U.S. Department of
Transportation

**Federal Railroad
Administration**

Rail Tank Car Total Containment Fire Testing

Office of Research,
Development
and Technology
Washington, DC 20590

DOT/FRA/ORD-18/35

Final Report
October 2018

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 2018	3. REPORT TYPE AND DATES COVERED Technical Report – October 2015

4. TITLE AND SUBTITLE
Rail Tank Car Total Containment Fire Testing

5. FUNDING NUMBERS
DTFR53-12-D-00004

6. AUTHOR(S)
Anand Prabhakaran, Mike Birk, and Gray Booth

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sharma & Associates Inc.
100 W Plainfield Road
Countryside, IL 60525

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development and Technology
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-18/35

11. SUPPLEMENTARY NOTES
COR: Francisco Gonzalez, III

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA website.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Given the frequent incidences of Non-Accident Releases (NARs) of hazardous materials from tank cars, there is increased interest in transporting hazardous materials in total containment conditions (i.e., no pressure relief devices [PRD]). The primary purpose of a PRD is to protect a tank car in a fire situation by limiting the maximum pressure buildup within the tank car through PRD venting. This would not be possible in the case of total containment. Before issuing a Special Permit authorizing total containment for NaOH and KOH solutions, FRA determined that an equivalent level of safety could be achieved if such tank cars were demonstrated through actual fire testing to meet the pool fire thermal protection requirement currently mandated for certain tank cars carrying higher risk hazardous materials. In such cases the Code of Federal Regulations (CFR) requires tank cars to survive a fully engulfing pool fire for 100 minutes, without catastrophic failure. Also, the modeling tool commonly used by industry to evaluate thermal protection, Analysis of Fire Effects on Tank Cars (AFFTAC), has not been validated under these conditions. The intent of this effort was to evaluate through a series of third-scale fire tests, the ability of tank cars to meet the thermal protection requirements under total containment conditions, as well as to generate data to validate AFFTAC for such conditions. A review of the test data, followed by subsequent extrapolation and scaling to estimate full-scale behavior, suggests that full-scale tank cars carrying caustics are unlikely to survive the 100-minute requirement specified in the CFR.

14. SUBJECT TERMS
Tank cars, fire testing, total containment, caustic transport, Analysis of Fire Effects on Tank Cars, AFFTAC, Non-Accident Releases, NARs

15. NUMBER OF PAGES
106

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

METRIC/ENGLISH CONVERSION FACTORS

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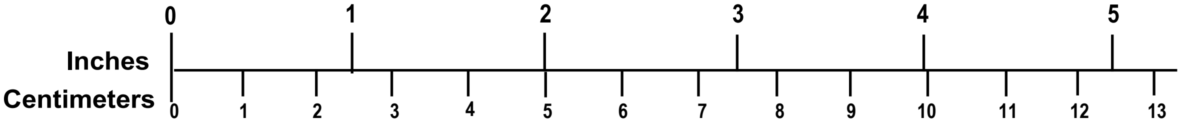

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Updated 6/17/98

Acknowledgements

The authors would like to thank the Chlorine Institute for their financial assistance with the test tanks.

This test program was carried out at the Bundesanstalt für Materialforschung und –prüfung (BAM) Fire Test Facility near the town of Horstwalde, south of Berlin, Germany. This was an excellent facility with a flexible fire test stand and fuel delivery system that allowed us to experiment with different burner arrangements, which was critical for us to develop and characterize the fire for this test program. The staff at BAM provided excellent support throughout the project. We would like to acknowledge the major contributions of BAM personnel including Frank Otremba, Jorg Borch, Christian Balke, T. Hilse, and Frank Burghardt.

We would also like to acknowledge the major contribution by DOW Germany for providing the NaOH solutions, and all the hardware, logistics and support for the handling the caustics for the hazardous material tests.

We would also like to acknowledge the significant contributions of Ian Bradley, Intern (PhD student, University of Edinburgh UK, as well as Luke Bisby and Michael Birk as supervisors).

We also owe our sincere thanks for Francisco González, III and Karl Alexy of the Federal Railroad Administration, and Jean-Pierre Gagnon, former Transport Canada Engineer, for their technical guidance, review, and support, throughout this project.

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Executive Summary

A series of seven fully-engulfing fire tests were conducted by Bundesanstalt für Materialforschung und –prüfung (BAM) personnel on one-third scale test tanks to evaluate the capacity of rail tank cars carrying hazardous caustic materials, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), to survive a fully engulfing pool fire for 100 minutes, under total containment conditions. These tests were carried out through October 2015, with funding by the Federal Railroad Administration (FRA), at the BAM Fire Test Facility near the town of Horstwalde, south of Berlin, Germany.

Extrapolating and scaling the results from the one-third scale tanks to the behavior expected on a full-size tank car, the authors estimate the failure time for the full-scale system, filled with 50% NaOH solution, to be between 62 and 88 minutes. This is strongly influenced by the insulation condition and tank fill (i.e., wall wetting). Clearly, this does not meet the 100-minute requirement.

It is suggested that if the thermal protection system were improved, tanks under total containment conditions could survive 100 minutes in a fully engulfing pool fire of liquid hydrocarbons. For example, there is potential for state-of-the-art thermal protection systems to protect the total containment system for 100 minutes. However, further analysis and fire testing are needed to confirm this.

Given the frequent Non-Accident Releases (NARs) of hazardous materials from tank cars, there is increased interest in transporting hazardous materials in total containment conditions, i.e., no pressure relief devices (PRDs).

The primary purpose of a PRD is to protect a tank car in a fire situation by limiting the maximum pressure buildup within the tank car through PRD venting. This would not be possible in the case of total containment.

Before issuing a Special Permit authorizing total containment for NaOH and KOH solutions, FRA determined that an equivalent level of safety could be achieved if such tank cars were demonstrated through actual fire testing to meet the pool fire thermal protection requirement currently mandated for certain tank cars carrying higher risk hazardous materials. In such cases the Code of Federal Regulations (CFR) requires tank cars to survive a fully engulfing pool fire for 100 minutes, without catastrophic failure.. Also, the modeling tool commonly used by industry to evaluate thermal protection, Analysis of Fire Effects on Tank Cars (AFFTAC), has not been validated under these conditions.

The intent of this research project was to conduct a series of one-third scale fire tests that can address whether a full-scale tank car carrying NaOH or KOH can survive 100 minutes in a full engulfment fire under total containment conditions, and generate data to validate AFFTAC for those testing conditions.

The goals of the research effort were:

- Design and fabricate model U.S. Department of Transportation (DOT) 111A100W1 (DOT-111) tanks, at one-third linear scale
- Design and implement the instrumentation and data acquisition tools for the fire tests

- Develop, calibrate, and demonstrate a simulated, liquid hydrocarbon, pool fire system using liquid propane burners
- Conduct engulfing fire tests of total containment test tanks

The test tanks were designed to be one-third scale in the diameter and length of DOT-111 tank cars, which are used to transport NaOH and KOH solutions, with the thickness being scaled to meet the same burst pressure, and the material being the same as or similar to actual tank car steels. The jacket (11-gauge steel) and insulation (4" of fiberglass) corresponded to that of a full-scale tank. A total of seven tanks and five jackets were constructed. One tank was tested hydrostatically to failure so the team could confirm that the strength requirements were met.

The fire test tanks were instrumented with two pressure transducers, 27 lading thermocouples, 11 jacket thermocouples, 22 tank wall thermocouples, and 10 directional flame thermometers (DFTs) and shipped to the fire test facility in Germany.

A series of three calibration tests with a calorimeter tank were conducted to ensure that the fire system developed in this program was a credible simulation of a large liquid hydrocarbon pool fire. This fire system was then used to conduct the fire test program. In total, seven fire tests were conducted as outlined in Table A.

Table A: Summary of Total Containment Fire Tests

Test Name	Insulation	Lading	Fill Level	Initial Temperature (˚C)
Test 0	Bare Tank	Water	97%	17
Test 1	Insulated & Jacketed	Water	97%	17
Test 1b	Jacketed – No Insulation	Water	97%	17
Test 2	Insulated & Jacketed	Water	49%	16
Test 3	Insulated & Jacketed	NaOH – 50% solution	98%	55
Test 4	Insulated & Jacketed	NaOH – 50% solution	66%	55
Test 5	Insulated & Jacketed	Water	97%	15

The fire tests lasted between 2 (Test 0) and 40 minutes (Test 5). The tanks employed in Test 0 and Test 1b ruptured and the tank in Test 1 suffered a minor fitting failure. Test 1b was done with a previously fire heated and damaged tank (from Test 1). In all the other tests, the fire was shut down prior to tank rupture to eliminate the possibility of test facility damage and/or hazardous material release.

These tests provided sufficient data for how the total containment pressure vessel responded to fire. The behavior of the test tanks was dominated by liquid stratification and boundary layer effects, and not by temperature increase of the bulk fluid. The results also showed that the tank response depended strongly on the degradation of the fiberglass insulation. As initially anticipated, the fiberglass insulation did not fully degrade away and there was always a notable amount of insulation remaining at the end of the tests. However, the effectiveness of the same was doubtful.

Using the test data from the one-third scale tests, the expected behavior from the full-scale tanks was estimated. This was done by:

- Extrapolating the one-third scale tests that did not result in failure to predict the expected failure times
- Scaling the tested and/or predicted one-third scale failure times to full-scale failure expectations

Using this scaling approach, the failure time for the full-scale system, filled with 50% NaOH solution, was estimated to be in the range of 62–88 minutes. This estimation is strongly influenced by the insulation condition and tank fill (i.e., wall wetting). However, the scaling approach does not include the effects of liquid boiling, which could add another layer of complexity to the scaling effort and potentially make the survival estimates non-conservative.

As noted earlier, improved thermal protection systems may be able to meet the 100-minute requirement under total containment conditions, but these systems need to be verified through test and analysis.

This test program has generated a wealth of detailed data on how total containment pressure vessels respond to fire heating. The developers of AFFTAC may use this data to validate and improve their model for this application.

We recommend future research to validate the scaling assumptions made during the current study, with particular focus on understanding the complex 2-phase processes that influence the maximum wall temperatures and pressurization in total containment.

We also recommend the development of analytical models that can accurately simulate the total containment and also effectively predict (or estimate):

Temperature stratification, so that tank pressurization can be properly predicted for a range of fill levels, commodities, and heat fluxes.

Boiling and swell, for vapor space wall wetting at high fill levels. This is also required for a range of commodities, heat fluxes, and fill levels.

Finally, we recommend that the following experimental data should be gathered to validate these new models:

- The boiling characteristics of commodities such as NaOH or KOH
- Detailed temperature mapping inside a vessel exposed to heat fluxes in the range of 20–100 kW/m^2

1. Introduction

This report describes a research project that evaluated the potential for railway tank cars that carry caustic materials to survive a pool fire under conditions of total containment for 100 minutes. This was done through a series of fire tests on one-third scale test tanks, with the results being scaled to predict full-scale behavior.

1.1 Background

Tank cars that carry certain hazardous materials are required to survive a fully engulfing pool fire for 100 minutes without catastrophic failure [1]. However, fluid pressure buildup under fire conditions combined with loss of strength in the steel due to elevated temperatures can lead to catastrophic failure of tank shells under certain circumstances. In general, the 100-minute requirement is met through the use of thermal protection and pressure relief devices (PRDs). PRDs help to limit the pressure buildup in tank cars, thereby reducing the potential for a tank explosion. The expectation is that PRD use will result in smaller quantities of hazardous material being released while avoiding the potential for a catastrophic failure. In some cases, PRDs alone may not be sufficient to meet the 100-minute test requirement and the tanks need thermal protection, which is ‘high-performance’ insulation designed to survive fire conditions. Thermal protection, which in most cases is applied between a steel jacket and the tank, will reduce the heat input to the commodity tank and lessen both the temperature rise and pressure rise, which helps the commodity tank meet the 100-minute test requirement.

PRDs have a history of leaking and releasing product under nominal operating conditions for a range of reasons unrelated to an accident, and the industry has focused on reducing the incidences of these frequent Non-Accident Releases (NARs). Reducing NARs associated with PRDs has resulted in an increasing interest in transporting such materials without the use of PRDs (i.e., conditions of total containment). Total containment is common practice in Europe, where there is no 100-minute fire survival requirement. While total containment would help avoid NARs, the only mechanism to relieve pressure buildup under fire conditions would be lost. Thus, the question becomes whether a tank car that carries caustics can survive a 100-minute fire under total containment conditions without a tank shell failure.

Caustics such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) are currently transported in non-pressure (DOT 111) tank cars that are insulated, but not thermally protected. The tank car industry currently uses a computer program called AFFTAC (Analysis of Fire Effects on Tank Cars) to determine the behavior of tank cars subjected to fire conditions [2]. Simulations conducted by the industry using AFFTAC have indicated that tank cars carrying caustic materials could survive a 100-minute fire under total containment conditions.

AFFTAC was originally developed to determine if tank car designs meet the requirements for thermal protection as provided in the Title 49 Code of Federal Regulations (CFR) Section §179.18, assuming that PRDs would be used to relieve pressure. With the above simulations, the application of the program has been expanded to analyze the behavior of tank cars without thermal protection, as well as, tank cars without pressure relief devices. Further, the program was initially developed to consider pure substances and over time, subroutines have been developed to allow for the analysis of solutions. While these additions are founded on the principles of chemistry, thermodynamics, and material science, they have not been validated.

However, use of this program to underpin a tank car design and or the use of an existing design in a new way requires validation by experiment.

Full-scale fire testing of tank cars can be a very expensive proposition (which is one reason why the last full-scale tank car test was done more than 40 years ago) [3]. Given the number of tests needed to address the issues raised and fully characterize the behavior under fire conditions, a series of full-scale tests would be cost prohibitive. On the other hand, given the number of physical properties that would affect the results of this study, their interactions, and non-linear behavior, scaling the results from a small-scale test (one-tenth scale or less) would require the project to use many assumptions of material behavior that cannot be easily substantiated. A medium scale (one-third scale) test was therefore chosen as a reasonable compromise between cost and scalability of results. The methodology for the tests followed the outline described by Birk in an earlier paper [4].

1.2 Objectives

The overall goal of this research project was to conduct a series of one-third scale fire tests to accomplish the following key objectives:

- Address whether a full-scale tank car carrying NaOH or KOH can survive 100 minutes in a full engulfment fire under total containment conditions
- Generate test data for the verification of the fidelity and performance of the AFFTAC model

1.3 Overall Approach

This approach was used to meet the objectives listed above:

1. Develop an overall framework for the testing
2. Design and fabricate model DOT-111 tanks at one-third linear scale
3. Design and implement instrumentation and data acquisition for the fire tests
4. Develop, calibrate and demonstrate a simulated pool fire system using liquid hydrocarbon and liquid propane burners
5. Conduct engulfing fire tests of total containment test tanks
6. Extrapolation and scaling of the test results to full-scale tanks

1.4 Scope

This project focused on the performance of tank cars in fully engulfing pool fires, particularly tank cars carrying caustics such as NaOH and KOH, under conditions of total containment. Specifically, this effort focused on tank cars with a layer of fiberglass insulation for the purposes of commodity transport, and not on tank cars that had thermal protection.

While elements of this research can be applied to tank cars with PRDs, tanks carrying other commodities, or tanks with thermal protection, those conditions are outside of the scope of this effort. Thus, any extrapolations to cover such cases should be done with care and restraint.

1.5 Organization of the Report

The report is organized as follows:

Section 1 introduces the project to the reader.

Section 2 describes the design and construction details of the test tanks and the instrumentation.

Section 3 covers the design of the fire and the fire calibration tests.

Section 4 discusses the total-containment, commodity tests and key results.

Section 5 provides the details of the extrapolation and scaling to full-scale.

Section 6 presents the project's conclusions.

Section 7 contains recommendations and suggestions for future work.

Detailed test results from each of the individual tests are provided in Appendix A through Appendix G and additionally Appendices H and I.

2. Specimen Tanks

This section describes the design and construction elements of the test tanks, and an overview of the instrumentation.

2.1 Tank Design and Construction

As required, the specimen tank was designed to equate to third-scale of DOT-111A100W1, also referred to as DOT-111 tank car. Usual materials for tank car construction are TC-128 Gr. B or American Society of Testing and Materials (ASTM) A-516 Gr. 70. As neither material was available in the smaller thicknesses needed for appropriate stress/pressure scaling (one-third scale model requires wall thickness from 0.10” to 0.13” depending on material strength), an alternate pressure vessel material, ASTM A414 Gr. G was selected. This material has similar properties to standard tank car steels, including yield, tensile and chemical properties as shown in Table 1 and Table 2 below. The thermal properties of the steel (specific heat, thermal conductivity, etc.) are also very similar.

Table 1. Material Strength Comparisons

Steel Type	Spec No.	Type/Grade	Min Tensile (ksi)	Min Yield (ksi)
Carbon Steel	A-414	G	75	45
Carbon Steel	A 516	70	70	38
Carbon Steel	TC-128	B	81	50

Table 2. Chemical Property Comparisons

Element	Composition %			
	TC128 Gr B	**A-516-70**	**A-414-G Spec.**	**A-414-G Material Cert.**
Carbon (max)	0.26	0.25	0.31	0.24
Manganese	1.00-1.70	0.79-1.26	1.35	1.11
Phosphorus (max)	0.025	0.025	0.035	0.015
Sulfur (max)	0.015	0.015	0.035	0.005
Silicon	0.13-0.45	0.15-0.45	-----	0.25
Vanadium (max)	0.084	Per ASTM A20	0.04	<0.01
Copper (max)	0.35	0.35	0.02	0.01
Nickel (max)	No Limit	Per ASTM A20	0.43	<0.01
Chromium (max)	No Limit	Per ASTM A20	0.34	0.03
Molybdenum (max)	No Limit	Per ASTM A20	0.13	<0.01
Aluminum	0.015-0.060	0.015-0.060		0.03

The specimen tank design is based on the DOT requirements for tank cars maintaining burst pressure of at least 500 psig, which is based on the following equation [5]:

$$t=Pd/2SE$$

where:

t = shell thickness required

P = Burst pressure of the tank

d = outside diameter of tank

S = Minimum Tensile Strength

E = Weld joint efficiency

The thickness and diameter were further adjusted as per the actual strength values for the material used, based on the mill certifications. The final design dimensions were:

Outside diameter = 36”

Fabricated nominal shell design thickness: 0.121”

Fabricated head nominal thickness: 0.176”

Heads: 2:1 ellipsoidal

Shell Length: 136.2”

Jacket: 11 gauge ASTM A1011

Insulation: 4” fiberglass

Several ports were added to the tank to allow loading and unloading (two top, two bottom), as well as to serve as feed-throughs for instrumentation (for thermocouples and pressure transducers), with the appropriate reinforcement. Figure 1 contains a photograph of one of the specimen test tanks.

Figure 1. Specimen Test Tanks
(shown upside-down)

A hydrostatic test of one of the specimen tanks was conducted, primarily as a quality control exercise. The test was meant to confirm that the as-built tank would meet the design requirements from a strength perspective. Figure 2 shows that the tank ruptured at about 575 psig; the theoretical burst pressure based on actual material properties and joint efficiency of 0.9 is 562 psi. The tank’s behavior and rupture pressure demonstrated that the tank design, construction and material were acceptable for the fire testing. As intended, the rupture was a tensile failure of the parent material and did not occur at any of the weld seams or other discontinuities, such as the saddles or ports. Figure 3 and Figure 4 presents photographs of the ruptured hydrostatic tested tank.

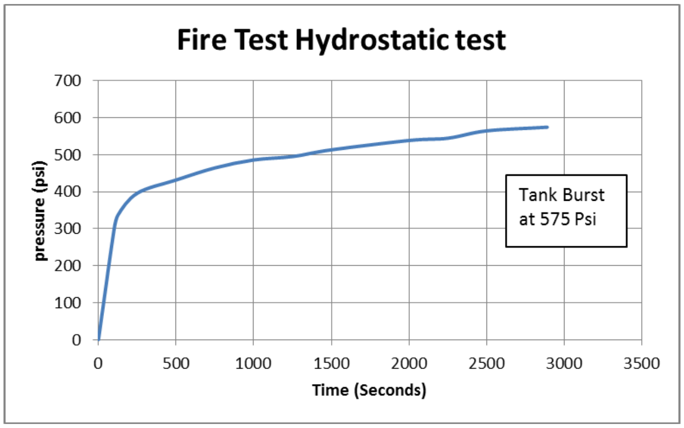

Figure 2. Pressure Curve for the Hydrostatic Test

Figure 3. Burst Hydrostatic Tested Tank – Overview

Figure 4. Burst Hydrostatic Tested Tank – Tensile Tear

2.2 Jacket and Insulation

While the specimen tank itself (the pressure vessel) was at one-third scale, the jacket and insulation system were kept at full-scale. The jacket participates only as a heat shield and does not provide any structural support or lading containment during normal operations or under fire conditions. Therefore, for the purposes of this test, the jacket ends were simplified as flat sheets, instead of ellipsoidal heads. Further, the jacket was connected to the test tank only at the bolsters, but was structurally detached from the test tanks otherwise.

The fiberglass insulation was not expected to last very long in a pool fire; it is primarily used to keep the transported commodity at an elevated temperature to assist with loading and unloading, and *is not intended as thermal protection*. Therefore, using full-scale (4”) insulation was expected to have minimal effect on the survivability of the tank. Additionally, using full-scale insulation would allow the team to directly quantify any ‘thermal protection’ benefits that it might offer, rather than trying to scale another parameter that would affect only the first few minutes of performance in a fire. The degradation of the insulation system in this test should be similar to that of the full-scale system. The fiberglass insulation used in this test program was Knauf Insulation KN Series. The data for this insulation is summarized in Table 3, which is similar to the insulation used on nominal tank cars carrying caustics. Figure 5 presents sample images of the insulation applied to the test tanks.

Table 3. Insulation Properties

Type	Knauf KN 75
Density	0.75 pcf or 12 kg/m^3
Maximum Service Temperature	650 °F or 271 °C
Thermal Conductivity at 75 ºF	0.28 BTU inch/(hr.ft^2 °F)
Thickness Used	4”
R-value	14.29 BTU/(hr.ft^2 °F)

Figure 5. Insulation Before Fire Test (Test 5 Tank)

2.3 Instrumentation and Data Acquisition

The tank instrumentation was designed to capture key metrics, including the internal pressure in the tank, the temperature distribution in the lading and the jacket, and the shell temperatures as well as the fire temperature. The instrumentation consisted of the following

1. 2 pressure transducers
2. 27 lading thermocouples
3. 11 jacket thermocouples
4. 22 wall thermocouples
5. 10 directional flame thermometers

The internal lading thermocouples were fed into the tank using multi-thermocouple feed-throughs. The wall and jacket thermocouples were fixed to the surface using thin stainless steel strapping that was spot-welded to the surface. In the middle of the tank, seven thermocouples were provided at multiple heights (1”, 6.67”, 12.34”, 18” (mid-height), 23.67”, 29.33”, and 35” from bottom) so that temperature stratification can be captured. Figure 6 presents an overview of the instrumentation details on the lading tanks.

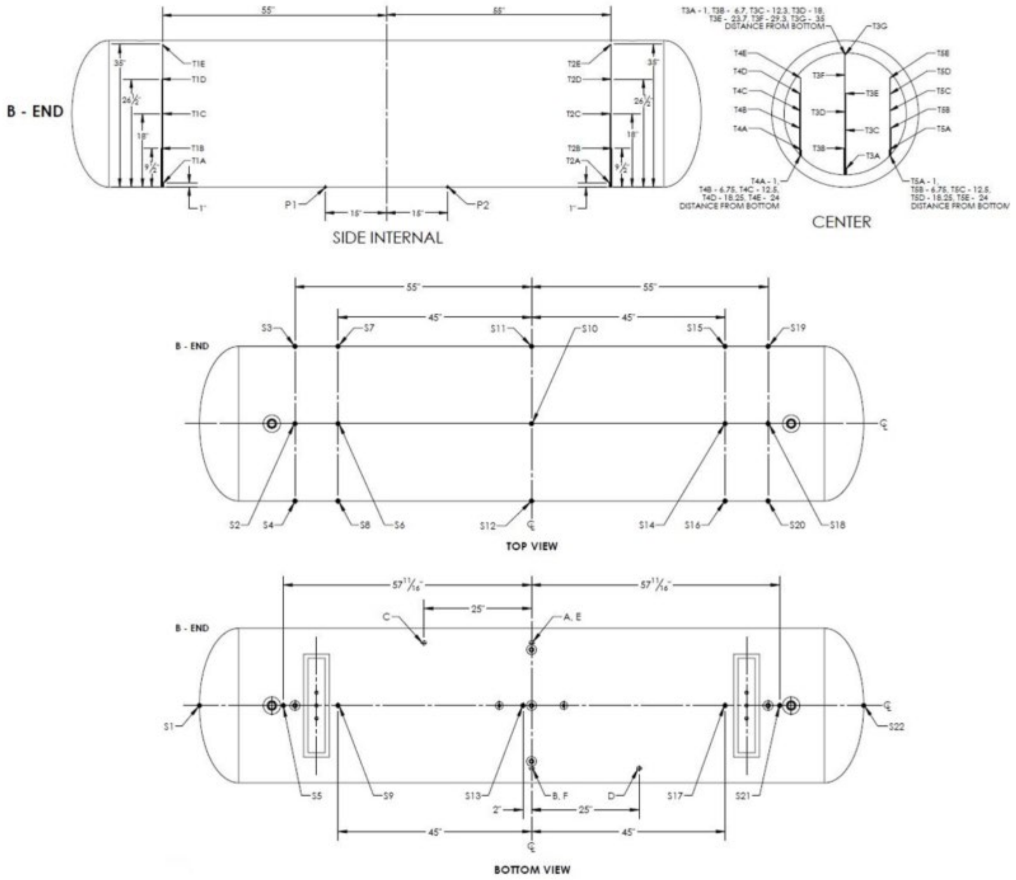

Figure 6. Overview of Instrumentation on the Lading Tanks

The pressure transducers were connected to the bottom of the tank, either on the dump pipe or on separate pressure tubes. These connections were insulated from the fire to minimize boiling in the pipes and tubes.

