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14. ABSTRACT
Tank cars use pressure relief devices (PRDs) to protect the tank from overpressure situations, such as those resulting from derailment related fire exposure. However, these devices are not tested/certified under such high temperature conditions. The intent of this research program was to characterize PRD performance under these critical conditions through testing. The research team successfully conceptualized, prepared, and executed two series of fire tests, which effectively evaluated the performance of PRDs under fire conditions. The first series of tests used water as the lading, and the second series of tests used ethanol as the lading. The PRDs survived the fire and functioned normally when subjected to moderately high temperatures for 30 to 60 minutes. Recommendations for future work include extending the ability to model and predict tank and PRD behavior considering the results from these tests.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches: 0 1 2 3 4 5

Centimeters: 0 1 2 3 4 5 6 7 8 9 10 11 12 13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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The second series of tests were carried out at the BAM (German Federal Institute for Materials Research and Testing) Fire Test Facility near Berlin, Germany. The research team would like to acknowledge the major contributions of BAM personnel including, Dr. Otremba, Mr. Gunzel, and Mr. J. Borsch. The team is also happy to acknowledge the insight offered by Dr. Phani Raj, from the FRA's Office of Safety, during test planning and execution.

The authors would like to thank Fort Vale Inc. for donating the PRD valves and assisting with testing.

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Executive Summary

Tank cars use pressure relief devices (PRDs) to protect the tank from overpressure situations, such as those resulting from derailment related fire exposure. However, these devices are not tested/certified under such high temperature conditions. The intent of this research project was to characterize the performance of PRDs under fire conditions through testing. The Federal Railroad Administration (FRA), in an ongoing effort to improve safety in the transportation of hazardous materials by rail, funded this research project from June 2017 to December 2020 to quantify the behavior and performance of tank cars' PRD when exposed to fire conditions resulting from a derailment.

Sharma & Associates, Inc. successfully conceptualized, prepared, and executed two series of fire tests, which effectively evaluated the performance of PRDs under fire conditions. The team conducted these tests on one-third scale tanks, but with full size PRDs. The first series of tests, using water as the lading, was conducted at an indoor test facility at Underwriters Laboratories in Northbrook, IL. The second series of tests, using ethanol as the lading, was conducted at an outdoor test facility at the German Federal Institute for Materials Research and Testing (**B**undes **A**nstalt fur **M**aterial Forshung and Pruefung [BAM]), near Horstwalde, south of Berlin.

The test matrix included:

- Low flow capacity (11,000 scfm) and high flow capacity (32,000 scfm) PRDs, consistent with the types that are commonly used in flammable liquid service
- Gaseous flow, mixed (two-phase) flow, and liquid flow conditions
- Three simulated derailment scenarios with the car upright (0 degrees), slightly rolled over (45 degrees), or significantly rolled over (120 degrees) conditions

For each type of lading (i.e., water and ethanol), the research team conducted three tests, covering the three derailment and flow conditions, for a total of six tests. The test setups were effective in providing a realistic fire exposure to the PRDs and the team successfully collected the desired performance data. Key findings include:

- The PRDs survived the fire and functioned normally when subjected to moderately high temperatures for 30 to 60 minutes.
- Multiple releases of the PRD occurred in each of the six tests, with each release resulting in a reduction of pressure and mass (i.e., due to lading expulsion). Continued fire exposure resulted in the pressures rising again, and subsequent releases.
- For both the water and ethanol tests, start-to-discharge pressures were close to the nominally expected value of 75 psi.
  - For the water tests, subsequent release pressures also stayed close to the 75 psi value, showing consistent behavior.
  - For the ethanol tests, while an initial release (leakage) was seen near 75 psi, subsequent energetic releases were seen at lower pressures, ranging from 35 psi to 55 psi. This is thought to be the result of PRD springs weakening due to fire exposure from the flammable lading release. This reduction in pressure is, however, considered

to be safe, especially given the prospect of weakened tank material under fire conditions.

- The float with attached thermocouples, along with the internal thermocouple trees, confirmed that the extent of temperature stratification in the liquid lading was minimal for both the water and the ethanol tests; the boundary layer appeared to be fairly thin and without significantly higher temperature than the rest of the liquid lading.
- The flammable material being released during PRD activity (e.g., ethanol tests) was notably contributing to the fire environment being experienced by the test tank and the PRD.

Recommendations for future work include:

- Extending the ability to model and predict tank and PRD behavior considering the results from these tests
- Conducting a limited set of additional tests to better understand the nature and reasoning behind the lack of thermal stratification, which has been observed in prior total containment fire tests. Among others, these tests could help establish whether the lack of stratification was the result of insulation on the top half of the tank, which prevented the top half of the tank from becoming a significant radiant heat source, or if this was the result of mixing (churn) due to PRD activity.
- Observations that PRD releases are high energy events even when the lading being released is not flammable, and even more so when the lading is flammable, would be useful to integrate into training materials being used by emergency responders

1. Introduction

This report describes and documents two series of fire tests that were conducted on one-third scale tanks, to characterize the performance of Pressure Relief Devices (PRDs) under derailment fire conditions. The first series of tests used water as the lading, and the second series of tests used ethanol as the lading. The report describes the test design and setup, the safety controls, the test processes, results, and the conclusions of the study and recommendations for future work.

1.1 Background

PRDs are used in tank cars to protect the tank from overpressure situations, such as those resulting from fire exposure. Tank cars carrying hazardous materials are required to survive a 100-minute, fully engulfing pool fire without catastrophic failure. Fluid and vapor pressure buildup under fire conditions combined with loss of strength in steel due to elevated temperatures can lead to catastrophic failure. In general, the 100-minute requirement is met through the use of thermal protection and PRDs. The PRDs help limit the pressure buildup in the tank cars, thus reducing the potential for tank explosion. The expectation is that PRD use will result in smaller quantities of hazardous material being released while avoiding the potential for catastrophic failure. In certain cases, PRD's alone may not be sufficient to meet the 100-minute test requirement and thermal protection (i.e., high temperature insulation that is designed to survive fire conditions) is required. Thermal protection, which in most cases is applied between a steel jacket and the tank, will reduce the heat input to the tank's lading and lessen both the temperature rise and the pressurization rate, thereby helping the tank meet the 100-minute test requirement.

Recent tank car accidents, especially with crude oil, ethanol, and other flammable materials, have resulted in significant fires with thermal shell tears and fireballs; this has further highlighted the need to ensure that PRD's and thermal protection systems are effective under fire conditions.

As seen above, current tank car designs rely significantly on PRD performance to survive a 100-minute fire. Malfunctioning PRDs can have a significant effect on the ability of a tank to survive fire conditions. However, the performance of these PRDs under fire conditions has not been established.

Tests specified by railroad industry standards require flow testing of the PRDs to ensure that they have the capacity to evacuate the tank as needed; these requirements are defined in the AAR Manual of Standards and Recommended Practices, Volume C-III, under Section 6 of Appendix A, "Flow Capacity Tests." However, these tests are not required to be conducted at the elevated temperatures expected under fire conditions. In addition, Section 3.2.5 of Appendix A of C-III covers testing of non-metallic materials and specifies a temperature of 150 °C, but this temperature is well short of the expected temperatures.

This research effort evaluated PRDs under realistic fire conditions, similar to those defined in Title 49 Code of Federal Regulations Section 179.18, and documented their performance in evacuating the tank, considering:

- Activation (start-to-discharge)
- Set pressure
- Reclosing
- Flow, under gaseous, liquid flow, and two-phase flow conditions
- Potential for transferring heat to insulated tank sections, etc.

The results of the test effort may be used by the Federal Railroad Administration (FRA) to tag any safety concerns and for the industry to take any corrective action, if needed.

1.2 Objectives

The objective of this test program was to investigate the performance of multiple PRD designs and configurations when exposed to fire conditions. This was accomplished through instrumentation and testing of one-third scale test vessels, with full-size PRDs under a variety of test conditions, when subjected to a fully engulfing fire.

1.3 Overall Approach

Long duration fire testing is very complex and challenging. Minor, and often unexpected, issues can lead to loss of test data or a poor test outcome. In addition, issues like the availability of sensors qualified for high temperature operation, and protecting sensitive cabling from the rigors of the fire can be quite challenging and potentially expensive. However, analytical techniques have not been refined to the point where the data that can be collected from a fire test can instead be generated analytically.

The technical approach for this effort was as follows:

- Designing one-third scale specimen tanks, instrumentation setups, and fire setups for the tests
- Subjecting the specimen tanks with a full-size PRD to an engulfing pool fire
- Documenting PRD performance with respect to opening pressure, reclosing, and evacuating the tank
- Documenting tank and lading conditions through tank pressure, wall and lading temperatures, and lading mass expelled
- Determination of the level of temperature stratification in the tank's liquid lading
- Understanding the impact of PRD capacity and orientation on PRD performance

1.4 Scope

The intent of this project was to evaluate PRD performance under fire conditions through high temperature fire testing. No analytical evaluations of PRD performance were planned. This effort was delivered through the development of a test matrix, the development of a suitable fire test setup, confirmatory/demonstration testing of the setup, followed by execution of the full test matrix.

The program tested both non-hazardous and hazardous flammable commodities. Testing included both low and high capacity PRDs and a one-third scale tank. This effort tested valves releasing vapor, liquid, and combinations of both.

1.5 Organization of the Report

Section 2 describes the test planning and the test matrix. Section 3 describes the instrumentation and data acquisition. Section 4 explains the test setup and the fire design. Section 5 depicts the safety plan, and Section 6 presents the results for both series of tests. Section 7 summarizes the effort and recommendations for future work.

2. Test Planning and Specimens

Large-scale fire testing, especially using flammable materials is a complex process requiring significant efforts in planning, test design, safety controls, and attention to detail. This section describes the test planning effort including the intended test matrix, and specimen design.

2.1 Test Matrix

Based on discussions with FRA and industry, review of potential derailment conditions, and different valve types used in flammable material service, the research team developed a test matrix for this effort.

Three different derailment positions were selected:

- There are many cases where tank cars derail in an upright condition. This was considered using a PRD located at the top of the test tank.
- Researchers considered two scenarios where a tank car derails in an overturned condition. In one overturned case, the valve is assumed to be at an angle of 120 degrees from the vertical with liquid flow through the valve, and in the other overturned case the valve is assumed to be at an angle of 45 degrees with the expectation of mixed phase flow.

The choice of PRDs involved issues of commodity, capacity, and commonality, with specific focus on high risk and/or high exposure models. The valve models that are used in tank cars carrying flammable materials (e.g., crude oil and ethanol) were given preference with a focus on external valve models. The most prolific companies in the valve manufacturing industry were considered to ensure commonality.

- Valves can be either external or internal. Researchers focused on external valves from a fire exposure consideration.
- Every valve considered had a start-to-discharge pressure of 75 psig, as these were the most commonly used in flammable liquid service.
- A simulation of a full-size tank engulfed by fire indicated that a valve with capacity greater than 4,000 scfm would suffice for the upright position (vapor flow), while the overturned position (liquid flow) would require a valve of capacity 20,000 scfm. Commonly available valve capacities in flammable liquid service are 11,000 and 32,000 scfm.
- Any valve that can handle liquid flow can also be expected to handle mixed phase flow. Hence, the same valve type could be used for both of the overturned positions (45 and 120 degrees).
- Given that the performance characteristics for a given flow capacity were similar across manufacturers, choice of manufacturer was not a key consideration.

Liquid flow and mixed phase flow scenarios require valves with much higher capacity as compared to vapor flow. Hence, a lower capacity valve (11,000 scfm) for the upright position, and higher capacity valves (32,000 scfm) for the overturned positions were selected. The rationale for using a lower capacity valve for upright position is to ensure that substantial valve activity is captured, preferably with the valve being fully open for some periods.

The final test matrix with respect to the PRDs was:

- 11,000 scfm PRD in the upright position (gaseous flow)
- 32,000 scfm PRD in the 45 degree position (mixed flow)
- 32,000 scfm PRD in the 120 degree position (liquid flow)

Two test series were planned:

- The first series was with water as lading; this was intended to confirm the effectiveness of the test setup, the vessel design, and the instrumentation.
- The second test series was with a flammable commodity (ethanol) as lading.

2.2 Test Vessel and Support Structure

The test article is based on a one-third scale model of a DOT-117 tank car, but with a thicker shell for additional factor of safety. It is worth repeating that the focus of the test is to analyze PRD performance, so using an exactly scaled tank car model is not required. The test vessel is made of carbon steel with an outside diameter of 36 in., length of 156 in., and wall thickness of 0.75 in. The capacity is 621 gallons and the empty weight is 3,400 pounds.

The vessel was designed and fabricated according to Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code. The maximum allowable working pressure is specified in UG-27 of the ASME code by the following formula.

$P = SEt / (R + 0.6t)$

where:

P = internal design pressure, psi

S = maximum allowable stress value, psi

E = joint efficiency in cylindrical shell

t = shell thickness, inches

R = inside radius of shell, inches

The shell and heads are made from SA-516-70 steel plate. Welds are full penetration, from the outside, with a backing strip, and they were spot checked by radiography. This type of weld is considered to have an efficiency of 0.80 for the purpose of determining allowable internal pressure. Allowable stress values as a function of metal temperature for various materials are specified in UG-23 of the ASME code. The following graph shows, as a function of temperature, these allowable stress values for SA-516-70 steel plate as well as the maximum allowable internal vessel pressure as determined by the above formula.

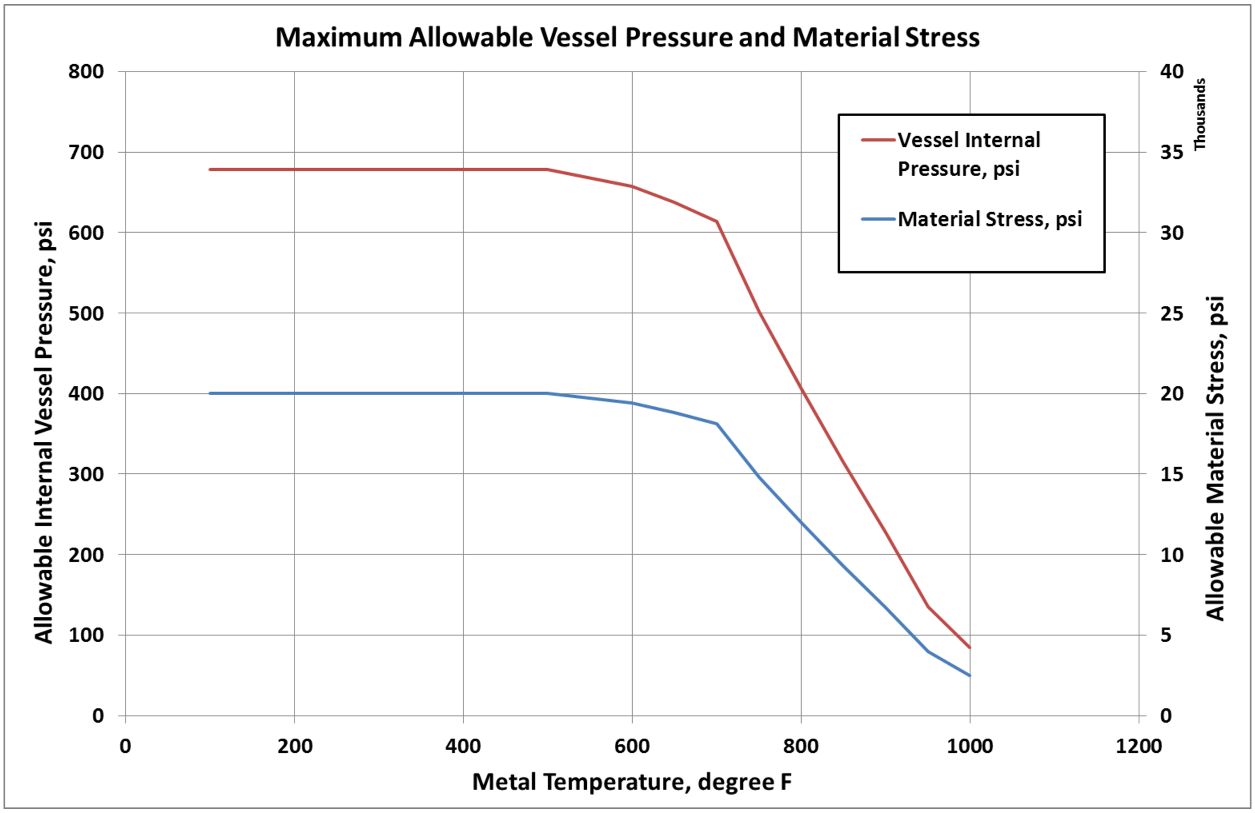


Figure 1. Maximum allowable vessel and material stress

As can be seen from Figure 1, the maximum allowable working pressure at room temperature, and up to 500 °F, is 678 psi. The ASME code allows SA-516-70 material to be operated up to 1000 °F (i.e., mean metal temperature, through the thickness). For these tests, the vessel shell exterior temperatures were monitored (i.e., via thermocouples in multiple locations on the shell) with a particular focus on any thermocouples that approach or exceed 800 °F. The allowable working pressure with a (mean) metal temperature of 800 °F is 400 psi.

