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Thermal Protection System Evaluation for DOT-117 Hazardous Materials Car Tanks

DOT/FRA/ORD-26/11

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14. ABSTRACT The Federal Railroad Administration sponsored a research team from Engineering Services, Inc. to perform an analysis of the effectiveness of the thermal protection system on a DOT-117 rail car as a fire protection measure. This research was carried out between February 2022 and March 2023 at multiple ESi locations; the experimental tests were performed at ESi's Houston, Texas office. The objective of this work was to evaluate the performance of the thermal protection system in rail cars as a risk mitigation control to prevent a catastrophic thermal event. The research group also analyzed the heat transfer from a fire to rail car contents to understand the effectiveness of a potential fire response from a local fire department.			
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Executive Summary

Every year, millions of tons of hazardous material (HAZMAT) is transported by rail in the United States. Transporting HAZMAT carries an intrinsic risk of accidental release, exposing nearby communities to potential danger during the interaction between rail tank cars and the industrial sites that use them. Industrial facilities receive raw products in rail docks, where they offload the products to storage tanks; however, sometimes, due to logistic reasons, facilities encounter an accumulation of rail tank cars in offloading areas. These tank cars must wait until docks are available, leaving rail cars idling in a waiting zone, sometimes for long periods.

Fire Marshals in local communities have expressed concern over the accumulation of rail tank cars containing flammable materials and have requested that the facilities provide extra fire protection against catastrophic ruptures and potential fires in layover areas. However, the extension of a fixed fire protection system is costly and rail tank cars already have an existing thermal protection system that comprises multiple layers of insulation materials. Therefore, the Federal Railroad Administration (FRA) sponsored a research team from Engineering Systems, Inc. (ESi) to perform an analysis of the effectiveness of the thermal protection system on a DOT-117 tank car as a fire protection measure. This research was carried out between February 2022 and March 2023 at multiple ESi locations; the experimental tests were performed at ESi's Houston, Texas office.

The objective of this work was to evaluate the performance of the thermal protection system in rail tank cars as a risk mitigation control to prevent a catastrophic thermal event. The research group also analyzed the heat transfer from a fire to commodity inside the rail tank car to understand the effectiveness of a potential fire response from a local fire department.

The research project consisted of three main phases:

1. Phase 1: Research and data collection

   The team identified and collected relevant information for the evaluation, including the thermal properties of the evaluated rail tank cars and the specific conditions during a pool fire event.

2. Phase 2: Fire and heat transfer simulation

   Researchers developed and performed a fire simulation, transient heat transfer calculation, and thermodynamic modeling to evaluate the impact of an ethanol pool fire under a DOT-117 tank car loaded with ethanol. Additionally, a thermal conductivity experimental test was conducted to evaluate thermal conductivity dependency with temperature at fire conditions. This conductivity was used as a parameter in the modeling.

3. Phase 3: Effect of cooling water

   The team evaluated the thermal protection system performance when cooling water is added as part of an emergency response strategy. This phase included a series of ethanol pool fire experiments to determine the effect of cooling water.

The simulation results indicated that a DOT-117 tank car's thermal protection system is adequate for protecting the rail car from a catastrophic thermal rupture due to fire impingement during a 1-

hour ethanol pool fire. Figure 1 shows the ethanol temperature, pressure, and liquid fraction inside the tank car when it was loaded to 80 percent of its capacity with ethanol.

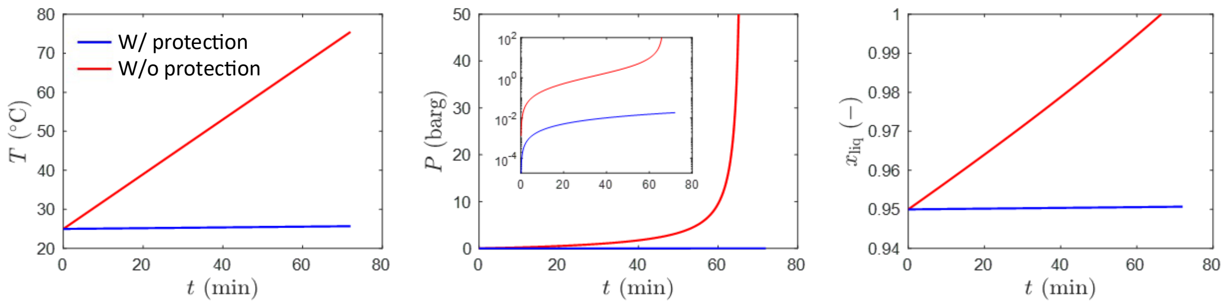

Figure 1. Thermodynamic response of a rail tank car's ethanol contents

Additionally, the cooling water experimental tests showed that adding cooling water to the outside of the tank car below the recommended NFPA[1] flow density (i.e., 0.25 gpm/ft^2) may still be adequate for cooling and protecting the tank car. Figure 2 shows the temperature difference in the protected and unprotected sides of the experiment for various levels of cooling water flow density. The unprotected side is the section directly exposed to the flame of the fires, while the protected side is the section not exposed to the fire and protected by the thermal protection system.