All the tank instrumentation was installed in the tank at the SA laboratories near Chicago, IL, and the instrumented tanks were shipped to the test facility near Berlin, Germany in specially designed crates. Figure 7 highlights some images from the instrumentation. Special precautions were taken to ensure that the instrumentation could stand up to the very high temperatures expected during the tests.

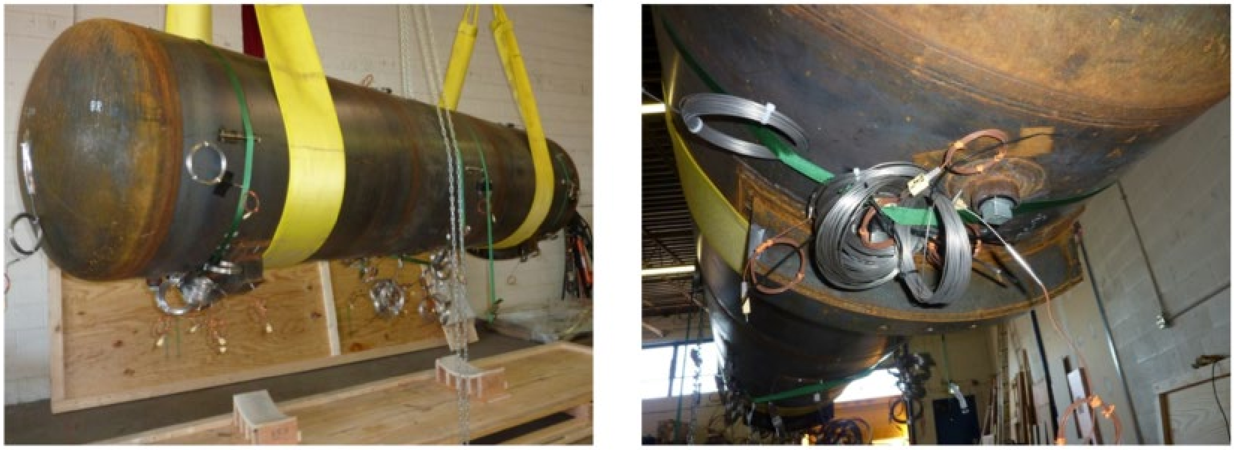

Figure 7. Instrumentation on a Test Tank

In addition to the tank and fire instruments discussed above, the following data were recorded:

1. Wind speed and direction
2. Burner fuel pressure and mass flow
3. Still and video images
4. Thermal imager (for some fire calibration tests)
5. High speed images

All data was acquired and recorded using a digital data acquisition system. The tank and fire data were recorded at one second intervals.

3. Fire System Development

3.1 Fire Requirements

The fire used for the test needed to be a credible simulation of a large liquid hydrocarbon pool fire (relative to full-scale fire test) with the following requirements [6]:

- Full engulfment (top, sides, bottom)
- Effective black body flame temperature between 816 °C and 927 °C
- Heat flux of around 100 kW/m^2
- Heat should be transmitted predominantly by radiation

The temperature range outlined above is as defined in the CFR [6], and the other requirements are consistent with the behavior expected from large liquid hydrocarbon pool fires. The above set represents a fairly tight set of requirements for a test fire, and one that is more highly constrained than most fire standards. For example, "ASTM E1529 14a Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies" [7], specifies the temperatures and the temperature rise, but does not prescribe a heat flux or a radiation requirement. Underwriters Laboratories has a similar standard, UL 1709, but with a faster rise time [8]. The temperature rise requirements outlined in both ASTM E1529 and UL 1709 are expected to result in high heat flux levels (158 kW/m2 and 200 kW/m2 respectively), but this is not part of the test measurement or test requirements. It is also worth noting that both the above standards are usually implemented through a controlled furnace setup, not an actual pool fire, even though they are intended to simulate a hydrocarbon pool fire.

For this project, we used the following targets:

- Heat transfer is mostly by thermal radiation (80%) and the remainder is convection (20%). This will vary over the tank surface and time period of heating.
- Blackbody fire temperatures are achieved on average on the tank top, sides and bottom 90% of the time during a steady burn period.
- Fire start-up and shutdown within 2 minutes.

3.2 Fire Calibration Tests

After several initial rounds of experimentation, an appropriate burner and fuel flow configuration was selected for the fire tests. Using this configuration, a series of three fire tests were conducted from September 1, 2014, through September 5, 2014. The objective of these tests was to demonstrate three consecutive, consistent fire burns.

The fire system consisted of 24 elevated rail burners, and 34 ground burners with 1.08 mm nozzles. The propane fuel flow rate was 4,000 kg/hr. A test tank (filled with water) that was very similar in dimensions to the specimen tanks was used for these tests. Note that the test tank was vented to atmosphere and not allowed to pressurize. In addition, a mechanical mixer was used to keep temperature stratification effects low, which allowed the test tank to be used as a calorimeter. The blackbody temperature of the fire was measured using multiple Directional Flame Thermometers (DFTs), located at the top, bottom and sides of the test tank. In addition, the water temperature was measured using thermocouples. Nominal weather metrics, such as the wind speed, were also recorded.

The tests showed very good consistency and the measured temperatures showed that the fire met the requirements for the test. Based on the temperature rise of the water, the heat flux and the estimated radiation fraction were calculated. The results are summarized in Table 4.

Table 4. Summary of Calibration Fire Test Results

Test	DFT Temperature (˚C)			Average Temp. (˚C)	Average Heat Flux kW/m²	Estimated Radiation Fraction
	Top	Bot.	Side			
Test 1	909	877	886	887 SD=112	103	81%
Test 2	914	885	868	888 SD = 78	108	77%
Test 3	937	900	892	907 SD = 55	111	81%
Average	920	887	882	896	107	80%

The target average black body radiating temperature for the fire was between 816 and 927 ˚C (average 871 ˚C). All the test averages are in this range. The test repeatability was excellent, as seen in Figure 8.

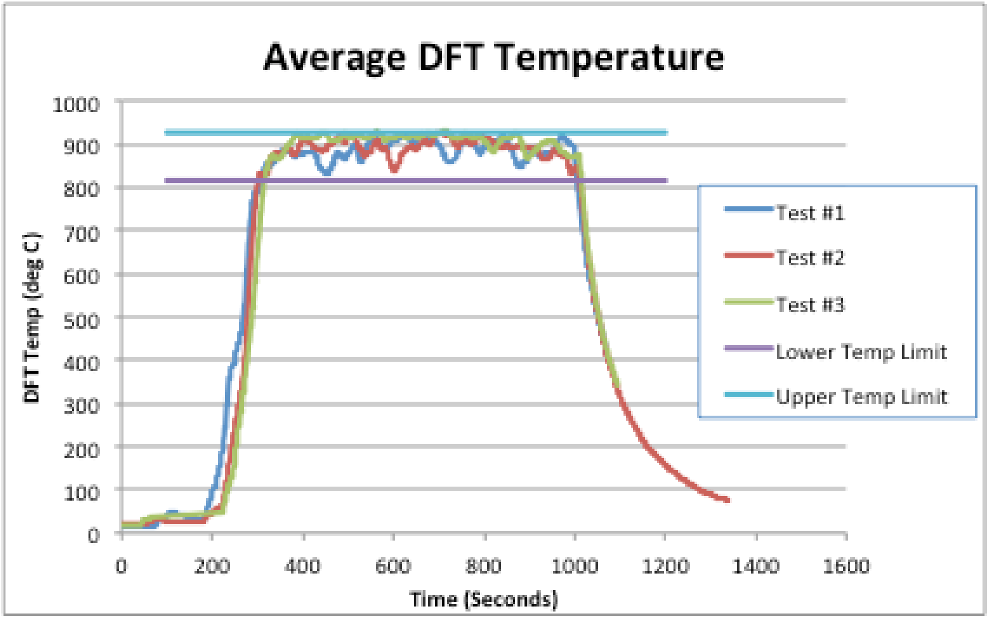

Figure 8. Plot of Average DFT Temperature vs. Time - Three Calibration Tests

Additionally, the following observations can be drawn from Figure 8:

1. Fast fire start (<2min) and shut down (<2min)
2. Steady fire with minor fluctuations as expected in a turbulent diffusion flame of this scale.

The calibration fires also compared very well with DOT's fire test of a full-scale tank car (RAX 201) [3]. The RAX 201 test was a full-scale fire test of an unprotected DOT 112 tank car, and is considered to be the Federal Railroad Administration (FRA) standard for a large, fully engulfing fire. The RAX 201 test started with the tank 94% full of propane, the PRD opened after 2 minutes, and the tank failed 24 minutes into the test while it is 40% full of propane. A comparison of data from the RAX 201 tests to the calibration tests conducted as part of the current study suggests that the developed fire test setup generates fire conditions very similar to the RAX 201 tests (see Figure 9).

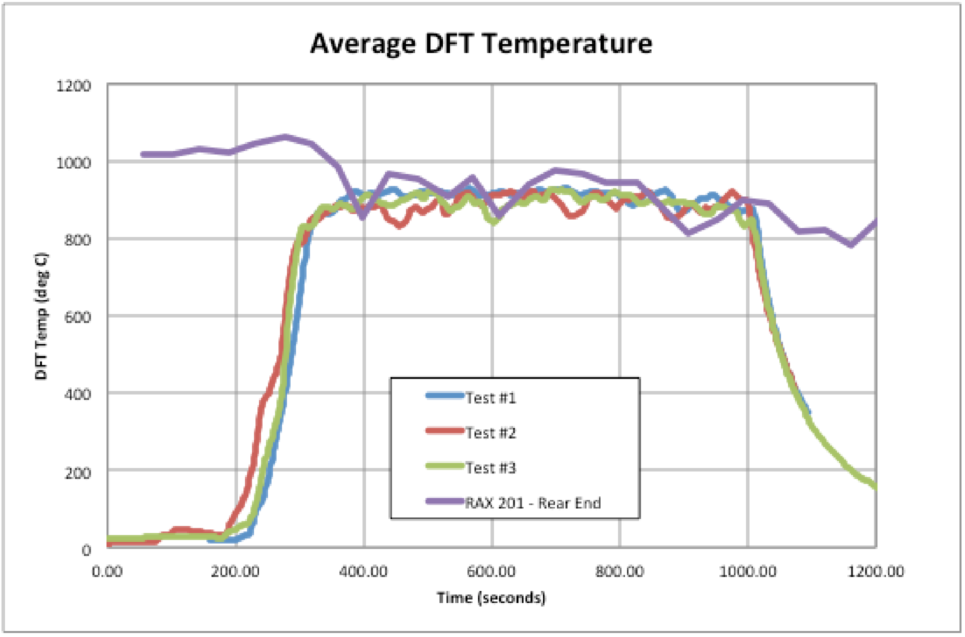

Figure 9. Calibration Fire Performance Compared to RAX 201

The test-set-up calibration tank is shown in Figure 10 and a picture of the fire from test #3 is shown in Figure 11.

Figure 10. Picture of the Fire Calibration Test Tank and Setup

Figure 11. Picture of the Fire from Calibration Test # 3

In summary, the calibration tests successfully demonstrated that the fire test setup was a credible simulation of a fully engulfing, hydrocarbon pool fire. This test setup was used to conduct the main total containment tests (as discussed in the next few sections).

4. Total Containment Tests

The test effort for the total containment tests was planned around a series of increasingly complex tests to ensure that significant confidence in the test approach was developed as the effort progressed. The test effort started with a test of bare tank filled with water to 98%, followed by the tests of jacketed tanks with water, before continuing on to the tests of the tanks with the caustics. Table 5 presents a list of the seven total containment tests that were conducted as part of this effort. This follows the intent of sequencing tests of increasing complexity, with some minor variations to address test results and scheduling concerns.

Table 5. Summary of Total Containment Fire Tests

Test Name	Insulation	Lading	Fill Level	Initial Temperature (˚C)
Test 0	Bare Tank	Water	97%	17
Test 1	Insulated & Jacketed	Water	97%	17
Test 1b	Jacketed – No Insulation	Water	97%	17
Test 2	Insulated & Jacketed	Water	49%	16
Test 3	Insulated & Jacketed	NaOH – 50% solution	98%	55
Test 4	Insulated & Jacketed	NaOH – 50% solution	66%	55
Test 5	Insulated & Jacketed	Water	97%	15

This section presents an overview of the results and findings from the tests, including a discussion of key test elements. More descriptive results from each test are provided in Appendix A through Appendix G of this report.

4.1 Overview of Test Setup

Long-duration fire testing is very complex and challenging. Minor and often, unexpected issues can lead to lost test data or poor test outcomes. Therefore, researchers on this project spent considerable effort to ensure that several initial key issues were reviewed and addressed.

One key test-related issue was handling hazardous materials for the caustic tests. The hazardous materials of interest in this test program are NaOH and KOH at 50% solution in water. NaOH and KOH are both highly corrosive. Both substances will burn skin, eyes, and mucous membranes on contact. Breathing their vapor is very dangerous. These materials are incompatible with organic materials, aluminum, tin, zinc, wood, paper, and glass. They are both non-flammable, but they will produce other hazardous materials if exposed to fire. Protective clothing/equipment is needed to protect skin, eyes, and breathing passages.

Chlorine Institute and their partners, Dow-Germany, played a critical role in preparing for effective handling of the hazardous materials. Dow worked with the researchers and the team at BAM to ensure that the hazardous materials were delivered in time for the tests, ensured that the right fittings were available to load and unload the test tanks. Also, they were ready with emergency response and personnel, including fire trucks, if the equipment were needed. Figure

12 is an image of the hazardous materials and emergency response trucks that DOW brought to the test site to ensure that the test was successful.

Figure 12. Support Provided by Dow – Germany for Hazardous Material Tests

For tests with significant saved energy or hazardous materials use, it was critical to ensure that fires could be stopped and the tank's contents could be dumped to a secure container in a safe manner. Therefore, one or more mechanisms to stop the fire and to dump the contents was developed and implemented for each test. The fire was always under the control of the BAM staff with the necessary computer control and manual override. For the water tests, a remotely controlled ball valve was implemented to assist with dumping fluid. For the caustic tests, a pressure relief valve was preset to release at 8 Barg to provide dump functionality, and it allowed the released contents to be captured by specifically designed containers.

Given that these tests are done outdoors; weather can influence the test process. In particular, wind direction and magnitude might significantly alter the performance of the fire, with the result of reducing the 'fully engulfing' intent of the test approach and, critically, making the fire input inconsistent from test to test. Throughout the fire development and fire calibration process, the researchers collected weather data during the tests to give us assurance that the tests would maintain reasonable consistency at wind speeds up to 3 mph. In addition, the weather forecasts for the local region were reviewed before the test each morning to ensure that the conditions were favorable. Wherever appropriate, the tests were rescheduled to ensure reasonable weather conditions.

Finally, special care was taken to ensure that all instrumentation performed as intended in the fire. This required the use of high temperature instrumentation, the use of high temperature insulation to protect exposed cables, the need for cables to flow through the water bath at the base of the test tank, and several other minor but critical details.

A sample test setup is shown in Figure 13.

1. The tank was supported above the water filled fire pan, on water-cooled supports. The ground level fire nozzles were immersed in a pool of water to protect the pipes and valves from the fire. The water was constantly replenished with fresh cold water to avoid boiling, as boiling has a tendency to affect fire performance (which is not desirable).
2. The elevated burner system was also engulfed by the fire, and thus the elevated burners were also kept cool with a water jacket (which contained flowing water).
3. An emergency dump line was connected to the bottom of the tank at the west or east end.

This dump line was connected to a pipe with a remote-controlled pressure release valve (or a PRV) so that the pressure in the tank could be relieved if necessary. The dump line emptied into the fire pan for the water tests and into a container for the NaOH tests. This dump line above the water line was insulated.

4. A wind barrier wall (16 m long by 2.5 m high) was located 6 m from the tank centerline to the North.
5. All instrument lines and pipes were taken to the North though the fire pan water, under the wind barrier to the necessary connectors for data acquisition.
6. Thermal insulation was used to protect all the tank penetrations, the support legs, the dump pipe and the pressure transducer lines.
7. The fire test was controlled from a remote and safe bunker.

Figure 13. Test 4 in Final Preparation for Test

4.2 Key Results from Individual Tests

Seven total containment tests were conducted from September to November 2014. Table 6 presents a brief summary of the key results from these tests. The fire tests lasted between 2 (Test 0) and 40 minutes (Test 5). The tanks employed in Test 0 and Test 1b ruptured and the tank in Test 1 suffered a minor fitting failure. Test 1b was done with a previously fire heated and damaged tank. Test 1 suffered a minor fitting failure. In all the other tests, the fire was shut down before tank was ruptured.

As seen in Table 6, the fire heat flux was very consistent from test to test. Test 0 was very brief and the fire did not reach a steady state. The heat flux calculated for that test may not be accurate due to the fire's short duration. The heat flux to the jacket is the actual average heat flux absorbed by the tank and lading. As can be seen, the improved insulation systems reduced the heat flux by a factor of around four. The original insulation system reduced the heat flux by a factor of around three. The jacket only reduced the flux by a factor of two.

Table 6. Results Summary

Test Name	Estimated Average Heat Flux[1] kW/m^2	Estimated Average Heat Flux to Jacket[2] kW/m^2	Test Duration (sec)	Max Pressure Barg	Max Wall Temp Measured °C	Outcome
Test 0	114 (approx.)	NA	130	7.3	759	Rupture
Test 1	106	33.6	1540	10.4	580	Minor failure and leak, near rupture
Test 1b	98.3	55.2	362	11	700	Rupture
Test 2	103	21.8	1250	5.2	780	Test terminated at 5 Bar
Test 3	96.4	22.7	1800	8.2	436 (wall wetting)	Test terminated with PRV activation at 8 Bar
Test 4	103	22.2	1210	7.4	560	Test terminated at 7.4 Bar
Test 5	99.1	29.7	2433	21	623	Test terminated at 21 Bar, near rupture

Primary observations from each of the tests are noted below. Other general observations are presented in Section 4.3, and more detailed test observations are presented in the appendices.

4.2.1 *Test 0 – Bare Tank – 98% Full - Water*

The key observations from this test were:

1. The tank failed very rapidly; in a little over 2 minutes.
2. The bulk liquid remained cool and this resulted in very little liquid volume expansion—the tank never went shell full
3. Pressure built up rapidly because of heating and compression of the vapor space air and temperature stratification and boiling in the liquid
4. Tank deformation was substantial before rupture and this increased the size of the vapor space, and the area of the unwetted wall (see Figure 14).
5. Appendix A provides more details, including additional pictures and charts.

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[1] To a cool surface

[2] This is the average heat flux absorbed by the tank and lading.

Figure 14. Test 0 - After Test - View of Deformed and Failed B-End

4.2.2 Test 1 – Jacketed and Insulated Tank – 98% Full - Water

The key observations from this test were:

1. This test lasted longer than the bare tank due to the effects of the jacket and insulation, with lower pressurization rates and lower tank temperatures at the top.
2. A minor failure and pressure leak occurred at 11 Barg pressure and a measured peak wall temperature of 550–610 °C. This failure occurred due to very high temperatures near the top (east) fill fitting.
3. Insulation fell away from the tank sides, shrank and separated on the tank top and melted/burned away completely in some locations where there was direct fire contact (see Figure 15).
4. The insulation at the openings in the jacket (e.g., top fill fittings) melted away leaving unprotected and exposed wall areas. These wall areas also experienced very high wall temperatures and significant plastic deformation.
5. The jacket experienced very high temperatures (700–850 °C) causing large thermal expansion relative to the cool water filled tank. This relative expansion led to high loads on the fill pipe extension and this contributed to the failure of the weld in that location. Other fittings also experienced large loads and deflections. Modifications were made to the remaining tanks to ensure that this loading was removed.
6. After this test ended, the team concluded that the failure time and failure mode for the vessel depends significantly on the insulation's performance. Previous data had suggested that the fiberglass insulation degraded away in about 5 minutes. While

significant insulation degradation was seen on this test as well, insulation failure was not quick. It could be the formulation of this modern insulation is much different than the one tested previously. Also, the previous test (which was a plate test) may have had the insulation fall down, which led to a total loss of the insulation's effectiveness. This was partially observed in this test.

7. Appendix B provides more details, including additional pictures and charts.

Figure 15. Test 1 - View of Separated Insulation on Tank Top at Mid Span. Picture also shows severe thinning of insulation.

4.2.3 Test 1b – Jacketed with No Insulation – 98% Full - Water

This test reused the tank from Test 1 with repaired fittings. The annular insulation was removed, but the jacket was re-installed in a manner that allowed it to expand with respect to the inner tank. Jacket openings (e.g., at the fittings) were covered with high temperature insulation to ensure that there was no direct fire exposure to the tank.

The key observations from this test were:

1. This test lasted just over 6 minutes when the tank burst at 12 Barg due to high wall temperatures (see Figure 16).
2. This test was the second test for this tank and some plastic deformation of this tank was observed in the first test. Therefore, this tank was not in new condition.
3. The heat flux to the tank was about half of the bare tank test, due to the radiation shield effect from the jacket.


06.10.2014 07:00

Figure 16. Test 1b - View of Vessel Rupture

The changes made during this test, including the reduced jacket restraint and improvements to the protection of the top fittings (from the fire), were made to all subsequent test tanks.

4.2.4 Test 2 – Jacketed and Insulated – 50% Full - Water

When the tank pressure was at 5.2 Barg, this test was terminated by shutting down the fire at 1,250 seconds. The key observations from this test were:

1. The extremely high wall temperature was measured at the tank top location, where a gap formed in the insulation at the mid length of the tank. This very high wall temperature could be the result of thermocouple separation from the tank wall (due to plastic deformation in that location).
2. It was expected that the tank would pressurize more slowly in the 50% fill test than in the 98% fill case. However, the pressurization was actually very similar to the 98% fill case.


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Figure 17. Test 2 - Insulation Separation at Mid-Tank

4.2.5 Test 3 – Jacketed and Insulated – 98% Full – NaOH Solution

This was the first test of a tank filled with hazardous material. The tank in this test was filled with a 50% solution of NaOH. There were some key differences in this test compared to the earlier tests, as listed below:

1. Improved insulation, such as a double layer in the center where separation was observed in the previous test, and the use of full-length pieces to prevent separation in the bottom half of the tank.
2. The use of a pressure relief device, which was set to 8 Barg, to avoid potential rupture and hazardous material release.

The test was terminated at 1,800 seconds, when the PRV was activated with the internal pressure reaching 8 Barg. At this time, the pressure was rising rapidly and the tank wall temperature was around 450 °C. Key observations from the test were:

1. The NaOH tests were expected to pressurize more slowly, because the saturation pressure vs. temperature curve is shifted to higher temperatures, by 50 °C (see Figure 18). However these tests started at higher temperature (55 °C for NaOH vs. 17 °C for water tests). This gave the NaOH test a head start to build up pressure. Thus, the pressurization of the tanks in the NaOH tests was very similar to that of the water tests.
2. Figure 19 shows the tank pressure measured by the two pressure transducers. The pressure started to rise above 0 Barg after 200 seconds, and it took another 400 seconds to reach 1 Barg. The rate of pressure rise was clearly increasing, and it took only about 100 seconds to go from 7 to 8 Barg when the PRV activated and the test was terminated.
3. Figure 20 shows the middle extra sheet of insulation being lifted back to show the gap between the two main sheets covering the cylinder. The extra sheet protected the other sheets, provided protection in the gap that forms due to insulation shrinkage, and reduced the insulation degradation. This change of insulation combined with other insulation improvements affected the tank pressurization rate and the wall temperatures. The average net heat flux to the hot jacket in this test (Test 3) was 22.6 kW/m^2 while it was 29.6 kW/m^2 for Test 1 (insulation and jacket, 98% fill with water), which is a reduction of 23 percent.
4. Some tank deformation was observed just beyond the double insulation layer, suggesting higher wall temperatures in those areas. Unfortunately, no thermocouples were located in those areas. Since the pressure was limited to 8 Barg, it suggests that wall temperatures on those areas must have been above 600 °C for plastic deformation to take place.
5. Wall temperatures, similar to the 98% fill water test case, were expected in this case but were not observed in the test data. Figure 21 shows the measured lading space temperatures. The thermocouples in the vapor space recorded temperatures as high as 330 °C. Lower down in the liquid, the temperature ranged between 70 and 190 °C. This is clear evidence of temperature stratification, which drove the tank pressure.
6. The lading temperatures vary dramatically due to boiling phenomena. Boiling leads to bubble formation in the liquid, which causes the liquid level to increase. When the increased level of liquid or swell comes in contact with the vapor space wall, it gets cooled very rapidly. This cooling effect is clearly seen in Figure 22 where wall

temperatures are shown. Sometime after 1,400 seconds, this boiling and wetting effect was reduced or stopped and the wall temperatures began to rise. This could be due to the increased pressure in the tank, which might have suppressed the boiling and reduced the size of the bubbles formed.

7. Once again the pressure in this test was dictated by the boiling boundary layer in the tank. This is shown in Figure 23 where the calculated saturation temperature based on the measured tank pressure correlates well with the warmest liquid in the tank.