The test vessel was designed to accommodate PRDs of varying capacities installed at any one of three different angular positions, with the aim to capture PRD performance under multiple flow regimes (see Figure 2 and Figure 3). The PRDs could be set up at angles of zero (upright), 45 and 120 degrees from the vertical. The test vessel also has a manhole for the purposes of instrumenting the tank interior.

Two 2-inch ports on top of the vessel for filling and venting were added; along with two 2-inch ports on the bottom of the vessel, one of which is available for draining and the other for instrumentation. Lastly, the team provided a safety relief valve and a manually operated emergency dump valve located outside the fire area as additional safety features in the event of PRD malfunction. The vessel is supported on a pair of saddles and four steel pipes.

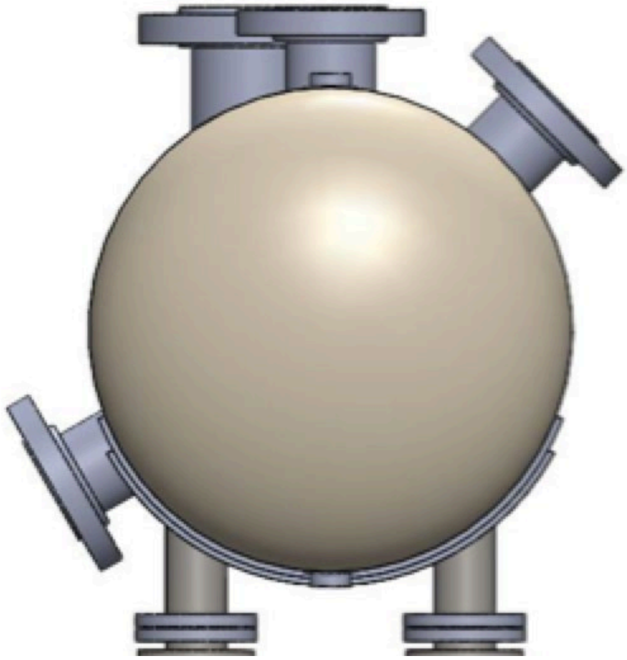


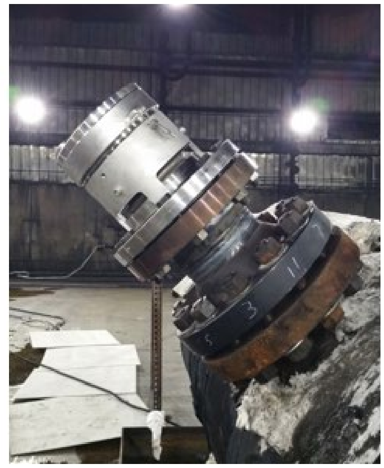
Figure 2. PRD test vessel schematic

Figure 3. PRD test vessel

2.3 PRD Test Articles

As noted earlier, the team used representative PRDs that are commonly used in crude oil service for these tests. For the upright position, a lower flow capacity PRD was used, whereas for the 45 and 120 degree positions a higher flow capacity PRD was used (see Figure 4). The PRDs tested were the external type, with capacities of 11,000 scfm (for the upright position) and 32,000 scfm (for the overturned positions). All PRDs tested were rated for a start-to-discharge pressure of 75 psig, which is common in flammable liquid service. An ANSI adapter flange was designed and fabricated to mount the PRDs to the nozzles on the test vessel.

Test # 1 - Low capacity PRD mounted in upright orientation



Test # 2 - High capacity PRD mounted at 45° orientation

Test # 3 - High capacity PRD mounted at 120° orientation

Figure 4. PRD test articles mounted for the three test orientations

3. Instrumentation and Data Acquisition

The research team designed the instrumentation for the tests, considering:

- Test data needs (e.g., pressure profiles, liquid, vapor, shell temperature profiles, lading mass, and fire temperature)
- Instrumentation survival under fire test conditions
- Redundancy needed from both safety and data perspectives

Instrumentation was largely identical for both series of tests (e.g., water and ethanol). The instrumentation consisted of the following (shown in Table 1).

1. Directional flame thermometers (DFT) for fire temperature
2. Thermocouples on tank exterior shell and at fixed locations inside vessel for liquid temperatures
3. Floating thermocouples to measure thermal stratification in liquid
4. Pressure gauges for tank internal pressure
5. Load cells to measure loss of lading

Table 1. Tank and PRD instrumentation

Measured Item	Quantity	Sensor Description
Temperature, vessel exterior shell	30	K type thermocouple
Temperature, vessel interior (lading and vapor space)	16	K type thermocouple
Temperature, fire	4	DFT: K type thermocouple in insulated box
Temperature, on PRD	4	K type thermocouple
Temperature, near lading surface	3	Thermocouples attached to float
Pressure, vessel interior	2	0–200 psig pressure transducer
Liquid lading level	1	Differential pressure transducer, 0–2 psig
Weight of vessel and contents	4	Compression-only load cells
Video imagery of test	3	Video cameras

3.1 Thermocouples

Thermocouples were used extensively to measure temperatures of the tank wall and internal lading at various locations. Given the potential for the fire to heat the tank in a non-uniform manner, having thermocouples at various locations can identify potential 'heat zones.' Figure 5 illustrates the layout of thermocouples on the test vessel exterior.

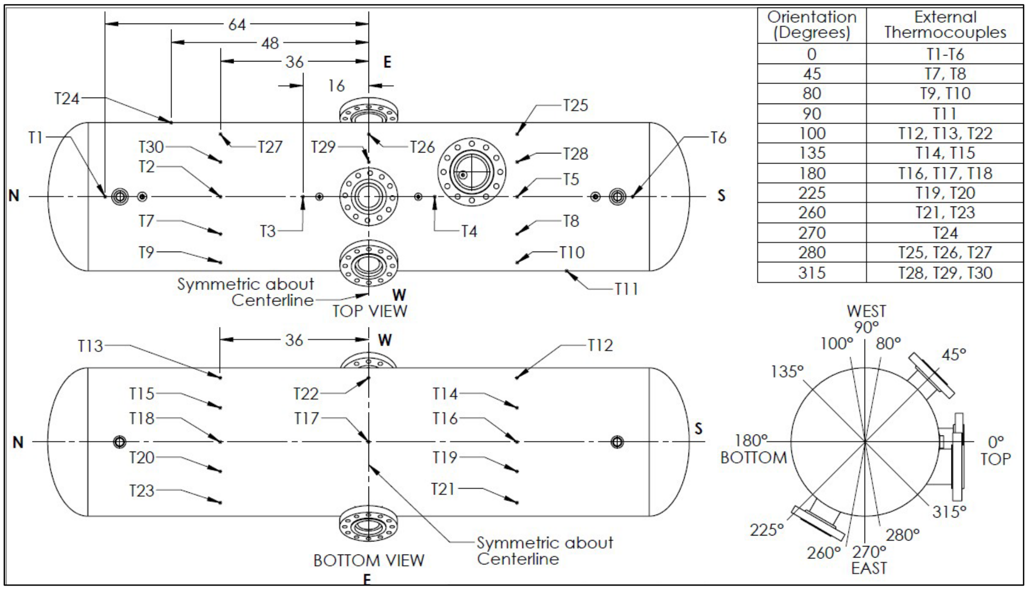


Figure 5. Layout of vessel exterior shell thermocouples

Two additional sets of thermocouples measured the temperature of lading inside the tank at various locations, as shown in Figure 6. These thermocouples were arranged as trees that are inserted from the top of the vessel (i.e., through compression fittings) and drop down toward the bottom with thermocouples terminating at various heights. The evidence from literature review of previous fire tests suggests the potential for significant temperature stratification in the liquid, especially close to the liquid surface (Birk, A. M., 2000) (Birk, A. M., 2005) (Gonzalez, F., Prabhakaran, A., Robitaille, A., Birk, A. M., Otremba, F., 2016) (Li, H., 2014) (Moodie, K., Cowley, L. T., Denny, R. B., Small, L. M., & Williams, I., 1988) (Townsend, W., Anderson, C., Zook, J., & Cowgil, G., 1974). These trees have a higher density of thermocouples at the top to capture the higher temperature gradient expected in this region.

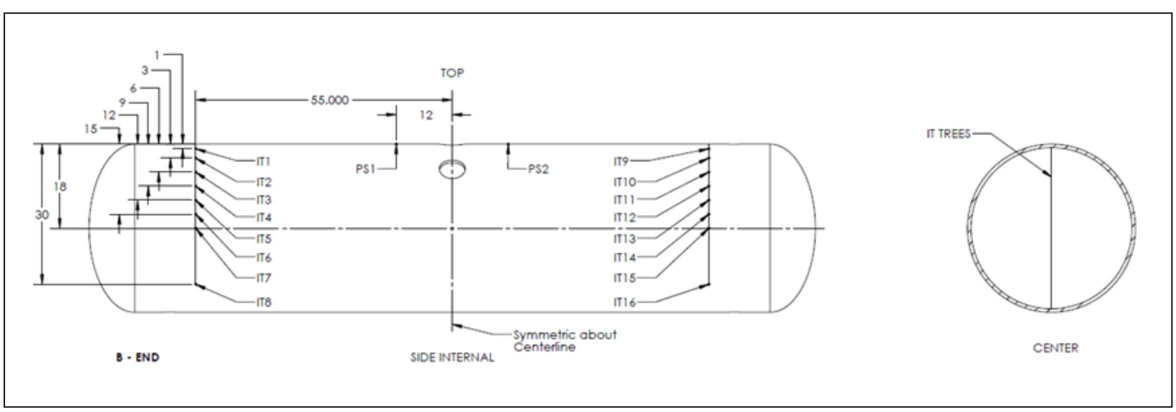


Figure 6. Schematic of internal thermocouple trees

3.2 Pressure Transducers

The test setup used two pressure transducers located on the top of the tank to measure internal pressure. A differential pressure transducer was installed to measure the pressure head of the lading and thus estimate the liquid height in the test vessel.

3.3 Float Thermocouples

The data obtained on liquid temperatures and tank pressure from previous tests indicate the presence of a boundary layer near the surface of the lading that is at a higher temperature than that of the bulk liquid (Birk, A. M., 2000). This boundary layer controls the tank pressure in the vapor space under saturated conditions. The inability to accurately determine boundary layer temperatures can lead to the inaccurate prediction of tank pressure. The test setup used thermocouples mounted on a float, at multiple heights to capture the boundary layer (see Figure 7 and Figure 8).

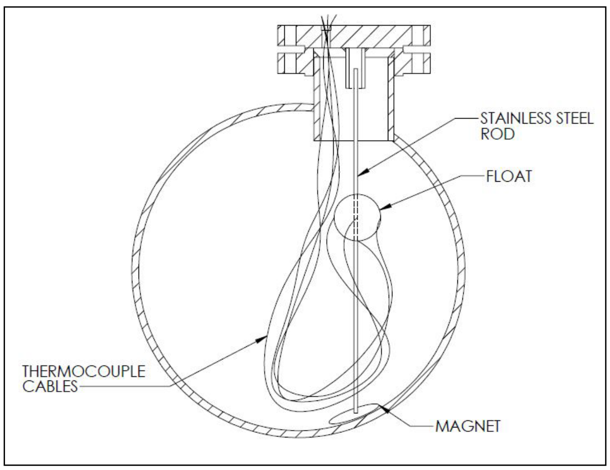


Figure 7. Schematic of thermocouple float assembly

Figure 8. Float installed in tank, looking down through top nozzle

3.4 Load Cells and DFTs

For the water test, four load cells, positioned under each support leg, were used to record PRD activity. The monitoring of the entire assembly's weight allowed determination of the amount of lading expelled from the PRD over the course of the test. The data from load cells were also used to calculate the liquid height in the tank throughout the test. The highest expected weight of the assembly was about 10,000 lbs. including 5,000 lbs. of water at minimum outage. The sensitivity of the load cell is an important criterion to obtain data on PRD activity with an acceptable level of resolution. The load cells also had to be effective in a high temperature environment due to their close proximity to the fire.

For the ethanol tests, only three load cells were used due to some of the setup intricacies at BAM. Nonetheless, the full load of the tank and lading passed through the three load cells, and these worked in a similar fashion to the load cells used for the water tests.

A DFT is essentially a thermocouple housed in a stainless steel (e.g., or other high temperature resistant alloy) box and backed with insulation, which is then mounted on the outside surface of the test vessel. They are commonly used to measure fire temperature. Four DFTs were placed on the top and sides of the test vessel to measure the temperature in the fire environment.

3.5 Other

All the thermocouples (e.g., interior, exterior, and float) were installed at SA's laboratory in Maywood, IL, and the tanks leak tested (under pressure) before being shipped to the test facilities. Researchers shipped the tank for the initial (water) tests by road to Underwriters Laboratories (UL) in Northbrook, IL, whereas, the tank for the ethanol tests was air-freighted to BAM in Berlin, Germany.

4. Test Setup and Fire Design

As noted earlier, the research team planned the tests in two phases, with the first phase being tests with water as lading, an intended as a 'proof-of-concept' test for the test setup, vessel design, and instrumentation, and the second phase being a test conducted with flammable lading.

The first set of tests was conducted at UL in Northbrook, IL, at one of their large indoor fire test facilities. The second set of tests was conducted at a remote, outdoor, test facility at BAM, near Berlin, Germany.

4.1 Tests with Water as Landing

The water tests were conducted at an indoor fire test facility at UL, which had a floor plan of 120 ft. x 120 ft., with an adjustable height ceiling to better control fire patterns. The test facility was large and tall enough to accommodate the size of fire that would engulf the tank and PRD. A 'viewing/control room' located along one edge of the test laboratory enables constant monitoring of the fire test while ensuring the safety of personnel involved. Figure 9 through Figure 11 presents the test setup.