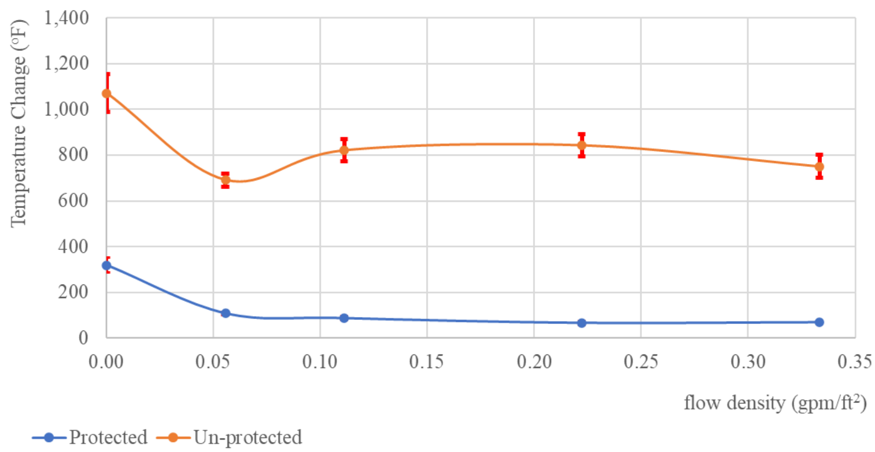

Figure 2. Temperature changes on the protected and unprotected side against cooling water flow density

[1] NFPA 15, Standard for Water Spray Fixed Systems for Fire Protection, 2022 edition

1. Introduction

The Federal Railroad Administration (FRA) sponsored a research team from Engineering Services, Inc. to perform an analysis of the effectiveness of the thermal protection system on a DOT-117 tank car as a fire protection measure. This research was carried out between February 2022 and March 2023 at multiple ESi locations; the experimental tests were performed at ESi's Houston, Texas office.

The objective of this work was to evaluate the performance of the thermal protection system in rail tank cars as a risk mitigation control to prevent a catastrophic thermal event. The research group also analyzed the heat transfer from a fire to the commodity in the rail tank car to understand the effectiveness of a potential fire response from a local fire department.

1.1 Background

Every year, millions of tons of hazardous material (HAZMAT) is transported by rail in the United States. Transporting HAZMAT carries an intrinsic risk of accidental release, exposing nearby communities to potential danger.

Many of the materials transported by rail have flammable or combustible characteristics. If a fire occurs, other rail cars may be exposed to heat from the flames, increasing the internal temperature and pressure inside them. As heat is transferred to the commodities within the tank cars, there is an increased risk of a secondary event.

This secondary event may expose the community and first responders to greater danger, such as explosions, catastrophic ruptures, increased heat impact to the surrounding structures, and release of toxic materials. To prevent this greater impact, first responders are often instructed to apply cooling tactics to rail tank cars that contain HAZMAT. However, first responders may be limited by the equipment they have on hand.

Due to the intrinsic risk posed by these rail tank cars, it is important to consider the interaction between the tank cars and the industrial sites that use them. Many industrial facilities receive raw products in their rail docks, where they offload the products to storage tanks. Nevertheless, many times, due to logistic reasons, the facilities encounter an accumulation of rail tank cars in the offloading areas. These tank cars must wait until the docks are available to offload their product, leaving the rail tank cars idle in a waiting zone for long periods.

1.2 Objectives

The objective of this work was to evaluate the heat transfer from a fire to the commodity of a rail car and the associated thermal response to understand the effectiveness of the tank car's existing passive thermal protection system and the potential fire response from local first responders. The results of this research can be used as an input for emergency planning and response strategies related to fires involving rail tank cars.

1.3 Overall Approach

This research consisted of three main phases:

Phase 1: Research and data collection

Phase 2: Fire & heat transfer simulation

Phase 3: Effect of cooling water evaluation

1.3.1 Phase 1: Research and Data Collection

Phase I focused on identifying and collecting relevant information needed during testing and evaluation. This information included the thermal properties of the evaluated rail tank cars and the specific conditions during a fire event. The team created an assumption register from this research (Appendix A), which includes all the data used in the simulations.

1.3.2 Phase 2: Fire & Heat Transfer Simulation

In Phase 2, the research team developed and studied models of an ethanol pool fire impacting a DOT-117 tank car. These models included a pool fire event modeled in Fire Dynamic Simulator (FDS), a heat transfer model evaluating the heat input to the tank car from this fire, and the thermodynamic model for the vaporization of ethanol contained inside a tank car potentially leading to its over-pressurization.

FDS is a Computational Fluid Dynamics (CFD) package developed by the Fire Research Division of the National Institute of Standards and Technology (NIST). This software package enables estimation of the wall temperature of an object, given a fire scenario and the thermal properties of the wall materials, including composite wall based on layers of materials. The simulation uses this data to estimate the surface temperature and incident heat flux during a pool fire event.

