U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

www.nhtsa.gov

DOT HS 811 303

March 2010

Localized Fire Protection Assessment for Vehicle Compressed Hydrogen Containers

1. Report No. DOT HS 811 303	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Localized Fire Protection Assessment for Vehicle Compressed Hydrogen Containers		5. Report Date March 2010 6. Performing Organization Code NHTSA/NVS-321
7. Author(s) Craig Webster – Powertech Labs, Inc.		8. Performing Organization Report No.
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Industry has identified localized flame impingement on high pressure composite storage cylinders as an area requiring research due to several catastrophic failures in recent years involving compressed natural gas (CNG) vehicles. Current standards and regulations for CNG cylinders require an engulfing bonfire test to assess the performance of the temperature activated pressure relief device (TPRD). In the case of real world fires which are often localized at a point distant from the TPRD, the structural integrity of the cylinder can be compromised to the point that rupture occurs before the TPRD activates. This failure mode has become an area of concern for standards developing organizations (SDO's) drafting requirements for high pressure hydrogen storage systems. They have called for research to develop a localized fire test based on real world fire conditions, and assessment of mitigation technologies, which are documented in this report.

17. Key Words Hydrogen, CNG, TPRD, fire		18. Distribution Statement Document is available to the public from the National Technical Information Service www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 32	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

1.0 INTRODUCTION

The design of compressed hydrogen fuel systems for hydrogen vehicles has been largely based on the compressed natural gas (CNG) vehicle experience. In addition to installation requirements, the test procedures used to qualify on-board hydrogen fuel systems for service use the test protocol developed for the CNG industry. For example, evaluation of fire performance of the fuel system is limited to the fire testing of the hydrogen fuel tank and thermally-activated pressure relief device (TPRD) itself.

Between 2000 and 2008, there have been over 20 failures of CNG tanks onboard vehicles. The single largest cause of these failures (over 50%) was fire. These CNG cylinder failures have occurred on OEM passenger vehicles (Ford Crown Victoria, Honda Civic), as well as on OEM transit buses (Heuliez, Man Bus). Note that the effect of localized fires is more pronounced on cylinders of longer length, as TPRD locations are typically spaced far apart.

Some of the fire failures could be attributed to slow reacting TPRD designs, but the majority of the failures were caused by localized fire effects where the flame exposure was at a location on the tank remote from the TPRD location. Note that TPRDs do not tend to activate unless they are exposed directly to a high heat source, or direct flame impingement.

All CNG or draft compressed hydrogen tank standards worldwide only specify a bonfire test of a tank where the fire source is a standard 1.65 m length. This fire length is derived from a US DOT fire test developed in the 1970s for application to composite air-breathing cylinders of relatively small size. To address the issue of localized fire, some standards include a statement to the effect that one should optimize the location of TPRDs on cylinders depending on the installation configuration [1]. However, one reason the localized fire issues have not been addressed in the standards is because cost-effective methods of protecting cylinders have not been investigated.

2.0 Task A - Testing of Fire Protection Technologies

2.1 Overview

The fire protection of hydrogen tanks for vehicles currently relies on the use of thermally-activated pressure relief devices (TPRDs). Most compressed natural gas (CNG) and hydrogen tank standards specify that this pressure relief device shall only activate when exposed to heat. Pressure-activated relief devices are not used as the excessive pressures required for activation will not be achieved if the tank is only partially filled.

Typically the TPRDs can be found attached to a valve at one or both ends of a tank. As specified in the bonfire test requirements of various CNG and hydrogen tank standards, the length of the fire used to evaluate the effectiveness of a TPRD to protect a specific tank design, is 1.65m [2,3,4]. Current TPRD designs will only function if they are exposed to excessive heat, thus a fire occurring on a tank remote from the TPRD will not activate that device. Thus on tanks exceeding this length, it is often necessary to introduce high pressure piping and additional TPRDs along the tank to ensure at least one TPRD is within the bonfire.

The use of an exposed high pressure tube to support additional TPRDs introduces a risk that currently does not exist with OEM hydrogen vehicles – high pressure lines external to the tank. This design approach introduces the risk of the uncontrolled release of high pressure hydrogen in a collision. In addition, additional TPRDs are only effective if their position on the tank happens to correspond to the location of a localized fire condition.

Alternative methods for protecting a tank from fire effects involve coating systems that insulate from the heat, and methods of detecting heat or fire that will remotely activate a pressure relief device. Installation considerations can also significantly reduce the likelihood of a tank being exposed to localized fire effects. However, installation requirements are not considered in this report due to the fact there is a wide variation in vehicle designs, and multiple ways a vehicle fire can manifest itself, including:

- Passenger compartment fire
- Vehicle cargo fire
- Tire fire
- Collision fire from spilled liquid fuel

An effective fire protection system for an individual tank will minimize the need to try and address all external possibilities of a localized fire condition occurring. Methods of protecting hydrogen tanks from fire effects, other than the standard use of TPRDs, may be separated into 3 types of systems:

- Coating systems that have intumescent properties
- Heat insulating wraps or shells
- Heat detection systems that activate remote pressure relief devices

Factors to be considered in the selection of fire protection systems for evaluation include:

- Cost
- Weight
- Volume
- Ability to withstand vehicle tank service conditions (expansion associated with tank pressurization, extreme temperatures, drop impact, environmental exposure, etc.)
- Resistance to handling damage

Based on a review of information on the internet, recommendations from an automotive OEM, and private developers testing detection concepts, the following examples were selected for testing:

- An intumescent paint coating
- An intumescent epoxy coating
- Two examples of insulating wrap materials
- Three examples of heat detection systems

In addition, an insulating metal shell protection system is tested under Section 3 (Task B).

2.2 Intumescent Paint Coating

Paint coatings that resist fire effects would be an attractive approach to improve fire protection as they would be inherently thin, low weight, and likely lower cost than other options. Fire resistant coatings are typically intumescents, swelling when heated to provide an insulating layer.

An intumescent flame retardant coating from PyroTech of Addison, Illinois, trade-name "PyroCide II" (an intumescent system in a water resistant polymer latex) was evaluated. Various layers were applied to steel half-pipe sections, which were then heated on the coated side while temperatures were monitored on the uncoated side (see Figures 1 and 2). Figure 3 summarizes the temperature difference generated on the inside steel surface through the use of coatings of different thickness. The results were not encouraging, since the coating would break-down and flake off after several minutes of exposure to the high temperatures used in the test. Note that these test temperatures exceeded the specifications for the coating.