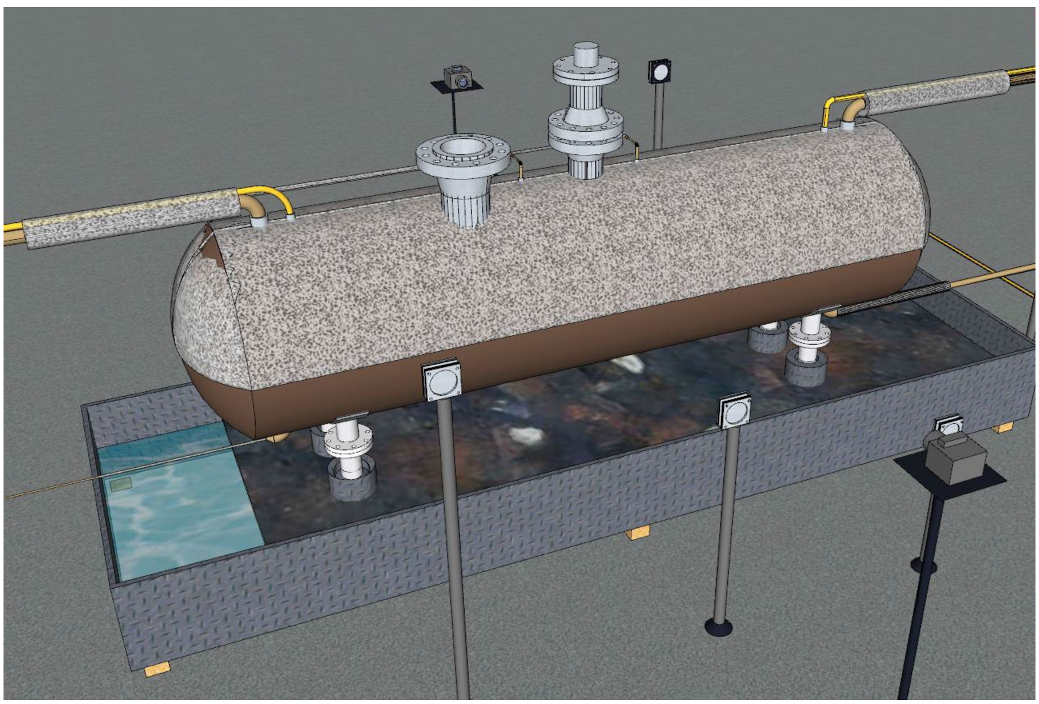


Figure 9. Setup for water tests

A fire pan was fabricated to hold water during the test to protect the laboratory floor from the direct heat of the fire. The vessel is supported on a pair of saddles and four steel pipes. The vessel support legs pass through tubes welded to the base of the fire pan, thus isolating the legs from the fire pan. Further, the legs are covered with insulation to prevent the legs from heating and transferring the heat to the load cells placed under them. Load cells between the support legs and the floor were used to measure the change in lading weight within the vessel during the test.

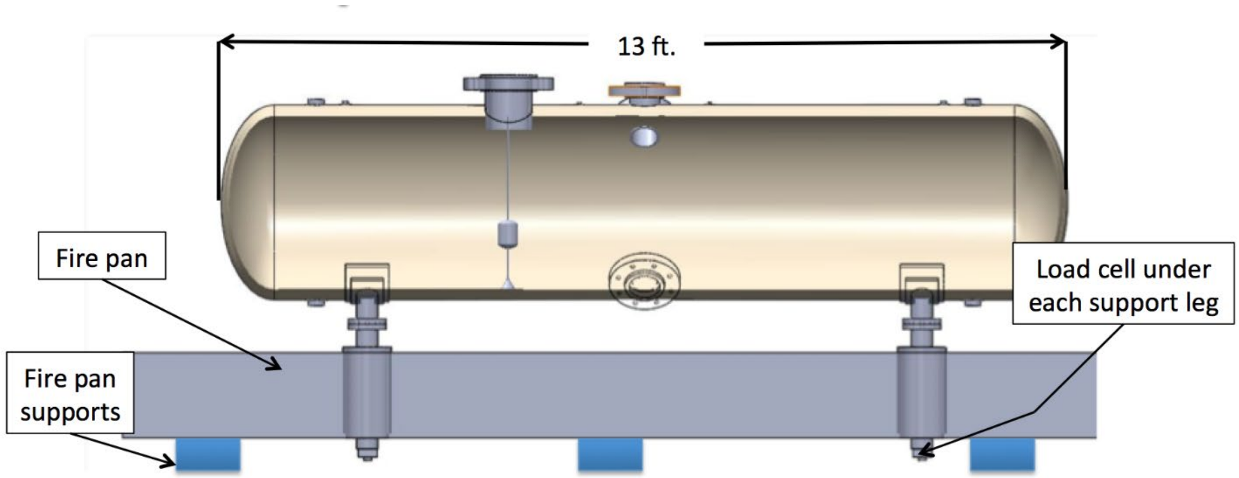


Figure 10. PRD fire test vessel and fire pan

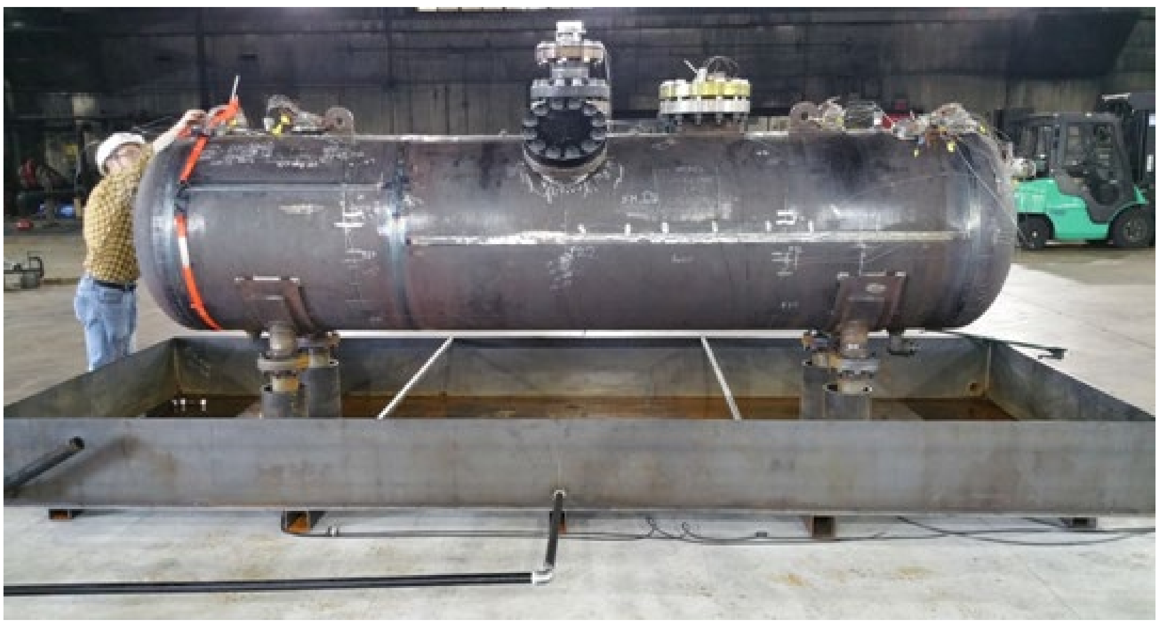


Figure 11. Test vessel sitting in fire pan, with PRD mounted on top, center nozzle

Frames were used for supporting pipes, cables and other instrumentation equipment, as well as to keep them away from the fire and off the floor. The instrumentation cables and pipes within the fire and in the high temperature zone were covered with high-temperature ceramic fiber insulation material. The top portion of the test vessel, which was in contact with the vapor phase of the lading, was also insulated with a high-temperature ceramic fiber blanket to preserve the integrity of the non-wetted tank shell. Figure 12 and Figure 13 shows the test layout at the UL facility.

A safety relief valve and a manually operated emergency dump valve located outside the fire area were installed as additional safety features in the event of PRD malfunction or other eventuality.

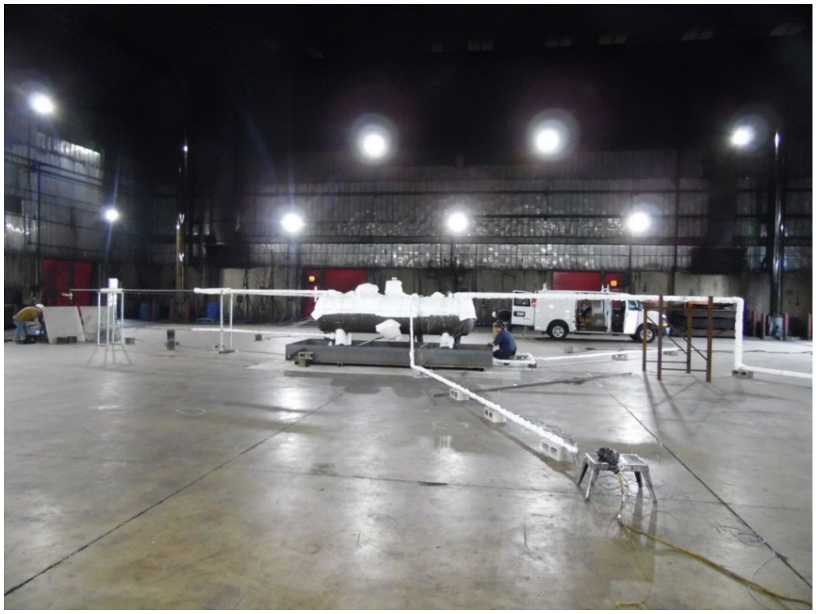


Figure 12. PRD fire test vessel with insulation

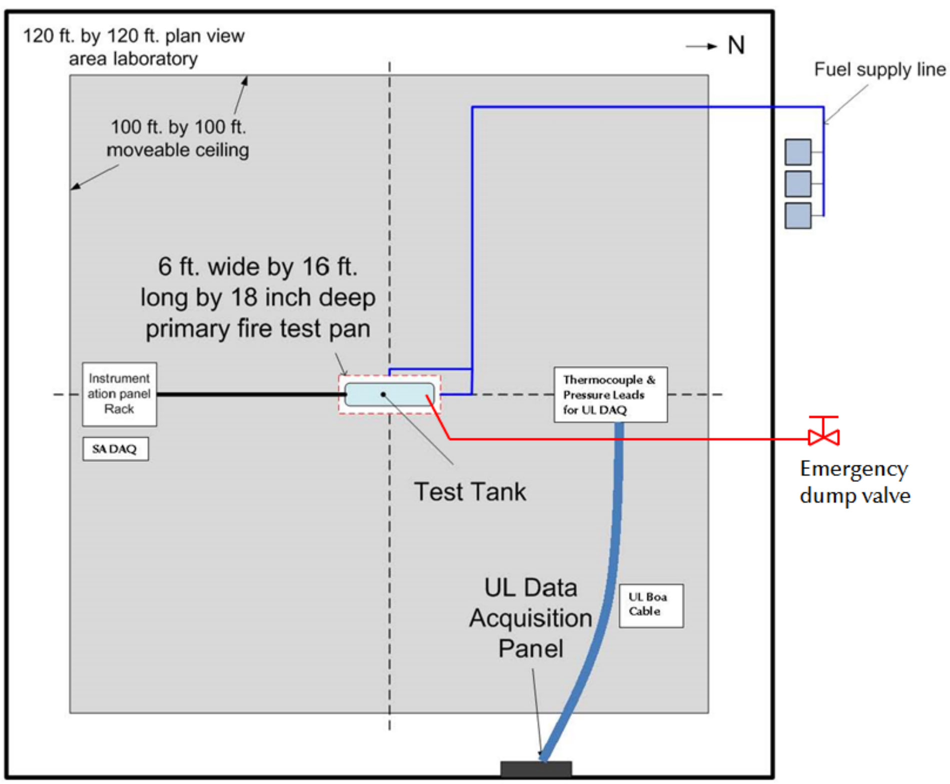


Figure 13. Test layout at UL

Preliminary tests were conducted with a pan fire setup, wherein diesel fuel was floated on top of the water in the fire pan and set on fire. However, this produced a tall and dense (sooty) fire that the smoke abatement system of the laboratory could not keep up with for a long duration fire such as the one intended for this study. Considering the smoke abatement constraint, a system of burners with nozzles that supply heptane fuel was specifically designed for this test. There were three rows of burners with six burners in each line. One line was directly beneath the tank along the longitudinal centerline and one line of burners on either side (see Figure 14).

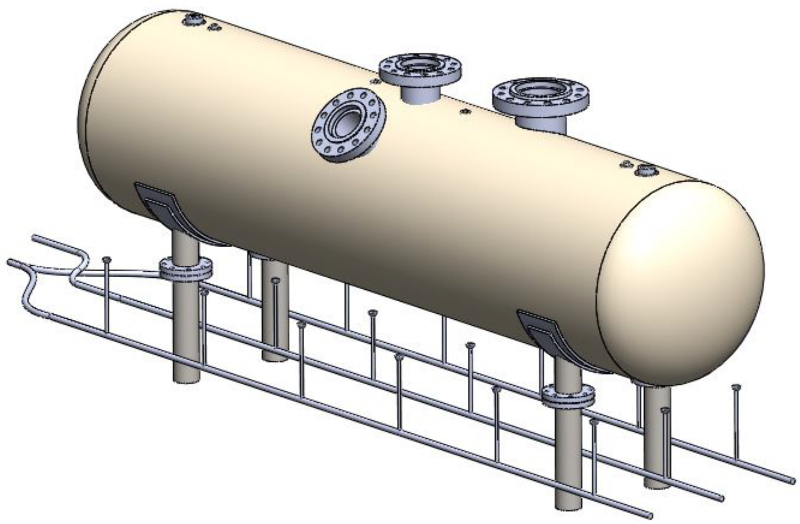


Figure 14. Burner arrangement for heptane fire to engulf the tank

This set-up allowed for better control and targeting of the fire by varying the flow in each line and allowing specific nozzles to be capped off to reduce fire at specific areas of the vessel, depending on the test. This burner system produced a much cleaner burning fire that did not tax the smoke abatement system, while also providing sufficient heat to the test vessel. This arrangement also made it possible to observe the tank and PRD better during the fire. Figure 15 is a depiction of the vessel engulfed in flames from this burner system.

Figure 15. Vessel engulfed in fire-water tests

4.2 Tests with Ethanol as Lading

Fire testing of PRDs with flammable lading was performed at BAM, a facility well equipped for outdoor fire testing, monitoring, and data collection. The remote test site, which is normally used for blast tests, is located outside the village of Horstwalde, about 60 km from Berlin, Germany. The instrumented test vessel, support saddle, and the specimen PRDs were shipped to the test facility.

An extensive fire safety plan was prepared and executed by BAM to evaluate the possible hazards and develop appropriate mitigating strategies. Since the BAM test site is located in the middle of a pine forest with nearby villages, a primary concern was the environmental consequences of releasing large amounts of toxic material to the surroundings. For this reason, using crude oil as the lading was ruled out and ethanol was chosen as the flammable lading. To capture and contain any unburned ethanol, a protection zone was created around the tank and in the direction where the PRD would release. A basin 1 foot deep was excavated, lined with an impermeable layer of plastic film, and covered with sand. In this basin, liquid ethanol was safely collected and either evaporated or burned off in a controlled manner. Pilot flares were used to ensure ignition and controlled burning.

The top of the tank was covered with 0.5-inch thick high-temperature ceramic fiber insulation, similar to the configuration used for the water lading tests, to protect the unwetted portion of the tank shell from excessive temperatures. However, unlike in the water test, the insulation for the ethanol test was covered with a 1/8-inch thick steel jacket-like shield. This was to prevent ethanol that may be released through the PRD from collecting and soaking into the insulation, continuing to burn, and thus provide an additional source of heat on the top of the test vessel. The test vessel, installed at the test site in preparation for the first test, with the low capacity PRD installed in the upright orientation on the top center of the tank, is shown in Figure 16.