Once the surface temperature of the rail tank car was estimated, it was used as an input into a separate transient heat transfer analysis to evaluate the transfer of heat through the rail tank car walls and its thermal protection system. The calculation applies conduction heat transfer equations to evaluate the heat flux and temperature profile across the wall.

Finally, employing the heat transfer results from the previous step, a thermodynamic model was used to predict the impact of the transferred heat on the temperature and pressure of the rail tank car's contents. This tool enabled the team to estimate the potential over-pressurization of the railcar leading to rupture and escalation. Figure 3 below shows a diagram with the overall simulation approach.

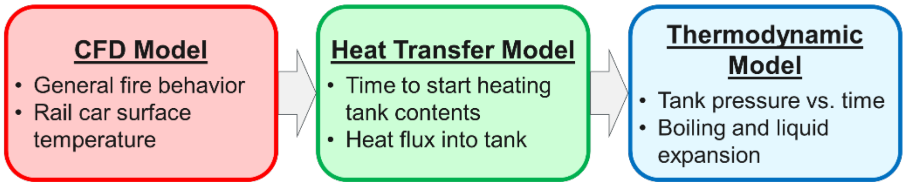

Figure 3. Overall simulation approach

The team tested the different materials in the thermal protection system to understand their thermal properties at fire temperature. The thermal conductivity values reported in Phase 1 only considered temperatures far below fire temperatures. For more accurate modeling, this phase included a test of these materials to determine their thermal conductivity when exposed to fire temperatures.

1.3.3 Phase 3: Effect of Cooling Water Evaluation

First responders address rail tank car fires by cooling the tank cars that are in contact with the flames to avoid a secondary event. To evaluate this effort, the team performed a series of ethanol pool fire experiments to determine the effect of cooling water.

1.4 Scope

The scope of this research project was limited to the performance of the thermal protection system for the DOT-117 tank car while transporting ethanol, considering a DOT-117 tank car with a thermal protection system while exposed to an ethanol pool fire on an industrial site.

1.5 Organization of the Report

This report includes the following sections:

- Section 2: Thermal protection system overview
- Section 3: Research and data gathering
- Section 4: Fire & heat transfer testing
- Section 5: Effect of cooling water evaluation
- Section 6: Results
- Section 7: Conclusions

2. Thermal Protection System

The thermal protection system is a layered protection jacket installed inside the tank car between two layers of external and internal steel, which has the purpose of resisting heat transfer between the exterior and interior of the car. This system consists of two layers of insulating materials and one layer of steel. Figure 4 shows the layers inside the DOT-117 tank car. The tank car comprises a 9/16-inch thick inner shell of the tank, in contact with the transported liquid, and the thermal protection system. The thermal protection system itself consists of a 4-inch thick fiberglass insulation, a thermal insulation material (Unifrax Fyrewrap), and a 1/8-inch thick carbon steel.