Figure 1 – Arrangement for fire testing steel pipe half-sections with one side coated by intumescent paint. Note thermocouple touching pipe surface on side opposite burner.

Figure 2 – Results of fire testing on PyroCide II paint coating of various thicknesses (#0 = bare steel, #3 = 3 coats of paint).

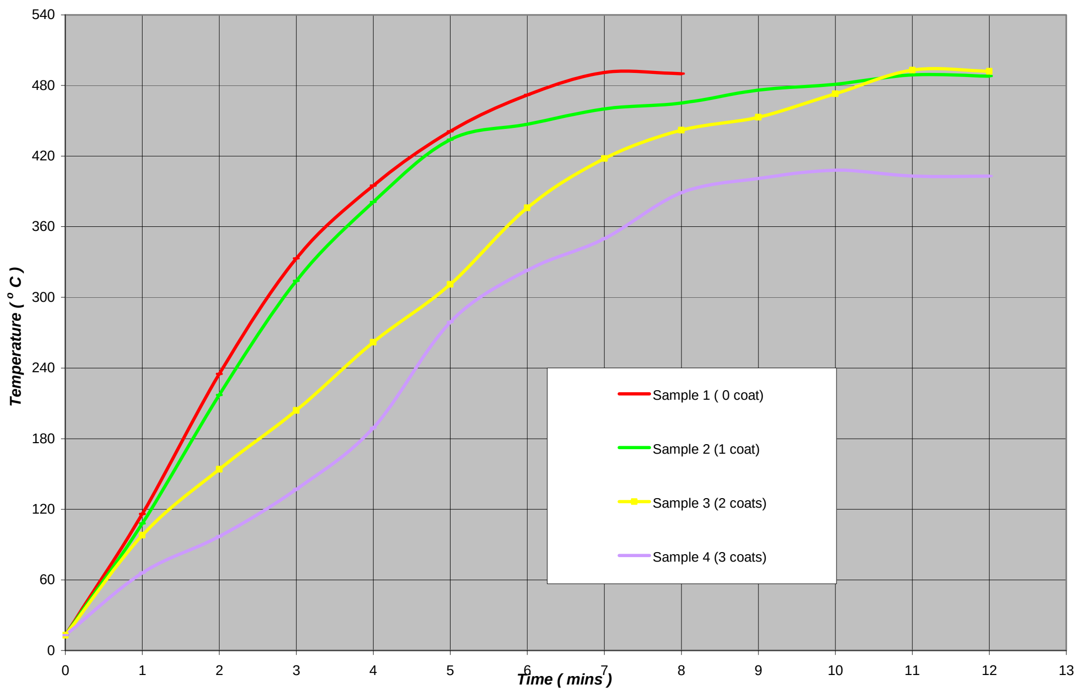

Figure 3 – Illustrates effect of paint coating on temperature rise on internal surface of steel pipe section when heated on external surface.

It was concluded that the test method above using steel pipe sections could not be used to predict how a tank might survive a fire test using an intumescent paint system, thus it was decided to switch to testing coatings on complete tanks of carbon fiber composite design. The fire test method was modified to a 3 burner system such that the area being exposed to fire was approximately 0.45m in length (about 25% of the tank length typically burned by a standard 1.65m bonfire test).

A base-line fire test was conducted on an uncoated 39L carbon fiber composite tank with an aluminum liner. The 200 bar tank design was sealed at atmospheric pressure, and heated using the new fire test arrangement for 10 minutes, while the increase in internal temperature was measured. The underside of a tank of the same carbon fiber design was then painted with 4 coats of the PyroCide II coating (approximately 5 mm dry thickness), and subjected to the same test. The test is illustrated in Figure 4. Figure 5 is a graphical comparison of the results between the baseline tank and the coated tank. The data suggests that intumescent paint coatings will only offer limited protection from heat effects, especially where high flame temperatures might be encountered.

Figure 4 – Performance of PyroCide II intumescent paint coating on bottom of carbon fiber composite tank during exposure to 3-burner fire test.

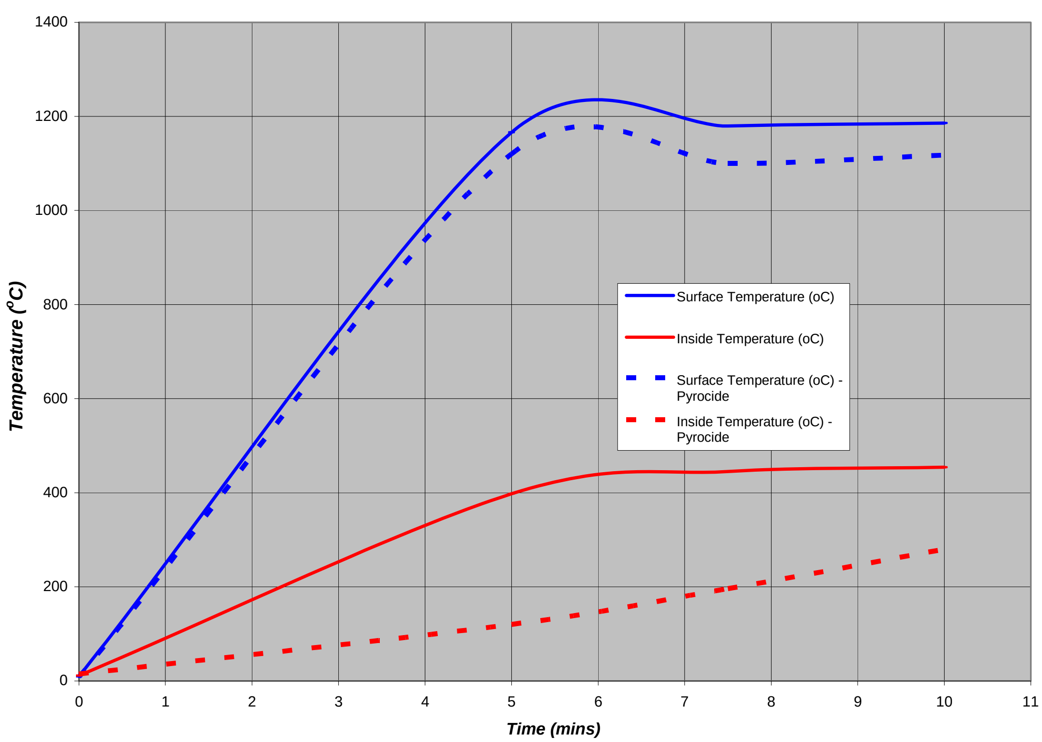

Figure 5 – Comparison of temperature performance of PyroCide II coated tank vs uncoated tank

2.3 Intumescent Epoxy Coating

A proprietary product "Pitt-Char XP", manufactured by PPG Industries, was identified by an automotive OEM as a candidate material. This 2-part epoxy-based intumescent coating can be applied to any thickness, and is thus able to withstand the high temperatures associated with automotive fires. As described by the manufacturer; "When exposed to fire, its unique chemical composition transforms its surface into ceramic-like, insulating char that provides thermal protection for the substrate even under hydrocarbon and jet fire conditions."