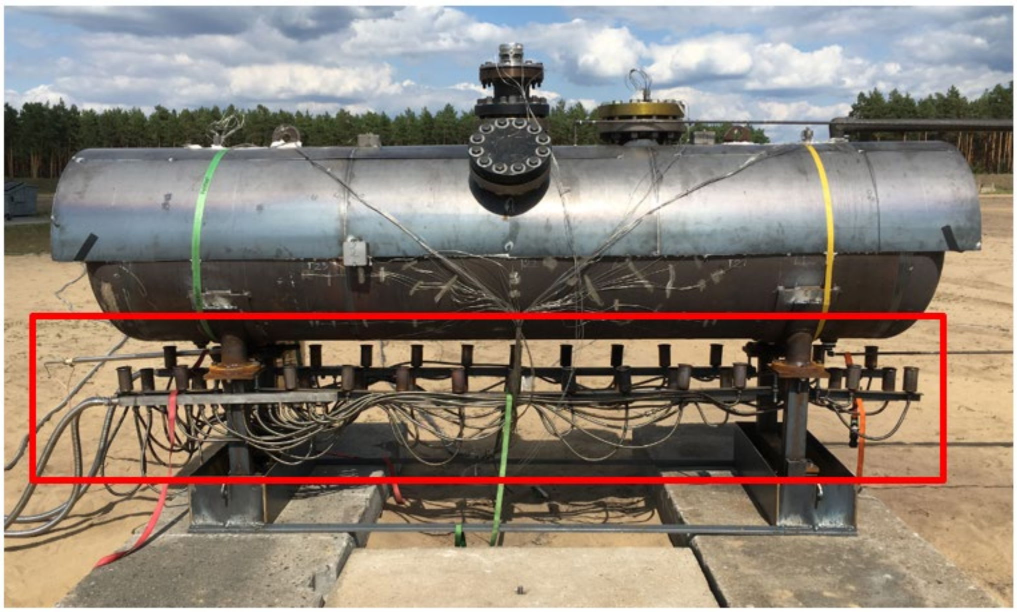


Figure 16. PRD fire test vessel with shield and burner system

A propane burner system consisting of a propane gas storage tank, supply lines, evaporator, nozzles, ignition device and pilot lights provided the fire input to the test vessel. The burner configuration can be seen arrayed below the vessel (see red rectangle in Figure 16). There are three rows of burners with propane fed to each burner through metallic hoses. Load cells under the support legs were used to measure the total vessel load and thereby determine the mass of lading loss with each PRD release. The load cells were submerged in a water bath to keep them cooled and the support legs and water bath tubs were covered in insulation (Figure 17).

Figure 17. Support legs and water bath with insulation

The vessel nozzles were also covered with insulation, up to the mounting flange of the PRD under test. The nozzle at 45 degree orientation relative to the vertical, with large capacity PRD mounted and ready for test #2, is shown in Figure 18. The insulation around the top nozzle in Figure 18 protects an additional PRD, set to release at 165 psi, that was used as a redundant safety measure during tests #2 (45 degree orientation) and #3 (120 degree orientation). Additional measures to assure safety include a pressure relief valve (100 psi setpoint) and a remotely operated dump valve, with failsafe control, mounted outside the flame area at the end of a 2-inch diameter emergency discharge pipe that extended 20 feet beyond the end of the vessel. This piping was also covered with fire protection insulation.

The small boxes containing DFT for measuring flame temperature can be seen mounted on the vessel in Figure 18.

Figure 18. Nozzles with insulation and large capacity PRD at 45 degree orientation

The tank with all connected pipelines was subjected to a leak test with nitrogen at 60 psi. Video cameras mounted on tripods, and some directly on the ground, were arrayed around the test vessel. A fortified bunker with viewing platforms located about 200 m from the test specimen provided the base for operation and control of the test, as well as test observation.

Between tests #2 and #3, the entire vessel and connected piping was rotated 180 degrees. Since the nozzle at 120 degree orientation relative to the vertical was on the opposite side of the tank from that shown in Figure 18, it was necessary to rotate the tank so that the discharged ethanol would collect in the basin that had been prepared with the impermeable lining.

5. Safety Plan

There are multiple potential hazards associated with fire testing, and the research team always incorporated various preventative and mitigation strategies to address these hazards. An appropriate risk analysis was prepared in each case, in collaboration with the test facility, and the resulting risk mitigation methods implemented. The potential for the mitigation strategies to fail were also considered, and appropriate backup methods were implemented. Critical hazardous events that were considered, included:

- Rupture in the test vessel due to localized loss of strength
- Rupture from pressure build up due to insufficient release by PRDs
- Uncontrolled fire fed by lading exhausting from PRD

The above-mentioned hazards were addressed by the following mitigation measures:

- Introducing a high factor of safety in the design of the test vessel.
- Adding additional venting devices to the test vessel
- Having the appropriate emergency response team ready, with the needed fire suppressant material on hand

In addition, in the case of the ethanol tests, given the potential for additional fires/damage or human injury, multiple safety perimeters were maintained to prevent the potential for damage/injury.

5.1 Vessel Design

The research team designed and fabricated the test vessel according to Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code. As described in the test vessel design section, the unit was designed with a Maximum Allowable Working Pressure of 678 psi, at temperatures up to 500 °F.

Given that the PRDs were designed to release pressure and vent at an internal pressure of 75 psi, this provided a significant margin of safety, even considering the elevated test temperatures. The allowable working pressure with a (mean) metal temperature of 800 °F is 400 psi. The internal pressure is not expected to rise much above 75 psi, the PRD setting. In addition, the vessel will be protected with a 2-inch safety relief valve, mounted outside the fire, which is set to 100 psi. So, even under the extreme conditions of 800 °F exterior shell temperature and 100 psi internal pressure, the factor of safety for the vessel is at least four. Note that this is in relation to the ASME allowable pressure, which already includes a safety factor.

5.2 Venting

The capacity of the relief valve was determined according to the AAR Standard M-1002, Appendix A (tank car engulfed in fire). An un-insulated tank is assumed, which is conservative since the test tank will be insulated on its upper half thereby significantly reducing the heat input. The basis of this calculation is that the safety relief valve be able to exhaust the vapor created by the heat from a pool fire without the internal pressure exceeding 110 percent of the relief valve set point. A heat flux value of 34,500 BTU/h ft2 (109 kW/m2) is specified by the AAR standard based on experimental data from free-burning hydrocarbon fires. Relevant ethanol properties assumed for this calculation include a molecular weight of 46.1, heat of vaporization equal to 300 BTU/lbm (698 kJ/kg), and vapor temperature at flowing conditions of 135 °C. The latter two properties were evaluated at the saturation temperature and pressure when the PRD opens. Using this procedure, it was determined that a 2-inch safety relief valve set at 100 psi has a sufficient capacity (i.e., with a safety factor of two) to exhaust the vapor generated from the ethanol lading in the test vessel under conditions equivalent to a pool fire. A similar procedure was used to size the safety relief valve for the water lading tests, using relevant water properties instead of those for ethanol. It was determined that a 1.5-inch safety relief valve set at 100 psi is sufficient to exhaust the steam generated from water lading in the test vessel under conditions equivalent to a pool fire.

As an additional safety measure, a 2 inch electrically operated solenoid valve was be installed on the vessel, connected by piping so it is located outside the fire and exhausting away from the fire. This allowed test personnel to remotely exhaust the pressure in the vessel whenever they feel it is prudent to do so, based on continuously monitored vessel pressure and shell temperatures. The valve is configured as normally open, so it is failsafe in that a loss of power will cause the vessel pressure to be exhausted.

The PRDs being tested are designed for a full-size rail car tank, whereas the test vessel is a one-third (approximately) scale model of a full-size tank. Hence, the PRDs used in these tests have a much larger capacity than is required to protect the test vessel. Note that the volume of the test vessel is approximately 1/27th that of a full-size tank. So, it is expected that when lading is exhausted from an open PRD the tank pressure will quickly reduce allowing the PRD to reclose. This will limit the amount of ethanol released that could contribute fuel to the fire. In addition, the PRD will forcefully eject the ethanol away from the test vessel such that a significant portion of the burning ethanol will not impinge on the test vessel.

5.3 Other Safety Measures

In addition to the safety redundancies built into the tank design, and the venting protocols, the following safety measures were implemented for both the water and ethanol tests:

- The fuel for the fire test was stored far from the vicinity of the fire
- A suitable method to shutoff the fuel to the fire was implemented
- An emergency response team, with the appropriate fire suppression material and gear was on standby at the test site.

For the ethanol test, multiple safety perimeters, with appropriately limited access were implemented (see Figure 19).

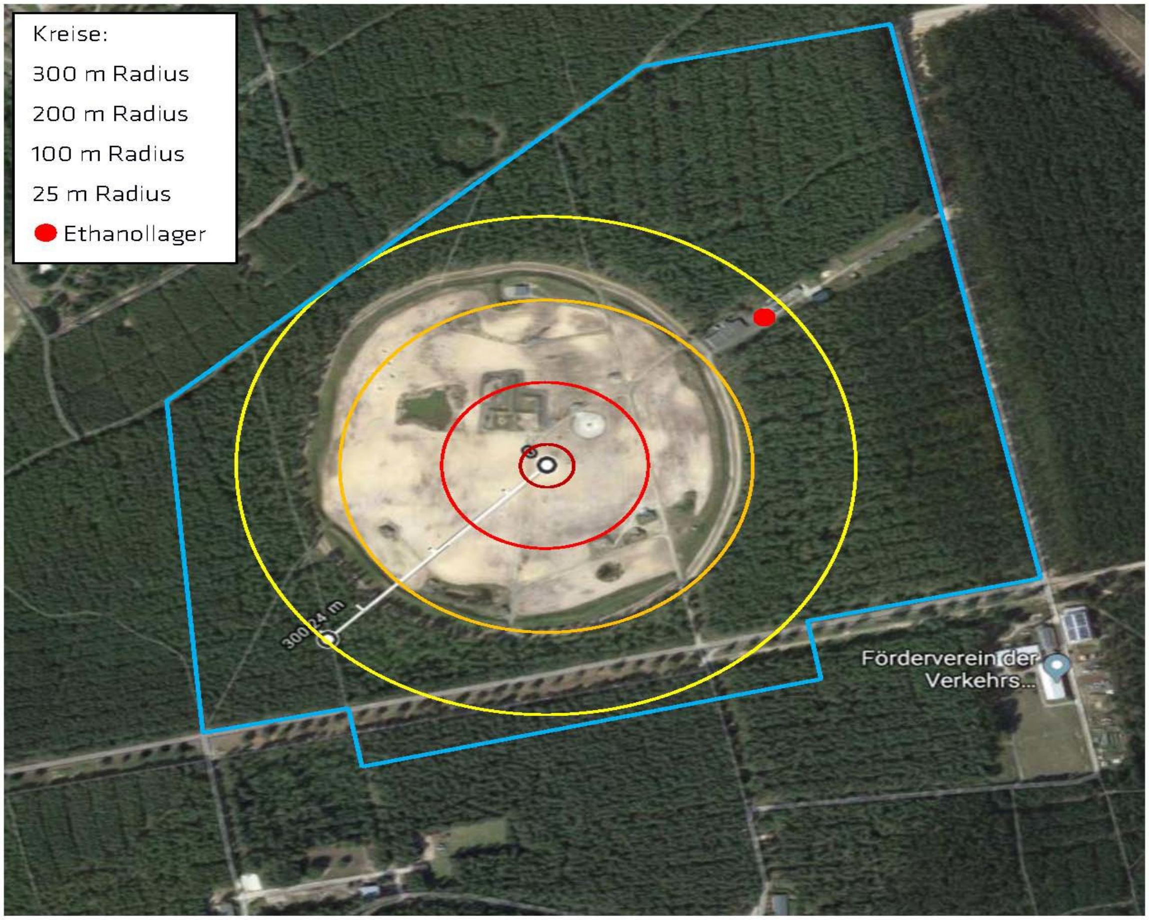


Figure 19. Safety perimeters around fire test site

6. Results and Discussion

All the tests resulted in notable PRD activity and lading release, followed by reclosure. This section outlines the results from the tests describing overall observations, as well as a discussion of data measured during the test, and consequent implications.

6.1 Test Series 1 (Water Lading)

The research team carried out three tests, with the PRD at angles of zero (upright), 45, and 120 degrees from the vertical, respectively. In each case, the fire burned for about 2 hours, heating the water and pressurizing the vessel, before the PRD activated. Upon opening, the PRD typically expelled a mixture of steam and water, reducing the pressure and reclosing. The fire continued to burn and thereby, build pressure in the tank, and the PRD release cycle was repeated. Testing continued until two or three substantial release events occurred or until it was determined that the loss of lading was enough that the un-insulated portion of the tank shell would be in danger of losing the cooling effect from the water lading. Three cycles of PRD release and reclosure occurred for the first two tests, while only two cycles of release and reclosure occurred for the third test. In general, the PRDs survived the fire and functioned normally when subjected to moderately high temperatures for 30 to 45 minutes. Set pressures and blowdown pressures were close to nominally expected values, providing confidence that the PRDs performed as expected.

In this section, the research team has discussed the results from test #2 (i.e., high capacity PRD at 45 degrees), as these are typical of the observations from the three tests. This position of the PRD is expected to result in observation of mixed flow (i.e., vapor and liquid) through the PRD. As can be seen from the pressure plot (Figure 20), it takes some time to build pressure in the tank, reflecting the fact that the top of the tank was insulated, limiting the amount of heat entering the system, as well as the more controlled heat rate from the burner system that is appropriate for an indoor test. As the water temperature increases, the pressure rapidly builds up as steam accumulates in the vapor space. The PRD opens and vents lading (i.e., liquid and vapor) at around 75 psig as designed. The test was terminated after the third opening and release of the PRD.

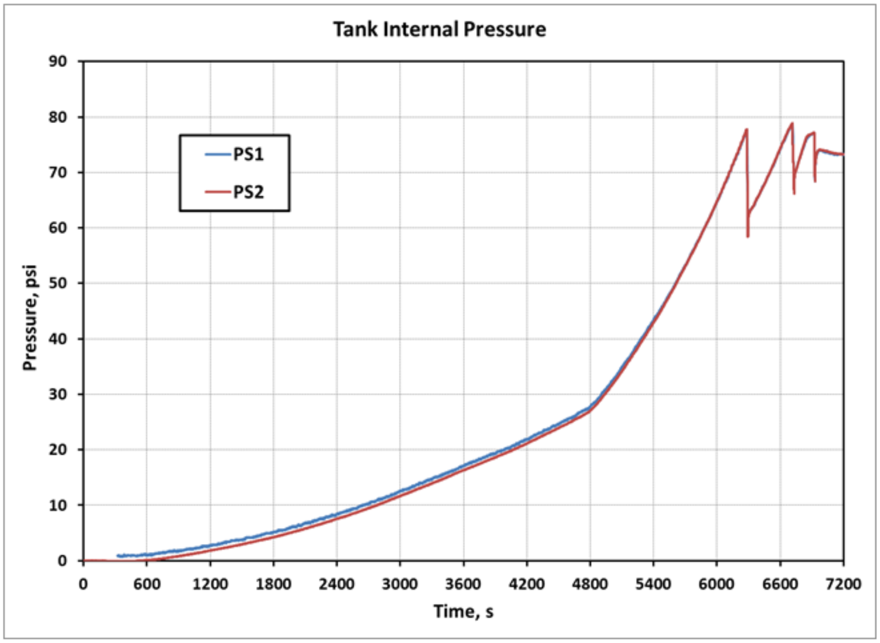


Figure 20 Pressurization of vessel during fire exposure, test #2

Figure 21 and Figure 22 show detailed views of the PRD releases for each of the three tests. Note that these tests were performed sequentially; the common time scale in the figures does not imply simultaneity. A time interval of 1,200 seconds spanning the PRD release activity was selected from each of the three tests for display in these figures. Figure 21 shows the opening and reclosing pressures for each release. The initial drop in pressure for test #1 reflects the minor release of lading that was observed at the PRD, prior to a more substantive release. Figure 20 shows the total tank weight. The difference in tank weight before and after a PRD release indicates the amount of lading expelled during that event.