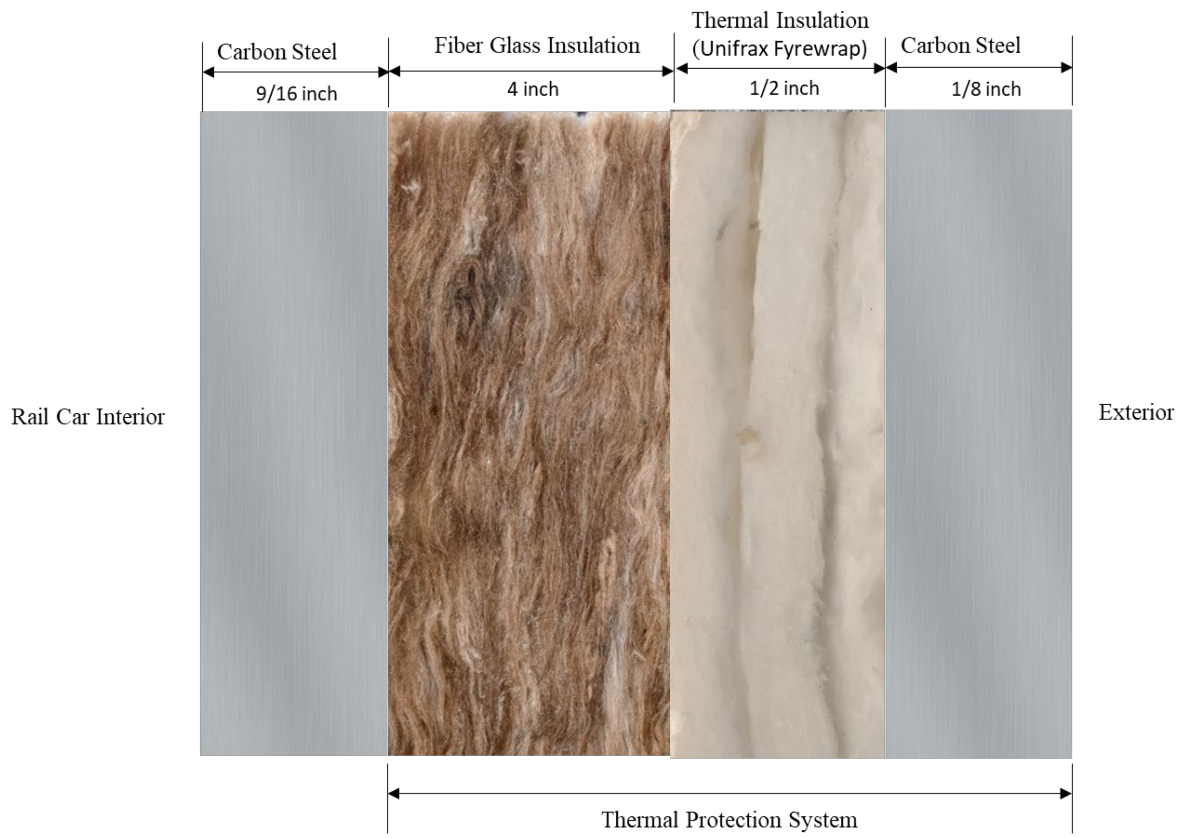

Figure 4. Layers inside DOT-117 Railcar

Due to the low thermal resistance of steel, this analysis considered the thermal transfer through the thermal protection system only (i.e., carbon steel, Unifrax Fyrewrap, and fiberglass). This assumption was verified by performing a transient conduction calculation through the steel, which shows that the temperature not exposed to the fire would reach 2,192°F (1,200°C) in 2 minutes; therefore, evaluating the protection system without considering the outer steel layer would only delay heat transfer by about 2 minutes.

3. Research and Data Collection

In Phase I of this research, the team focused on identifying and collecting relevant information needed during Phase II testing. This information included the thermal properties of the DOT-117 tank cars and the specific conditions during a fire event.

All the information gathered was documented in an assumption register, which includes all the data used for the simulation. The assumption register clarified and documented the parameters used in the modeling before performing the simulations. This document described the fire scenario of concern and indicated the thermal properties (i.e., density, thermal conductivity, and heat capacity) for different materials used in the model, such as soil, terrain ballast, railroad track ties, carbon steel, and thermal protection system insulation materials (i.e., Unifrax Fyrewrap, fiberglass). Additionally, the data indicated the thickness of the different materials in the thermal protection and soil considered in the modeling calculation. This document is attached to this report as Appendix A.

4. Fire & Heat Transfer Simulation Approach

In Phase II of this research, the team conducted simulations of fire and heat transfer and over-pressurization to evaluate the performance of the thermal protection system. A description of the approach followed during this phase of the project is included below.

4.1 Computational Simulations

This section describes the computational simulation conducted to evaluate the DOT-117 tank car under fire conditions, as described above. It details the model development and small-scale material fire tests conducted for data generation and model validation.

4.1.1 Pool Fire

The pool fire model was performed in FDS, a CFD tool developed by NIST. The model considers a simplified version of a DOT-117 tank car exposed to an ethanol pool fire beneath the tank car with a 5 m/s (16.40 ft/s) wind measured at a height of 32.8 ft (10 m). The simplification of the rail car geometry involves the removal of features smaller than 10 cm in length or diameter (e.g., chain, ladder steps), which is necessary to achieve the numerical stability of the model while maintaining reasonable run times for the simulation. Nevertheless, this modification does not meaningfully impact the accuracy of results, as the focus of the analysis is the large container.

Due to the high computational power required by CFD models, the simulations were divided into two models. The first simulation considered higher cells and domains sizes to observe the pool fire characterization and thermal impact to the environment. This first simulation predicted heat flux and temperatures in the atmosphere to assess first responders' ability to approach the tank car and the pool fire. The second model used a smaller domain and was focused on evaluating the heat flux and temperatures at the rail tank car surface.

The first model was divided into six smaller domains with cubic cells of 10 cm (3.94 in) in length. This subdivision was needed to assign specific computational cores to each subdomain. To prevent numerical instabilities, any component smaller than 10 cm was removed from the model. The ethanol pool was located at the center of the rail car with a surface area of 469.3 ft^2 (43.6 m^2). Rail tracks with wood and steel were included in the simulation. Nevertheless, to simplify the calculation, it was assumed that the wood of the track would not burn but rather only provide thermal mass to the heat transfer model. The pyrolysis of the wood is a complex reaction that would not provide a large contribution to the heat production when compared with the heat produced by the ethanol combustion and therefore can be omitted. Additionally, the ground was considered flat, with no change in elevation. The ground was modeled as typical compacted ballast – a 20-inch-deep layer of porous media consisting of a mixture between the ballast material and air with a 35 percent void volume. The ballast and soil thermal properties were taken from the AREMA 2016 Manual for Railway Engineering[2], Sussmann, T.R. et al[3], and the

[2] AREMA 2016 Manual for Railway Engineering – Part 2 – Ballast

[3] Sussmann, T.R. et al, J. Transport. Res. Board, 2289, 87-94, 2012

O.B Andersland book of Geotechnical Engineering for Cold Regions[4]. Table 1 shows the thermophysical properties of the ballast and soil used. Figure 5 and Figure 6 show the model.