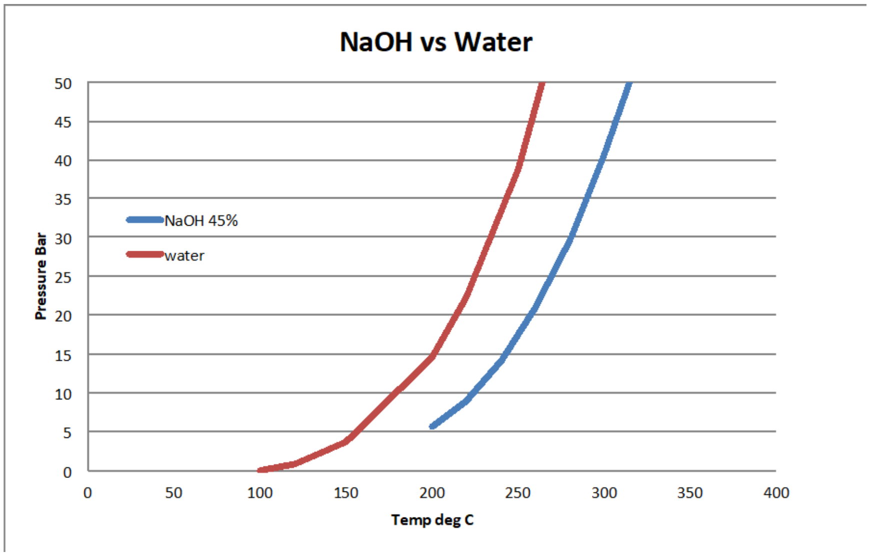


Figure 18. Saturation Pressure vs. Temperature for Water and NaOH 45% Solution

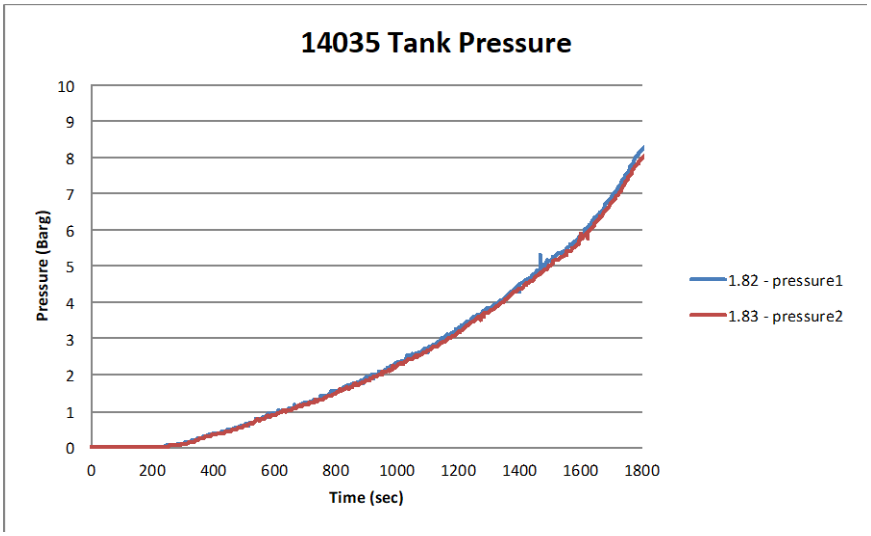


Figure 19. Test 3 - Tank Pressure

Figure 20. Test 3 - Second Layer of Insulation.
Note the condition of the protected insulation

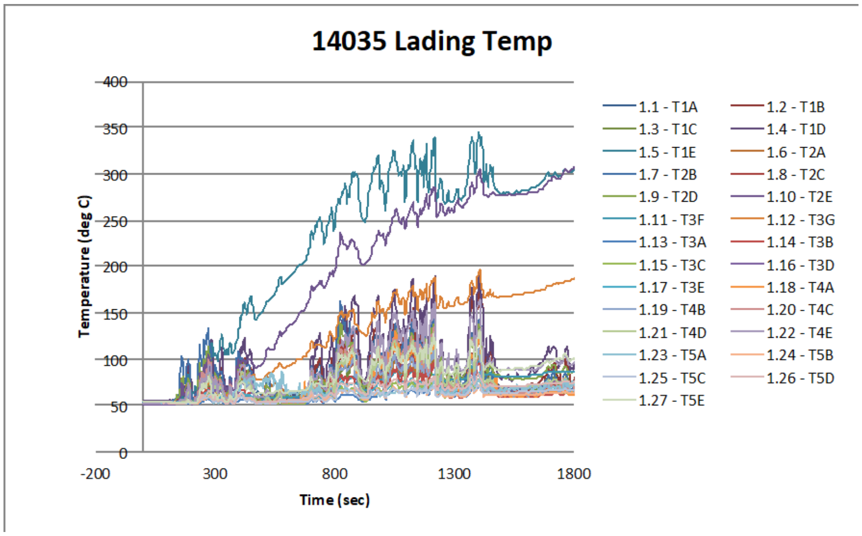


Figure 21. Test 3 – Lading Temperatures

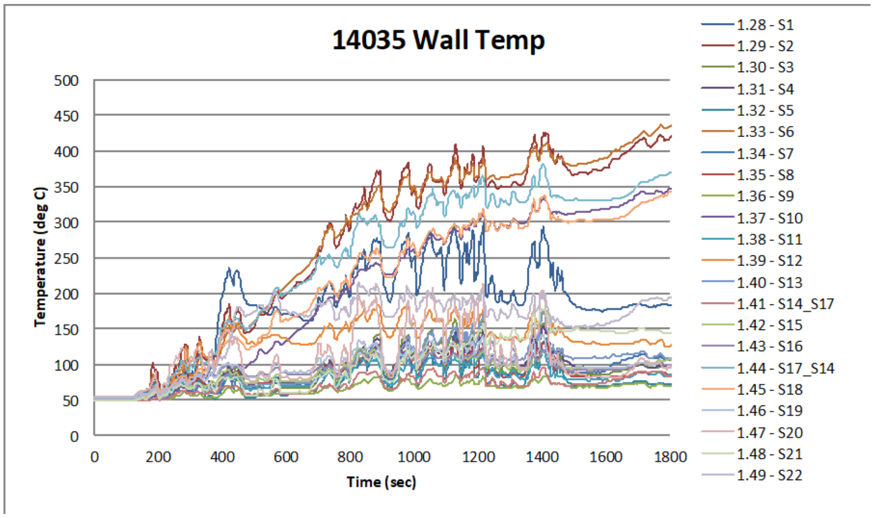


Figure 22. Test 3 - Wall Temperatures

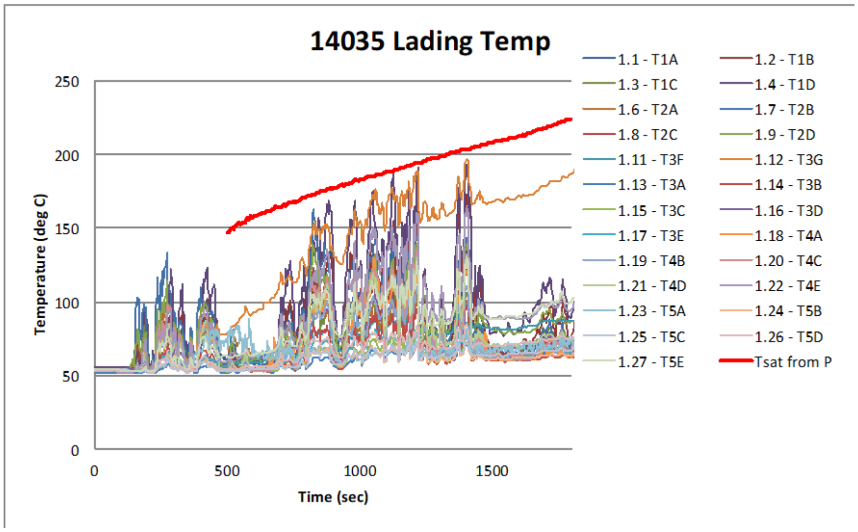


Figure 23. Test 3 - Wet Lading Temperatures - Note Line Showing Psat vs. Tsat

4.2.6 Test 4 – Jacketed and Insulated – 66% Full – NaOH Solution

The test went well with good fire conditions. This test also had the improved insulation (see Figure 24). Key observations from this test include:

1. This tank pressurized fastest of all the test tanks with jacket and insulation (including the water tests), which is not in line with the expectation that it would pressurize slower than Test 3 (98% NaOH).
2. Wall temperatures were in line with expectations for lower fill case.
3. Tank fill was around 66%, and not 50% as originally intended (see Figure 25); however, this did not have any negative consequences on the test execution, test results, or applicability of data.

4. There was much less boiling effect on the lading temperatures in this test, compared to Test 3.

Figure 24. Test 4 - Note Double Layer of Insulation at Mid Span

Figure 25. Test 4 - End View after Jacket Removal
Note liquid level markings on tank end. Tank was probably filled to 66%

4.2.7 Test 5 – Jacketed and Insulated – 98% Full – Water

This test was very similar to Test 1, except that the fittings mode of failure was eliminated. This test used the spare tank that was built in case there was a lost test. The test was terminated at 2,440 seconds. The measured pressure and peak wall temperature indicated the tank was at or very near failure. The insulation's failure modes were similar to those previously observed.

4.3 Overview of Other Key Observations

4.3.1 Liquid Stratification and Boundary Layer Effects

Over the entire test series, the team observed the extent to which liquid stratification and boundary layer effects dominated pressurization and resultant tank behavior. Figure 26 and Figure 27 highlight the extent of stratification observed in the tests; in both figures, measured temperatures at multiple heights inside the tank, ranging from 1” from the bottom to 1” from the top (35” from the bottom) are presented. As seen in Figure 26, the bulk temperature of the water as measured by most of the thermocouples is well below boiling, but the surface of the water is boiling to generate the significant pressures needed to rupture the tank. Figure 27 highlights the temperature stratification seen in the Test 3 with NaOH. Again, the bulk temperature of the liquid, even as seen at 9.5” from the top of the tank, is well below the surface temperature.

Significant temperature stratification was seen independent of the lading, the fill level, and the insulation condition. A review of the pressurization curves also indicates that the pressurization was not driven by bulk temperature rise and liquid expansion, but by the boiling of hot surface layers. This phenomenon is complex, poses modeling challenges and does not give itself to simple predictions. While this effect was clearly evident in these total containment tests, it is expected that similar behavior will also be present in cases where a PRD is used. Care should be taken when weighing survival predictions made with algorithms that do not account for these effects.

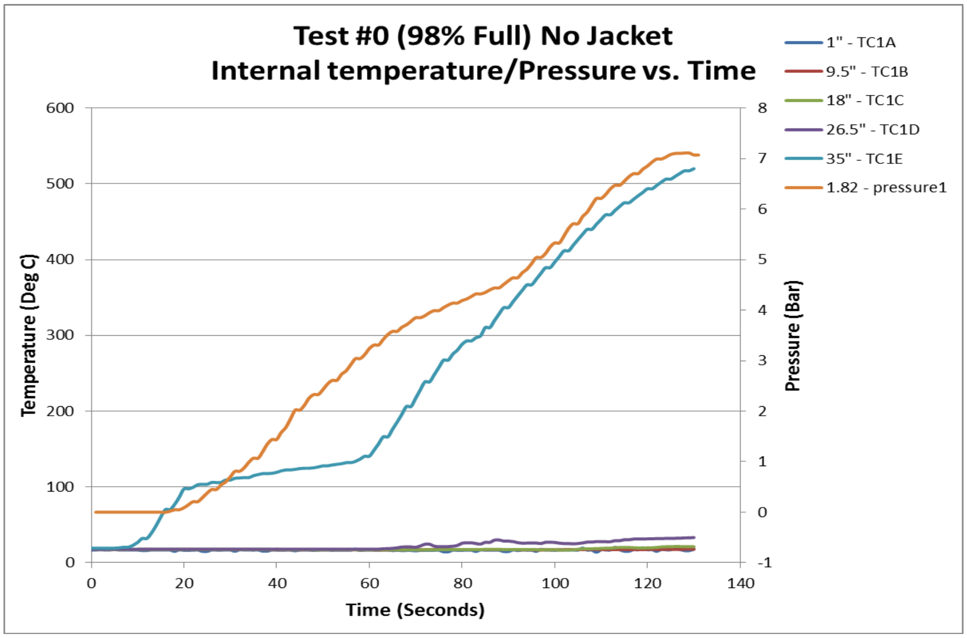


Figure 26. Temperature Stratification – Test 0 – Bare Tank – W/ 98% Water

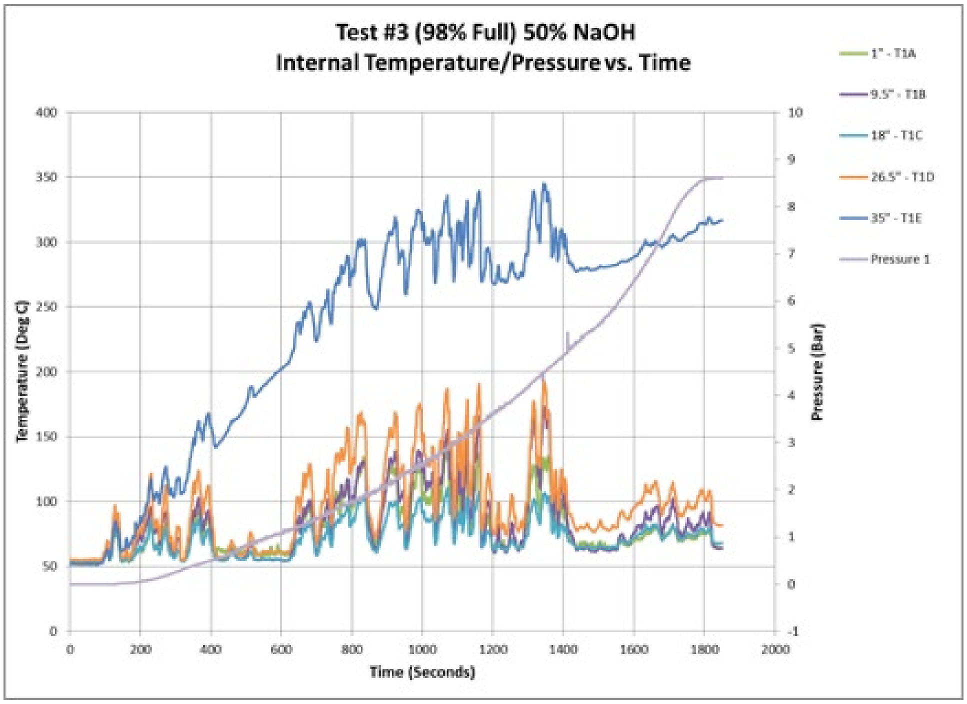


Figure 27. Temperature Stratification – Test 3

4.3.2 Insulation Performance

A review of the insulation after Tests 1 and 2 indicated that the insulation was not completely failing within 5 minutes, as initially expected. It was also observed that, as the test progressed, the insulation would separate and sometimes fall away, which would lead to portions of the tank being exposed to additional thermal input. Failure modes of insulation included melting, burning, sagging, compacting, stretching and tearing, as well as dropping and separating. It is understood that such behavior is common and consistent with nominal tank car construction, and as such, it is expected that insulation behavior in Tests 1 and 2 was consistent with expected full-scale behavior.

Figure 28. Test 1 – Images of Insulation Failure

However, the insulation installation was improved for Tests 3 and 4 (the NaOH tests) due to safety concerns, and also to consider if better insulation would help. For example, insulation seams that were likely to separate were covered with an additional layer of insulation, and additional constraints were employed to make sure that the insulation stayed. Therefore, we would consider the NaOH tanks to have a "premium" level of insulation compared to nominal full-scale tanks.

Figure 29. Test 4 – Images of Insulation Failure

Overall, it was seen that insulation degradation had a big effect on the observed fire performance of these test tanks. Given that the insulation was a "full-scale" insulation on a one-third scale tank, it is possible that insulation performance had a larger effect on performance of these test tanks than would be observed in full-scale tests.

4.3.3 Pressurization

For the water tests, the insulated and jacketed tanks experienced lower peak wall temperatures and slower pressurization than the bare tank and the tank with jacket but no insulation. In all cases, the average liquid temperature was well below the boiling point and therefore the pressurization was due to air compression and local boiling in the boundary layer. None of the 98% full water tanks came close to liquid full conditions (i.e., no wetting effects at tank top).

For the water tests, it was also seen that the variation of pressure rise time was not linear with heat flux. Tank with insulation and jacket had heat flux about 50% of that of jacket only case—but took four times as long to pressurize. It was also expected that the 50% fill tank would take longer to pressurize, which it did, but not by very much.

Test 4 (66 percent full NaOH) had the fastest pressurization of all the tests with insulation and jacket. On the other hand, Test 3 (14035 – 98 percent full NaOH) had the slowest pressurization of all the insulated and jacketed tests.

For the 98 percent fill cases, the NaOH had much lower (by 150 $^{\circ}$C) peak wall temperatures due to wall wetting. Water tests did not show any wall wetting, the reason for which was not clear. It could be due to minor differences in the fill level, boiling characteristics of NaOH vs. water or possible pressure tube boiling effects.

4.3.4 Other Questions

While the tests were successful in addressing the key question from the objective, these tests raised some questions that are not simple to answer without significant additional testing, including:

1. Why did the NaOH pressurize so quickly relative to the water tests? It was expected that the NaOH would pressurize more slowly due to its saturation pressure curve. Was it due to different boiling characteristics? Or, was it the higher initial temperature (the NaOH started at 55 °C vs. the water at 17 °C), or was it due to differences in the way the insulation degraded?
2. Why did wall wetting happen with 98 percent fill NaOH and not with water? Was it due to slightly higher fill? Or, was it the NaOH boiling properties (bigger bubbles causing more swell, and more wetting)? Or, was there boiling in the pressure measurement tubes causing added liquid swell?
3. Why did the 50 percent (66 percent) fill NaOH test pressurize the fastest of all the insulated and jacketed tank tests (water and NaOH)? Does NaOH boil more violently than water?
4. In the 98 percent fill NaOH test, did the pressure above 5 Barg suppress the boiling and cause the wall temperatures to smooth out and rise? How high would these wall temperatures have gone?
5. Why did the 98 percent fill NaOH pressurize so much slower than the 50 percent (66 percent) NaOH test? Was this delayed pressurization due to NaOH boiling properties or added insulation, or boiling in pressure tubes (i.e., mixing caused by rising jets from pressure tubes)?

Many of the above questions can be answered by better characterizing the behavior of NaOH solutions under high temperature conditions. However, there is a significant lack of detailed information on NaOH behavior that would be critical to gather if one needs to better model the survival behavior on tanks carrying such lading under fire conditions.

5. Extrapolation and Scaling to Full-Scale

The one-third scale fire tests provided pressurization and temperature rise data of the tanks under fire conditions. This section describes how the raw test data was extrapolated and scaled to answer the question of whether a full-scale tank carrying NaOH could survive a 100-minute, fully engulfing, pool fire. The specific steps were to:

1. Extrapolate the one-third scale tests that did not result in failure, to predict the expected failure times, and
2. Scale the tested and/or predicted one-third scale failure times to full-scale failure expectations

5.1 Extrapolation (One-Third Scale)

Several of the tests were stopped before failure. This was done to reduce damage to the test facility and also to ensure a hazardous materials spill/explosion does not take place. In three of the five water tests the vessel did fail (i.e., Test 0, Test 1 and 1b – all 98 percent full). Tests 2, 3, 4 and 5 were stopped before failure. The two NaOH tests (3 and 4) were terminated well before failure (at or before 8 Barg) because the Test Facility had zero tolerance for a hazardous material spill. Thus, it was necessary to extrapolate the measured pressure and peak wall temperatures to estimate the time to failure.

We need to extrapolate both wall temperature and tank pressure to estimate time to failure. Pressure was extrapolated linearly from the point where the test was terminated.

Peak wall temperature had to be extrapolated up to a time of around 2,000 seconds or around 600 °C whichever came first. This extrapolation was done manually to fit the shape of the curve.

Figure 30 shows the extrapolated plots for temperature, pressure, and the temperature pressure combination. Several independent extrapolations were attempted and failure times were calculated. The resulting uncertainty in the failure time was of the order of ±10%.

Except for the non-insulated cases, it was seen that the NaOH 66 percent fill case pressurized the fastest and the 98 percent NaOH pressurized the slowest. Note that all the insulated and jacketed tanks are extrapolated to reach 20 Barg within 31–39 minutes. At that pressure, we expect tank failure with a wall temperature of around 550 °C. All the tests but one (NaOH 98 percent with wall wetting) achieved this temperature in less than 28 minutes.

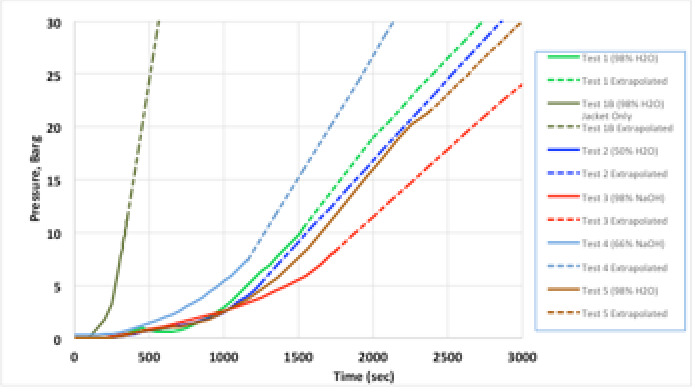
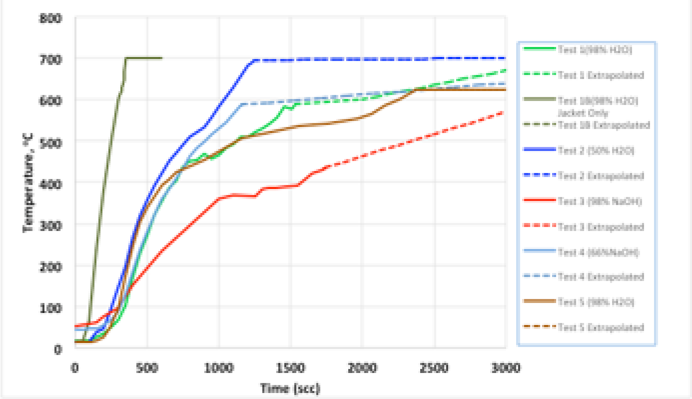
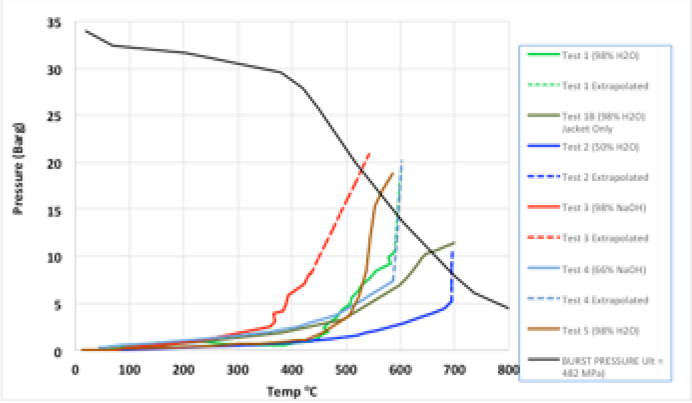
	P Vs. Time
	T Vs. Time
	P Vs. T and failure limit

Figure 30. Extrapolated Plots from Main Tests – One-Third Scale

5.2 Scaling to Full-Scale

These tests involved a reduced scale model of a rail tank car. The model tank diameter was approximately one-third that of the full-scale tank. To have the same burst pressure, the model tank also had a wall thickness about one-third that of the full-scale system. The model tank volume was one-third that of the full-scale system while the tank surface area was one-ninth that of the full-scale system. The one-third scale test results must be scaled to full-scale tank cars. The time for failure of the full-scale tank will be longer than that of the one-third scale model. This scaling depends on the following:

1. Material properties

2. Thermal protection system
3. Fire heat flux
4. Wall temperatures (and material degradation)
5. Pressurization (and stress)

The tank surface area (the area where heat enters the tank) to volume ratio (the part that is heated up by the fire) varies approximately with 1/D for a long cylinder. This means the bigger the vessel (the larger the D) the more slowly it will heat up. That suggests the one-third scale tank should heat up approximately three times faster than the full-scale tank.

The insulation used on this tank was approximately full-scale. The jacket was 3 mm thick and the insulation was 100 mm thick. For a fixed fire heat flux (to a cool surface) of around 100 kW/m^2, the tank scale and the insulation system determine how quickly the tank will heat up. There was a difference in that the ratio of the jacket diameter to the tank diameter for the model (44/36=1.22) was different from that of the full-scale (116/108= 1.07).

It is expected that the insulation will degrade away in a similar fashion to that in the full-scale system. That assumes the failure modes (burning, melting, thinning, sagging, tearing, etc.) of the insulation are similar in the scale model and the full-scale system.

The tank wall material properties are nearly the same (density, specific heat, thermal conductivity, ultimate strength, yield strength, etc.).

The fire heat flux was similar to that expected in an engulfing liquid hydrocarbon pool fire at full scale (around 100 kW/m^2 to a cool surface). The heat flux to the one-third scale model tank was slightly higher due to the jacket diameter ratio issue noted earlier. We estimated that the fire heat flux will be about 6 percent higher due to this.

The wall temperatures will rise more slowly in the full-scale tank because of the thicker wall. We are assuming surface emissivities and the convective heat transfer coefficients are nearly the same for the small and large-scale systems. The time to heat the wall will increase by a factor of the scale (s = 3).