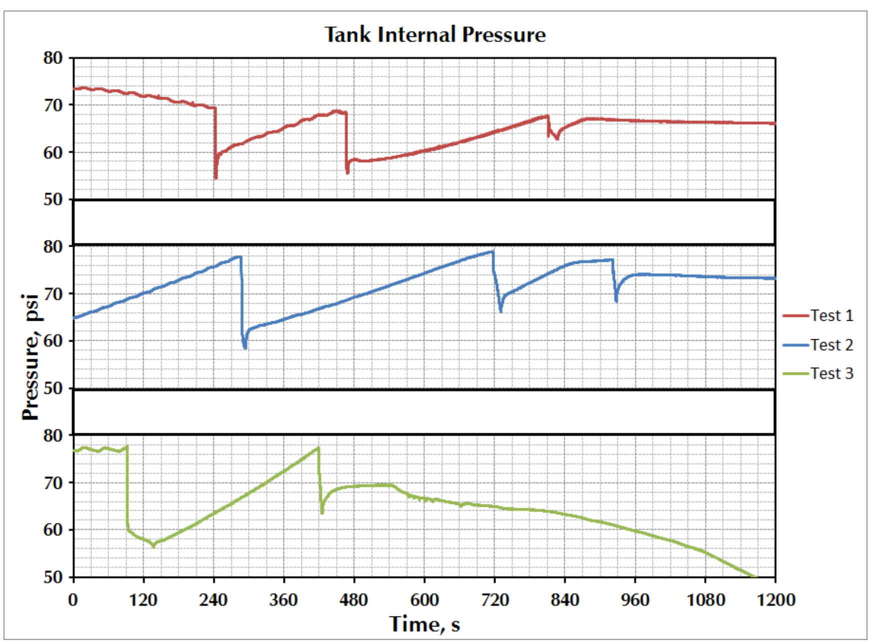


Figure 21. Vessel pressure during release events for each of the three tests

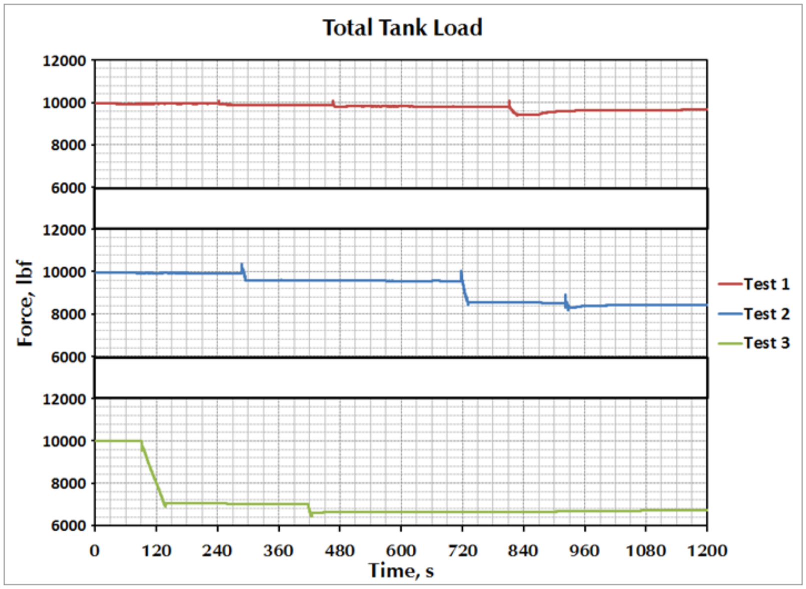


Figure 22. Total weight of vessel and lading during release events for each of the three tests

Focusing again on test #2, selected parameters are shown together (Figure 21) to illustrate the correlation between vessel pressure, lading temperature, and the loss of lading during PRD release events. The upper plot of Figure 23 shows the weight of the tank with its lading (blue) along with the height of the lading in the tank as measured by the differential pressure transducer (red). These two independent measures of lading expelled during each PRD opening are well correlated. The lower plot of Figure 23 shows the pressure inside the tank along with the temperature readings of two internal thermocouples in the vapor space. It can be seen that the vapor temperature drops during a release event as the pressure is falling, and then rises again as the pressure increases after the PRD has reclosed.

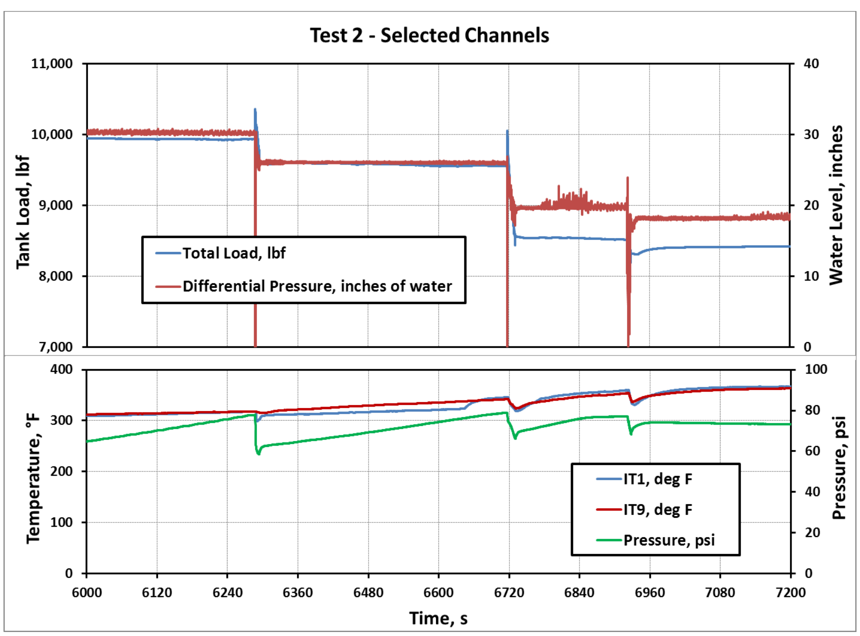


Figure 23. Comparison of selected parameters for test #2 during release events

Figure 24 shows the flame temperatures recorded by the four DFTs during test #2 release events. Temperatures above 1,400 °F were measured, which is typical for this type of hydrocarbon fire. As can be seen, DFTs 2 and 4, which are on the sides of the tank, see much higher temperatures than DFTs 1 and 3, which are on the top of the tank, and thus comparatively shielded from the flames. Some mild flame temperature reduction occurred as the cooler lading was released into the fire environment. The fire was extinguished shortly after the third release at about 6,960 seconds and the DFT temperatures began to decay at that time.

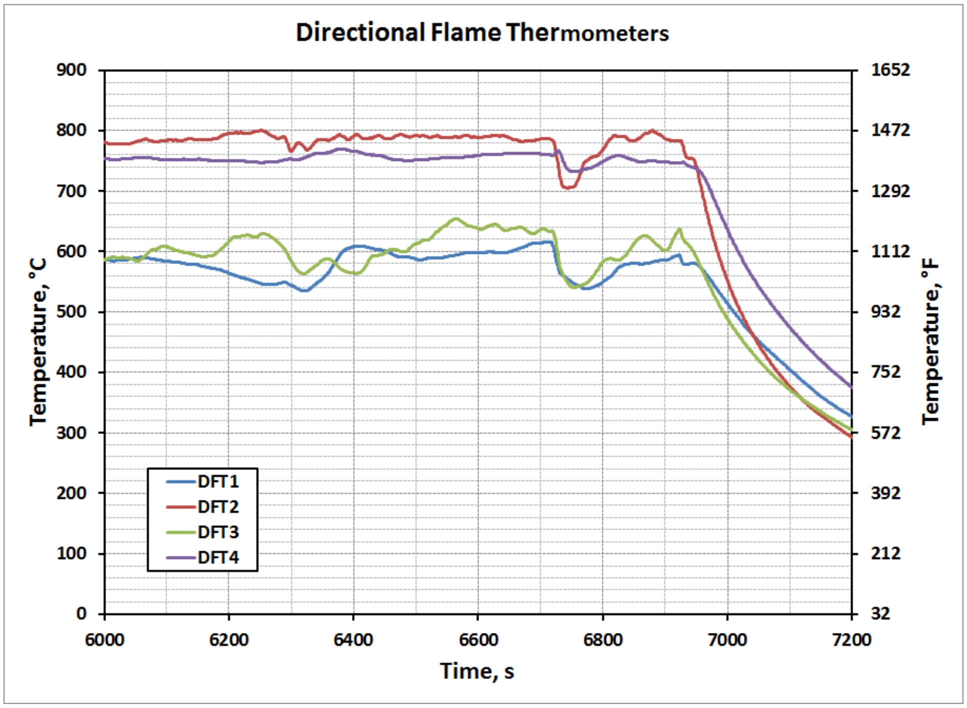


Figure 24. Fire Temperature, test #2 during release events

External vessel shell temperatures ranged from 300 °F under the insulation, to about 750 °F at the bottom of the tank which was directly exposed to the flame (Figure 25).

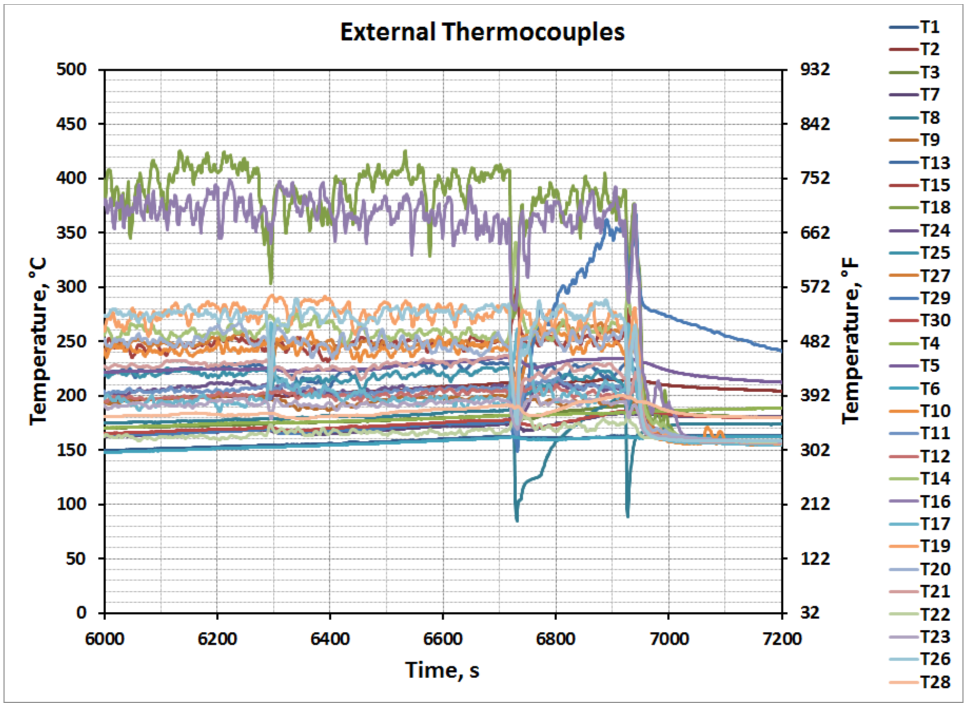


Figure 25. External vessel shell temperatures, test #2 during release events

During the initial heating and pressurization portion of each test (90 to 120 minutes), the PRD was insulated to protect the integrity of the seal—an elastomer with a temperature rating of about 300 °F. While the seal would not be protected in an actual fire, the primary purpose of these tests was to observe other aspects of the PRD behavior, such as start-to-discharge pressure, that required a functioning seal. When the internal pressure reached about 60 psig and well before the initial release, the PRD insulation was removed, exposing it to the fire. Figure 26 shows the temperatures recorded by the four thermocouples attached to the PRD during the release events of test #2. The temperature drops correspond to the release events.

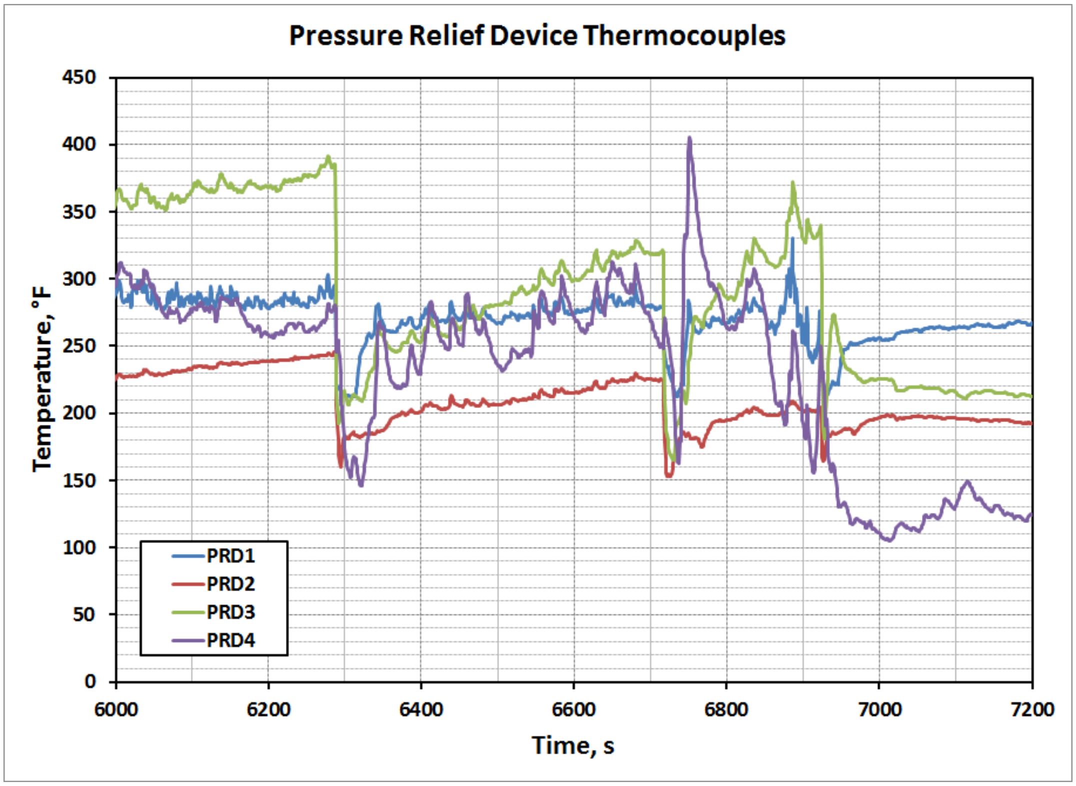


Figure 26. Temperature at various points on PRD, test #2

Figure 27 shows the temperatures recorded by the thermocouples of the two internal trees during the release events of test #2. The two highest curves (green and blue) are thermocouples measuring the vapor temperature at the top of the tank, while the lower band of many thermocouples are measuring the liquid temperature at various heights in the tank. The vapor (i.e., steam and some residual air) is about 10 °F hotter than the liquid as the tank heats up and begins to pressurize. The PRD releases are marked by a sudden drop in lading temperatures, both liquid and vapor, due to the energy extracted to vaporize and expel lading. The vapor temperatures recover more quickly than the liquid temperatures after each release event. As the water level drops, due to expelled lading, some additional thermocouples (i.e., red and purple curves) that were in the liquid become exposed to the vapor and their temperatures rise noticeably. Data from the float thermocouples (Figure 26) echoes this behavior.