Table 1. Soil thermophysical properties

Material	Density	Thermal Conductivity	Heat Capacity
Ballast	110 lb/ft3 [1,762 kg/m3]	15.7 BTU-in/hr-ft^2-°F [2.26 W/m-K]	0.27 BTU/lb-°F [1.129 kJ/kg-K]
Native Soil	110 lb/ft3 [1,762 kg/m3]	13.2 BTU-in/hr-ft^2-°F [1.90 W/m-K]	0.19 BTU/lb-°F [0.7946 kJ/kg-K]

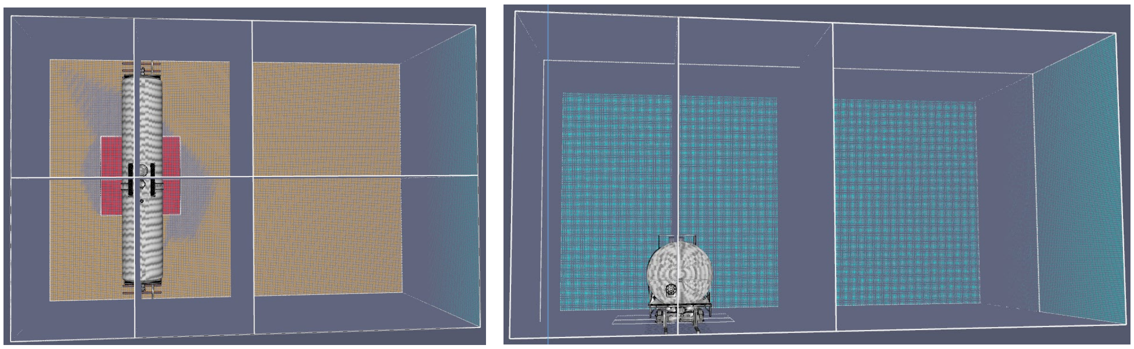

Figure 5. First FDS Model (left: top view; right: side view)

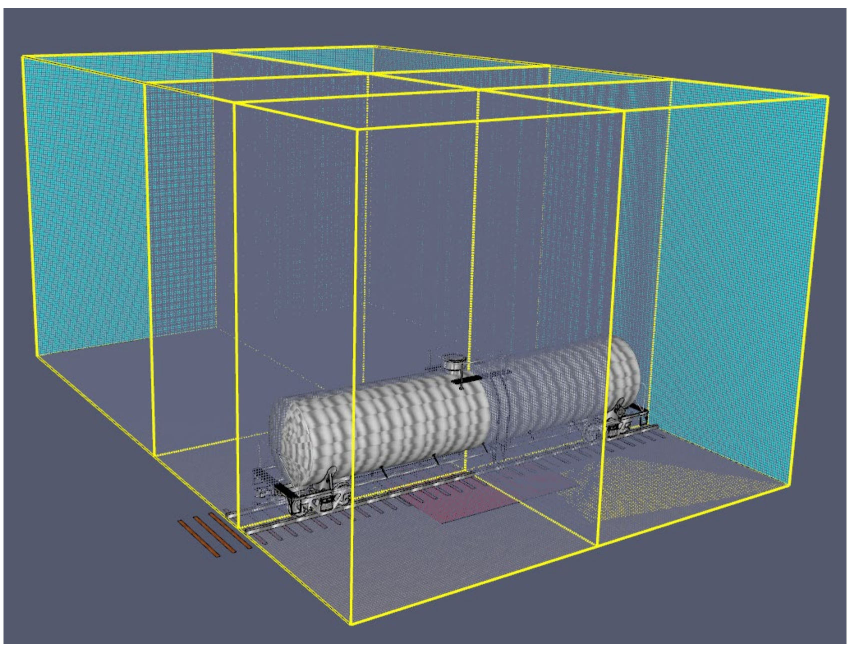

Figure 6. First FDS Model – isometrics

The second FDS Model used a smaller domain size, which only included the rail tank car and the pool fire. Eight subdomains were used with cubic cells of 10 cm (3.94 in) of side for the section

[4] O.B. Andersland, Geotechnical Engineering for Cold Regions, McGraw-Hill Inc., 1978

immediately above the ethanol pool and 20 cm (7.87 in) of side for the rest of the tank car. This simulation used the same railcar 3D model and pool fire characteristics from the first simulation. Figure 7 and Figure 8 show the model for this second simulation.