As an approximation, the free convective boundary layer thickness on a vertical wall was used to scale the pressure results. In this case, the boundary layer thickness is proportional to the wall height (i.e., tank D) to an exponent of 0.6 (i.e., h^0.6) (Eckert and Jackson [10]). This factor is 1.93 when the scale factor, s = 3. Therefore, we expect the full-scale tank to pressurize slower than the one-third scale model by a factor of around 1.93. Appendix H provides some additional details on scaling and discusses a brief validation effort on this scaling approach.

The following method was used to scale failure times from one-third scale to full-scale.

- The failure plot of burst pressure vs. wall temperature was plotted for each test using high temperature material tensile data for SA 455 steel. This material properties data proved to be quite accurate for the tests where failure did occur.
- Where tests were terminated early it was necessary to extrapolate the plots to failure.
- The scaling to full-scale required the adjustment of the time for reaching the specified wall temperature and tank pressure. A factor of s = 3 was used for the temperature time correction and a factor of s = 3^0.6 = 1.93 for the pressure time correction.

For example, let us take the following data from a one-third scale fire test:

1. *At time = 300 sec*
    a. *Tank P = 2 Barg*
    b. *Peak wall T = 400^o C*

When we scale to full-scale, this becomes:

- a. *Tank P = 2 Barg at 1.93 x 300 = 579 seconds*
- b. *Peak wall T = 400^o C at 3 x 300 = 900 seconds*

Now the time is different for the tank pressure and T, which means they can no longer be plotted together on the original failure plot of burst pressure vs. wall temperature. We must plot the P vs. T that both occur at the same time. Note also that we have not accounted for continued insulation degradation for the much larger full-scale times. We have assumed the P and T are the same for small and full-scale tank. With continued insulation degradation we would expect higher P and T at later times.

Figure 31 shows the scaled plots for peak wall temperature versus time and pressure versus time, as well as burst and tank pressure versus peak wall temperature for the full-scale tank. The failure plot curves for full-scale have also shifted due to the time change. From the figures, we see a cluster of failures for the full-scale tank around P = 17.5 Barg with wall temperatures around 540 $^{\circ}$C. This takes place around 3800 seconds or 65 minutes.

It must be noted that the scaling approach does not include the effects of liquid boiling, which could add another layer of complexity to the scaling effort, and potentially make the survival estimates non-conservative.

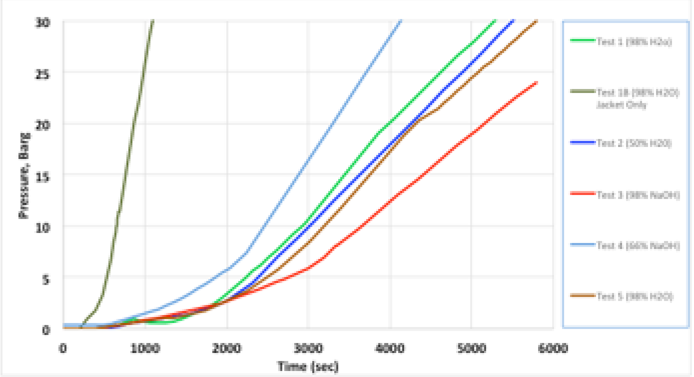
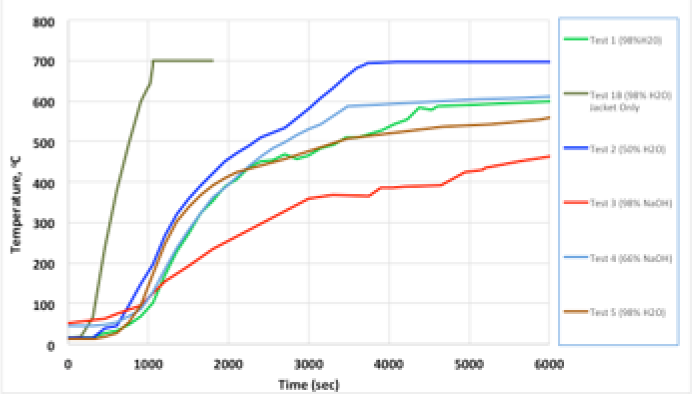
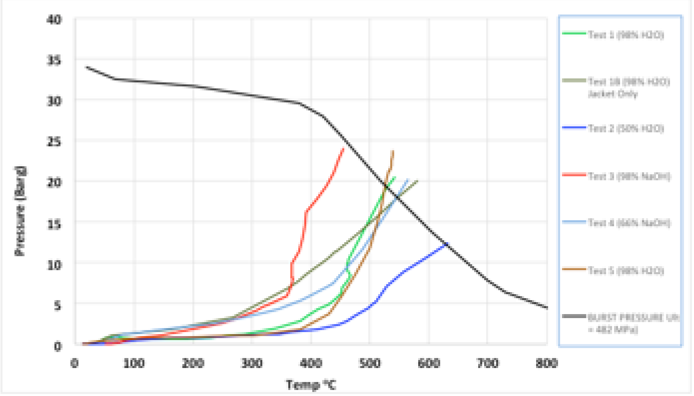
	P Vs. Time
	T Vs. Time
	P Vs. T and failure limit

Figure 31. Scaled Plots from Main Tests – Full-Scale

Table 7 gives a summary of all the extrapolated test results and the calculated full-scale results based on the scaling method proposed here. The uncertainty in the results from the time scaling and time extrapolation is around ±10% on the failure times.

Table 7. Summary of Extrapolated & Scaled Failure Times

Test	Test conditions	One-third scale failure P and T	One-third scale estimated failure time	Full-scale estimated failure P and T	Full-scale estimated failure time
0	98% water Bare tank	7 Barg 740 °C	120 s 2 min	13 Barg 620 °C	312 s 5 min
1	98% water Insulation and Jacket	15 Barg 630 °C	1,750 s 29 min	19 Barg 560 °C	4,250 s 71 min
1b	98% water Jacket only	12 Barg 670 °C	370 s 6 min	17 Barg 580 °C	790 s 13 min
2	50% water Insulation and Jacket	8 Barg 700 °C	1,500 s 25 min	13 Barg 630 °C	3,300 s 55 min
3	98% fill NaOH 50% solution Improved insulation and Jacket	20 Barg 560 °C	2,700 s 45 min	26 Barg 460 °C	5,300 s 88 min
4	50% fill NaOH 50% solution Improved insulation and Jacket	8 Barg 700 °C	2,100 s 35 min	17 Barg 590 °C	3,700 s 62 min
5	98% water Insulation and jacket (repeat of test 1)	17 Barg 560 °C	2,100 s 35 min	20 Barg 540 °C	4,300 s 72 min

Note that the NaOH tests are considered to have better insulation conditions than what are nominally seen. The following can be seen from the results in the table:

1. Full-scale tank fails at a higher pressure and lower wall temperature than one-third scale. This is because the wall temperature rises more slowly than the pressure at larger scale.
2. None of the estimated failure times is larger than 100 minutes for the full-scale system.
3. We are estimating full-scale tank failure with NaOH between 62 and 88 minutes. The longer time was for the 98 percent full case, where there was wall wetting in the vapor space.
4. Test 5, which was a repeat of Test 1, was in generally in agreement with Test 1, which suggests that the test results are very repeatable.

A discussion of the heat transfer coefficients associated with these tests is presented in Appendix I.

6. Conclusion

This research set out to answer the question of whether tank cars carrying caustics can meet the 100-minute fire performance requirement under conditions of total containment? Review of the results from the one-third scale tests, and subsequent scaling to full-scale suggests that the failure time for a full-scale tank car filled with 50 percent NaOH solution to be in the range of 62–88 minutes. This estimation is strongly influenced by the insulation condition and tank fill (i.e., wall wetting). Clearly, these do not meet the 100-minute survival requirement.

While focused on the above question, the research also addressed several issues that were related to the fire performance of tank cars, ranging from setting up a fire test to effectively simulate a pool fire, to insulation performance, liquid stratification and boundary layer effects, and finally, extrapolation and scaling factors between one-third scale and full-scale. Several of these key findings are outlined below.

6.1 Development of Simulated Liquid Hydrocarbon Pool Fire

1. It has been shown that liquid propane burners can be used to produce a realistic simulation of a liquid hydrocarbon pool fire.
2. Instrumentation used to characterize this fire showed that the fire had a heat flux of approximately 100 kW/m^2 to a cool surface, a fire black body temperature of 896 $^{\circ}$C and the heat flux was approximately 80 percent by radiation. **When the fire was set up to give full engulfment it had fire characteristics almost identical to the rear end (fully engulfed end) of the RAX 201 full-scale fire test.**
3. The fire was shown to have consistent behavior from test-to-test. This was demonstrated in three 15-minute calibration burns. These tests showed consistent black body fire temperatures and total heat flux to the water calibration tank.
4. The fire was able to provide full engulfment testing in winds up to 3 m/s (7 mph).

6.2 Total Containment Water Tests

1. The unprotected tank and the jacket-only tank failed rapidly due to high wall temperatures and pressures. The jacketed tanks resulted in longer failure times as expected, because the jackets reduced the heat flux by about 50 percent. The failures were well-explained using SA 455 material property data at elevated temperatures.
2. The insulated tanks pressurized much slower, and the peak wall temperatures were much lower.
3. There was clear evidence of boiling and liquid temperature stratification in the liquid. However, this boiling action did not appear to wet the vapor space wall and reduce the peak wall temperatures in a significant way.
4. The insulation did not degrade away fully but did show several different failure modes including shrinking, melting, compacting, separating, and dropping down in the annulus. These failure modes had very significant effects on the observed peak wall temperatures and wall plastic deformation. The details, of how the insulation is installed, are very important to understand/estimate the insulation failure.

5. There were local hot spots that led to local plastic deformation on the tank. These local hot spots could have led to local tank failure, if the tests ran for longer times.
6. The 98 percent fill cases did not go shell-full and re-wet the top surface, as initially expected. This resulted in the wall temperatures at the top staying high and not reducing.

6.3 Total Containment Hazmat Tests

1. The rates of tank pressurization in the tests with NaOH solution were not very different from those of the water tests. We expected to see slower pressurization with NaOH due to the different saturation pressure curves, but this was not observed. It could be due to the starting temperature and the boiling characteristics of the NaOH solution.
2. The NaOH test involving the 98 percent full tank also did not go shell-full, but it showed very different wall temperature results than the water test. Transient wetting caused by boiling and liquid level swell reduced the vapor space wall temperatures. It is not clear whether this was caused by a small change in the liquid fill level or the boiling characteristics of the 50 percentage NaOH solution.
3. The wall temperatures for the 66 percent full NaOH test were similar to those seen in the water test.
4. The pressurization time to 8 Barg for the 98 percent full NaOH test was delayed by about 7 minutes when compared to the same test with water. However, it is not clear whether this was due to the NaOH characteristics or the improved tank insulation. The estimated heat flux to the tank from the DFT and jacket temperatures suggests the heat flux entering the NaOH lading was 24 percent less than in the same water test. The insulation was clearly in better condition at the end of this test.
5. The full containment test with 66 percent fill of NaOH pressurized faster than the 98 percent fill case, and it was faster than both the 50 percent and 98 percent fill water tests. This is an unexpected result. This could be due to the boiling characteristics of the NaOH solution.

6.4 Scaling Test Results to Full-Scale

The scaling of the test results to full-scale was done as follows:

1. The time scale for wall temperature rise was increased by a factor of 3
2. The time scale for pressure was increased by factor of 1.93
3. The material ultimate strength was adjusted down to 482 MPa at ambient temperature

The following estimates are provided for the failure time of the full-scale systems. Please note that these tests had a better level of insulation than nominal.

98% Full, 41 °C, NaOH 50% Solution in Water

Failure by combined high wall temperature and pressure at 88 minutes. The uncertainty of the estimate is ±10 percent.

50% Full, 41 °C, NaOH 50% Solution in Water

Failure by combined high wall temperature and pressure at 62 minutes. The uncertainty of the estimate is ±10 percent. This tank was filled to 66 percent not the desired 50 percent. However, it is not expected that this would change the failure time by any significant amount.

7. Recommendations

This test effort generated significant amounts of data that could be used to estimate fire performance of tanks and, specifically, to validate the models that predict tank car performance. It also revealed the need for additional analysis and testing so that we may better understand and model the fire performance. Key recommendations from this effort are discussed below.

7.1 Full-Scale System Performance

The total containment system may be able to survive 100 minutes in a fully engulfing liquid hydrocarbon pool fire if the insulation/thermal protection system were to be improved. It is believed a number of state-of-the-art thermal protection systems could protect the total containment system for 100 minutes. Further analysis and fire testing is needed to confirm this.

7.2 Scaling of Total Containment Model Test Results

The scaling from one-third scale to full-scale in these tests was not straightforward and required simplifying assumptions that are not fully validated. Further research is required to understand the complex 2-phase processes that influence the maximum wall temperatures and pressurization in total containment.

The following work is needed to develop a computer model that can accurately model total containment:

1. Development of a temperature stratification model so that tank pressurization can be properly predicted for a range of fill levels, commodities and heat fluxes.
2. Development of a boiling and swell model for vapor space wall wetting at high fill levels. This is required for a range of commodities, heat fluxes, and fill levels.

The following experimental data is needed to validate these new models:

1. Data on the boiling characteristics of commodities such as NaOH or KOH.
2. Detailed temperature mapping inside a vessel exposed to heat fluxes in the range of 20-100 kW/m^2.

8. References

1. Code of Federal Regulations, Title 49, Part 179, Specifications for Tank Cars, Section 179.18, Thermal Protection Systems, October 1, 2007.
2. Johnson, M. R., "Temperatures, Pressures, and Liquid Levels of Tank Cars Engulfed in Fires: Volume 1, Results of Parametric Analyses," Technical Report, DOT/FRA/OR&D-84/08.1, Federal Railroad Administration, Washington, DC, 1984.
3. Townsend, W., Anderson, C. E., Zook, J., and Cowgill, G., "The Effects of a Fire Environment on a Tank Car Filled with LPG," Technical Report, DOT/FRA/ORD-75/31 Federal Railroad Administration: Washington, DC, 1974.
4. Birk, A. M., "Scale considerations for fire testing of pressure vessels used for dangerous goods transportation," *Journal of Loss Prevention in the Process Industries*, Vol. 25, pp. 623-630, 2012.
5. Code of Federal Regulations, Title 49, Part 179, Specifications for Tank Cars, Section 179.201-1, Individual Specification Requirements, August 14, 2003.
6. Code of Federal Regulations, Title 49, Part 179, Specifications for Tank Cars, Appendix B, Procedures for Simulated Pool and Torch-Fire Testing, October 5, 2012.
7. ASTM E1529-14a, Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies, ASTM International, West Conshohocken, PA, 2014.
8. UL 1709, Standard for Rapid Rise Fire Tests of Protection Materials for Structural Steel, Underwriters Laboratories, August 2011.
9. Townsend, W., Anderson, C. E., Zook, J., and Cowgill, G., "Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled with LPG Subjected to a Fire Environment," Technical Report, DOT/FRA/ORD-75/32, Federal Railroad Administration: Washington, DC. 1974.
10. Eckert, E. R. G., Jackson, T. W., "Analysis of Turbulent Free-Convection Boundary Layer on a Flat Plate," NACA Report 1015, 1951.

Appendix A.
Test 0 – Bare Tank - 98% Fill - Water (BAM 14031)

Test 0 tank was a bare tank, without any insulation and jacket. The tank was filled approximately with 98% water at 18 °C. This test was very brief, lasting approximately two minutes when the tank burst, even before the fire was fully established. There was very little energy stored in the tank and therefore the failure had low energy.

This test showed that even with a very small vapor space, extremely high wall temperatures can be achieved very quickly in a severe fire environment. The pressurization rate was also very fast due to the high fill level, thin wall (3mm), temperature stratification and the lack of thermal insulation and jacket.

Significant observations from this test were:

1. The fire conditions were fully engulfing and of the desired intensity even within the short duration. There was almost no wind during this test.
2. The bulk liquid remained cool and this resulted in very little liquid volume expansion -- the tank never went shell full
3. Pressure was built up rapidly because of heating and compression of the vapor space air, temperature stratification and boiling in the liquid
4. Tank deformation was substantial before rupture and this increased the size of the vapor space, and thus the area of the unwetted wall

Figure 32 shows the tank before and Figure 33 and Figure 34 after the test. The plots of tank performance over the 2-minute burn are presented as given below.

1. Internal Temperature/Tank Pressure vs. Time (Figure 35)
2. Shell Top Temperature/ Pressure vs. Time (Figure 36)
3. Wall Temperatures vs. Time (Figure 37)
4. Liquid Wetted Wall Temperatures vs. Time (Figure 38)
5. DFT Average Temperature vs. Time (Figure 39)
6. Burst pressure/ Tank Pressure vs. Wall Temperatures (Figure 40)

Figure 32. Test 0 (Bam 14031) - Before Test

Figure 33. Test 0 - View of Deformed and Failed B-End

Figure 34. Test 0 - View of Deformation and Failure Opening.

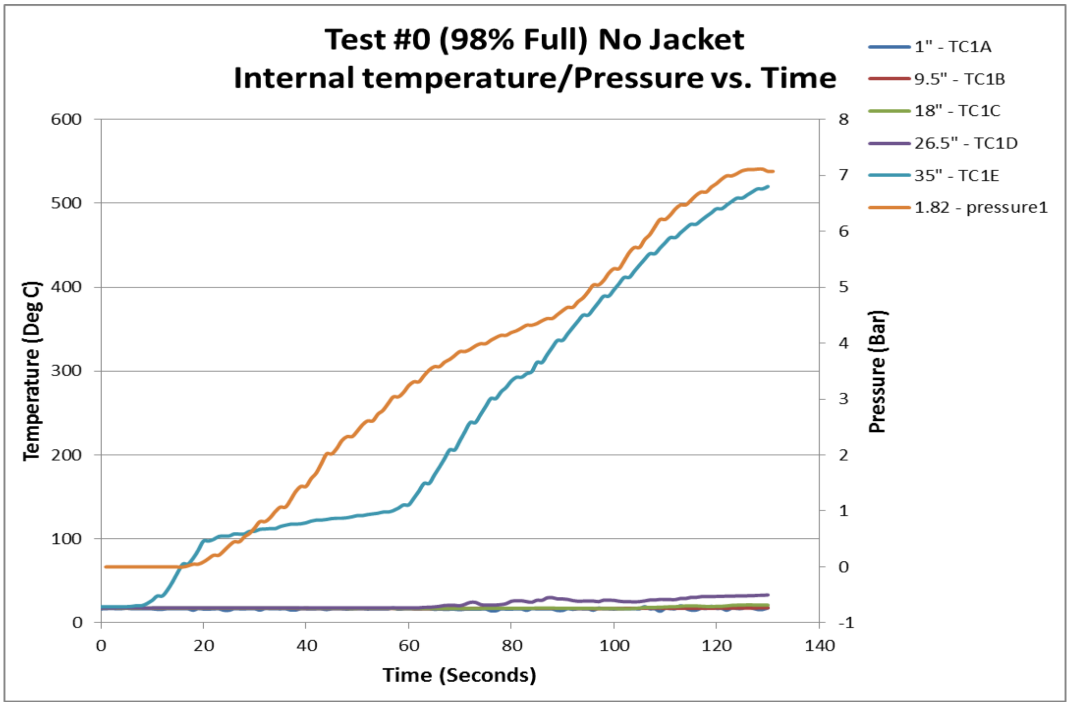


Figure 35. Test 0 (BAM 14031) - Internal Temperature/Tank Pressure vs. Time

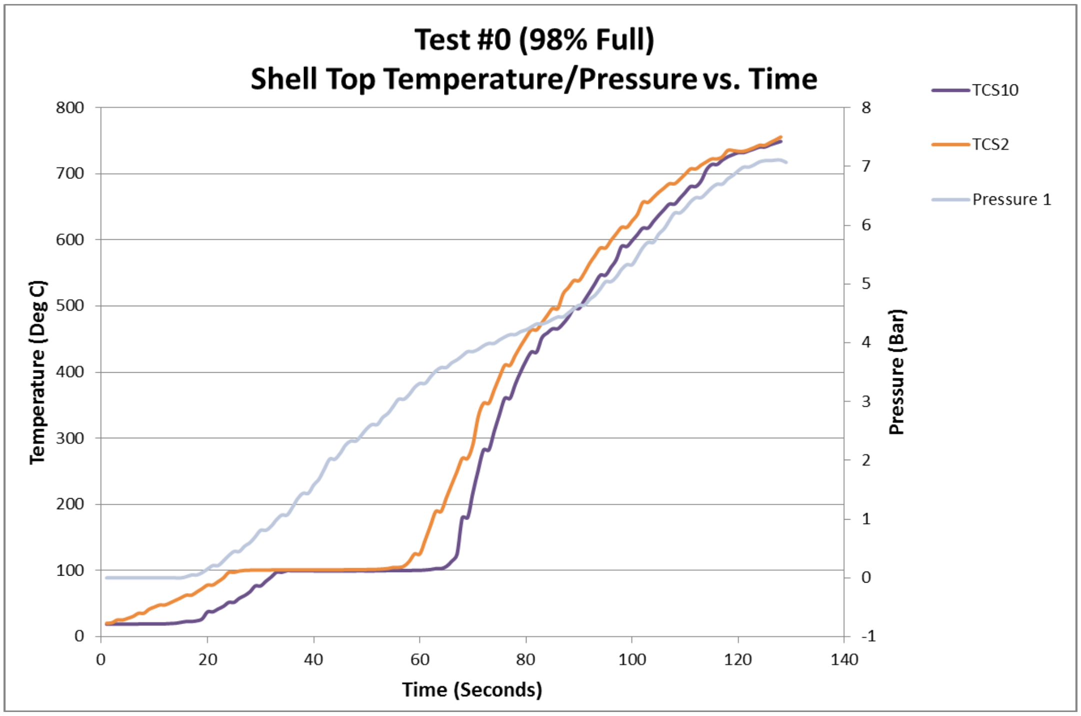


Figure 36. Test 0 - Shell Top Temperature/ Pressure vs. Time

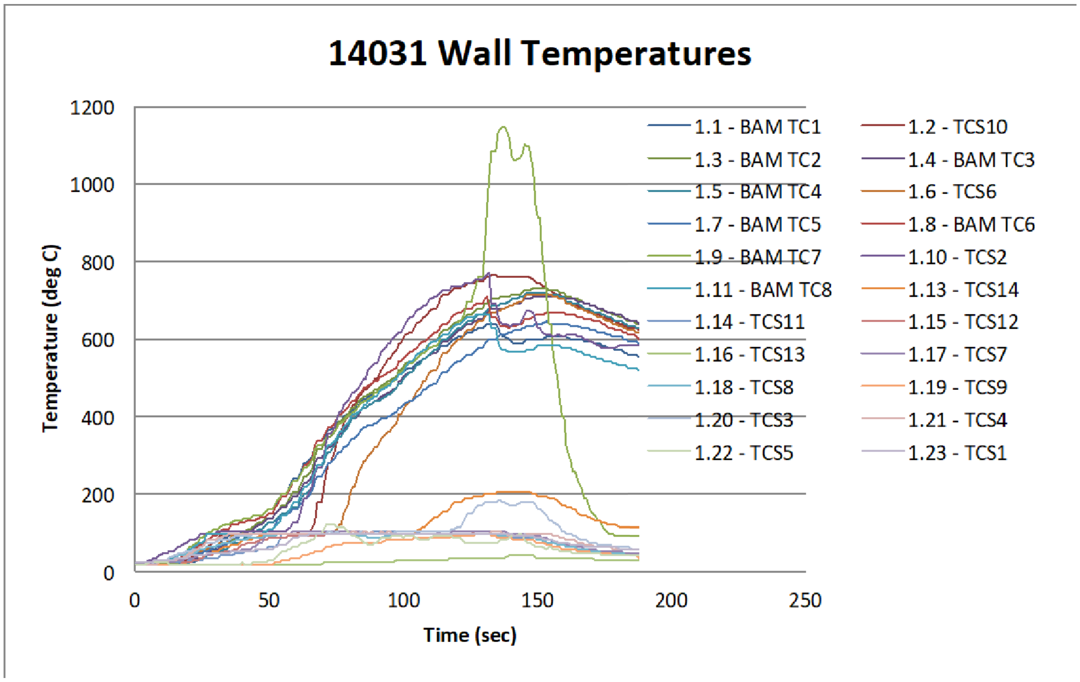


Figure 37. Test 0 - Wall Temperatures vs. Time

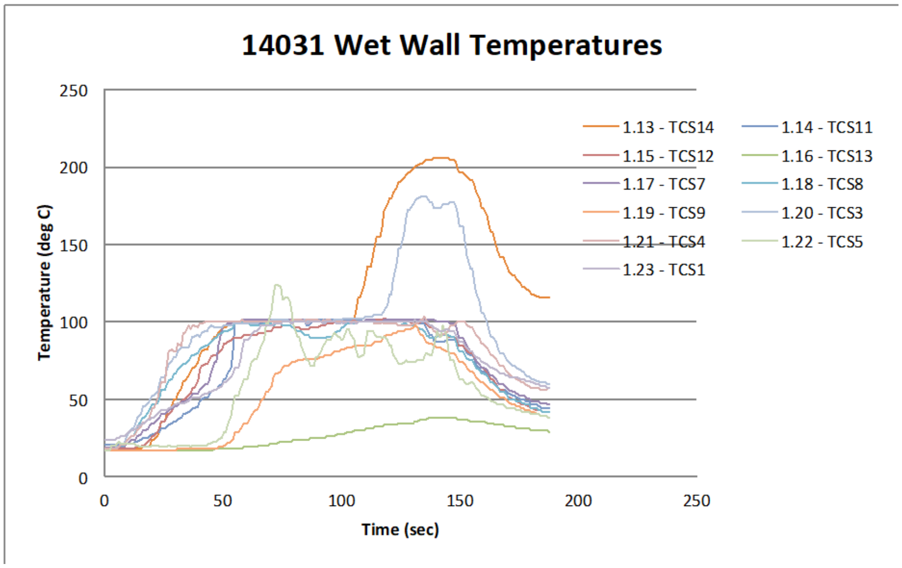


Figure 38. Test 0 - Liquid Wetted Wall Temperatures vs. Time.

