. In 2005, there were only 180 cars having spray on insulation, compared to 34,800 cars having jacketed system. Now most class 112 and 114 cars are manufactured with a jacketed thermal protection system consisting of a 13 mm thick blanket of high temperature ceramic fiber insulation, covered with a 3 mm jacket of steel.

Over time, insulation deficiencies have developed on cars for reasons such as continuous motion and vibration. Easily visible deficiencies on spray-on systems were repaired by patching. However, on jacketed system cars, insulation deficiencies are generally not visible because of the protective outer steel jacket; therefore they need different inspection techniques and repair methods. Thermal protection defects on the jacketed system may form if the blanket slips, or tears and drops down due to vehicle motion, or is crushed under the jacket. These defects can then lead to an open space between the jacket and the tank shell, and heat can be transferred across this air gap by thermal radiation and convection thus reducing the effectiveness of the thermal protection system. Limited field surveys of tank cars indicated that some tank cars might have significant deficiencies in their thermal protection systems. The question is what level of defect is acceptable from a safety standpoint? Answer to this question would provide criteria for compliance enforcement by Transport Canada inspectors. Transport Canada has undertaken a number of thermal protection studies to answer this question. The studies focused first on developing an inspection tool for detecting and quantifying the deficiencies of the thermal protection system on class 112J tank cars, secondly on analyzing the potential risk of these deficiencies on the performance of the thermal protection system.

Developing Inspection Technique for Detecting Defects

Looking for a reliable method of field inspection of thermal protection on tank cars, the infrared camera was determined as the most effective because it is non-destructive, non-contact and economical. It takes advantage of the fact that infrared camera can identify temperature gradients generated by insulation deficiencies when a temperature difference exists between the contents of the tank car and the ambient conditions.

Thermography is a method similar to photography, except that the "picture" taken is not visible light, but rather it is thermal radiation. Visible light and thermal radiation are forms of electromagnetic radiation. In this application we limit our interest to thermal radiation falling in the 3-5 μm or 8-14 μm wavebands of the electromagnetic spectrum. Infrared cameras use these wavebands because the atmosphere does not interfere (i.e. absorb radiation) strongly in these wavebands.

The task of developing an effective procedure for thermography inspection of thermally protected tank began with a technology review of infrared cameras. Cameras from a number of manufacturers including Agema, FSI, Texas Instruments, Raytheon, Inframetrics, Mitsubishi and others were compared based on price, performance, and features. A laboratory test program followed. A full scale, partial tank car mock-up was constructed with a pattern of insulation deficiencies. Using water to simulate the tank lading, thermal images were taken over a range of small temperature differences between the tank lading and the surroundings. It was found the selected camera could resolve the thermal insulation pattern under temperature gradient conditions comparable with day-night cycle temperature variations. However, the inspection, with the selected camera, was not effective when the temperature gradient between the lading and the ambient temperature was less than 5°C.

The lab tests were followed by limited field tests and validation. The infrared camera was taken into the field to view tank cars at sidings and industrial sites. It identified a number of tank cars with severe insulation deficiencies. One of these tanks was traced and when empty it was sent to a local repair shop. The tank was steam heated. This allowed the camera to once again identify the deficiencies. Cutouts were made in the steel jacket areas with the strongest indication of deficiency. In those areas it was found that no insulation was present in the gap between the tank shell and the steel jacket. In other areas, the insulation was either crushed or there was no insulation at all. This limited validation of the inspection procedure was followed by more field tests to gain experience with the inspection technique, to identify limitations of the inspection technique, and to obtain limited data on tank car insulation deficiency for statistical purposes.

The field test involved 200 tank cars of which 130 were analyzed in detail. The analysis resulted in estimates of percent deficient area on the tank tops and bottoms. The field tests proved the inspection technique to be practical, efficient and effective when the conditions were correct for the inspection, that is when minimal thermal gradients (greater than 5°C) were present.

As for the limitations, the technique does not work on silver painted or raw silver metal tanks due to the high reflection of the surfaces. The technique is very insensitive to tank surface condition for painted surfaces (glossy, flat, dirty, dusty rusted etc) but it is degraded by a wet surface because of the high reflection. It was also determined from these tests that the heat from the sun can greatly enhance the inspection when the lading temperature is cool. Some industrial process such as steam heating of lading, filling tanks with hot or cold lading and steam cleaning, also enhance the inspection.

Based on the field trials it was concluded that the inspection method is viable and the infrared camera is a suitable inspection tool for inspectors to evaluate thermal protection systems on in-service tank cars. It was also concluded that some tank cars might have severe insulation deficiencies.

A field test manual was produced for Transport Canada inspectors to use infrared camera to detect thermal insulation deficiencies on rail tank cars. The field test was followed by a heat transfer analysis to determine whether heat transfer considerations could be used to define an unacceptable defect size.

Further details on the inspection and procedure development can be found in References [1] and [2].