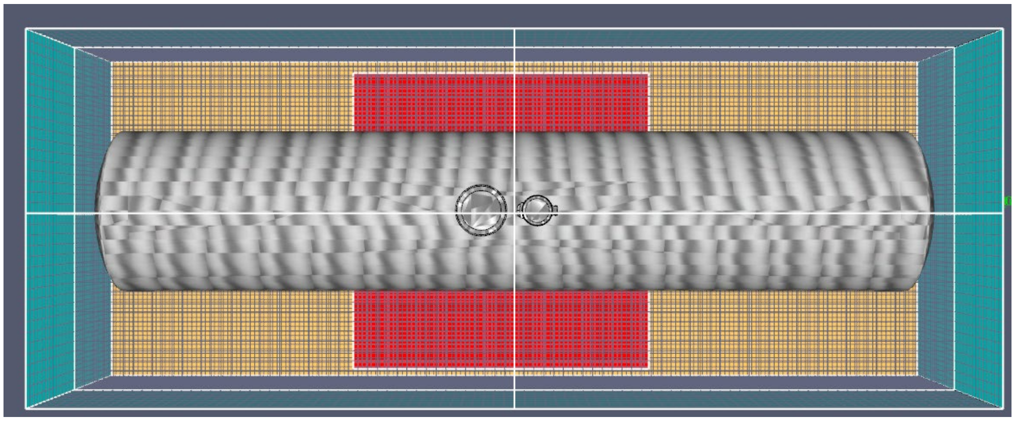

Figure 7. Second FDS Model (upper view)

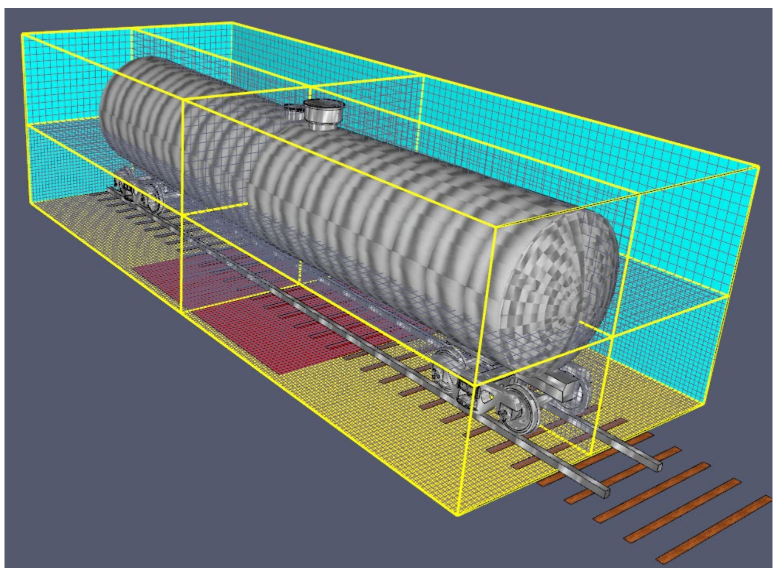

Figure 8. Second FDS Model – isometric view

4.1.2 Heat Transfer

While FDS was used to predict the outer surface temperature of the rail tank car, it is not a convenient framework for modeling the conductive heat transfer through the tank car walls and insulation. For this purpose, the team used ANSYS Fluent, a commonly used commercial software for modeling fluid dynamics and heat transfer. For this research the team used only the solid heat transfer modeling capabilities of ANSYS Fluent tool.

The solid heat transfer model was kept relatively simple for this research. Although this model is a transient model and considers heat transfer through multiple materials, the team made several assumptions to facilitate the analysis. First, only 1-dimensional heat transfer through the tank car walls was considered, as heat transfer along the walls was expected to be much smaller. Second, only conductive heat transfer was modeled, as it was expected that the conductive timescale should be much longer than that of radiation or convection. Next, the steel layer that is directly receiving heat from the fire was neglected, as the thermal resistance offered by this highly conductive material would be negligible compared to that of the FyreWrap® insulation. Additionally, the outer boundary of the FyreWrap, which contacts the hot steel, was assumed to reach the steady-state steel temperature evaluated in Section 4.1.1 instantaneously once the fire started. Finally, the thermal conductivity κ of each material was assumed to be independent of temperature; however, since vendor data[5] for the insulation indicates thermal conductivity increases strongly with temperature, multiple values were tested to quantify the impact of this assumption.

The conduction equation with the above assumptions was solved on a mesh of 100 cells, with 12 cells in the FyreWrap layer and 88 cells in the insulation layer, thereby yielding similar cell sizes across the two layers. The model was run until a steady-state temperature profile was achieved.

4.1.3 Thermodynamic Model

A simplified thermodynamic model was constructed in Matlab to predict the increase in pressure in the tank car associated with the heating rates predicted with the conduction model. This model assumed that the tank car's contents, for example ethanol would be heated uniformly without developing temperature gradients and that vapor-liquid equilibrium would be maintained. It also assumed a constant heat input rate to the tank car as well as constant fluid properties except for density; vapor density is governed by the ideal gas law, while liquid density is a function of temperature. Ethanol vapor pressure is also a function of temperature. The boiling point of ethanol was taken as that at atmospheric pressure and assumed not to change with pressure.

The thermodynamic model thus considered three contributors to pressure rise upon heating: liquid expansion, increased vapor pressure (below the boiling point), and boiling.

4.2 Experimental Testing

The previous analysis identified uncertainties in the model related to the thermal conductivity at high temperatures. Therefore, a test was performed to analyze the thermal transfer problem and reduce the uncertainty.

This test was performed for measuring the thermal conductivity of the insulation material at high temperatures (i.e., fire temperatures).