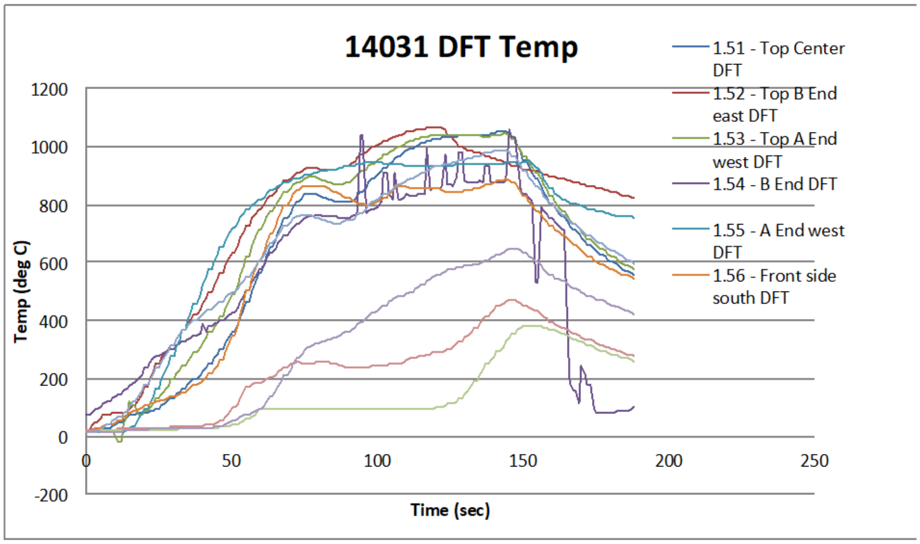


Figure 39. Test 0 - DFT Temperatures

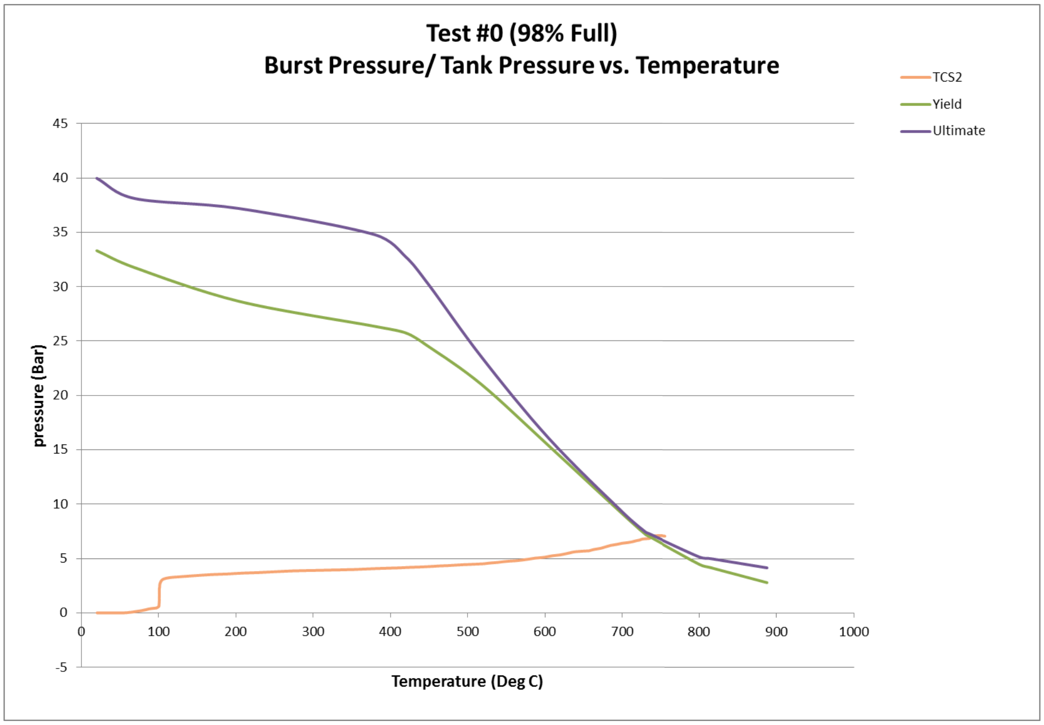


Figure 40. Test 0 - Burst Pressure and Tank Pressure vs. Wall Temperatures.

The following observations can be derived from the plots:

The pressure in the tank rose rapidly up to the failure pressure of 7.2 Barg. The majority of the liquid was well below 100 °C (TC1B, TC1C, TC1D, TC1E) showing that air space compression and boundary layer boiling dominated the pressure. The tank wall temperatures at the tank top rose up to around 700-760 °C (TCS10, TCS2). The liquid wetted wall temperatures mostly stayed below 100 °C with some rising to 200 °C. These areas of higher temperature may be local areas with boiling.

The lading thermocouples in the vapor space rose up to temperatures above 500 °C (TC1E), but this is probably a false high reading due to radiation from the very hot vapor space wall. The lading temperatures in the liquid clearly show temperature gradients (thermal stratification). This is due to the heat entering the boundary layer near the wall and this layer rising to the liquid surface. It is this hot and boiling boundary layer that is driving the pressure in the tank. The boundary layer temperatures could not be resolved with the thermocouples equipped in this tank.

Failure is well predicted using the maximum normal stress theory of failure and the data for SA485.

The conclusion is that a bare total containment vessel would fail quickly in a severe fully engulfing fire. This test simulated a tank with the jacket and insulation completely torn off in a derailment.

Appendix B.
Test 1 – Jacketed and Insulated - 98% Fill - Water (BAM 14032)

The Test 1 tank was insulated and jacketed (3 mm jacket, 100 mm fiberglass insulation), and 97.3 percent filled with 17 °C water (equivalent to 98 percent fill with 41 °C).

This test lasted much longer than the bare tank due to the thermal insulation. Pressurization was much slower and wall temperatures on the tank top were much lower compared to the bare tank test. The tank suffered a minor failure (split in weld heat affected zone near a fill fitting) at approximately 25 minutes. Figure 41 shows the tank before the test.

Significant observations from this test were:

1. There was some wind during the test, but all the data suggests that this was a fully engulfing fire as required by this test program.
2. There was severe distortion in the jacket. This probably occurred because the jacket expanded due to its very high temperature while simultaneously being constrained by the tank that was cool.
3. A minor failure and pressure leak occurred at 11 Barg pressure and a measured peak wall temperature of 500-610 °C. This failure was caused by very high temperatures near the top (east) fill fitting. This fill fitting came in hard contact with the jacket and was bent over by this contact (See Figure 42).
4. Insulation fell away from the tank sides, shrank and separated on the tank top and melted/burned away completely in some locations where there was direct fire contact. The insulation did not totally disappear or melt away. There were still significant amounts of insulation present in many locations especially where the insulation was in contact with the cold tank wall (wetted wall, See Figure 43).
5. On the tank top the insulation shrank down to a thickness of less than 2 cm from the original 10 cm, but mostly stayed in place (See Figure 44).
6. Separate pieces of insulation on the top separated to give a circumferential opening about 3 cm wide. This region experienced very high temperatures and significant plastic deformation. One thermocouple in this area registered very high wall temperatures.
7. The insulation melted away leaving unprotected and exposed wall areas where there were openings in the jacket (e.g., top fill fittings). These wall areas also experienced very high wall temperatures and significant plastic deformation (See Figure 45).
8. The 3 mm jacket experienced very high temperatures (700-850 °C) and this caused large thermal expansion relative to the cool water filled tank. This expansion was of the order of 25 mm. This relative expansion lead to high loads on the fill pipe extension and this contributed to the failure of the weld in that location. Other fittings also experienced large loads and deflections. Modifications were made to the remaining tanks to ensure this loading was removed (See Figure 46).

The following figures show the condition of the insulation and the site of the tank failure.

Figure 41. Test 1 (BAM 14032) - Before Test

Figure 42. Test 1 - View of Damaged Fill Pipe on B-End (East) (Location of Minor Failure)

Figure 43. Test 1 - View of Dropped Down Insulation on West End and South Side

Figure 44. Test 1 - View of Separated Insulation on Tank Top at Mid Span
Picture also shows severe thinning of insulation.

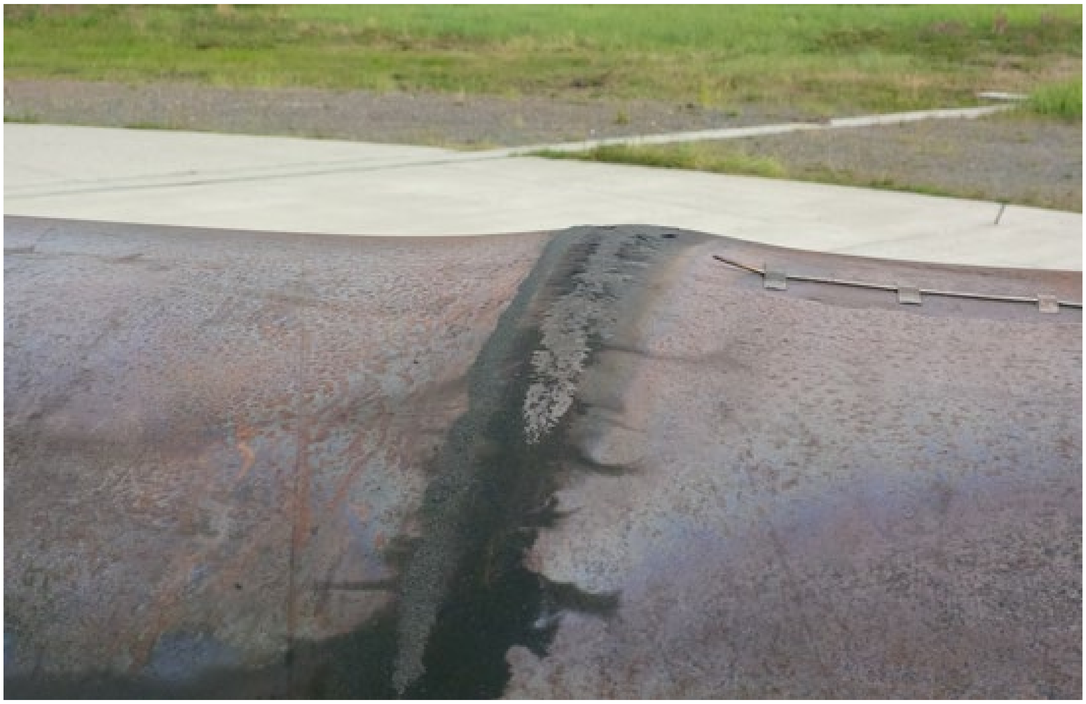


Figure 45. Test 1 - Plastic Deformation at Location of Separated Insulation

Figure 46. Test 1 - Burned Away Insulation at A-End Fill Fitting

The following plots from the Test 1 are shown in the figures mentioned below.

1. Internal Temperature/Tank Pressure vs. Time (Figure 47)

2. Shell Top Temperature/ Pressure vs. Time (Figure 48)
3. Average DFT and Jacket Temperatures (Figure 49)
4. Heat Flux from Fire and Net Heat Flux to Jacket (Figure 50)
5. Tank Surface Temperatures (Figure 51)
6. Wet Lading Temperatures (Figure 52)
7. Burst Pressure and Tank Pressure vs. Wall Temperatures (Figure 53)

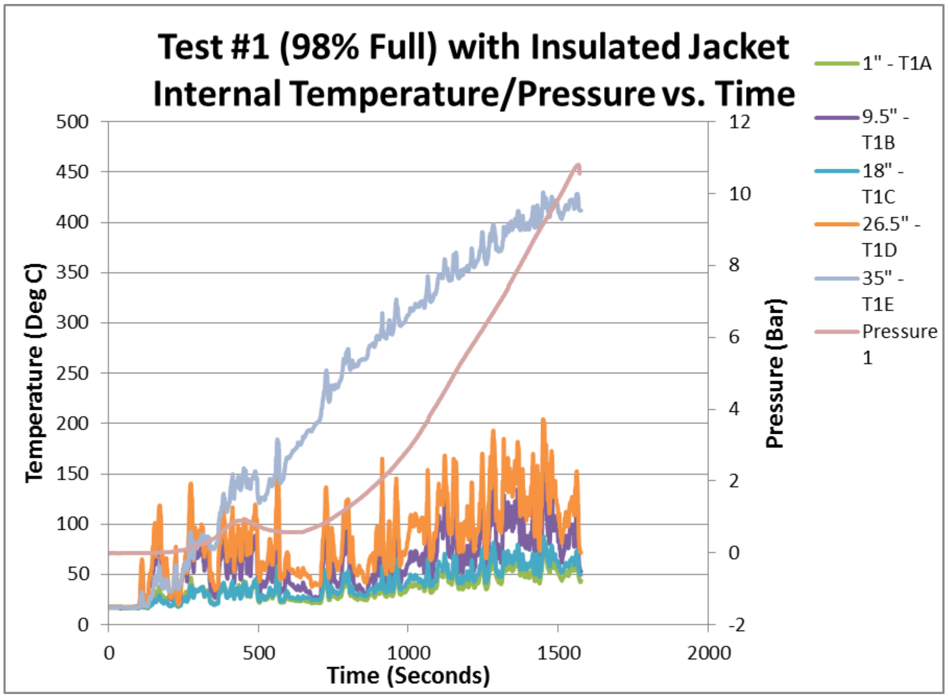


Figure 47. Test 1 - Internal Temperature/Tank Pressure vs. Time

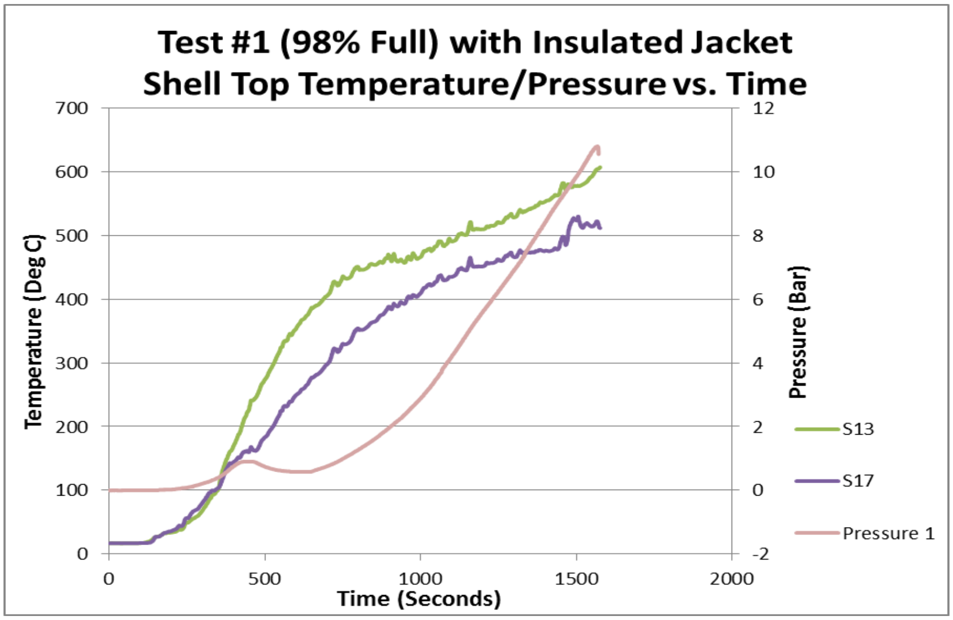


Figure 48. Test 1 - Shell Top Temperature/ Pressure vs. Time

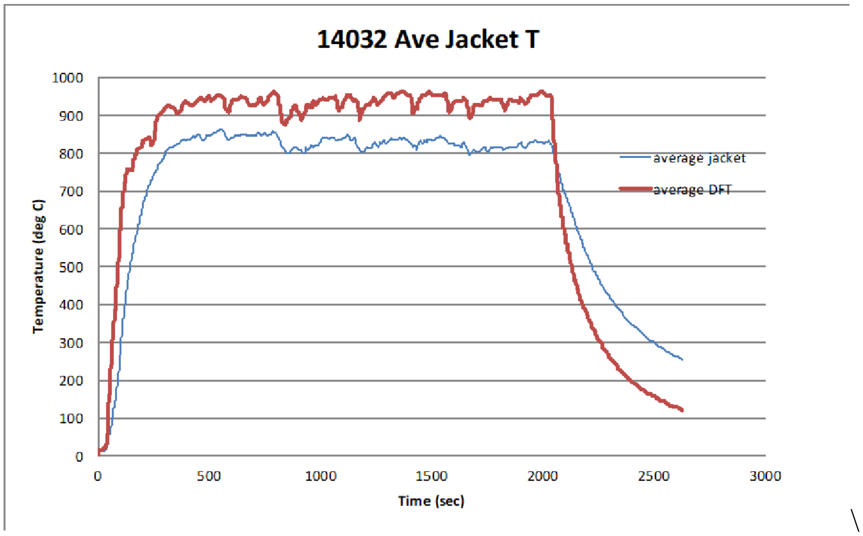


Figure 49. Test 1 - Average DFT and Jacket Temperatures

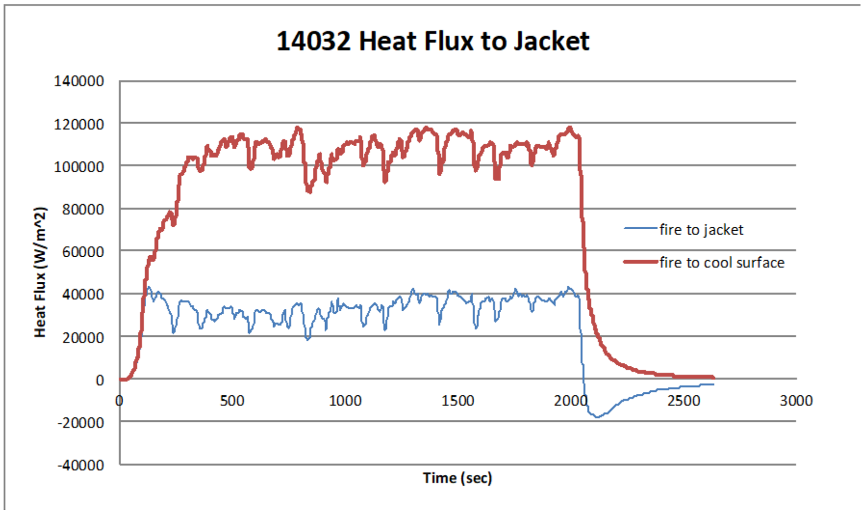


Figure 50. Test 1 - Heat Flux from Fire and Net Heat Flux to Jacket

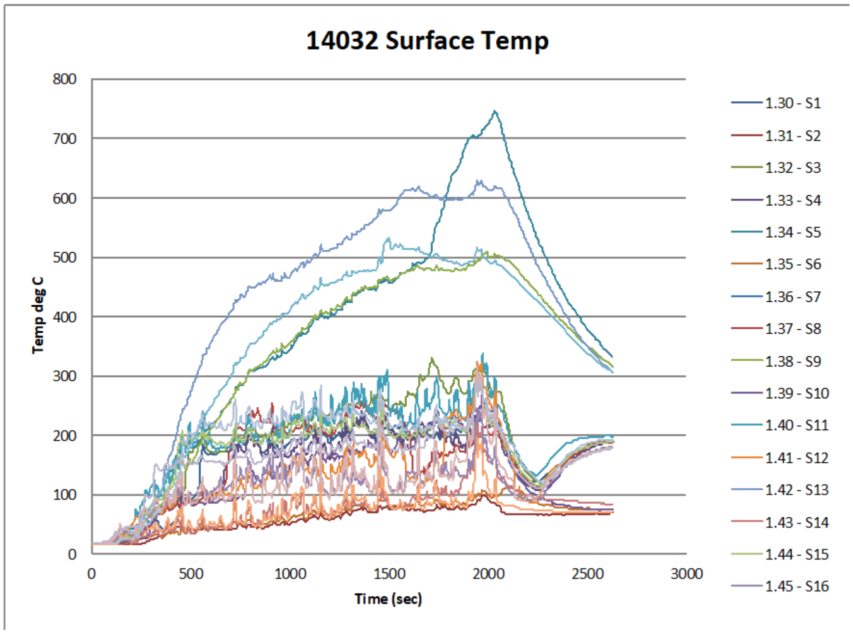


Figure 51. Test 1 - Tank Surface Temperatures

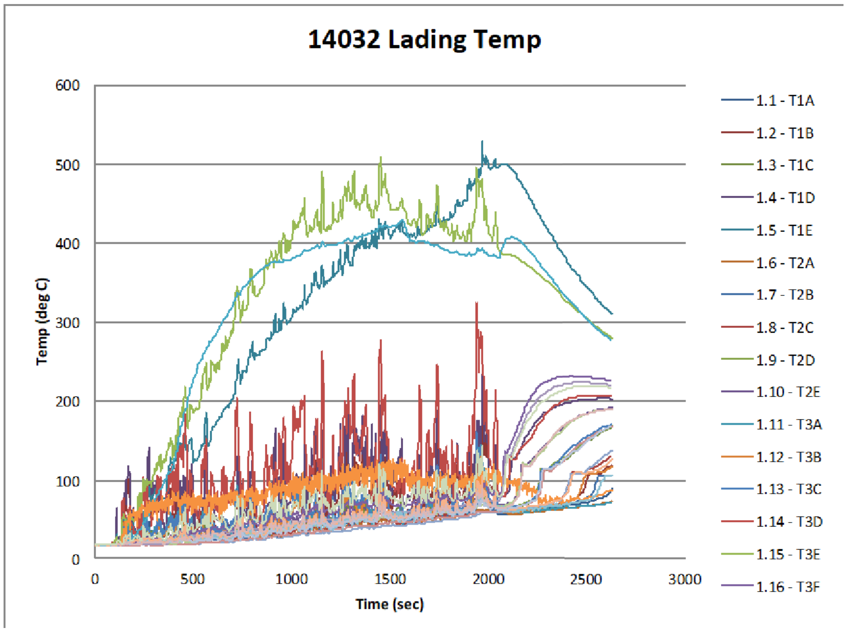


Figure 52. Test 1 - Wet Lading Temperatures

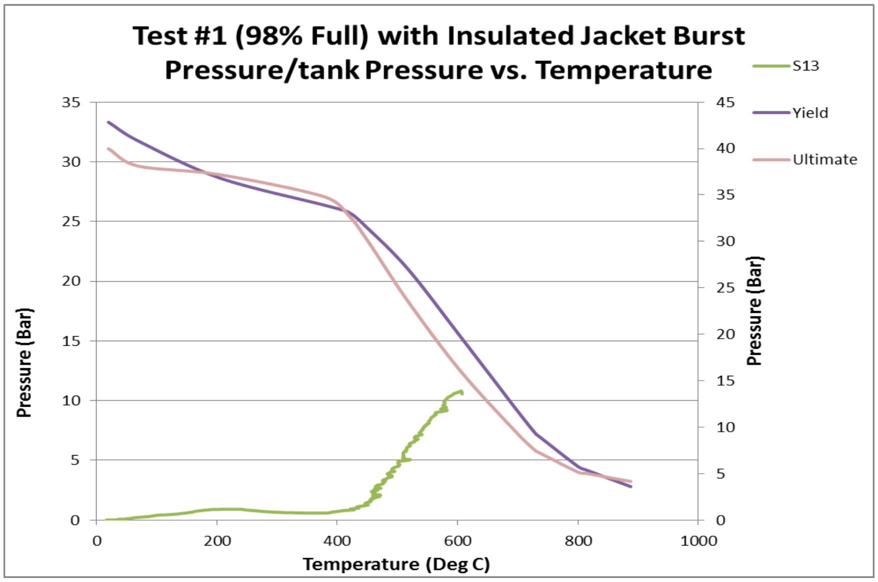


Figure 53. Test 1 - Burst Pressure and Tank Pressure vs. Wall Temperatures

Significant observations from this test were:

- The pressure increased much more slowly in the insulated tank
- The initial rise and fall of pressure could be due to the heating of the air in the vapor space
- The increase in pressure would cause more air to go into the water. This would make the pressure drop down. The pressure then goes up again as water vapor is generated in the hot liquid boundary layer.

- The average DFT temperatures show a good start and steady fire

The main conclusion from this test is that the failure time and failure mode for the vessel depends strongly on the performance of the insulation. Previous data [9] suggested that the fiberglass insulation degraded away in about 5 minutes. This was not experienced in this test. It could be that the formulation of this modern insulation is much different than the one tested previously. It may be that the previous test (which was a plate test) may have had the insulation fall down resulting in total loss of the insulation effectiveness. This was partially observed in this test.

The simple scaling rule (i.e., failure time scales with wall thickness – which is related to tank diameter) applies if the wall temperature dominates the failure process. The rule applies when the tank pressure remains nearly constant as in the case when a PRV opens or in the case when the tank goes shell full and the tank deforms plastically. In this test, the rule-based scenario did not occur. In this test, both the wall temperature and the tank pressure determine the time to failure. The tank pressure does not scale the same as the wall temperature.

In this test, the tank never went shell-full and the insulation continued to degrade during the entire test.