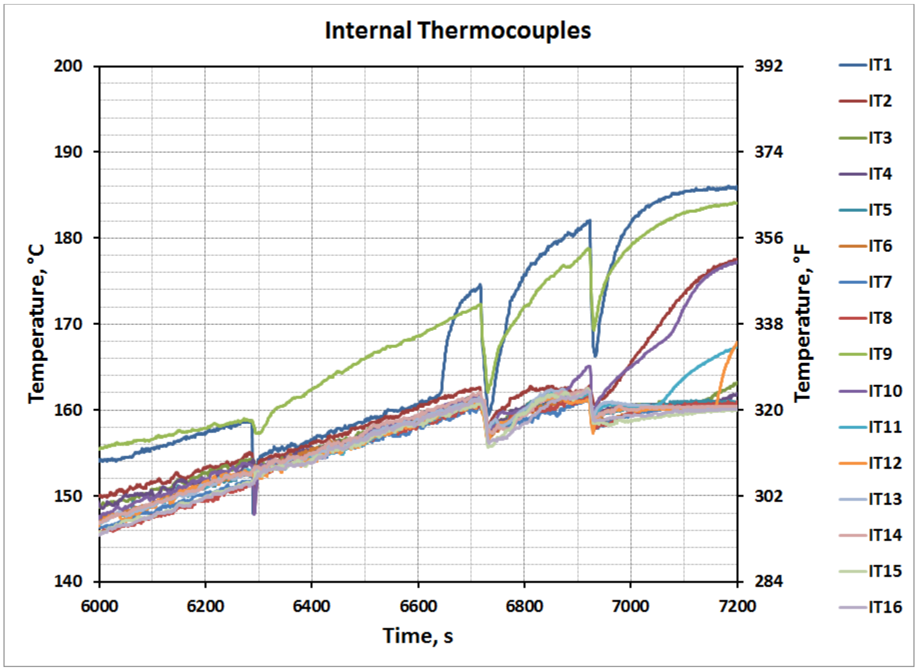


Figure 27. Lading temperatures, test #2

Figure 28 shows the temperatures recorded by the thermocouples attached to the float, measuring the lading temperature close to the liquid/vapor boundary. The temperature at the surface of the water (F3) is about 5 °F warmer than the temperature at a depth of 2 inches. The temperature at 1.75 inches below the surface (F4) is essentially the same as at 3.25 inches (F2). Temperature stratification, in this situation, is not significant and the warmer boundary layer appears to be less than 2 inches thick.

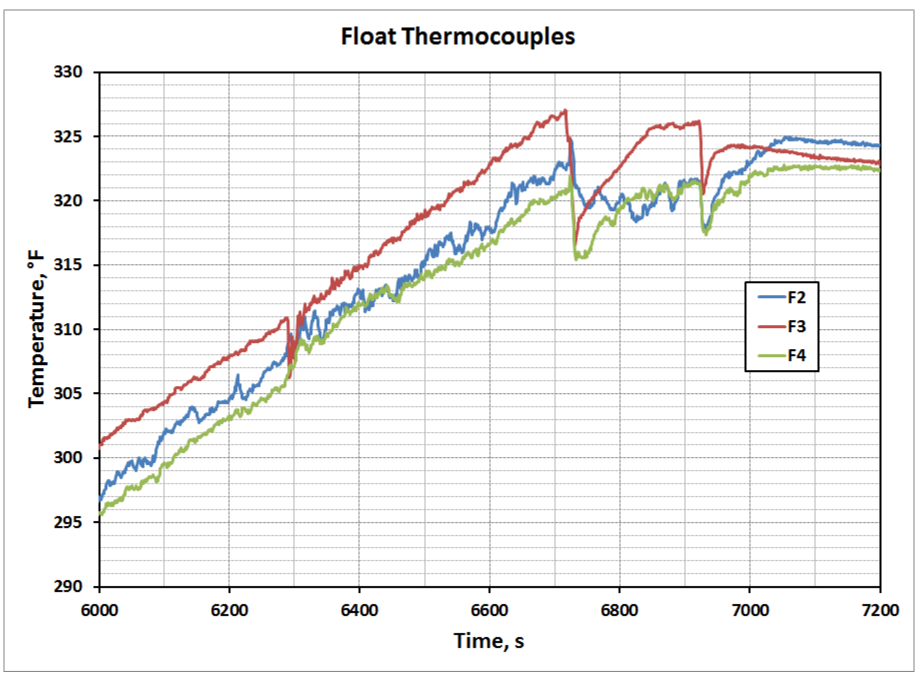


Figure 28. Lading surface (float) temperatures, test #2

A lack of significant temperature stratification in the bulk liquid lading is also indicated by the close grouping of liquid temperatures as measured by the internal thermocouple trees (Figure 27). These bulk liquid temperatures rose steadily with the vessel pressurization and were typically about 10 to 15 °F below the current saturation temperature as the vessel pressure increased. These observations tend to imply that, under these test conditions, the liquid was fairly well mixed and the pressurization was not driven by a significantly hotter layer near the lading surface. In contrast, results from total containment fire testing indicate that temperature stratification and boundary layer boiling was the primary cause of vessel pressurization (Birk, A. M., 2000). While vessel and fire designs were similar between these two sets of tests, the top of the vessel was bare in the total containment tests whereas it was insulated in these tests, thus reducing heat transfer to the unwetted portion of the vessel wall. A cooler vessel wall above the liquid results in less radiative heat transfer to the lading surface.

As noted previously, the bulk liquid temperatures rose steadily with the vessel pressurization and were typically about 10 to 15 °F below the saturation temperature corresponding to the current vessel pressure. This difference is due to the presence of air trapped in the outage volume after filling and closing the tank. The measured tank pressure is the combined partial pressures of this air and water vapor. The partial pressure of the water vapor is determined by the saturation pressure of water corresponding to the temperature of the bulk liquid water. Figure 29 through Figure 31 illustrate these partial pressure components of the total vessel pressure for each of the three tests. Total pressure was plotted from the pressure transducer data; water vapor partial pressure is the saturation pressure corresponding to temperature data from a thermocouple in the liquid water; and the air partial pressure is the difference between these two. In each test it is clear that the saturated water vapor partial pressure remains below the total pressure until the PRD first opens. Each time the PRD cycles open, air is vented. After several cycles, the air is essentially gone and the vapor in the tank consists only of water vapor. From this point on, the water vapor pressure and the total pressure curves coincide.

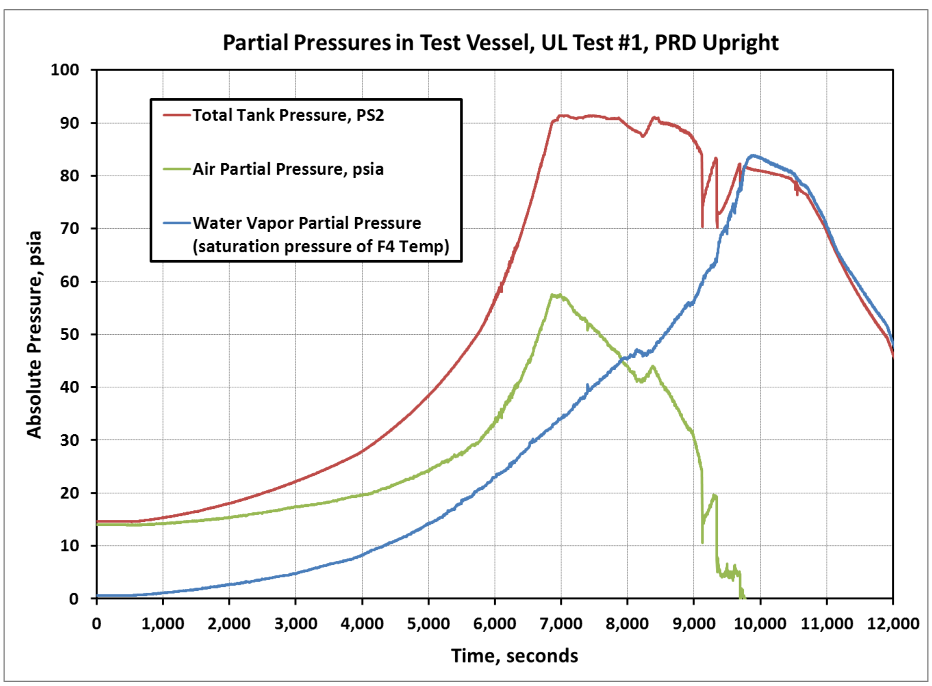


Figure 29. Partial pressures in test vessel, UL test #1

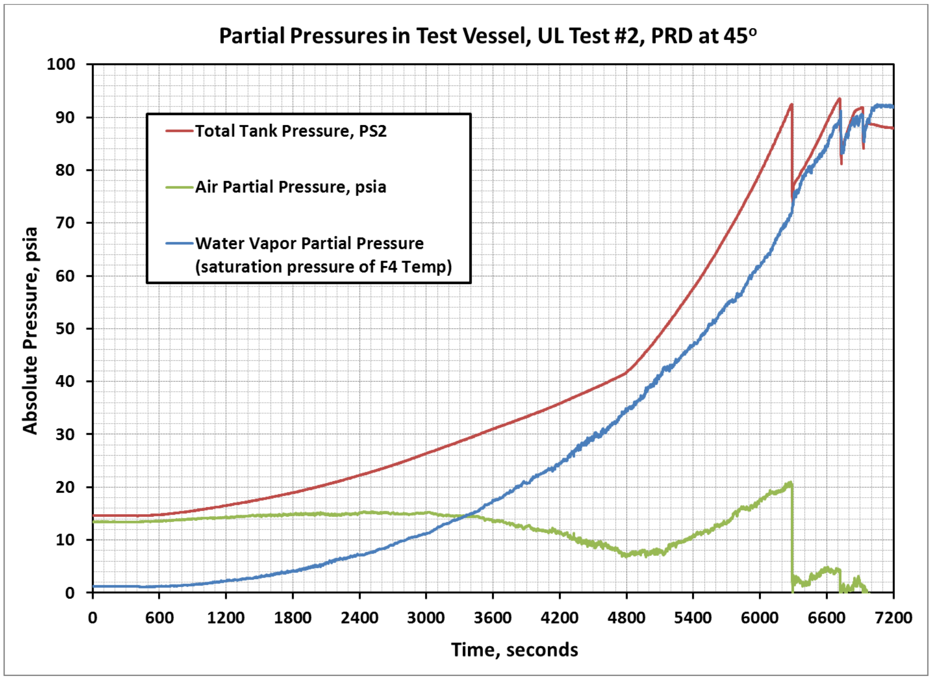


Figure 30. Partial pressures in test vessel, UL test #2

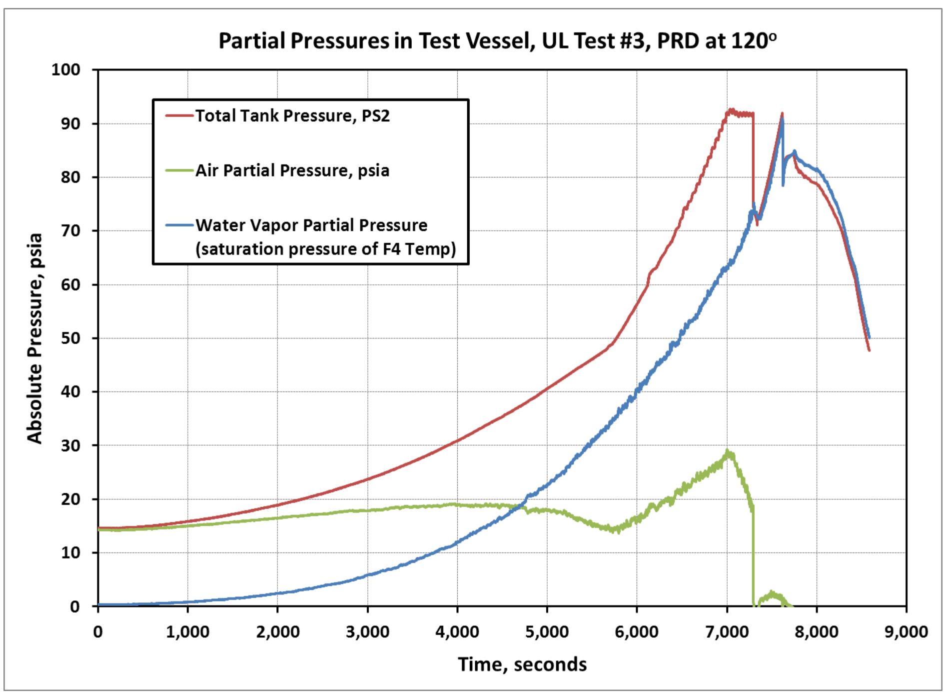


Figure 31. Partial pressures in test vessel, UL test #3

In summary, the PRDs behaved as expected in the water tests. The PRDs survived the fire and functioned normally when subjected to moderately high temperatures for 30 to 45 minutes. Start-to-discharge pressures and blow down pressures were close to nominally expected values. The float with attached thermocouples, along with the internal thermocouple trees, provided verification of the existence of temperature stratification in the liquid lading and an estimation of its extent, which appeared to be fairly thin and without significantly higher temperature than the rest of the liquid lading. Table 2 provides an overview of the test data from this series of tests.

Table 2. Summary of releases – water tests

	Test # 1			Test #2			Test #3	
Parameter	Release #1	Release #2	Release #3	Release #1	Release #2	Release #3	Release #1	Release #2
Mass Released (kg)	10.4	37.2	168.7	156.5	455.0	78.5	1348.1	179.2
Release pressure (psi)	69.3	68.3	67.4	77.0	78.5	77.1	77.2	76.6
Closing Pressure (psi)	59.6	58.2	65.0	62.5	69.5	70.2	57.3	67.0

6.2 Test Series 2 (Ethanol Lading)

The research team carried out three tests, with the PRD at angles of zero (upright), 45, and 120 degrees from the vertical, in that order. Figure 32 shows an overview of the events of test #1 (i.e., PRD upright).

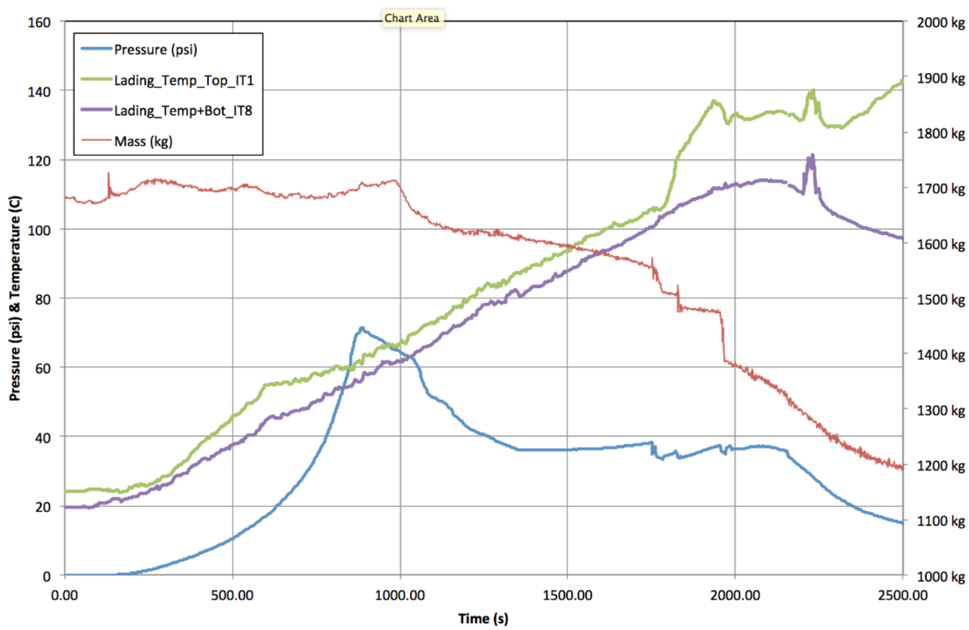


Figure 32. Overview of ethanol test #1

As shown in Figure 32, the pressure in the tank built up to near nominal start-to-discharge pressure (75 psi). Given that these tests were conducted with ethanol lading, which is a more volatile substance than water, the temperature rise, and the resulting pressure buildup were much quicker.[1] The PRD then started releasing/leaking lading slowly with a corresponding loss of pressure. The pressure stabilized at about 35 psi and multiple releases were seen at this pressure.[2] These release events are associated with a corresponding drop in pressure, which then rebuilds as fire input continues. Notable changes in mass were seen during the more energetic releases (see the red line).