Since specialized spray application equipment is required, 4 carbon fiber tanks were sent to PPG for coating. Two tanks were coated 5 mm thick, and 2 tanks coated 8 mm thick. One tank (5 mm thick) was pressured to 7 bar with nitrogen and placed on the 3-burner unit (see Figure 6) for exposure to 800ºC for 10 minutes. It was found that the intumescent expanded under heat (see Figure 7), and provided the required heat protection (see Figure 8).

The weight of the coating applied to the 39L (water volume) tank was 3.9 kg. The materials cost would be about US$ 50.

Figure 6 – Low pressure fire test of 5mm thick epoxy intumescent.

Figure 7 – Tank rotated after fire test to show foaming effect of coating. Note that the damaged area in the coating was caused by the metal support stand.

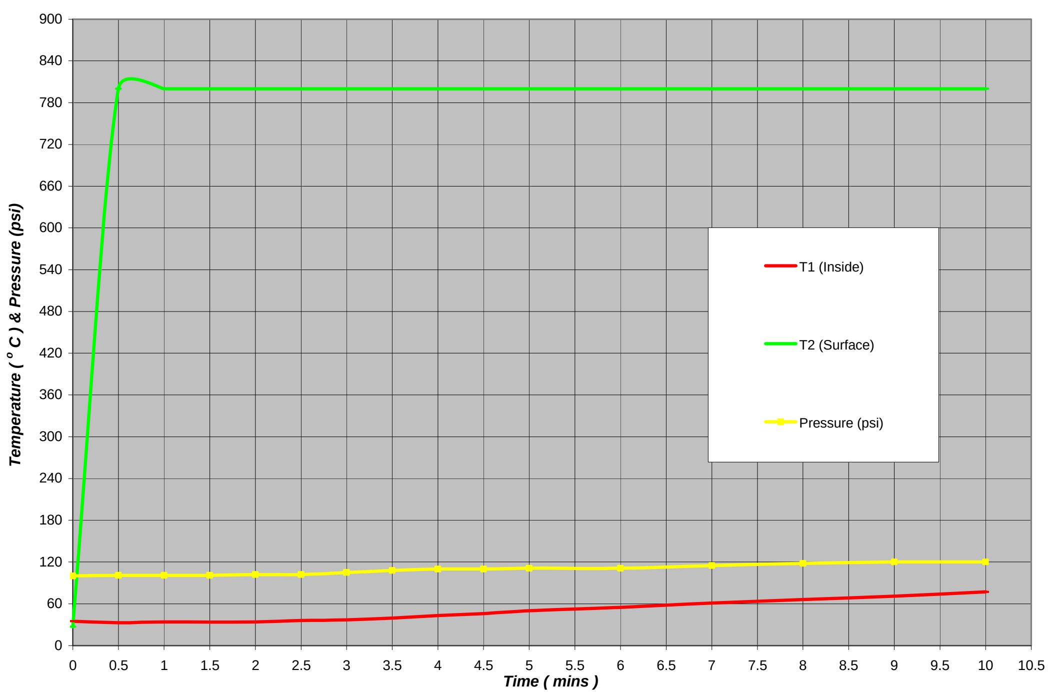

Figure 8 – Change in tank pressure and internal temperature during exposure to 800ºC surface temperature

One of the two 8mm thick tanks was then subjected to performance testing, to determine if it could withstand localized impacts. The 200 bar tank was drop impacted on the dome end (2 m drop onto a concrete surface at 45 degrees from horizontal (see Figure 9), then subjected to hydraulic pressure cycling between 20 bar and 250 bar. Five hundred pressure cycles were conducted at ambient temperature, 500 hundred cycles at -40ºC, and 500 cycles at +82ºC. There was no apparent damage to the epoxy intumescent coating.

Figure 9 – Appearance of drop impact damage (rebound end) on dome end of 8 mm thick epoxy intumescent coating.

The second 8 mm thick coated tank was initially pressured to 200 bar (2,900 psi) with hydrogen, and subjected to the 3-burner test for an intended 30 minutes. During the test, there was a concern that the localized fire could burn through the protective coating and destroy the composite underneath in a very small area, causing the tank to rupture. Theoretically, if this area of damage was small enough, it could occur without any significant increase in the internal tank pressure. As a result, the tank pressure was reduced during the test to 138 bar (2,000 psi). The fire test illustrated in Figure 10, and the temperature/pressure results are provided in Figure 11. Note that after the pressure was reduced to 138 bar, some of the pressure increase observed during the test was from the chilled gas returning to ambient temperature.

Figure 10 – Localized fire test of epoxy intumescent (8 mm thick) on carbon fiber tank containing 138 bar hydrogen for 30 minutes.