4.2.1 Thermal Conductivity

Due to the limited available information regarding the thermal conductivity of the materials that constitute the thermal protection system, an experimental test was performed to measure the thermal conductivity dependency on temperature, specifically at the high temperatures that the materials would experience during a fire.

This experiment was based on Fourier's law of conductive heat transfer in steady state. When a layer of a material with temperature-independent thermal conductivity is exposed to different surface temperatures on its two opposite sides, it will develop a linear temperature gradient through the layer. However, if the thermal conductivity is instead temperature-dependent, then the same scenario will yield a curved temperature profile, as regions of different temperature will

[5] Knauf Insulation, Inc., KwikFlex® Pipe & Tank Insulation Data Sheet, 2021

have different thermal conductivities and thus develop varying temperature gradients to maintain constant heat flux. This curvature, if measured, can be used to develop an expression for the thermal conductivity as a function of temperature.

As in the thought experiment above, the research experiment involved exposing the insulation material to a typical fire temperature on one side while being cooled on the other side. The hot side was heated by four propane burners each rated to 108,000 BTU/hr, and the cold side was kept at a constant temperature near 32°F using an ice-water bath. Multiple temperature readings were performed at different positions throughout the layers to extract the temperature profile. Once the temperature readings reached steady state, the temperature profile through the layers was recorded and used to calculate the heat flux through the insulation layers and thereafter the dependency of the thermal conductivity on temperature. Figure 9 shows a graphical representation of the temperature profile expected through the material layers during this experiment. This shows how temperature changes from the hot side (i.e., in contact with the fire) to the cold side (i.e., in contact with the water bath).

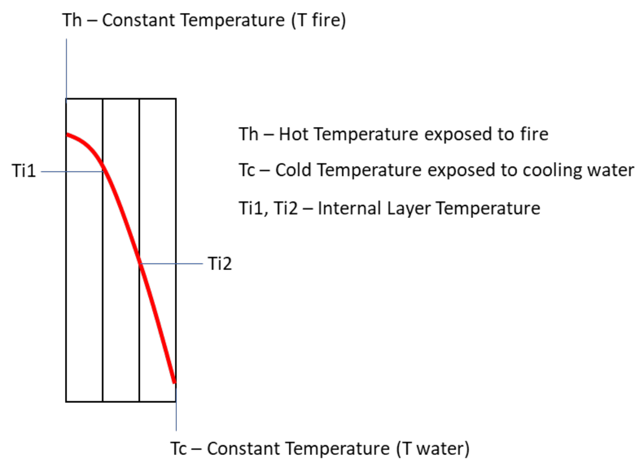

Figure 9. Experiment temperature profile

The experimental rig included a 1 ft^3 box (1 ft x 1 ft x 1 ft) with four propane burners in the bottom. These burners allowed air ingress feeding the flame with a propane-air premix flow. At the upper face there was a 1/8-inch thickness 1 ft^2 (1 ft x 1 ft) steel plate. The Unifrax Fyrewrap insulation layers were laid on top of this plate with k-type thermocouples in the interfaces between the different layers. Five thermocouples were used in each layer to measure any temperature differences in the transverse direction. A circular tank was located at the top of the last insulation layer, which was fed by a pump connected to a cooling ice-water tank. The circular tank allowed water movement to increase convection and heat transfer. Additional thermocouples were located between the last insulation layer and the contacting tank, as well as inside the ice-water tank. Figure 10 shows the experimental rig diagram.

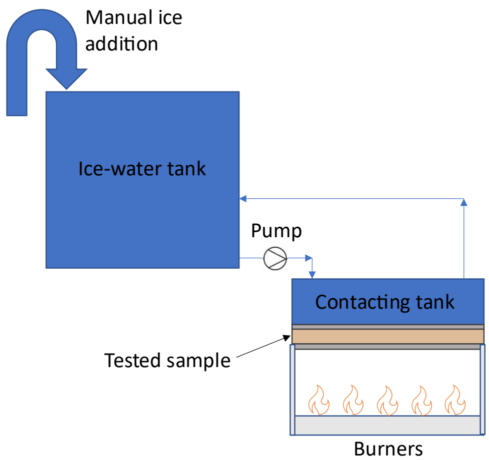

Figure 10. Thermal conductivity experimental rig diagram

5. Effects of Cooling Water Approach

Phase 3 included the evaluation of the emergency responder strategy of using cooling water to prevent a catastrophic thermal rupture due to over pressurization cause by the heat input from the fire. This section describes the approach followed to evaluate the performance of the thermal protection system and the effect that cooling water would have in overall protection.

5.1 Experimental Testing

Once the thermal conductivity dependency was evaluated, the team used this experiment to test the performance of the entire system. One important aspect of this experiment was to test the behavior of the thermal protection system when an emergency response team employs cooling water. Therefore, this experiment exposed a 3 ft × 3 ft plate, with the thermal protection system behind it, to an 18 ft^2 (3 ft × 6 ft) ethanol pool fire. During this test, temperatures were measured at the interface of the 1/8-inch-thick steel plate with Fyrewrap and at the fiberglass layer. Figure 11 below shows the thermocouple locations in the thermal protection system. During the experimental test, additional steel plate and fiberglass insulation was used behind the thermal protection system to prevent heat loss to the environment, which in reality would be transferred to the ethanol in the railcar. Both the insulation in the experiment and the ethanol in the rail car were heat sinks.