The tank pressure in this test was dictated by the boiling boundary layer (i.e., temperature stratification). Figure 52 shows the liquid lading temperatures vs. time in the fire. The plot also includes the calculated liquid saturation temperature based on the measured tank pressure. As can be seen, the tank pressure seems to correlate with the warmest liquid in the tank. The boiling action in the tank gives the wild swings in the liquid temperature.

Appendix C.
Test 1b – Jacketed, No Insulation - 98% Fill - Water (BAM 14033)

Test 1b tank was the repaired (B end top fill fitting rewelded) tank from Test 1. The insulation was removed and the jacket replaced, and filled to 97.3 percent with 18 °C water (equivalent to 98 percent fill with 41 °C).

The following modifications were made from Test 1:

1. The gaps in the steel jacket around the penetrations (nipples used for fill, drain and thermocouple feed-throughs) were increased to 20-30 mm so that hard contact would not be made between the tank fittings and the jacket. These gaps were well insulated for the following tests.
2. The bolts were removed holding the tank to the jacket so that the hot jacket could expand freely relative the cool tank
3. The flange on the jacket was stitch welded between the bolts to ensure a gap would not open

The above modifications were made to all further tests.

The Figure 54 and Figure 55 show the views of the ruptured tank. The plots of tank performance over the 6-minute burn from this test are included.

1. Internal Temperature/Tank Pressure vs. Time (Figure 56)
2. Shell Top Temperature/ Pressure vs. Time (Figure 57)
3. DFT Average Temperature vs. Time (Figure 58)
4. Tank Wall Temperatures (Figure 59)
5. Burst pressure/ Tank Pressure vs. Wall Temperatures (Figure 60)

Figure 54. Test 1b - View of Vessel Rupture.

Figure 55. Test 1b - View of Vessel

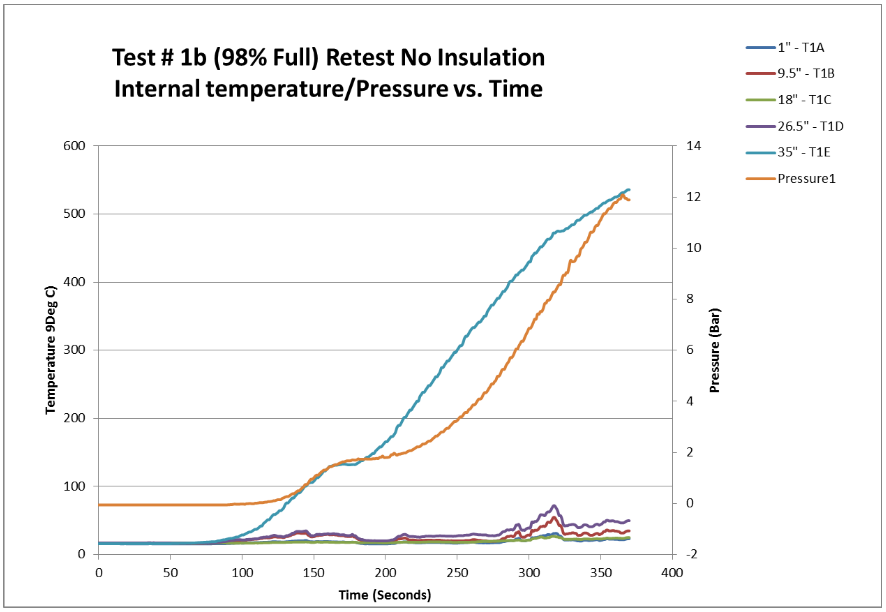


Figure 56. Test 1b - Internal Temperature/Tank Pressure vs. Time Tank Pressure

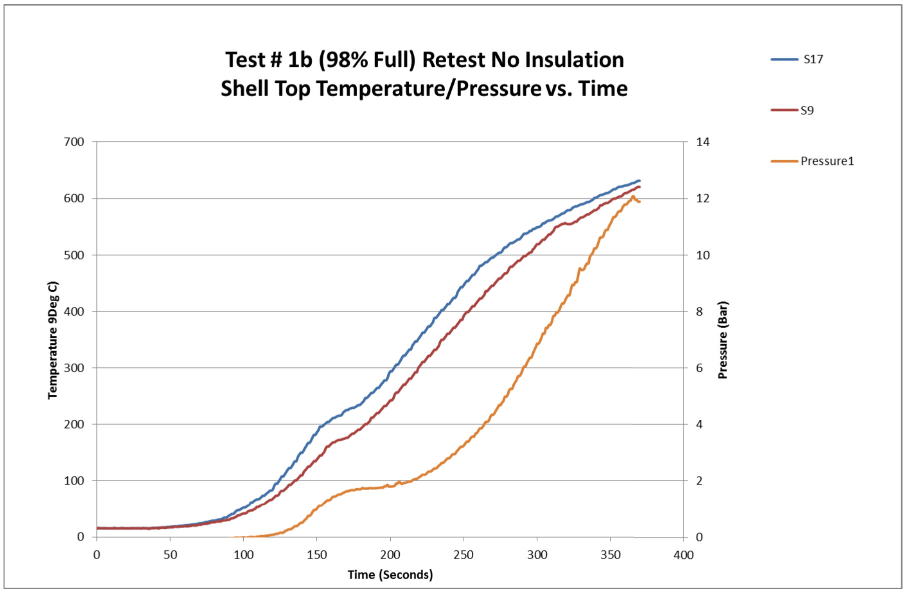


Figure 57. Test 1b - Shell Top Temperature/ Pressure vs. Time

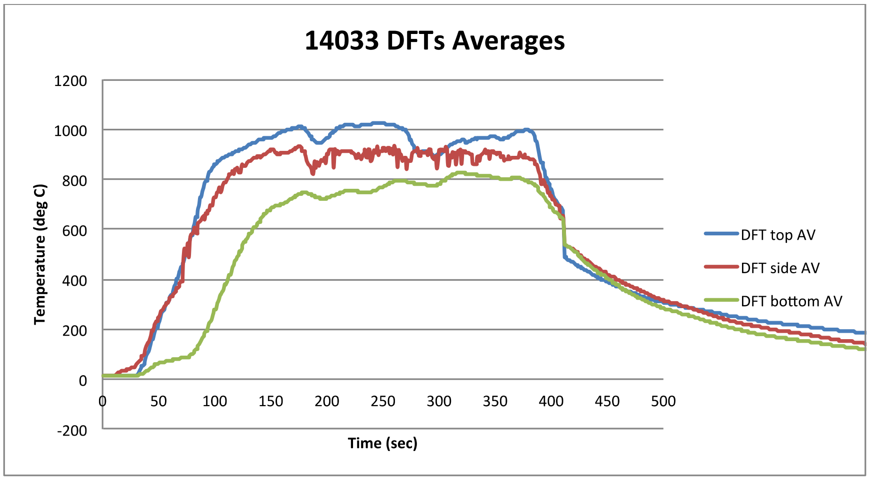


Figure 58. Test 1b - Average DFT Temperature

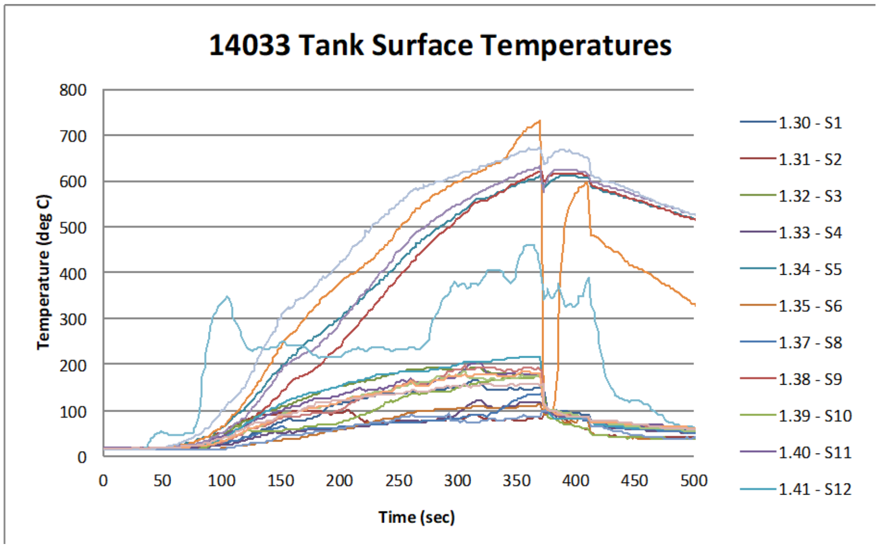


Figure 59. Test 1b - Tank Wall Temperatures

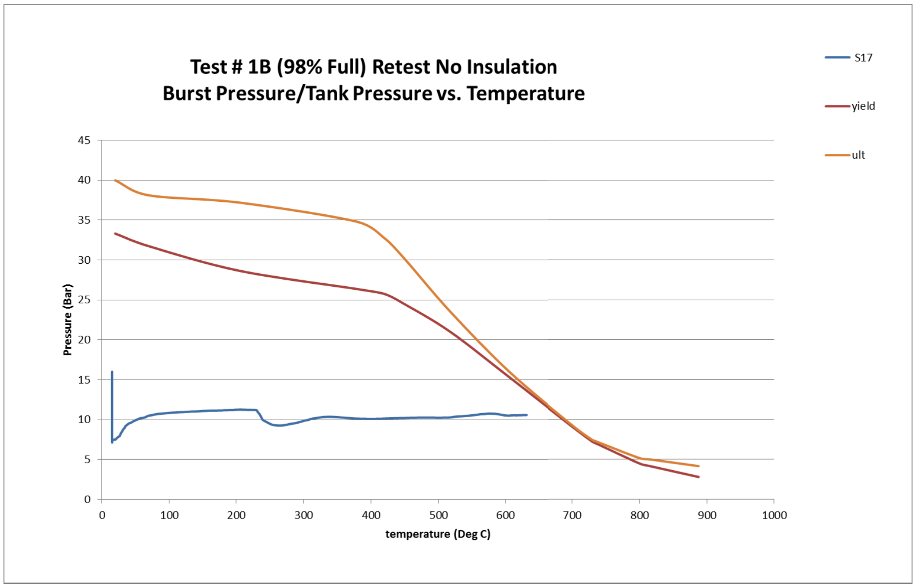


Figure 60. Test 1b - Burst Pressure and Tank Pressure vs. Wall Temperature

This test lasted just over 6 minutes when the tank burst at 12 Barg due to high wall temperatures. It should be noted that this tank was tested two times and in the first test some plastic deformation was noted. Therefore, this tank was not in new condition.

In this case, we expect the heat flux to the tank to be about half of the bare tank test due to the radiation shield effect of the jacket.

Appendix D.
Test 2 – Jacketed and Insulated – 50 Percent Filled - Water (BAM 14032)

Test 2 was conducted with an insulated and jacketed tank (3 mm jacket, 100 mm fiberglass insulation), and filled to 49 percent with 18 °C water (equivalent to 50 percent fill with 41 °C).

Significant observations from this test were:

1. Due to a very high indicated wall temperature, this test was terminated at 1250 seconds by shutting down the fire when the tank pressure was at 5.2 Barg. The emergency dump valve did not activate and as a result the pressure continued to rise after the fire was shut down.
2. The very high wall temperature was measured at the tank top location where a gap formed in the insulation at the mid length of the tank. The extreme temperature could be the result of thermocouple separation from the tank wall, due to plastic deformation in that location, which would make it an example of a very large radiation error due to the radiation of heat from the hot jacket to the thermocouple. The actual wall temperature in that location was probably between 630 °C and 670 °C.
3. It was expected that the tank would pressurize slower in the 50 percent fill test than in the 98 percent fill case. This is because of the large vapor space that must be pressurized. However, the pressurization was actually very similar to the 98 percent fill case. One possible explanation for this is as follows:
    a. With a tank fill of 50 percent, the water sits in the bottom half of the tank and only 50 percent of the tank wall is wet, and this is where most of the heat enters the liquid to pressurize the tank.
    b. There is only 50 percent of the liquid in the tank so the heat input per unit mass should be about the same as in the 98 percent test.
    c. But in this test, the insulation fell down from the bottom half of the tank. That means the liquid actually saw more heat per unit mass than in the 98 percent fill case. For this reason, the pressurization rates were very similar. It was likely, because of the way the insulation degraded.

Figure 61, Figure 62 and Figure 63 show the tank insulation after the test. The plots of tank performance for this test are presented as given below.

1. Internal Temperature/Tank Pressure vs. Time (Figure 64)
2. Shell Top Temperature/ Pressure vs. Time (Figure 65)
3. Average DFT and Jacket Temperatures (Figure 66)
4. Heat Flux from Fire and Net Heat Flux to Jacket (Figure 67)
5. Lading Temperatures (Figure 68)
6. Burst Pressure and Tank Pressure vs. Wall Temperatures (Figure 69)

Figure 61. Test 2 - Insulation After Test

Figure 62. Test 2 - Insulation Gap at Mid Tank

Figure 63. Test 2 - Insulation Dropped Down on Sides

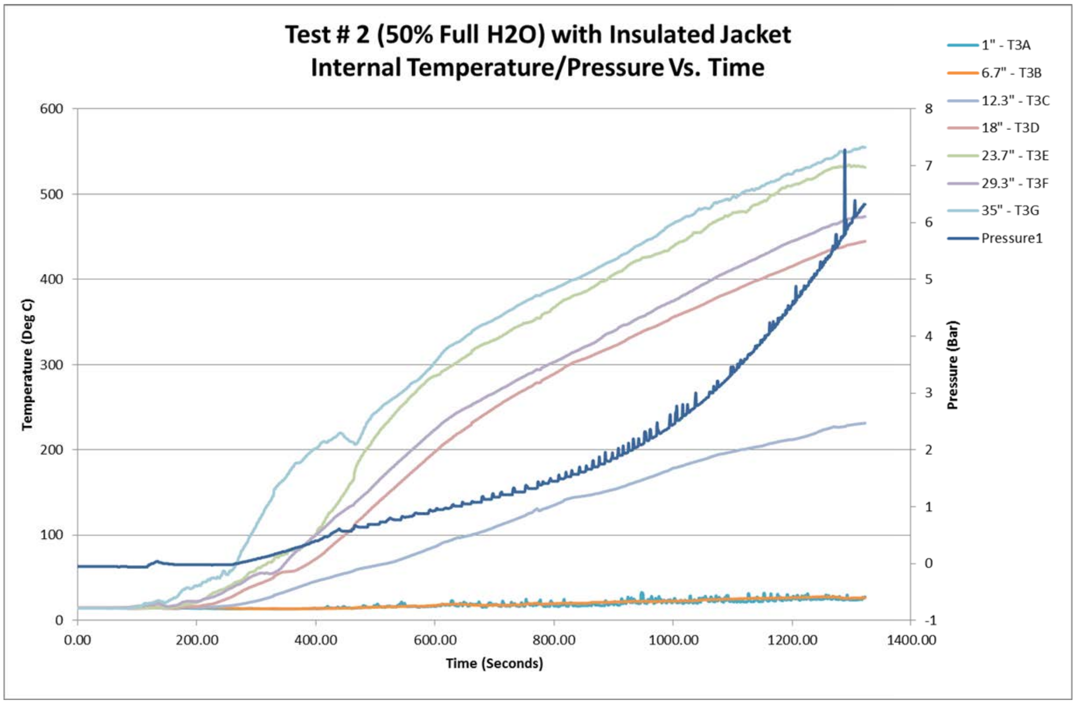


Figure 64. Test 2 - Internal Temperature/Tank Pressure vs. Time

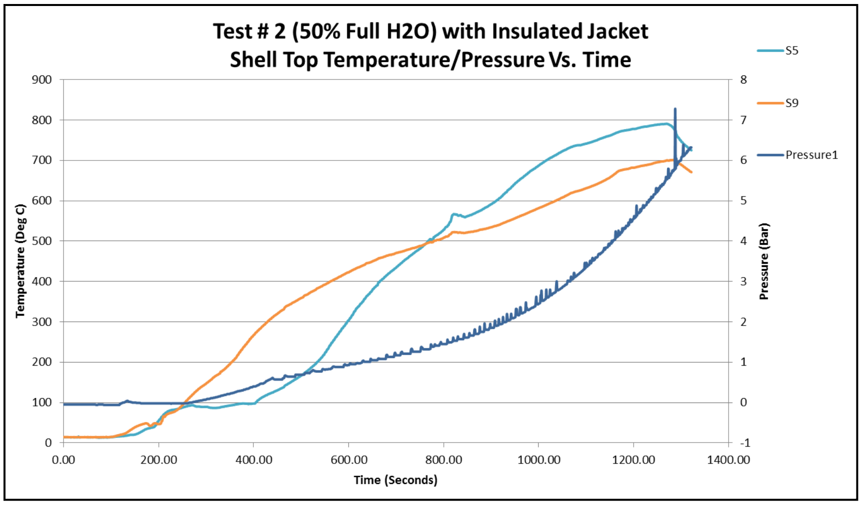


Figure 65. Test 2 - Shell Top Temperature/ Pressure vs. Time

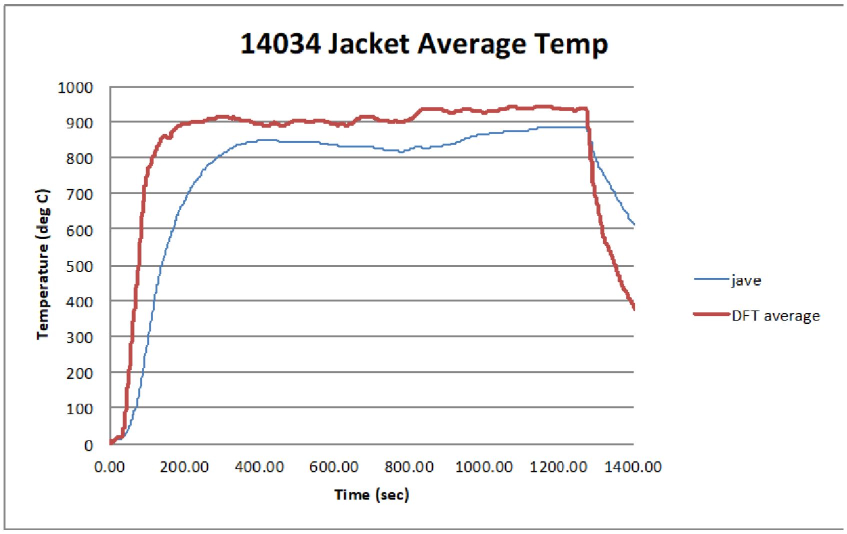


Figure 66. Test 2 - Average DFT and Jacket Temperatures

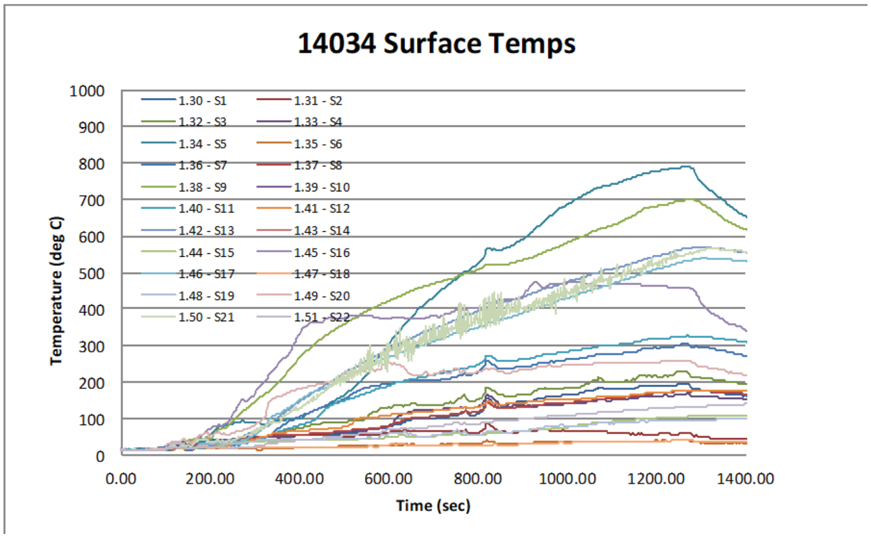


Figure 67. Test 2 - Tank Wall Temperatures

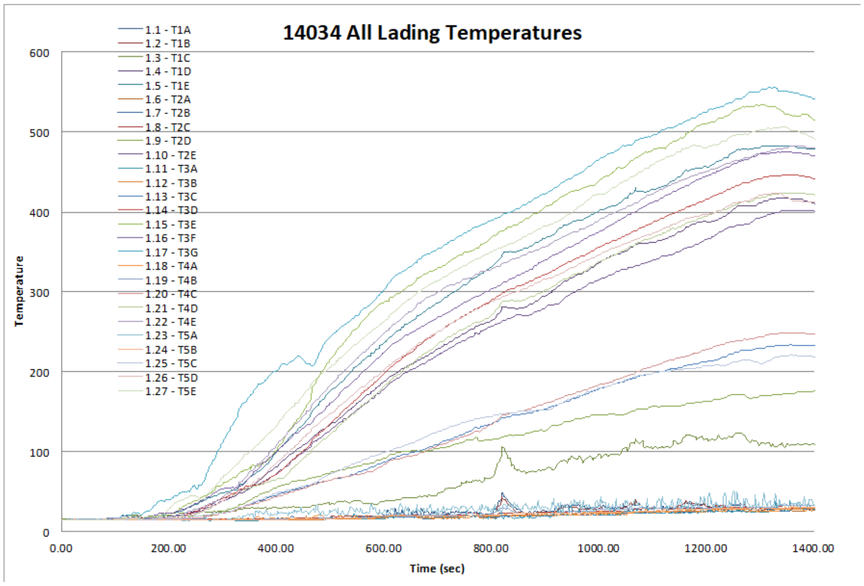


Figure 68. Test 2 - Lading Temperatures

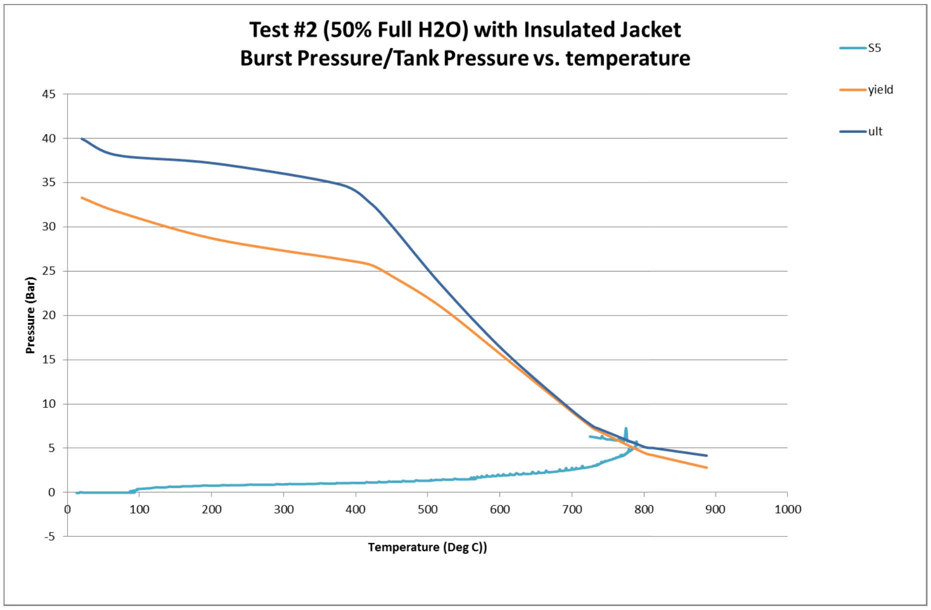


Figure 69. Test 2 - Burst and Tank Pressure vs. Wall Temperature

Appendix E.
Test 3 – Jacketed and Insulated - 98% Fill - NaOH (BAM 14035)

Test 3 tank was insulated and jacketed, (3 mm jacket, 100 mm fiberglass insulation) 98 percent fill with 55 °C NaOH 50 percent solution in water. PRV on the emergency dump line was set at 8 Barg. (Supplier of NaOH and BAM facility insisted on having this PRV to ensure tank rupture would not occur).

It was decided not to adjust the fill level back to 98 percent full at 41° C because this would have resulted in an initial fill of over 98 percent and there was a concern this would lead to upper wall wetting. In the end we still saw upper wall wetting. This will be discussed further in this appendix.

For this test, there were three changes from water Test 1 and Test 5 with 98 percent fill. The changes were:

1. Improved insulation
2. Dump line from bottom west end was removed and replaced with dump line from bottom at the east end
3. The pressure transducers were attached to two 6 mm ID tubes leading down from the bottom of the tank. These tubes were filled with liquid and insulated with one layer of 4 cm ceramic blanket insulation

In this test, the tank insulation was improved from the other tests. The improvements include the following:

1. There was a double layer of 100 mm insulation (i.e., 200 mm of insulation was compressed into the 100 mm jacket space) at the middle third of the tank.
2. There was overlap between the middle extra sheet of insulation and the two side-by-side sheets so that when the insulation degraded it could not separate to open up a gap along the tank circumference.
3. Extra insulation was added on the sides to reduce or delay the dropping down of the insulation into the annulus space

Wind with an average speed between 0 and 2.5 m/s was present during the test, with peaks as high as 3.4 m/s. In general, the fire exposure was good but there were some gaps in the flames at times, which are clearly visible in the DFT temperatures. However, even with these gaps the average DFT temperature was 851 °C (including the start) and 898 °C excluding the start. It is believed this was a credible and fully engulfing fire.

The test was terminated at 30 minutes because the PRV opened at 8 Barg. At this time, the pressure was rising rapidly and the tank wall temperature was around 450 °C.

Figure 70, Figure 71 and Figure 72 show the tank insulation after the test. The plots of tank performance from this test are included, as follows.