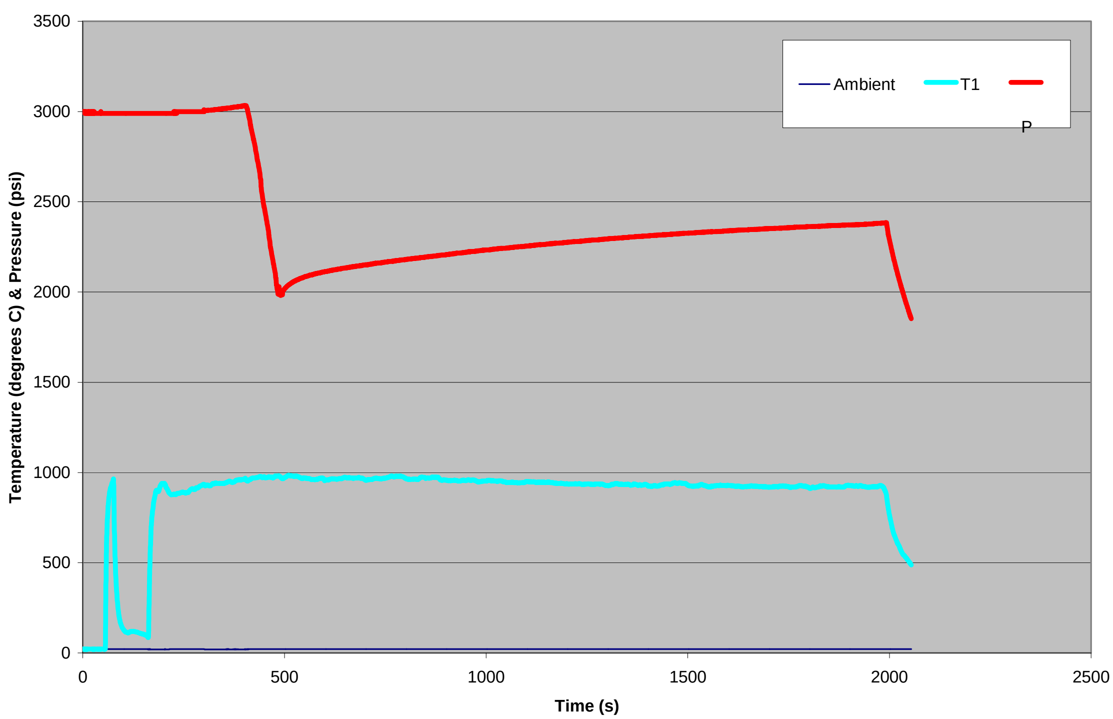

Figure 11 – Temperature/Pressure vs Time profile for epoxy intumescent during 30 minute fire test.

Upon conclusion of the test, it was observed that the intumescent epoxy was still intact, continuing to protect the carbon fiber composite from heat damage (see Figure 12). Based on the result of the 10 minute test of the 5 mm thick coating, and the 30 minute test of the 8 mm coating, it is likely that the 5 mm (or less) coating would provide adequate fire protection for a fuel tank.

Figure 12 – Appearance of 8 mm thick epoxy intumescent coating after 30 minutes exposure to 900ºC. Note that the flattened area is from handling after the test.

2.4 FIBER WRAP PROTECTION

2.4.1 Overview

Experience in a previous fire test program [5] involving fire resistant coatings applied to compressed natural gas cylinders indicated that relatively thick fibrous ceramic blanket materials would provide the necessary localized fire protection to hydrogen tanks. However, the key is to find a ceramic material that can conform to the shape of a tank, is thin, light-weight, and relatively low cost. For the sake of thoroughness, and to provide a performance benchmark for fire resistance, several ceramic blanket materials were tested.

2.4.2 Ceramic Fiber Blankets

Thermal Ceramics provided an alkaline earth silicate wool product (Tradename "SuperWool 607 Plus") in blanket form. Approximately 12.5 mm thick, it must be wrapped and fastened around a tank.

Figure 13 – Localized fire test of SuperWool 607 Plus blanket

As expected, the thick blanket provided complete insulation of the tank from the heat source. A thinner (6.5 mm) microporous blanket was also provided by Thermal Ceramics (Trade-name "Flexible Min-K"). Testing is illustrated in Figure 14, and the time and temperature plot provided in Figure 15. Again, the performance was excellent.

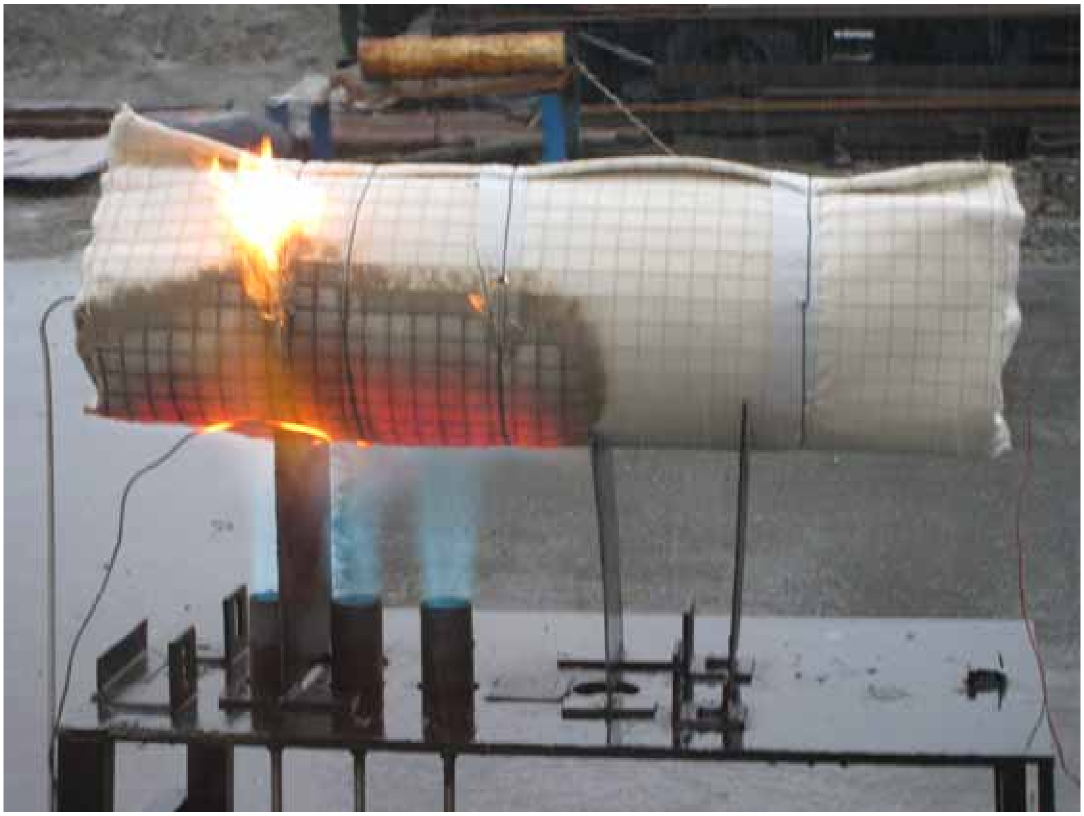

Figure 14 – Localized fire test of tank wrapped in Flexible Min-K blanket.