The temperature curves above show the liquid temperature (IT8) and the vapor temperature (IT1). It is observed that these temperatures are relatively close to each other, until the PRD starts discharging, after which a more significant difference—with the vapor temperature being higher—is noted.

The events with notable PRD activity also result in small fireballs (see Figure 33), as the releasing ethanol catches fire.

Figure 33. PRD release event – ethanol test #1

Similar results were also seen for the other tests, but the pressures at which the PRDs stabilized were a little different, as seen from the charts and images presented below. In the case of test #2,

[1] Ethanol is much more volatile than water, has a lower specific heat, and is less dense, all of which contribute to a more rapid pressurization with ethanol than with water.

[2] A key distinction between this behavior and the behavior from the water tests is that, in the case of the water tests, subsequent releases all occurred at/near the initial set point of 75 psi, rather than the reduced value of 35 psi, seen here. This may be the result of the PRD springs weakening as a result of exposure to the lading that burns as it is released.

there were several distinct releases as evidenced by distinct changes in mass (red curve) and pressure (blue curve), see Figure 34. The temperature profiles were similar to the other tests.

In the case of test #3, there were some small initial releases, followed by a significant release that emptied most of the tank (see Figure 36). This large event was followed by several smaller cycles that happened in rapid succession, which could almost be characterized as one long event. The fireballs resulting from the large release and the extended smaller releases were significant and dramatic, leading to questions about the best approach to such events from an emergency responder perspective. The images show an initial liquid ethanol release, which quickly ignites with exposure to atmospheric oxygen and an open fire.

In general, the PRDs survived the fire and functioned normally when subjected to moderately high temperatures from the fire for 40 to 60 minutes. Initial releases were between 14 to 20 minutes when PRD opened slightly, multiple releases occurred between 30 to 38 minutes.

While the release pressures for these tests was lower than the set pressure (75 psi) and lower than seen for the water tests, such behavior is still considered safe, especially considering that the tanks may have been weakened due to fire exposure.

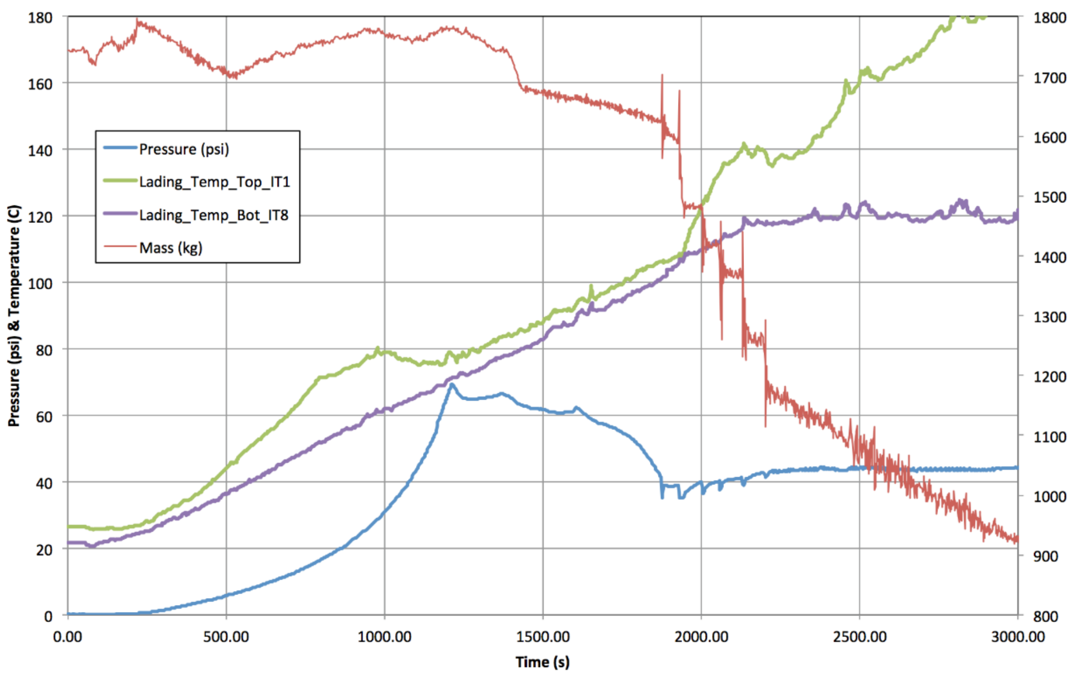


Figure 34. Overview of ethanol test #2

Figure 35. Liquid release followed by ignition – ethanol test #2

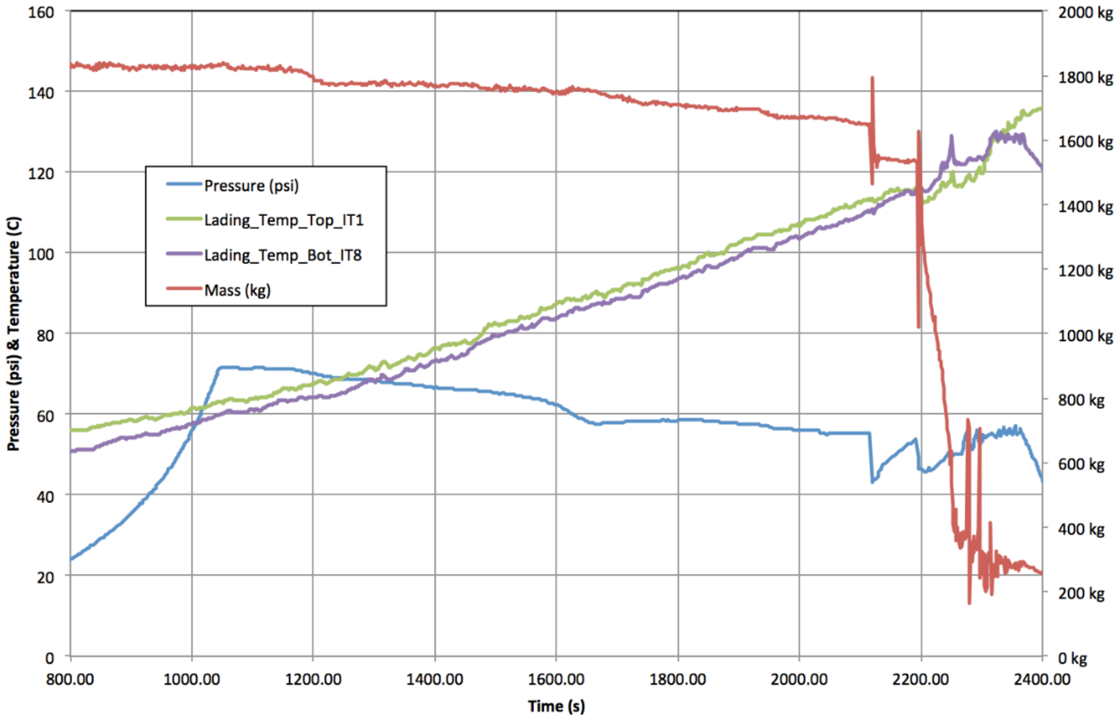


Figure 36. Overview of ethanol test #3

Figure 37. Liquid release followed by ignition – ethanol test #3

An overview of the data from the ethanol tests, covering the pressures, is further presented in Figure 38. As seen here, for test #1, which was defined gaseous release, only about 21 percent of the lading was evacuated. For test #2, which had mixed flow, nearly half the tank was evacuated. And for test #3, which was largely releasing liquid, more than 85 percent of the lading was evacuated. It can also be that the significant/extended release in test #3, was responsible for the most significant amount of lading lost.

Initial Mass (kg): 1800

Test 1	Parameter	Release 0 (slow)	Release 1	Release 2	Release 3	Release 4	Release 5+
	Mass Released (Kg)	142	13	36	35	89	67
	Release Pressure (psi)	71.4	38.2	37.2	36.0	37.2	35.8
	Closure Pressure (psi)	-	34.8	33.8	33.8	36.3	-

Remaining Mass (kg)	% Mass Remaining	Fire shutoff (minutes)
1418	79%	35

Test 2	Parameter	Release 0 (slow)	Release 1	Release 2	Release 3	Release 4	Release 5	Release 6+
	Mass Released (Kg)	155	31	114	60	48	101	329
	Release Pressure (psi)	69.4	42.6	38.8	40.2	40.1	41.1	42.7
	Closure Pressure (psi)	-	35.3	35.1	36.6	37.4	39.4	41.7

Remaining Mass (kg)	% Mass Remaining	Fire shutoff (minutes)
962	53%	47

Test 3	Parameter	Release 0 (slow)	Release 1	Release 2	Release 3 Extended	Release 4	Release 5+
	Mass Released (Kg)	183	112	190	965	40	59
	Release Pressure (psi)	71.7	55.2	53.9	-	55.3	55.6
	Closure Pressure (psi)	-	43.7	45.8	-	52.0	52.6

Remaining Mass (kg)	% Mass Remaining	Fire shutoff (minutes)
251	14%	38

Figure 38. Summary of results – ethanol tests

Results and evaluations from all three tests are further discussed below. As can be seen from Figure 39, it took 700–1,200 seconds to build pressure in the tank sufficient to open the PRD. This was much faster than for the water tests. The ethanol series was conducted outdoors using propane fuel and a burner system that allowed the flame temperature surrounding the tank to reach a consistent 1,300 °F (similar to the water tests with heptane fuel). Ethanol, however, is much more volatile than water, has a lower specific heat, and is less dense, all of which contribute to a more rapid heating, evaporation and vessel pressurization with ethanol lading as compared to water. The PRD opened and vented lading (e.g., liquid and vapor) at around 70 psig, as designed.

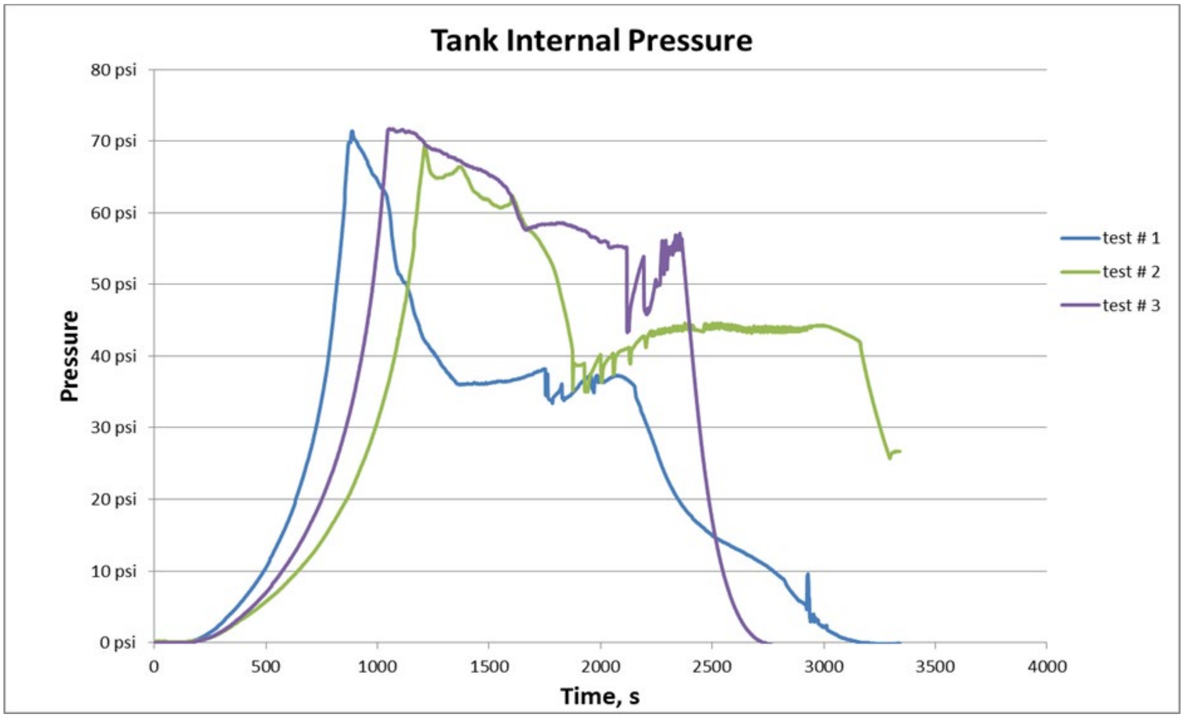


Figure 39. Pressurization of vessel during fire exposure – ethanol tests

A distinct correlation between the pressure changes and the mass reductions can be observed from Figure 40.

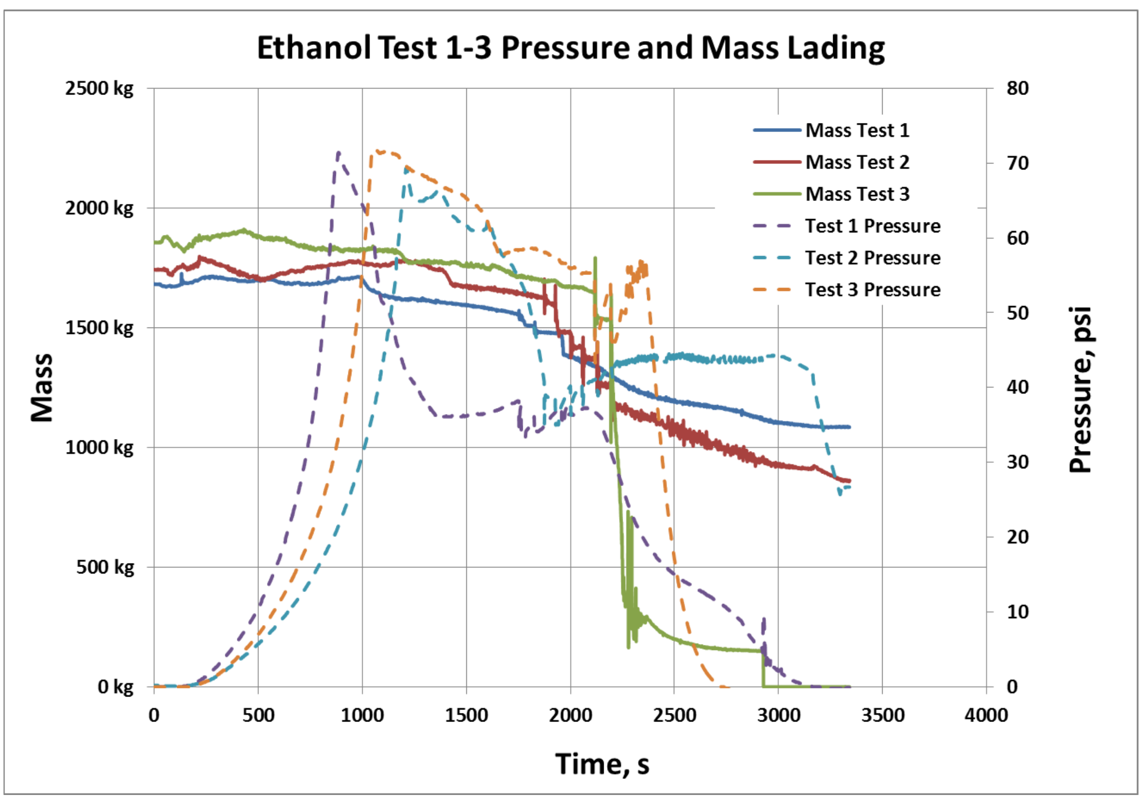


Figure 40. Measured mass and pressure during PRD release – ethanol tests #1–3

Figure 41 shows the temperatures recorded by the thermocouples of the two internal trees during the release events of test #3. The two highest curves (green and blue) are thermocouples measuring the vapor temperature at the top of the tank, while the lower band of many thermocouples are measuring the liquid temperature at various heights in the tank. As seen with the water tests, the vapor space is a few degrees warmer than the liquid as the tank heats up and begins to pressurize. The PRD releases are marked by significant fluctuations in the vapor temperature, due to the energy extracted to vaporize and expel lading. As the lading level drops, additional thermocouples that were in the liquid become exposed to the vapor and their temperatures rise noticeably.