1. Internal Temperature/Tank Pressure vs. Time (Figure 73)
2. Shell Top Temperature/ Pressure vs. Time (Figure 74)
3. Lading Temperature (Figure 75)

4. Wet Lading Temperature. Note line showing Psat vs. Tsat (Figure 76)
5. Wall Temperatures (Figure 77)
6. Average DFT and Jacket Temperatures (Figure 78)
7. Burst Pressure and Tank Pressure vs. Wall Temperature (Figure 79)

Some tank deformation was observed just beyond the double layer of insulation. This suggests higher wall temperatures in those areas. Unfortunately, no thermocouples were located in those areas. Since the pressure was limited to 8 Barg, the wall temperatures on those areas must have been above 600 °C for plastic deformation to take place.

Figure 76 shows the measured lading space temperatures. The thermocouples in the vapor space recorded temperatures as high as 330 °C. Lower down in the liquid the temperature ranged between 70 and 190 °C. This is clear evidence that temperature stratification drove the tank pressure.

The lading temperatures vary dramatically due to boiling phenomena. Boiling leads to bubble formation in the liquid and this caused the liquid level to increase. When an increased level of liquid or swell comes in contact with the vapor space wall, it gets cooled very rapidly.

This cooling effect is clearly seen in Figure 77**,** where the wall temperatures are shown. Sometime after 1,400 seconds, this boiling and wetting effect was reduced or stopped and the wall temperatures began to rise, which could be due to the increased pressure in the tank. Additional pressure might have suppressed the boiling and reduced the size of the bubbles formed. When the PRV opened, the peak measured wall temperature was around 430 °C. However, as noted earlier there was some tank bulging due to plastic deformation and this suggests temperatures above 600 °C. Unfortunately, we did not have thermocouples in those areas of observed deformation.

We would expect the tank to go shell full at some point later in this test as the liquid was heated. However, we would also expect plastic deformation of the tank and this would increase the tank volume and the size of the vapor space. It is not clear which one of these processes would dominate.

Unfortunately, this test was terminated early when the pressure reached 8 Barg to ensure we would not have a rupture with NaOH.

Once again, the pressure in this test was dictated by the boiling boundary layer in the tank. This is shown in Figure 76 where the calculated saturation temperature based on the measured tank pressure correlates well with the warmest liquid in the tank.

Figure 70. Test 3 - End View of Tank after Test. Note Liquid Level Mark on Tank. Note insulation on end dropped down.

Figure 71. Test 3 with Jacket Lifted Off
Note double layer of insulation at mid span

Figure 72. Test 3 - View showing Second Layer of Insulation Lifted to Show Gap. Note condition of protected insulation.

In Figure 73, we see some noise in the pressure signal. This could be due to boiling in the pressure tubes. In Figure 75 and Figure 76, we clearly see liquid temperature stratification and large variations in the liquid temperatures due to boiling.

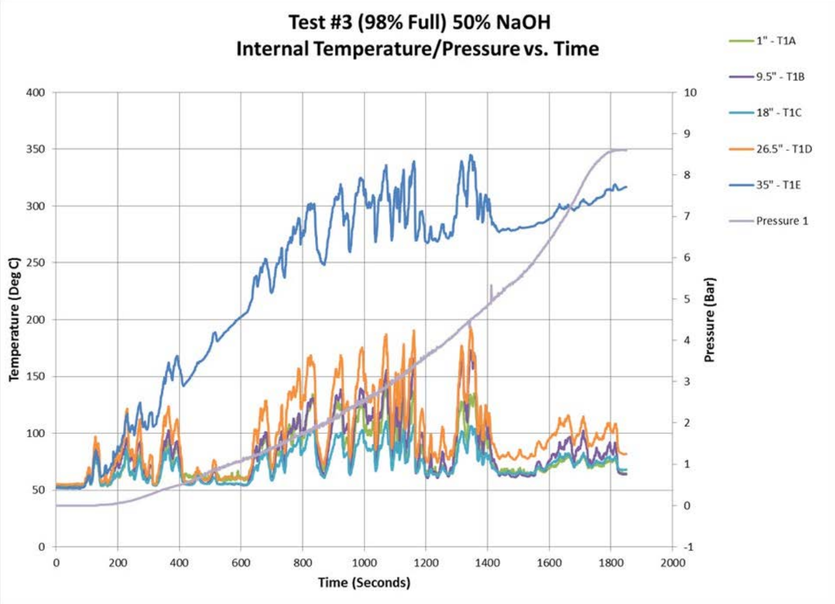


Figure 73. Test 3 - Tank Pressure

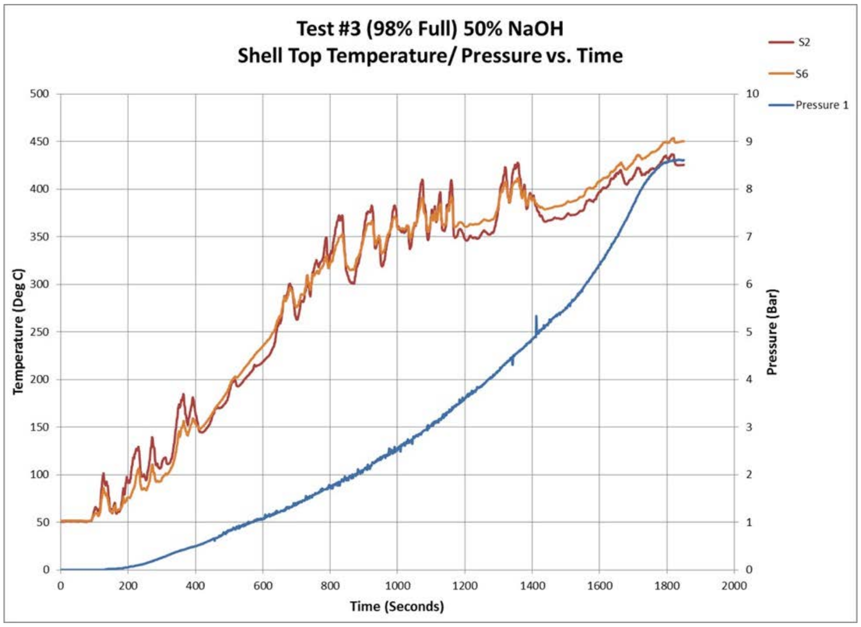


Figure 74. Test 3 – Shell Top Temperatures

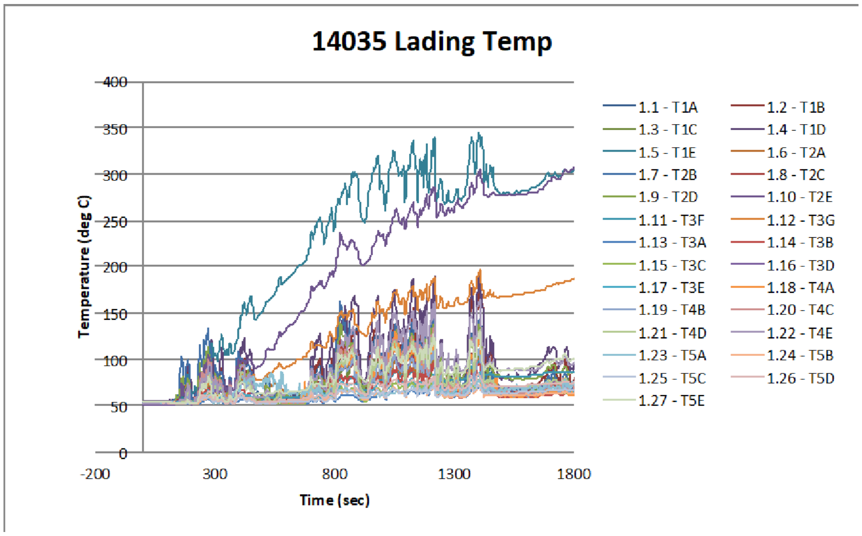


Figure 75. Test 3 - Lading Temperatures

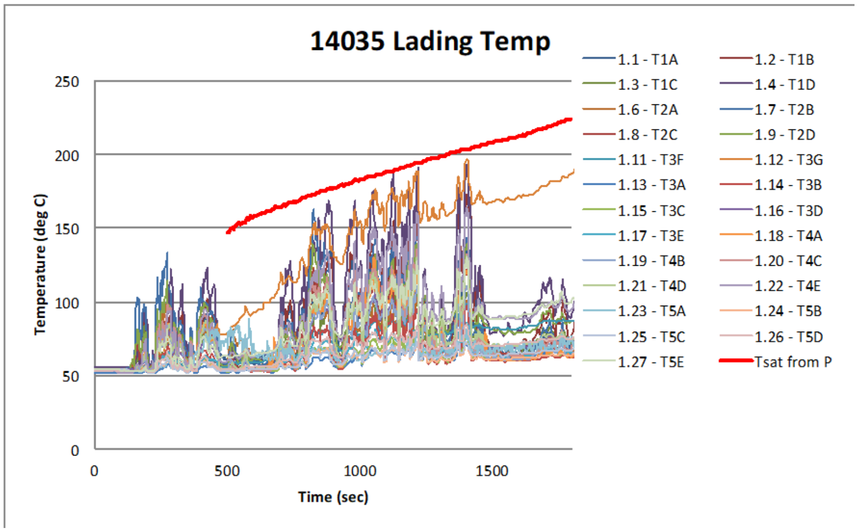


Figure 76. Test 3 - Wet Lading Temperatures. Note line showing Psat vs. Tsat.

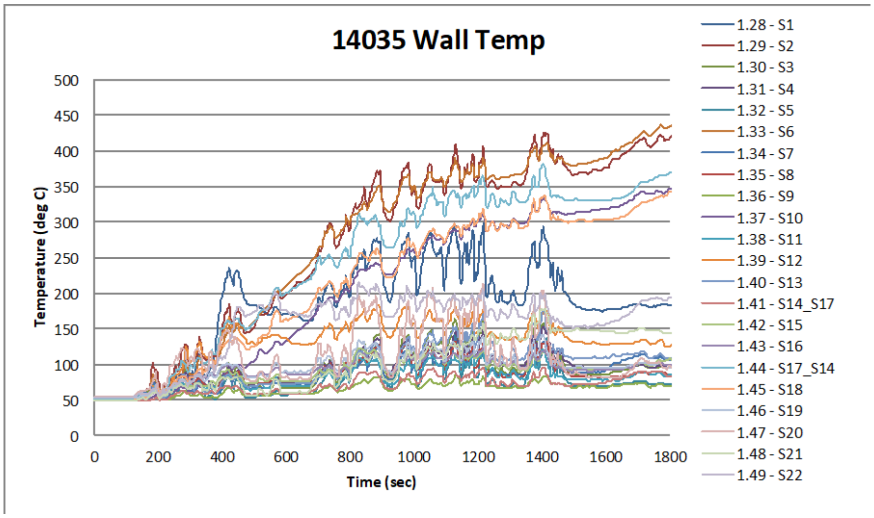


Figure 77. Test 3 - Wall Temperatures

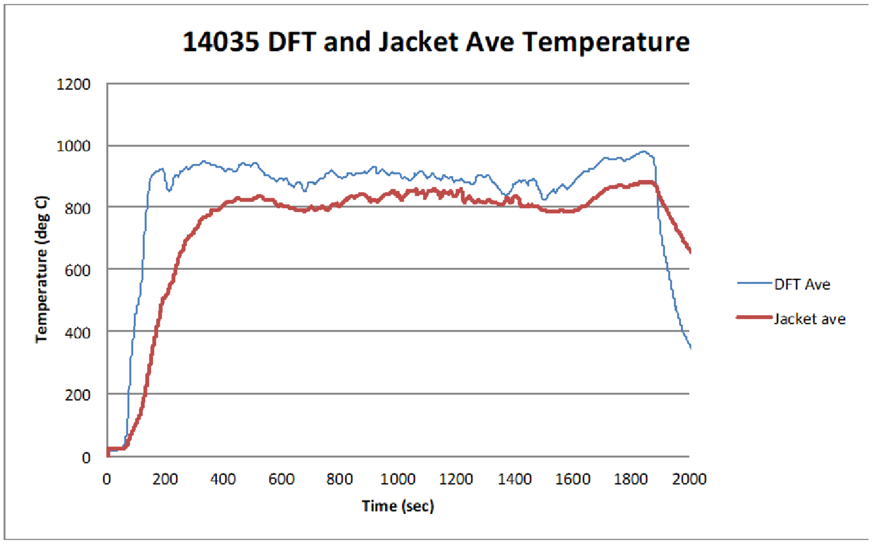


Figure 78. Test 3 - Average DFT and Jacket Temperatures

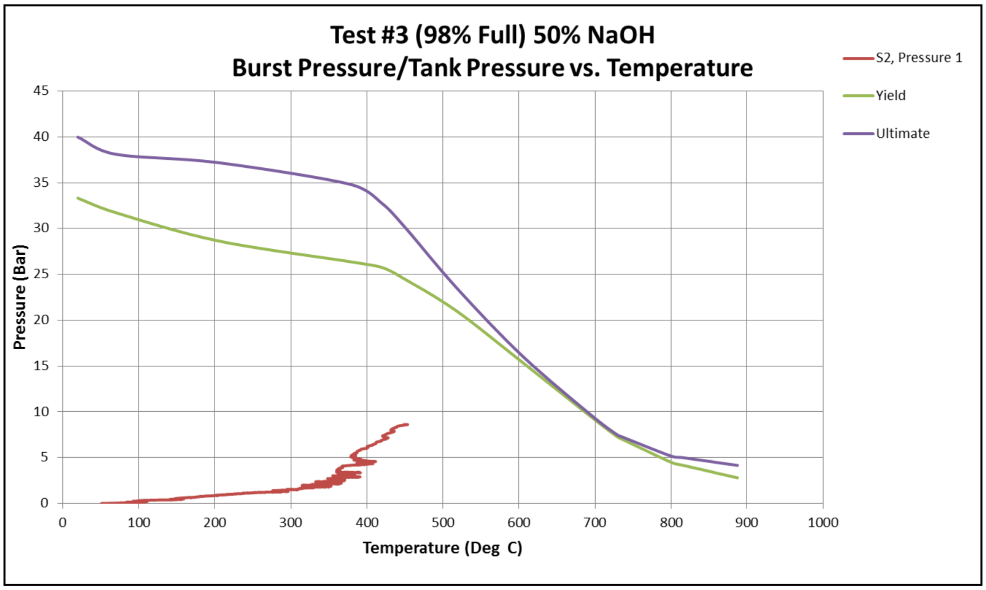


Figure 79. Test 3 - Burst Pressure and Tank Pressure vs. Wall Temperature

Appendix F.
Test 4 – Jacketed and Insulated – 66 Percent Fill - NaOH (BAM 14037)

The Test 4 tank was insulated and jacketed (3 mm jacket, 100 mm fiberglass insulation), 66 percent filled with NaOH 50 percent solution. Note that the data suggests the fill was not the intended 50 percent but closer to 66 percent. This was an error during filling of the tank with NaOH solution.

There were three changes from the similar water test with 50 percent fill.

1. Improved insulation
2. Dump line at west end replaced with dump line at east end
3. Two pressure 6 mm tubes were connected to the tank bottom for pressure transducers. In this test, two layers of 4 cm ceramic wool and a 1 mm steel jacket were used to insulate the pressure tubes (change from Test 3).

Significant observations from this test were:

1. This tank pressurized fastest of all tanks with jacket and insulation (including the water tests), which was not in line with the expectation that this will pressurize slower than Test 3 (98 percent NaOH).
2. Wall temperatures were in line with expectations for lower fill case
3. Tank fill was probably 66 percent not 50 percent. There must have been some confusion during filling of the NaOH solution.

Figure 80, Figure 81, and Figure 82 show the tank insulation after the test. The plots of tank performance for this test are given below.

1. Internal Temperature/Tank Pressure vs. Time (Figure 83)
2. Wall Temperatures (Figure 84)
3. Lading Temperatures (Figure 85)
4. Average DFT and Jacket Temperatures (Figure 86)
5. Tank Pressure and Burst Pressure vs. Wall Temperature (Figure 87)

Figure 80. Test 4 - Insulation Stretch and Tearing on Tank Side

Figure 81. Test 4 - End view after Jacket Removal.
Note liquid level markings on tank end. Tank was probably filled to 66%

Figure 82. Test 4 - View of Insulation Thinning and Compaction

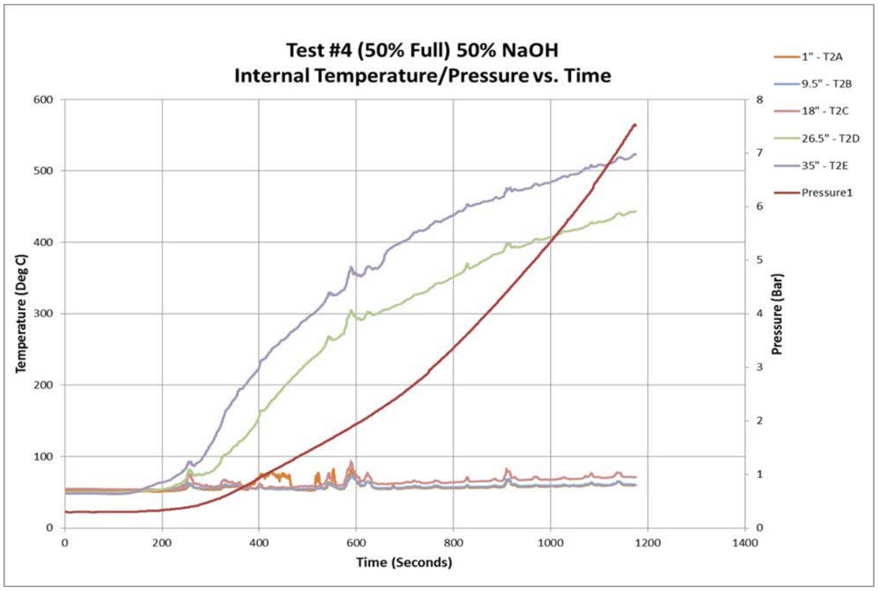


Figure 83. Test 4 - Internal Temperature/Tank Pressure vs. Time

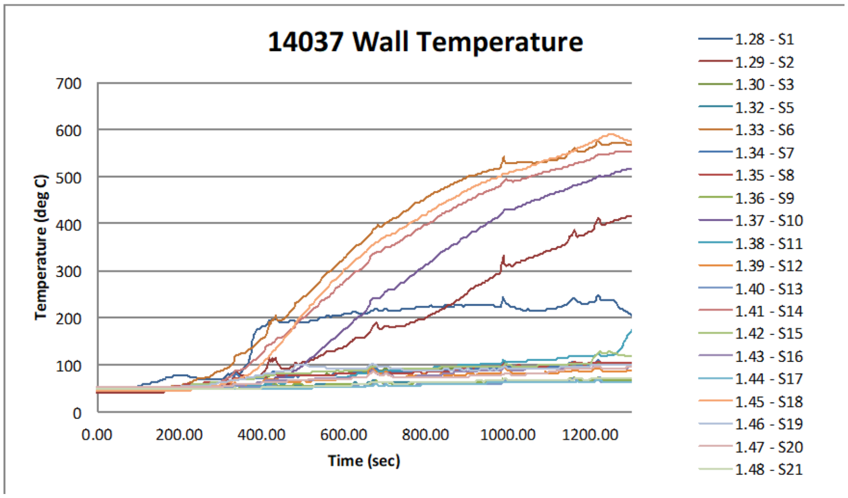


Figure 84. Test 4 - Wall Temperatures

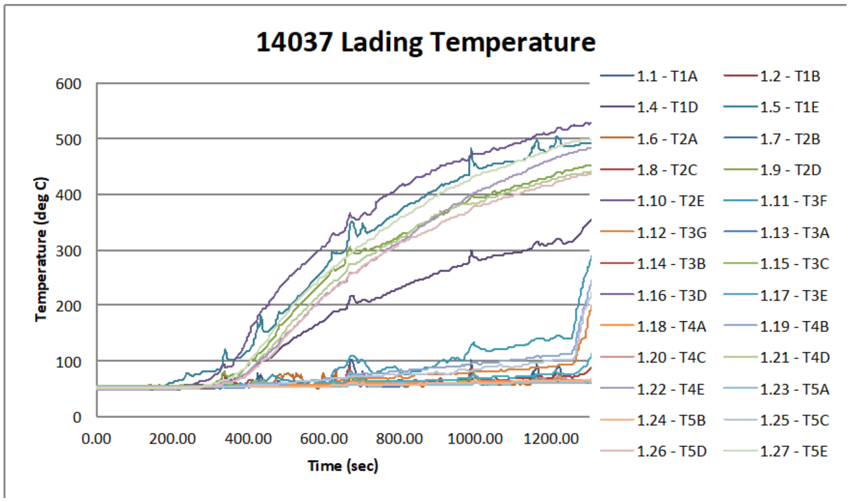


Figure 85. Test 4 - Lading Temperatures

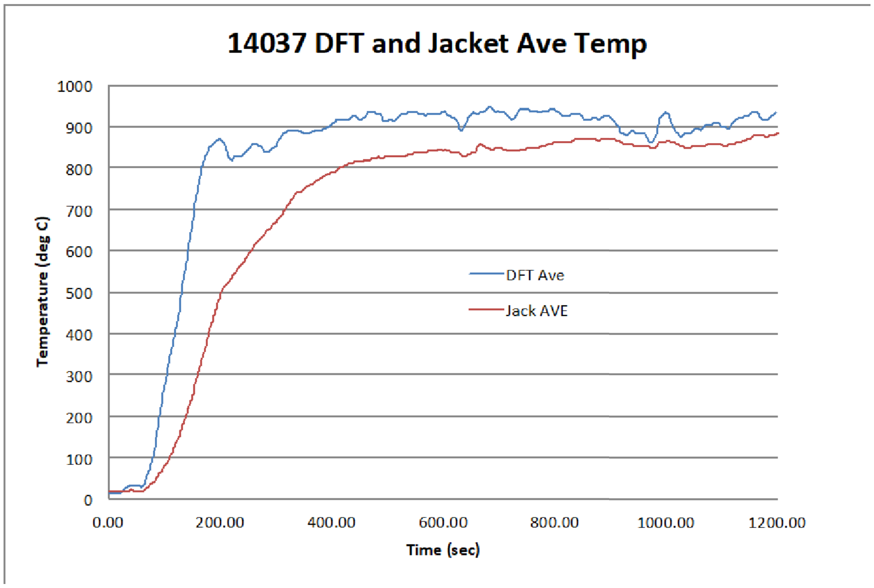


Figure 86. Test 4 – Average DFT and Jacket Temperatures

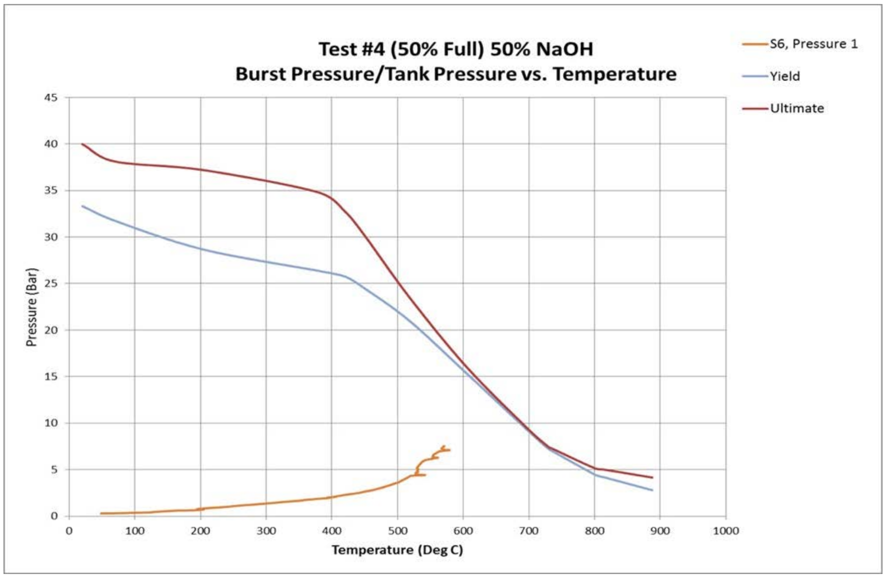


Figure 87. Test 4 - Tank Pressure and Burst Pressure vs. Wall Temperature

Appendix G.
Test 5 – Jacketed and Insulated – 98 Percent Fill - Water (BAM 14038)

Test 5 tank was an insulated and jacketed tank (3 mm jacket, 100 mm fiberglass insulation), and filled to 97.3 percent with 17 °C water (equivalent to 98 percent fill with 41 °C). This was the last test conducted and was a water test to repeat Test 1. This test used the spare tank that was built in case there was a lost test. In this test, there were three changes from the previous water test with 98 percent fill. The changes where:

1. The dump pipe at the east end was eliminated. No dump line was installed on this tank.
2. Two 6 mm pressure tubes were used for the pressure transducers. These lines were insulated with two layers of ceramic blanket and a metal jacket (same as in test 4 for 50 percent fill NaOH).
3. During the filling of this tank a significant amount of water entered the jacket space at the gap in the jacket near the fill fitting. This water did not fully drain from the jacket and some of the insulation was filled with water. This probably had some effect on the first few minutes of the test.