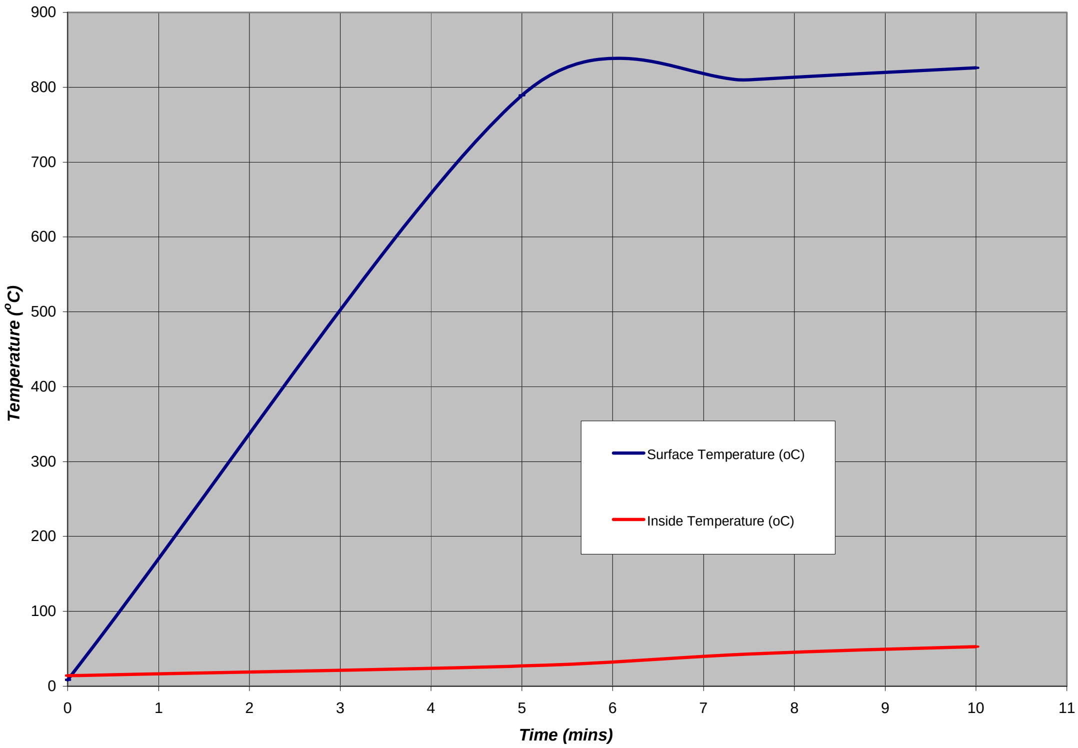

Figure 15 – Comparison of internal tank and external blanket temperatures on Flexible Min-K during localized fire test.

2.4.3 Wet Felt Blanket

A major concern with the use of wool wrap materials is that they must be held into place on the tank surface by some mechanical fixturing. To overcome this problem, ThermalCeramics supplied samples of another product (Trade-name I-2300 Wet Felt) that will assume the shape of the object it is wrapped around. Supplied in a wet condition, once removed from its sealed package and wrapped around a tank, it dries into place (see Figure 16). It was recommended that the dried product should be protected from damage by external cladding.

A carbon fiber type-3 composite tank wrapped on one end with the wet felt was pressured to 7 bar (100 psi) with nitrogen and subjected to the localized fire test for 5 minutes (see Figure 17). The internal pressure and temperature rise that occurred are provided in Figure 18.

The weight of the felt wrap required to cover a 39L tank would be about 1 kg, and the material cost about US$ 40.

Figure 16 – Application of wet felt wrap to tank

Figure 17 – Localized fire test of felt wrap after drying.

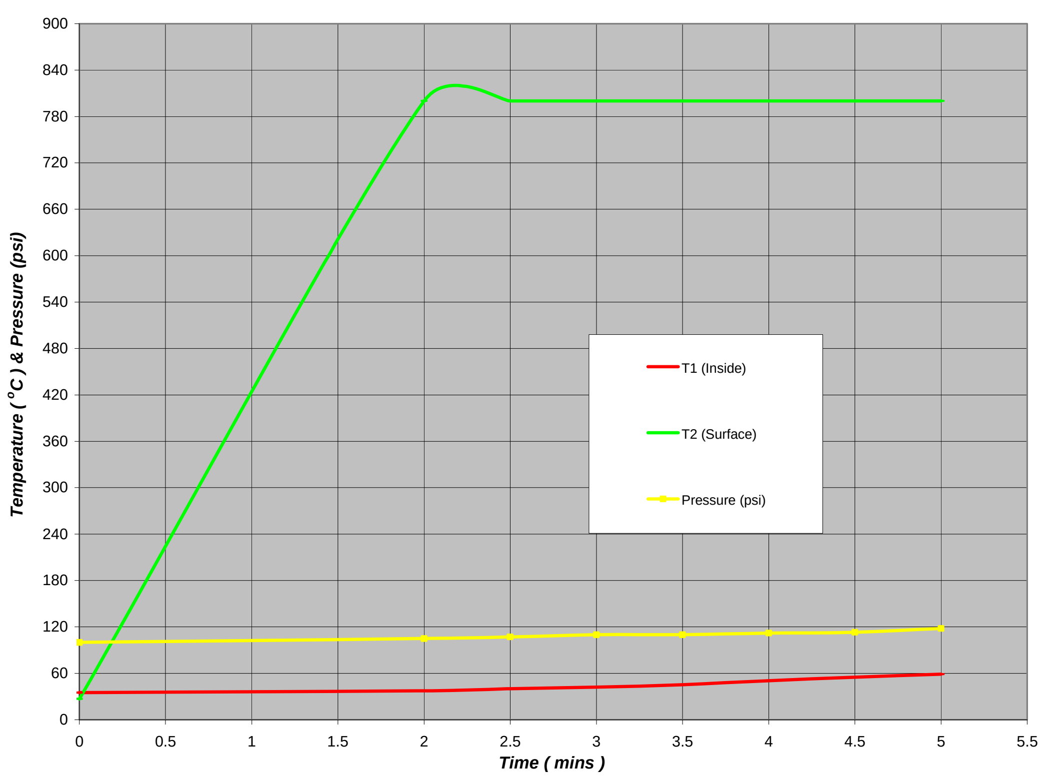

Figure 18 – Pressure and temperature rise inside tank during 5 minute localized fire test.