Analysis of Thermal Protection Defects on Tank Cars

After the testing and validation of an inspection tool for detecting and quantifying deficiencies in thermal protection, the next step was to determine the effect these defects have on the performance of the thermal protection system. That is, at what level of deterioration would a thermal protection system lose its ability to provide the level of protection required for a tank car during accidental fire impingement?

The analysis of thermal protection defects on tank cars carried out by Transport Canada consisted of fire testing of propane tanks with simulated thermal protection defects, high temperature stress-rupture testing of tank-car steels, and computer modeling of tank-cars with thermal protection defects in fires. The analysis conducted was designed from an enforcement standpoint to determine the levels of defect that are critical and thus require repair or replacement.

Fire Testing of 500-Gallon Propane Tanks with Simulated Thermal Protection Defects

In the summer of 2004, a series of fire tests was carried out to measure the effect of defects in thermal protection systems on fire-engulfed propane tanks. The tests were conducted at Defence R&D Canada – Valcartier's Munitions Experimental Test Centre.

The tests were conducted using 1890 L (500 US gal.) ASME code propane tanks as approximate one-third scale models of 112J type tank-cars. The model tanks have a diameter of 0.96 m, a wall thickness of 7.1 mm and an overall length-to-diameter ratio of about 3. The 112J type tank-cars have a diameter of about 3 m, a wall thickness of about 16 mm and an overall length-to-diameter ratio of about 6. At this scale, it is expected that the 500-gallon tanks will fail in about one third the time of a full-scale tank-car.

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. Credible liquid hydrocarbon pool fires range from 800 to 950°C.

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 vapor space, the vapor 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.

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 hydrocarbon pool fire for 100 minutes or a jetting fire for 30 minutes.

Tests were conducted with 16 and 8 percent insulation defects from bottom to top on one side of the tank. Failure times (corrected for poor fire conditions) were 24 and 36 minutes, respectively. This would scale to about 72 and 109 minutes, respectively, for a full-scale tank-car. These tanks failed with fill levels near 70 percent, which means the vapor spaces in the tanks were relatively small at the time of failure.

Following were some of the observations:

- Even small defects can lead to tank rupture when defect area is engulfed in a severe fire and is not wetted by liquid lading. Specifically, 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.
- A thermal protection defect is only a problem if it is located in the vapor space during a fire engulfment accident. This means the tank liquid level relative to the defect location is an important factor.

Further details on the propane tank fire tests can be found in References [5] and [6].

High Temperature Stress-Rupture Testing of Tank Car Steels

For the analysis of thermal protection defects on tank cars, understanding the high temperature stress-rupture properties of tank-car steels at specific stresses and temperatures is essential. This improves our ability to predict tank-car rupture when exposed to accidental fire impingement. 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 analysis did not consider large flaws in the tank. Failure in this study has been based on high-temperature, ductile stress rupture.

The samples used for tension and stress-rupture tests originated from four destroyed railroad tank-cars from the Melrose derailment in Ontario on February 21, 2003. Their reporting marks are TILX 302277, ACFX 18833, ACFX 17080, and ACFX 17026 and were constructed with TC128B steel in 2002, 1968, and 1964 and with A212B steel in 1964, respectively. The tank car steel was machined into a round specimen. Samples were cut in both hoop and longitudinal directions to determine whether the steel was isotropic in terms of high-temperature stress rupture.

The stress-rupture test was to determine the time to failure as a function of sample temperature and nominal stress under conditions of constant loading. It was conducted using a tensile testing machine with a furnace mounted on it so the test sample could be maintained at a constant high temperature. The tests were conducted under constant load (tensile force) conditions. The sample was heated to a specified temperature and the load was applied. The time to failure was then recorded.

Over 100 specimens of four different tank-car steels were tested for stress-rupture to obtain the relation of stress versus rupture time at a specific temperature. Among them, 80 specimens were from the tank-car hoop orientation, and 22 specimens were from the tank-car longitudinal orientation. Stress-rupture tests were conducted at 550°C, 600°C, 620°C, 650°C, 680°C, and 720°C.

Excellent data was obtained with very little data scatter in each sample. The data covers the range of temperatures and stresses of most interest in this study. The results show that stress-rupture properties vary between steel samples. The stress-rupture properties of TC128B (2002) are not greater than those of TC128B (1968), although these are both superior to the samples of TC128B (1964) and A212B (1964). However, all samples appeared isotropic when it came to high temperature stress rupture. The data collected is for use in the tank-car thermal model for tank failure prediction.

The failure of the tank car is dominated by the wall temperature in the vapor 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 failure times. Further details can be found in References [3 and 6].

Computer Modeling of Tank Cars with Thermal Protection Defects in Fires

Computer modeling offers an effective approach for the analysis of tank car thermal protection deficiencies. Once validated it gives flexibility to explore alternatives with various defined parameters. For example, the fire tests carried out with the 500-gallon tanks are not perfect models of the 112 and 114J type tank-car. For example, the initial fill levels were not the same. The 500-gallon 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 vapor space wall and therefore we must correct for this difference in initial fill levels. A validated thermal model of a tank-car in a fire would provide valuable predictions at higher fill levels.