Significant observations from this test were:

1. The fire was a good engulfing fire. The test was terminated at 2440 seconds. The measured pressure and peak wall temperature indicated the tank was at or very near failure.
2. Insulation had fallen down from the tank ends and sides.
3. Insulation remained on the top third of the tank. This insulation had thinned to about 1-2 cm from the original 10 cm.
4. A gap of about 3 cm had formed between the two blankets of insulation on the tank top. There was significant plastic deformation in the tank wall at this location due to high wall temperatures.
5. Test 1 and Test 5 were identical (98 percent fill with water, jacket and insulation) but the pressurization was a little slower in Test 5. The calculated net heat flux to the jacket was 13 percent lower in Test 5, which could be the cause for slower pressurization. This could be due to differences in the fire conditions or differences in the insulation degradation. Otherwise the results are very similar and show excellent repeatability for an open fire test.

Figure 88, Figure 89, Figure 90, Figure 91 and Figure 92 show the views of the tank and insulation. The plots of tank performance for this test are presented as given below.

1. Internal Temperature/Tank Pressure vs. Time (Figure 93)
2. Shell Top Temperature/Pressure vs. Time (Figure 94)
3. Wall Temperatures (Figure 95)
4. Lading Temperatures (Figure 96)
5. Average DFT and Jacket Temperatures (Figure 97)

6. Tank Pressure and Burst Pressure vs. Wall Temperature (Figure 98)


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Figure 88. Test 5 with Jacket Removed. End Insulation Dropped Down


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Figure 89. Test 5 with View of Side Insulation Dropped Down

Figure 90. Test 5 with View of Open Gap in Insulation
Note significant local plastic deformation to tank wall.

Figure 91. Test 5 with Insulation Removed.
View of tank deformation at location of insulation gap and separated thermocouple.

Figure 92. Test 5 Showing Tank with Plastic Deformation near Mid Span.

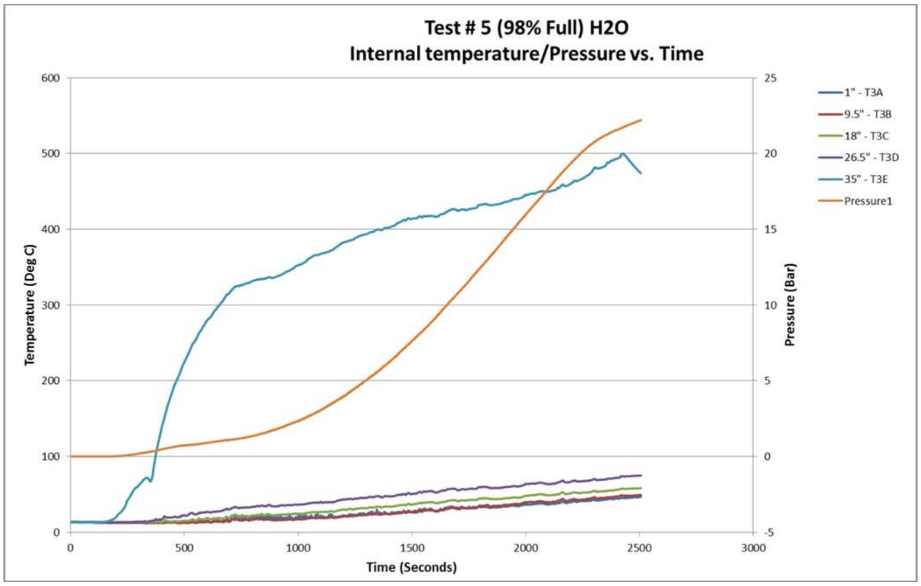

Figure 93. Test 5 - Internal Temperature/Tank Pressure vs. Time

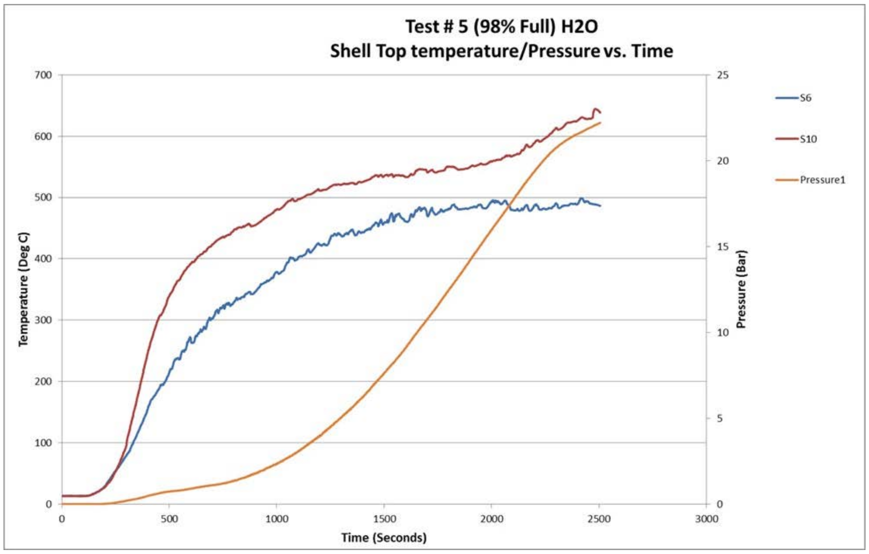

Figure 94. Test 5 - Shell Top Temperature/ Pressure vs. Time

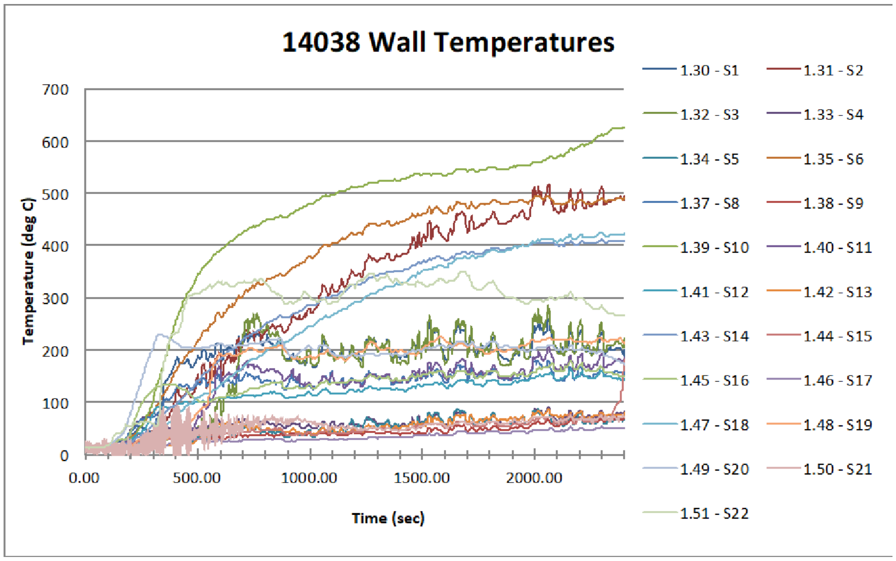

Figure 95. Test 5 - Wall Temperatures

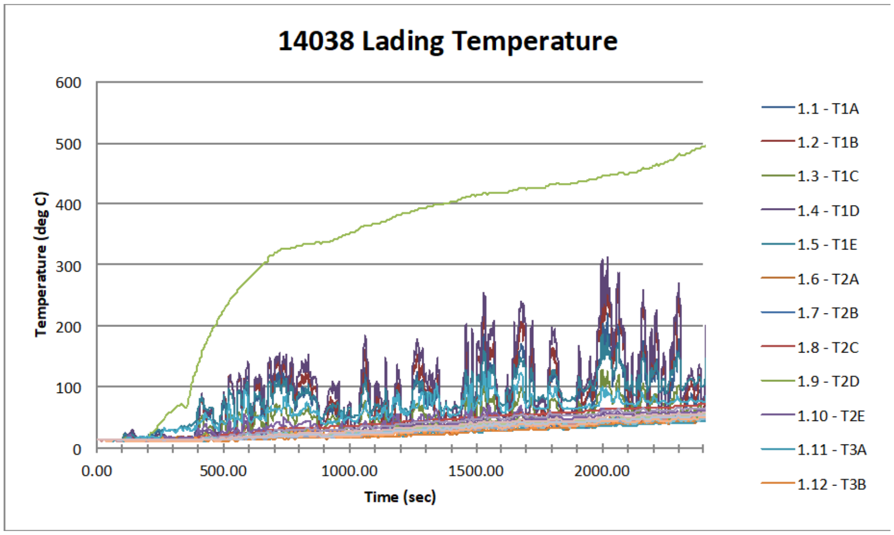

Figure 96. Test 5 - Lading Temperatures

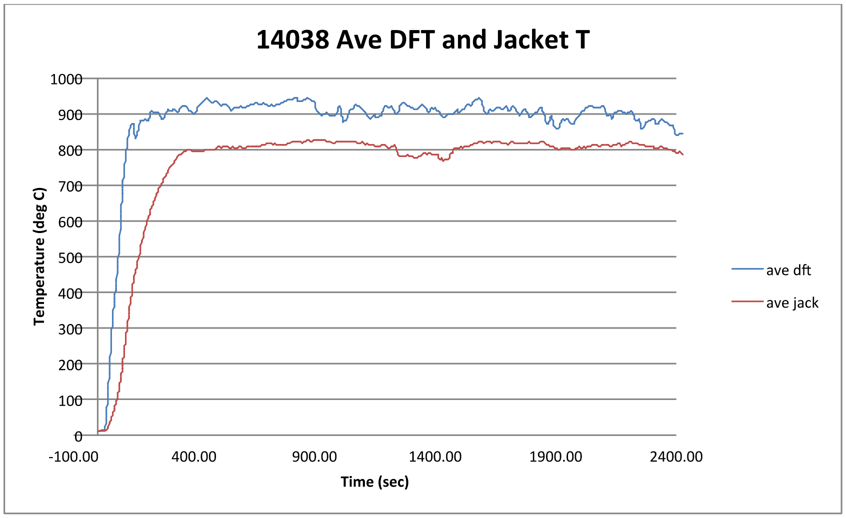

Figure 97. Test 5 - Average DFT and Jacket Temperatures

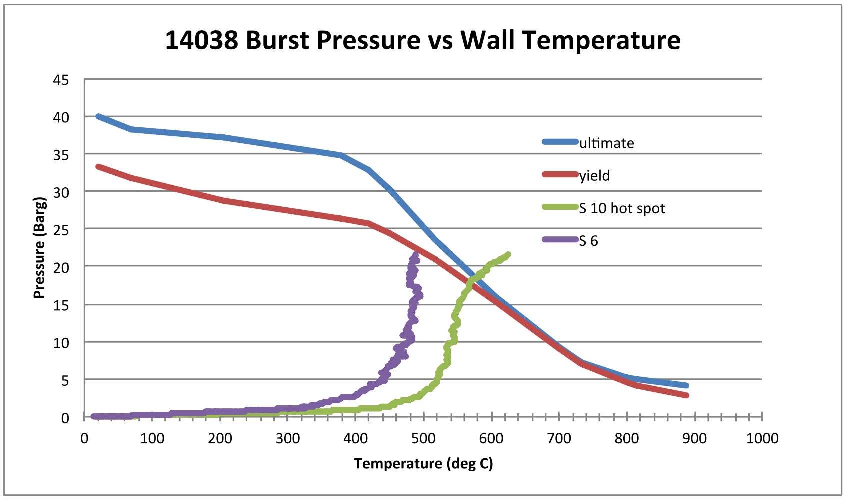

Figure 98. Test 5 - Tank Pressure and Burst Pressure vs. Wall Temperature

Appendix H.
Analysis of Liquid Temperature Stratification and Pressure Time Scaling

This appendix discusses how the pressure scaling factor of 1.93 was derived and provides a brief validation of the derivation process, showing how the results could be scaled using that method from a small one-tenth scale tank to a one-third scale tank.

The transient heating of the liquid boundary layer near the wall dictates the pressure in a test vessel. This boundary layer starts off as a free convective boundary layer. Later on, it becomes a boiling boundary layer with sub-cooled boiling followed by saturated boiling. Boiling in the boundary layer will cause liquid swell (i.e., the liquid surface will move up due to bubbles forming in the liquid).

Heat enters the tank wall by conduction and then it enters the stationary liquid by conduction near the wall. This warm liquid expands and becomes less dense than the surrounding fluid and therefore it begins to rise due to buoyancy. This produces a film along the wall that flows upward to the liquid surface where it spreads out across the surface. The flowing liquid in the boundary layer results in convection heat transfer from the wall to the liquid. The warm liquid at the liquid surface and near the wall produces vapor that pressurizes the vessel.

As a simple model, we will assume a steady state free convective boundary layer on a vertical wall. We will assume a turbulent flow.

The governing dimensionless variables for free convection heat transfer are the Nusselt number Nu (ratio of convection to conduction heat transfer), Grashof number Gr (ratio of buoyancy force to viscous force) and the Prandtl number Pr (ratio of viscous to thermal diffusion).

For a constant heat flux, the Grashof number is defined as:

$$Gr = \frac{g\rho^2\beta q_w'' x^4}{k\mu^2}$$

where, g = acceleration due to gravity, ρ = density, β is cubical coefficient of thermal expansion, q'' is the local wall heat flux, x is vertical dimension, k is thermal conductivity, and μ is viscosity.

If we assume the same fluid (water) then all the properties remain constant and only x and q'' are the variables. For turbulent flow, the displacement thickness is:

$$\delta^* \propto \frac{x}{Gr^{\frac{1}{10}}} \propto \frac{x}{q_w''^{1/10} x^{4/10}} \propto \frac{x^{0.6}}{q_w''^{1/10}}$$

The displacement thickness is one measure of the boundary layer thickness.

This suggests that when the tank scale increases by a factor of 3, the boundary layer thickness will increase by a factor of $3^{0.6} = 1.93$. This suggests that the large-scale system with the same heat flux will pressurize more slowly, by a factor of 1.93.

The Figure 99 shows the measured pressure from Test 0 (D = 0.91 m, bare tank, 98 percent full with water) and a similar test using a small propane cylinder (D = 0.27 m) filled to 98 percent with water. The small cylinder was held in the horizontal position and engulfed in fire. We would expect a similar pressurization scale factor of around 1.9 for these two tests (i.e., the small cylinder would pressurize 1.9 times faster than the larger cylinder). Figure 99 shows this to be true.

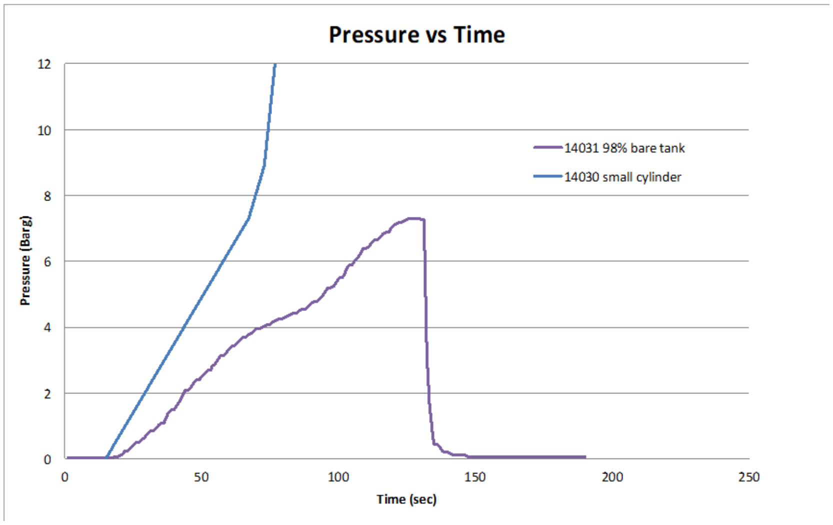

Figure 99. Comparison of Pressurization Rates for Small (D = 0.27m) and Large (D = 0.91 m) Cylinders Filled to 98% with Water

This analysis also suggests that if the heat flux is reduced by a factor of five (as in an insulated tank), the boundary layer thickness will decrease by a factor of $5^{1/10} = 1.17$. This shows that the boundary layer thickness does not change much with heat flux. But of course, the pressurization rate is strongly affected by the actual heat flux. If the heat flux goes down by a factor of 5, we expect the pressurization rate to go down by a factor of 5/1.17 = 4.3. This does not correlate well with the testing results. The actual factor observed in the tests (i.e., 98 percent fill bare water tank, vs. 98 percent filled insulated and jacketed water tank) was closer to 10. This may suggest boiling effects are taking place at higher heat fluxes.

This analysis is approximate and needs further validation, as it does not consider many factors that may be important, including:

1. Transient convection
2. Wall curvature
3. Fill level
4. Effect of liquid surface
5. Onset of boiling

Some of the above factors, such as the ‘onset of boiling,’ could make the scaling non-conservative. Therefore, further testing is recommended to support this scaling approach.

Appendix I.
A Liquid Wetted Wall Temperatures and Liquid Boundary Layer

As stated previously, the tank pressure was dictated by the liquid temperature near the fire-heated wall (i.e., in the boundary layer). Table 8 gives a summary of the pressures and liquid saturation temperatures required to generate these pressures. The table also includes the liquid wetted wall temperatures measured from the tests.

Table 8. Summary of Tank Pressures, Liquid Saturation Pressures and Observed Liquid Wetted Wall Temperatures

Test	Pressure at test end (Barg)	Liquid Saturation Temperature for P at End (˚C)	Measured Liquid Wetted Wall Temperature (˚C)	Comment
0 - Bare tank 98% water	7.3	172	200	Very short test
1 - Jacket + ins 98% water	11	188	200-320	
1b - Jacket only 98% water	12	192	200	
2 - Jacket + ins 50% water	5.2	160	200-250	
3 - Jacket + ins 98% NaOH	8	225	200-320	Tsat approximate
4 - Jacket + ins 50% NaOH	6.8	220	220	Tsat approximate
5 - Jacket + ins 98% water	21	217	200-300	

The liquid saturation temperature shown above is the liquid temperature required to generate the measured tank pressures. The liquid must have been at this temperature somewhere near the top of the liquid boundary layer. We can see the effects of the boundary layer when we measure the wall temperatures below the liquid level.

For a heat flux of 100 kW/m^2 (as seen by the bare tank in Test 0), we would expect a temperature difference from the outside to the inside of the liquid wetted tank wall (3 mm thickness) due to heat conduction (k = 40 W/mK for 1 percent carbon steel) to be of the order of 10 ˚C. The convective heat transfer coefficient for liquid water is in the range of 0.1 – 2 kW/m^{2}K for single-phase convection and 2 - 100 kW/m^{2}K for boiling heat transfer. Therefore, the temperature difference to drive the convective and boiling heat transfer should be on the order of 10-100 ˚C.

The radiation heat transfer from the liquid wetted wall is negligible for the heat fluxes considered here (critical heat flux for pool boiling of water is greater than 500 kW/m^2). This means that the outer surface of the liquid wetted wall could be of the order of 20-110 ˚C warmer than the liquid boundary layer. For the insulated and jacketed tanks, the heat flux was reduced to 20 – 50 kW/m^2 and this would reduce the wall outer temperature. For example, if we measured a tank pressure of 21 Barg, then the water must have been at least 217 °C and this suggests the tank wall in that location would have been around 237-327 °C on the outer surface exposed to the fire, assuming a 100 kW/m^2 fire heat flux. As seen below, the measured liquid wetted wall temperatures were of this order. Figure 100 and Figure 101 show the two 98% full cases with water and NaOH. The plots also show the liquid saturation temperature for the measured tank pressure.

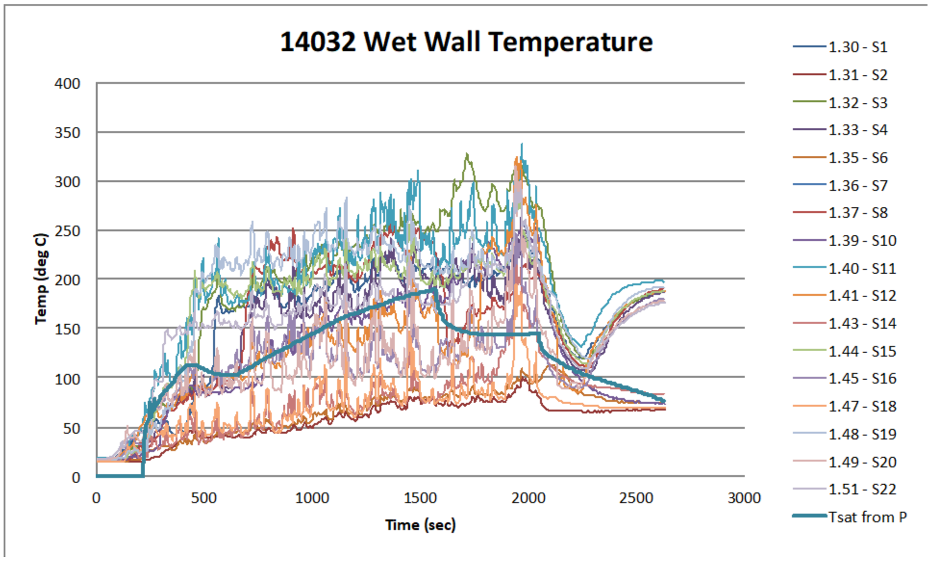

Figure 100. Test 1 (Water, 98%, Jacket and Insulation)

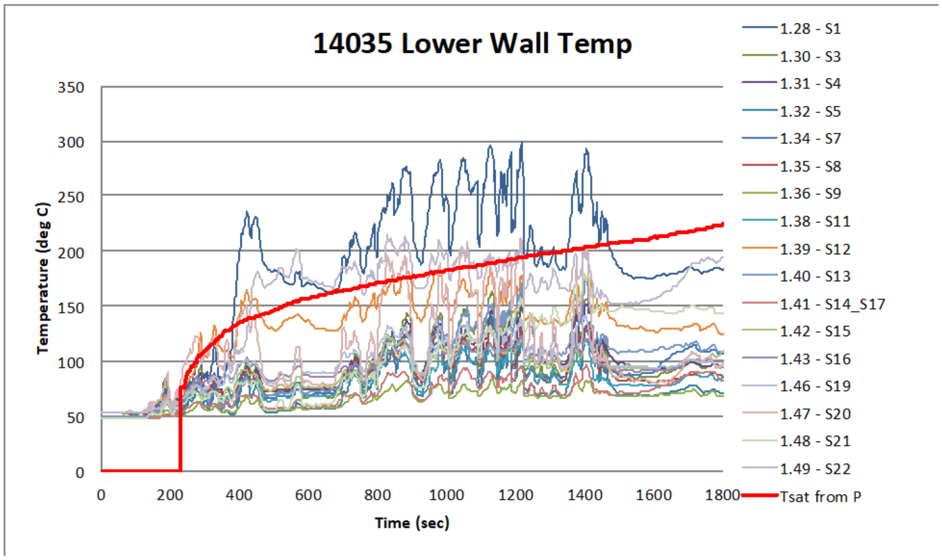

Figure 101. Test 3 (NaOH 50% Solution, 98% Fill, Insulation and Jacket)

As seen above, the measured wall temperatures are fluctuating above the saturation temperature based on the measured tank pressure. These fluctuations exceed the saturation temperature by as much as 100 °C as suggested earlier, and are caused by sub-cooled boiling. In this mode of boiling, the hot vapor bubbles are formed and rise from the wall. When the bubbles enter cooler liquid they collapse and the vapor condenses. The heat from this condensation mixes into the liquid on the outer edge of the boundary layer.

The tanks in Test 1 and 3 were insulated and jacketed. With this condition the heat flux to the liquid wetted wall was around 30 kW/m^2. The insulation and jacket reduced the amount of fire heat flux that entered the tank by about a factor of three. From this, we can now estimate the actual heat transfer coefficients in the liquid boundary layer. Let us consider the convection heat transfer in the liquid space as governed by the formula:

$$q = h \Delta T$$

where:

- q = the heat flux kW/m^2,
- h = convective heat transfer coefficient kW/m^{2}K, and
- ΔT is the temperature difference in Kelvin between the wall and the boundary layer (not the bulk liquid).

Note that the bulk liquid heats up much more slowly than the boundary layer. One way to model this system is to separate the liquid into two zones, the core and the saturated boundary layer. These two zones communicate by a free convective mixing process.

The *h* value is very difficult to quantify from a simple correlation in this application. On the liquid wetted wall, *h* can vary over a huge range (one or two orders of magnitude) in seconds. The coefficient depends on the wall size and shape and orientation, wall surface roughness, vessel pressure, local heat flux and of course fluid phase, properties and flow patterns.

When the heat transfer is by single phase free convection, the heat transfer coefficient may be around 0.3 kW/m^{2}K. As a result, there was a temperature difference of 100 K for driving the 30 kW/m^2 heat flux. However, when boiling takes place the convective coefficient jumps to 3 kW/m^{2}K or even higher, which led to a temperature difference of only 10K or less to drive the 30 kW/m^2. This explains why the wall temperature goes up and down quickly during the boiling cycles.

When NaOH boils, it behaves differently than boiling water. The boiling cycles are of lower frequency. It is possible the NaOH produces larger bubbles at lower frequencies. The larger bubbles could cause more liquid swell and this could lead to upper wall wetting. Upper wall wetting was seen with 98% fill NaOH and not with water. This wall wetting reduced the vapor space wall temperatures by more than 100 °C. This had a large affect (with 98% fill) on the time to failure and the pressure at failure.

Further research is necessary to develop detailed models for this process, for different commodities.

Abbreviations and Acronyms

Abbreviations	Acronyms
AFFTAC	Analysis of Fire Effects on Tank Cars (software program)
ASTM	American Society of Testing and Materials
BAM	Bundesanstalt für Materialforschung und -prüfung (German Federal Institute for Materials Research and Testing)
CFR	Code of Federal Regulations
DFT	Directional Flame Thermometer
DOT	Department of Transportation
FRA	Federal Railroad Administration
KOH	Potassium Hydroxide
NAR	Non-Accident Release
NaOH	Sodium Hydroxide
PRD	Pressure Relief Device
PRV	Pressure Relief Valve