The results of the 5 minute fire screening test were very promising for such a thin, light-weight wrap material. However, because the wrap was very brittle after drying, it was apparent that it would not be suitable for handling during tank installation into the vehicle fuel system. While external cladding over the felt is an option, the manufacturer has since communicated that they supply a "Kaowool Rigidizer" product that "increases surface hardness and resistance to erosion". The colloidal silica compound is applied to the surface of the felt wrap by brush or spray. Further investigation would be required.

2.5 HEAT SENSING TECHNOLOGIES

2.5.1 Overview

It was determined by discussions with automotive OEMs that any remote sensing technology could not be an "active" system, i.e. rely on the electrical supply of the vehicle to function. Various developers have approached Powertech with remote sensing technologies for evaluation. While a protective coating system could protect a tank from localized fire without the need for a TPRD, all remote sensing technologies require a pressure relief device, usually of some design specific to the heat sensing technology, to be an integral component of the system.

2.5.2 Heat Transfer Liquid Tube

One tank manufacturer experimented at Powertech with a copper tube containing a proprietary "heat conduction" liquid. The tube ran the length of the tank, and was connected to the fusible metal trigger on a pressure relief device located at one end. The tank was placed on a standard bonfire, whereupon it was found that before sufficient heat could be transferred to activate the PRD, the tube leaked due to pressure rise caused by the expansion of the proprietary liquid.

2.5.3 Heat Transfer Metal Tube

In a variation on the liquid tube concept, a PRD manufacturer experimented at Powertech with a metal line with high heat conduction properties. The line ran the length of the tank, and was connected to a pressure relief device located at one end. The tank was placed on a standard bonfire, whereupon it was found that the heat transferred was insufficient to activate the PRD.

2.5.4 Fuse Wire

Dynetek Industries provided a system that used an ignition cord that ran the length of the tank, and was connected to a VTI glass bulb pressure relief device located at one end. (see Figure 19). The ignition cord used in the product has a number of advantages:

- Does not ignite under impact, or cutting with a knife
- Encapsulated in a plastic sheath it is impervious to moisture, and will burn underwater

- It does not require direct flame to ignite – air temperatures over 150ºC are sufficient

The ignition cord can be wound around the length of a tank. Once ignited due to elevated temperatures, it will burn to the VTI glass bulb TPRD. The heat from the ignited cord will break the glass bulb and allow the release of gas through the TPRD. Tests showed that the device works very well (see Figure 20), although improvements to the fuse wire/glass bulb attachment are required to ensure reliable activation.

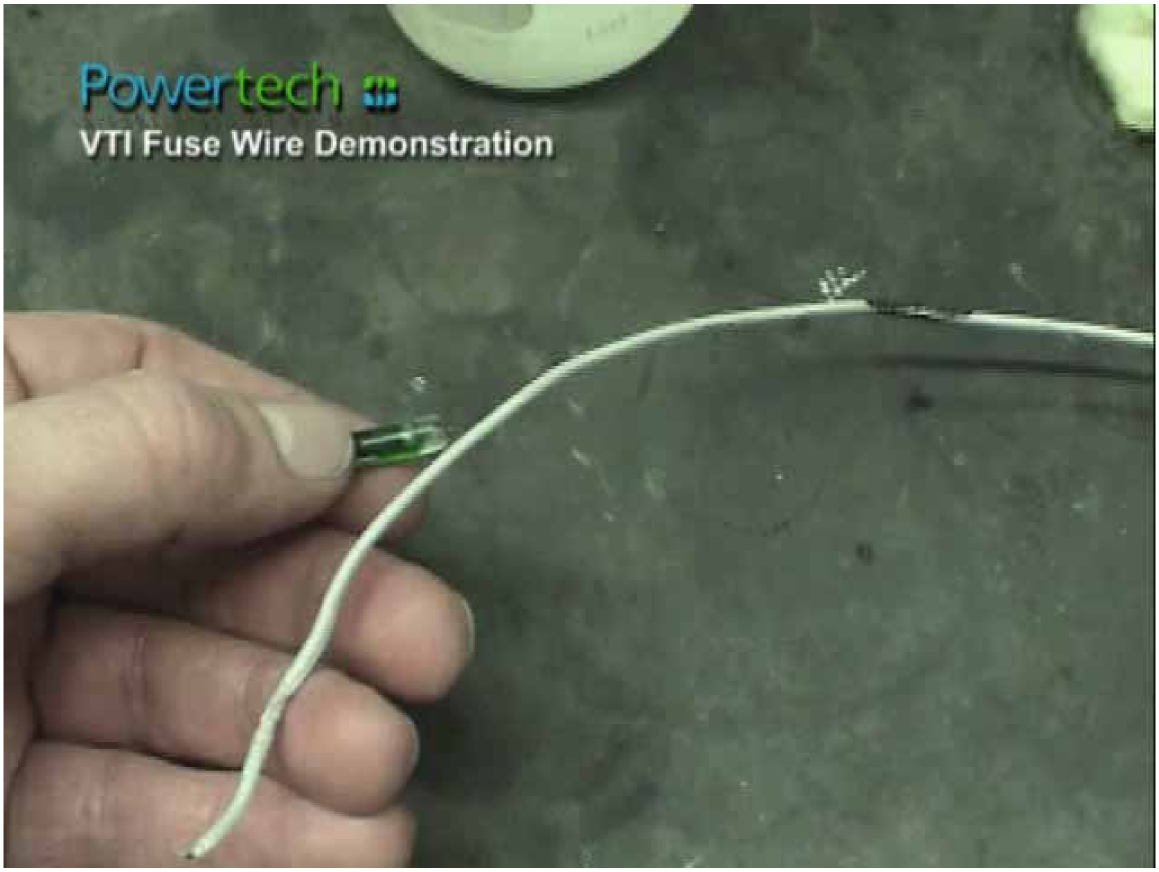

Figure 19 – Fuse wire and glass bulb used in VTI TPRD

Figure 20 – Video capture from fire test of carbon fiber composite tank protected with fuse wire and TPRD at one end. Note the fuse wire burning along the top of the tank towards the TPRD (not visible in picture).

2.5.5 Mechanical Activation Tube

Another promising heat detection technology is the use of a shape memory alloy (SMA) wire retained within a tube. When a small portion of the tube is heated (around 300mm), the SMA wire within contracts, and pulls open a piston in the pressure relief device, releasing the tank pressure. The SMA wire used in this device shrinks roughly 5% when heated to 108ºC. The SMA can be placed in a tube up to 2.4m long, and can therefore protect along the entire length of tanks up to 2.4m in length. An example of a localized fire test of the device is provided in Figure 21.