The tank-car thermal model undertaken for Transport Canada is as developed specifically to model fire effects on dangerous goods tank cars that have defects in their thermal protection systems. The tank-car thermal model is called Insulation Defect Analyzer (IDA) 2.1. IDA is based on the thermal model developed earlier by Birk in reference [4] and uses some methods similar to those of AFFTAC by Johnson. However, it has some improved features including 3D tank shape, two-node lading thermal model, cycling pressure relief valve, and high-temperature stress-rupture failure prediction. The model has been partially validated with recent fire test data mentioned earlier.

The IDA was able to predict the pressure relief device start to discharge time, tank pressure, tank fill, tank wall and jacket temperatures, and time to failure in reasonable agreement with fire test results. In general, the IDA model tends to predict a more rapid increase in wall temperatures, which leads to tank failures that are conservative by 3-5 minutes earlier than those observed in tests. This may be due to the fact that the model assumes the fire is 100% on at time = 0 while in the fire tests it takes several minutes to get the fire up to full intensity.

IDA was used to study thermal protection defects on class 112J tank-cars. The model predicted that even small defects can lead to tank rupture if the defect is located at the top of the tank vapor space and if the fire is severe and it fully engulfs the tank. It also showed that failure of a tank-car with thermal protection defects depends not only on the size and location of defects, but also on the condition of the remaining thermal protection that is not defective. If the overall thermal protection system is in good condition, this slows the rate at which the liquid level drops in the tank, thus delaying failure. If the overall condition of the thermal protection system is not very good, then the liquid level drops more rapidly, exposing thermal protection defects in the vapor space earlier and leading to earlier failure. The problem is that we do not know the overall condition of the thermal protection system on a tank with local defects in the thermal protection system. If there are no defects larger than 1.2 m x 0.4 m, then more defect area may be acceptable. It indicated that class 112 and 114J type tank cars equipped with 3500 scfm pressure relief devices should not be allowed to have any defects unless the overall thermal protection properties can be defined. Finally the model doesn’t account for end failures, defective pressure relief devices, defects and damage in tank shell, corrosion, torching fires and hard contact between the jacket and tank shell. Further details can be found in References [4 and 6].

Summary

Thermal protection system was mandated on class 2 tank cars after series of accidental catastrophic tank car ruptures in the 1960-70’s. In order to provide the necessary protection against accidental fire impingement the thermal protection system must be maintained to an acceptable standard. For compliance purposes, Transport Canada has undertaken a series of studies focusing on inspecting and establishing acceptable criteria for the thermal protection system for in-service class 2 tank cars. The studies established a procedure for field inspection of jacketed thermal protection systems using infrared cameras and to determine allowable defects on thermal protection system. The inspection technique and procedure will enable Transport Canada inspectors to find critical thermal protection deficiencies while cars are in service. Based on the results of the studies the following allowable thermal protection limits are proposed for adoption into the National Standard of Canada CAN/CGSB.43.147,:

Acceptable level of defects in thermal protection systems

a) An analysis must be performed for the combination of tank, lading, pressure relief device, thermal protection and insulation in order to determine the maximum single void and cumulative area of voids in the thermal protection that can be tolerated, and still meet the requirements of par. 15.8;

b) Tank cars with safety valve flow capacity exceeding 5000 scfm may use the criteria in the following table. Tank cars with safety valve flow capacity less than 5000 scfm must use an analysis tool. If the analysis tool results indicate that the maximum permissible void size or total void area is more stringent than that described in the following table, the results of the analysis tool must be used;

Maximum allowable Void Size for Thermal Protection

Void	Size / Area	Condition
Single isolated Void	Maximum allowable void is 48" on the longitudinal axis of the tank x 16" on the circumferential axis (1.2 m x 0.4 m).	Voids must be separated from other voids by more than one half of the largest dimension or must be considered a single void.
Total void area	Maximum allowable total void area is 9% of the total tank surface area.	

c) The inspection method, technique and procedure must be capable of detecting single square voids of 406 mm (16 in) X 406 mm (16 in) at any location on the tank car tank surface;

d) Areas of defects other than voids such as deteriorated thermal protection material significantly reducing the thermal performance of the material must be considered the same as voids.

These criteria establish a standard to which tank cars with thermal protection systems must be maintained and be qualified. The acceptance criteria will provide a clear guideline for inspectors to decide when a tank car will need thermal protection repairs while defining a level of inspection that tank car facilities must follow in order to find the size of defect established in the guideline.

To gain further knowledge on thermal protection, Transport Canada in conjunction with FRA and tank car industry plan to undertake fire testing first of 2,000 gallons tanks then full-scale fire testing of thermally protected 112J-type rail tank-cars.

References

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