Data from the float thermocouples, presented in Figure 42, highlight similar information, with the vapor space heating up further as the liquid level drops. Also evident from the fixed and float thermocouple data is the fact that temperature stratification is minimal—as also observed in the water tests. It is unclear whether this is the result of the insulation on the top half of the tank, or, if this is the result of the mixing (churn) that is caused by PRD activity.

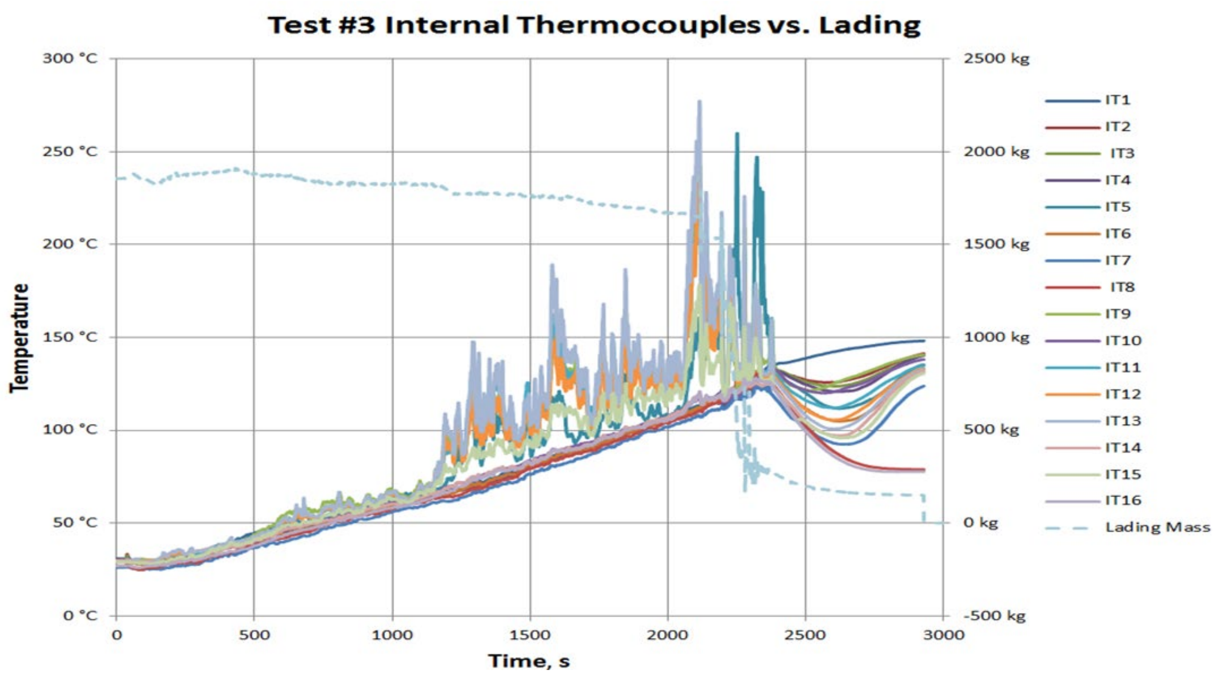


Figure 41. Lading temperatures, ethanol test #3

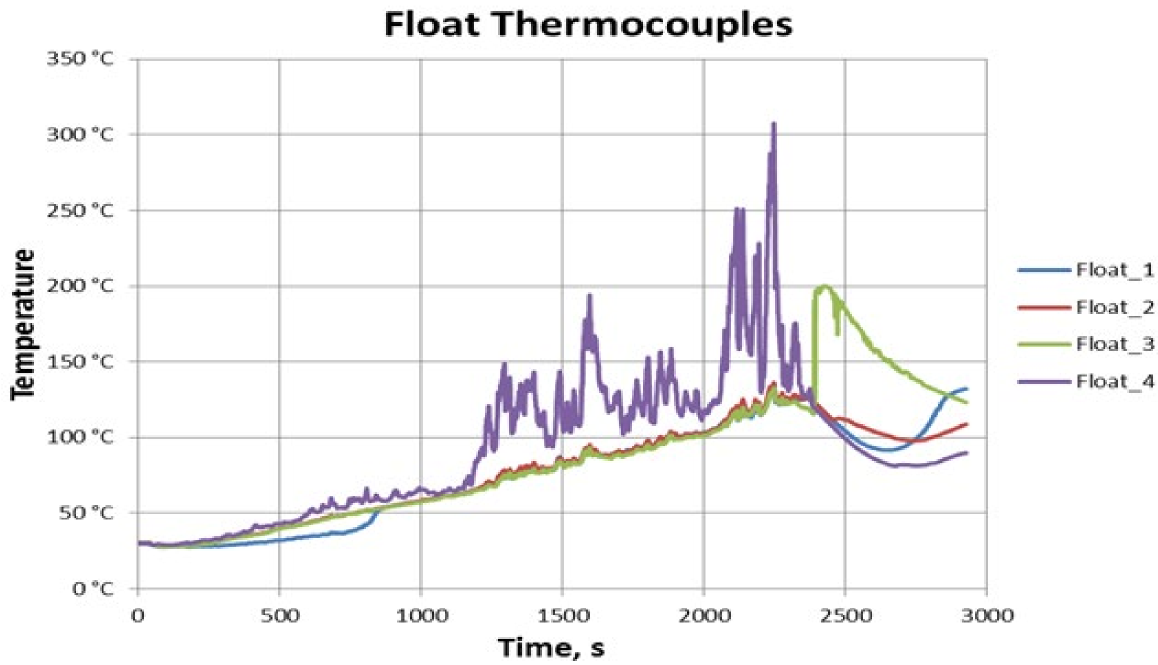


Figure 42. Lading surface (float) temperatures, ethanol test #3

6.3 Thermal Expansion of Ethanol

The thermal expansion characteristics of ethanol (Figure 43) and the high initial fill levels in the tank, lead to the expectation that the tank would go shell full due to the expanding ethanol as it was heated.

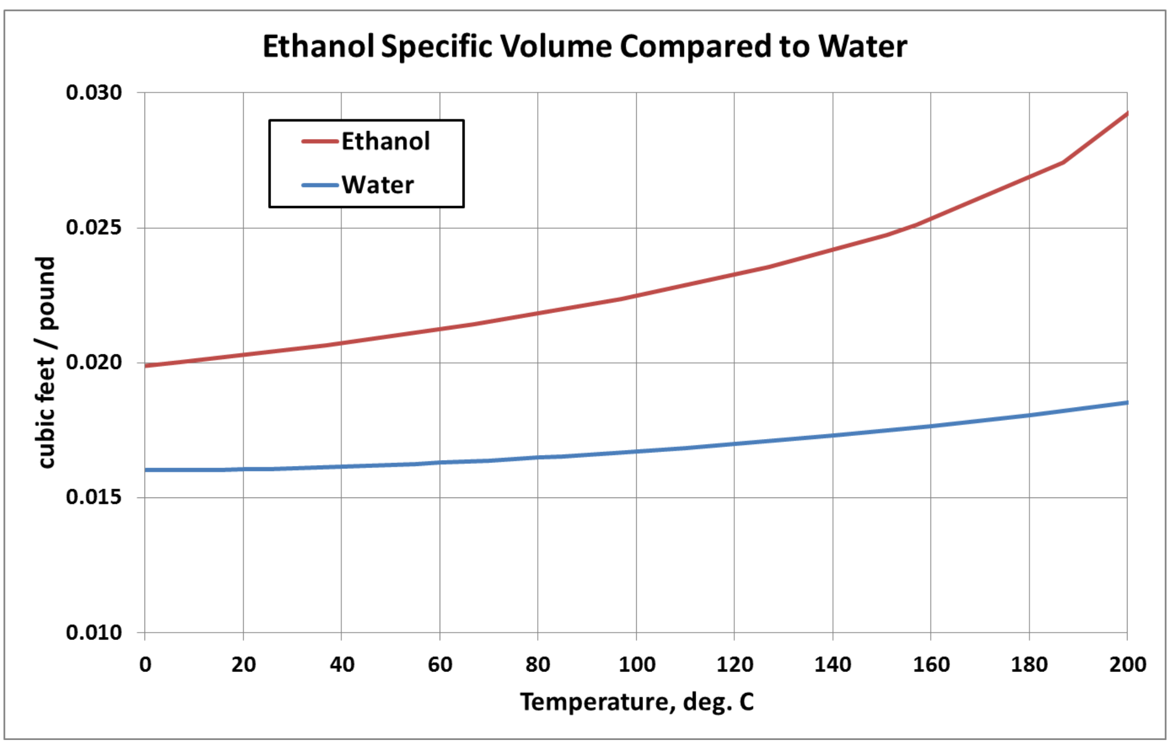


Figure 43. Ethanol specific volume compared to water

In each of the three tests, flames observed on the concrete pad below the tank prior to any obvious PRD release, is evidence of this happening. As the expanding ethanol compressed the nitrogen padding gas, the pressure eventually increased enough to open the PRD and expel lading. The PRD only had to crack open a small amount, since a low flow rate was sufficient to keep the internal tank pressure close to the PRD setpoint. After expelling vapor, the liquid level reached the PRD and liquid ethanol was also expelled, catching fire and dripping down the side of the tank to the concrete pad below. When this process began, the temperature of the ethanol was about 60 °C, which is significantly below its saturation temperature (about 135 °C) at the PRD setpoint pressure (nominally 75 psig); there was no significant vaporization of liquid. Large, energetic releases require a significant amount of vapor in the tank (i.e., to pop the PRD disc fully open), and with sufficient heat input to vaporize liquid at close to the rate that it is being exhausted.

To further explore this result, AFFTAC simulations were performed for the initial period of each test, until the internal pressure reached its maximum value indicating that the PRD had opened and was expelling lading. For each simulated test, an initial fill level (% innage) was determined such that the simulation correctly predicted the observed liquid temperature at the time of PRD opening. The observed liquid temperature at the start of each test was used for the initial temperature of each simulated test. Bulk liquid temperatures used in the simulations were obtained by averaging the observed liquid temperatures, as indicated by the internal thermocouples. An initial fill level was assumed and successively corrected over several runs until the observed temperature at PRD opening was correctly predicted. Table 3 presents the results of these simulations.

Table 3. Summary of simulations to determine initial fill level

Test #	**Initial liquid temperature, °C**	**PRD opening pressure, psig**	**Liquid temperature at PRD opening, °C**	**AFFTAC determined initial fill level, % full**
1	22.2	71	58.5	94.9
2	25.8	69	74.0	92.9
3	29.5	72	62.0	95.2

The target initial fill level for each of the three tests was 97 percent; the corresponding AFFTAC predictions are somewhat lower. Part of this discrepancy is due to the additional vapor volume contained in the nozzles, transition piece, and the 2-inch safety exhaust pipe. Taking these volumes into account, a nominal 97 percent fill level (based on tank shell only) is actually about 96 percent full. The assumptions and modeling fidelity associated with AFFTAC simulations might also explain some of the difference.

The observed bulk liquid temperatures are mostly consistent with ethanol thermal expansion predictions, with the possibility that the initial fill levels were overestimated due to the vapor space available in the actual setup. This analysis reinforces the conclusion that the liquid ethanol expanded to shell full at the beginning of each test, causing the PRV to crack open and vent liquid for some time before the energetic releases with more significant lading loss.

7. Conclusions and Recommendations

The research team successfully conceptualized, prepared, and executed two series of fire tests, which effectively evaluated the performance of PRDs under fire conditions. The first series of tests was conducted with water as lading, and the second series of tests was conducted with ethanol as lading. The test matrix included:

- Low flow capacity (11,000 scfm) and high flow capacity (32,000 scfm) PRDs, consistent with the types that are commonly used in flammable liquid service
- Gaseous flow, mixed (two-phase) flow, and liquid flow conditions
- Three simulated derailment scenarios with the car upright (0 degrees), slightly rolled over (45 degrees), or significantly rolled over (120 degrees) condition

For each type of lading (i.e., water and ethanol), the research team conducted three tests, covering the three derailment and flow conditions, for a total of six tests. The test setups were effective in providing a realistic fire exposure to the PRDs and the team successfully collected the desired performance data. Key findings include:

- PRDs survived the fire and functioned normally when subjected to moderately high temperatures for 30 to 60 minutes.
- Multiple releases of the PRD were observed for each of the six tests, with each release resulting in a reduction of pressure and mass (due to lading expulsion). Continued fire exposure resulted in the pressures rising again, and subsequent releases.
- For both the water and ethanol tests, start-to-discharge pressures were close to the nominally expected value of 75 psi.
    - For the water tests, subsequent release pressures also stayed close to the 75 psi value, showing consistent behavior.
    - For the ethanol tests, while an initial release (leakage) was seen near 75 psi, subsequent energetic releases were seen at lower pressures, ranging from 35 to 55 psi. This is thought to be the result of PRD springs weakening due to fire exposure from the flammable lading release. This reduction in pressure is considered to be safe, especially given the prospect of weakened tank material under fire conditions.
- The float with attached thermocouples, along with the internal thermocouple trees, confirmed that the extent of temperature stratification in the liquid lading was minimal for both the water and the ethanol tests; the boundary layer appeared to be fairly thin and without a significantly higher temperature than the rest of the liquid lading.
- The flammable material released during PRD activity (i.e., ethanol tests) was notably contributing to the fire environment being experienced by the test tank and the PRD.

Recommendations for future work include:

- Extending the ability to model and predict tank and PRD behavior considering the results from these tests

- Conducting a limited set of additional tests to better understand the nature and reasoning behind the lack of thermal stratification, which have been observed in prior total containment fire tests. Among others, these tests could help establish whether the lack of stratification was the result of insulation on the top half of the tank, which prevented the top half of the tank from becoming a significant radiant heat source, or this was the result of mixing (churn) due to PRD activity.
- Observations that PRD releases are high energy events even when the lading released is not flammable, and even more so when the lading is flammable, would be useful to integrate into training materials used by emergency responders

8. References

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Abbreviations and Acronyms

ACRONYMS	EXPLANATION
BAM	Bundes Anstalt fur Material Forshung and Pruefung
DFT	Directional Flame Thermometers
FRA	Federal Railroad Administration
PRD	Pressure Relief Devices
UL	Underwriter's Laboratories