Figure 21 – Localized fire test of carbon fiber composite tank protected using a long SMA tube connected to a piston-activated PRD located outside of the fire.

3.0 TASK B. FIRE TESTING OF OEM FUEL SYSTEM

A 700 bar hydrogen fuel storage system, complete with a manufacturer's proprietary fire protection system, was obtained from Quantum Technologies (see Figure 22). The Type 4 tanks were covered in a thin stainless steel shell of 0.635mm (0.025 inch) thickness. Within the stainless steel shell were pads of a ceramic blanket material of 12.5mm thickness separating the tank surface from the shell. The shell covering the approximate 35L (water volume) tank has a weight of 4.55 kg.

One tank was removed from the assembly, filled to 7 bar with compressed nitrogen, and subjected to a localized fire test. The resulting heat damage is illustrated in Figure 23. The tank temperature and pressure rise data is provided in Figure 24.

Figure 22 – Quantum fuel system assembly, complete with stainless steel shell covering.

Figure 23 – Heat damage to stainless steel shell. Note that the length of the burn area is approximately 0.45 m.

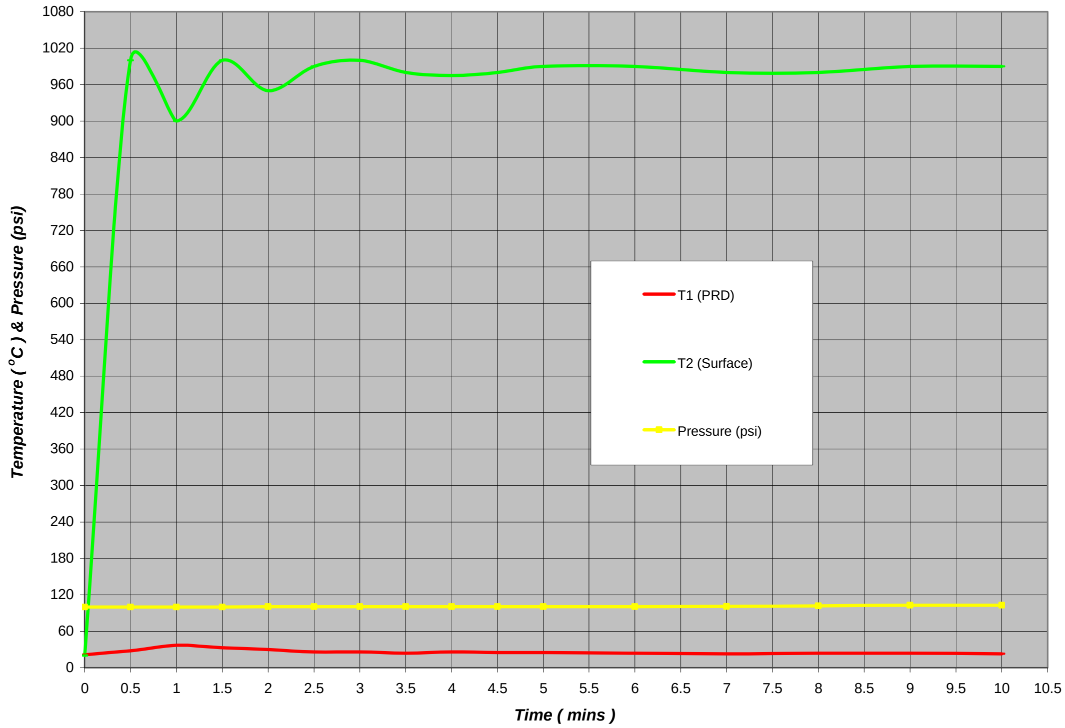

Figure 24 – Pressure and temperature change within the Quantum tank during localized fire at temperatures in excess of 950ºC.

The construction of the tank shell is illustrated in Figure 25. Aluminum foil is used to hold the white ceramic blankets in place. The ceramic blanket material is only placed on the end domes and the mid-wall portion of the sidewall. At the location of the assembly strapping, the only separation between the shell and the composite tank surface is a rubber strap. This strapping area also happened to be at the centre of the localized heat source. It is interesting to note that while a portion of the rubber strap melted away, the heat damage on the tank was not severe, i.e. the resin matrix did not burn away. This result suggests that perhaps the stainless shell by itself, with minimal separation from the surface of the tank, may be sufficient to prevent damage from localized fires.

A second Quantum unit from the fuel storage system assembly was removed and pressured to 700 bar with hydrogen for field testing (see Figure 26). The tank survived the 30 minute test at localized fire temperatures of 900ºC without incident. The temperature and pressure profiles are provided in Figure 27.

Figure 25 – Heat damage to surface of composite tank (right) revealed when heat-damaged half of shell folded open. Note the white ceramic blanket material exposed under the aluminum foil wrap (left).

Figure 26 – Localized fire test of Quantum fuel tank containing 700 bar hydrogen for 30 minutes.

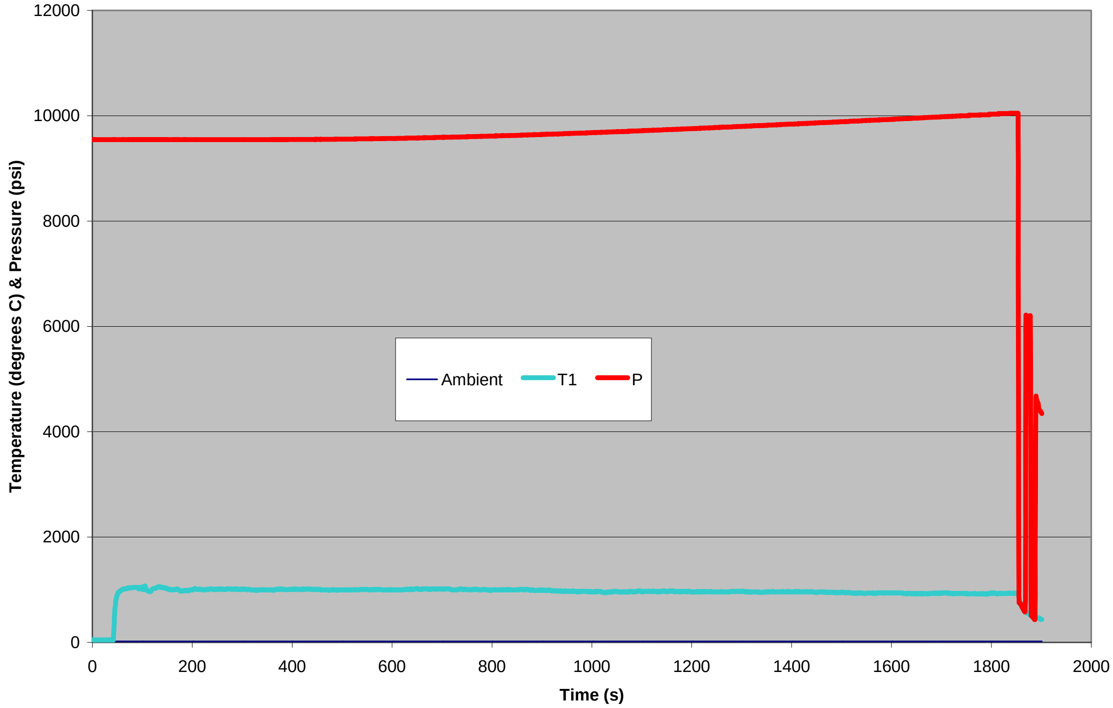

Figure 27 – Surface temperature and internal pressure measurements on Quantum during 30 minute localized fire test.

4.0 TASK C. LOCALIZED FIRE TEST PROCEDURE

4.1 BACKGROUND

In a previous study, in response to a specific definition of a localized fire condition involving several different heat zones on a tank, Powertech developed a "hot plate" method for testing [6]. This approach involved placing the tank on a curved metal cradle that matched its diameter (see Figures 28 and 29). By heating the metal cradle from below, it was possible to closely control the temperature on the surface of the tank.

Figure 28 – Metal cradle used to generate different heat zones on a tank. In addition to burners located under the sidewall area, note the torch under the valve end.


Figure 29 – Tank set-up for fire testing on the cradle.

However, during the evaluation of protective fire coating systems and heat detection systems for this project, it was concluded that the use of such a cradle apparatus was difficult. This is because the concept requires the construction of a cradle that matches the diameter of each tank tested. In addition, cradle heating may be incompatible with coating systems that expand when heated, or detection systems that are bulky and would prevent intimate contact of the tank to the cradle.

A hot plate approach, while providing more consistent surface temperatures, does not simulate the high peak temperatures that occur with actual flame impingement. Flames in direct contact with the tank surface can also produce instantaneous high temperature exposure, while a hot plate must first heat up to high temperatures. Accordingly, a realistic test procedure was adopted involving open flames impinging on the tank.

Due to the varying nature of flames, and susceptibility to air movement, it was not considered practical to define a precise area of exposure on a tank surface, or a specific thermal input. Instead, it was believed that providing a sufficiently severe fire over a local area would be a good test of any localized fire protection system, such that slight variations between test laboratories would not significantly affect the outcome of the test. Specifying the burner arrangement, burner separation distance from the tank surface, and temperature range to be achieved, provides a sufficiently repeatable test condition that would identify fire protection and detection systems that would significantly improve the safety of hydrogen fuel tanks. It is believed that slight variations of surface temperature, or heated area, between tests or test labs, will not materially affect test results, especially if test conditions are likely more severe than actual service conditions.

4.2 TEST METHOD:

4.2.1 Overview

A fire source of 250 mm length shall impinge a flame on the tank surface providing a minimum surface temperature of 900ºC for 30 minutes.

4.2.2 Burner Design

The fire source consists of 3 burner pipes, each 50 mm in diameter, fuelled by liquefied petroleum gas (propane). The pipes are placed in line, 100 mm center to center, for a total burner in-line length of 250 mm. The burners are placed 150 mm below the tank surface. The resulting fire typically impinges on an area on the tank surface that is about 450 mm long, and the full width of the tank (in the case of a 300 mm diameter tank). The surface temperature shall be measured by a thermocouple located directly over the central burner and in contact with the tank surface. The thermocouple shall be protected from direct flame impingement (and prevent erratic temperature readings) by a thin metal shield that is a maximum 25 mm in width. A minimum temperature of 900ºC must be achieved in less than 1 minute. The maximum temperature during the test shall be 950ºC.

4.2.3 Fire Temperature and Duration

The surface temperature of 900ºC is derived from a review of numerous vehicle fire tests [7]. In no case did any temperature reading exceed 900ºC within a vehicle.

The duration of 30 minutes is derived from the length of time that tires can burn. In addition, a study that reviewed 20 publications on vehicle fire data determined that the mean duration of a vehicle fire was 48 minutes, covering the time when the heat release rate from the burning vehicle was greater than 10% of the peak heat release rate measured during the test [8]. However, since only a portion of the vehicle would be on fire for a portion of the fire duration, it is conservative to estimate that 30 minutes would be a worst-case exposure time. In addition, temperature measurements made during some of the tests showed that the time at temperatures in excess of 800ºC was less than 30 minutes.

A fire of 900ºC intensity for a continuous 30 minutes likely exceeds any continuous source of heat in a vehicle fire.

A current fire test involves a source of 1,650 mm in length, and at 100 mm offset from the base of the tank, which typically covers some 1,800 mm in actual tank length [2,4]. The proposed local fire test would cover about 25% of that actual fire length.

4.2.4 Tank Orientation and Pressure

The fire source shall be located under the tank sidewall at the end opposite the valve end containing a TPRD, or equidistant between TPRDs if multiple devices are being used. In the case of a heat detection system being used to protect the tank, unless the system encompasses the entire circumference of the tank surface, the tank shall be placed on the burner such that if the burner is considered in the 6 o'clock position, the detection system shall be located in the quadrant between 9 o'clock and 3 o'clock.

The tank shall be filled to its service, or working, pressure with hydrogen. This represents a worst-case situation, in terms of stress on the wall structure, and time to vent to a safe pressure (if a TPRD is used).

4.2.5 Test Requirement

The fire shall burn for 30 minutes without tank leakage or rupture, or until a TPRD (if used) activates and vents the tank to a pressure of less than 7 bar.

5.0 CONCLUSIONS

1. A localized fire test procedure has been identified. Some variability will occur in fire tests between different test facilities due to air movement and flame characteristics. However, it is believed that the defined test is sufficiently severe (900ºC for 30 minutes in the same location) such that a tank design able to survive the test will be safe for service even if there are small differences in repeatability. Additional verification testing is required to support this preliminary conclusion.

2. Coatings, wraps, and heat detection methods exist that can protect tanks from localized fire effects.

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