Figure 11. Thermal protection system thermocouple locations

Additionally, to evaluate the system behavior when cooling water is deployed, the experimental rig included a water irrigation system at the top of the plate assembly that provided water to the external face of the steel plate at a given flow rate. Figure 12 and Figure 13 show the overall rig design including the dimensions, the water irrigation system, and the location of the thermocouples in each layer.

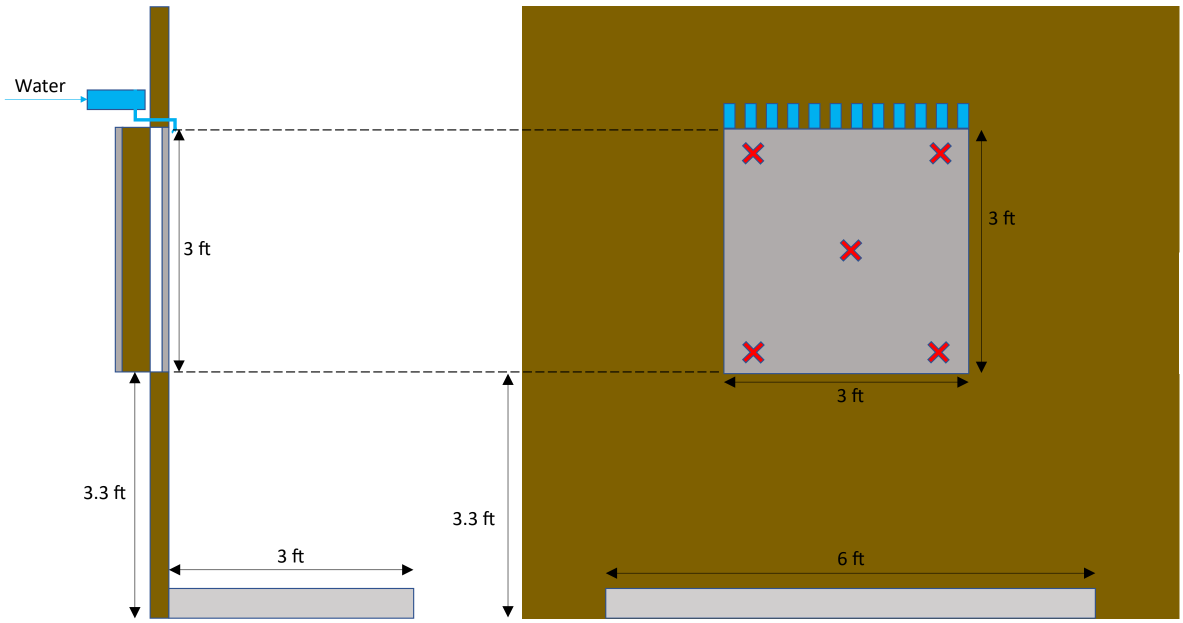

Figure 12. Experimental rig frontal and side view

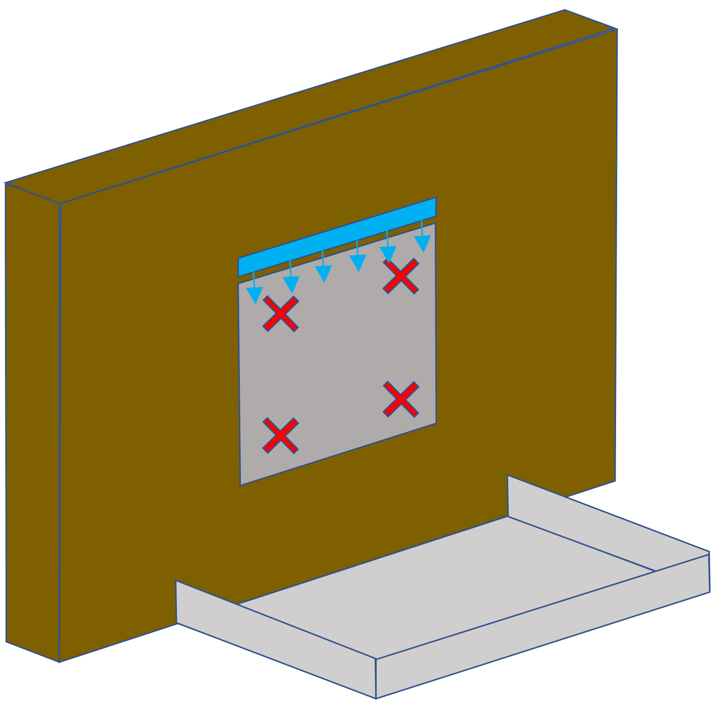

Figure 13. Experimental rig – isometric view

The test consisted of five experiments with different water flows. The plate was exposed to the pool fire for 10 minutes, then the cooling water was activated. The water flows considered included values below the level recommended by the NFPA[6] (i.e., 0.25 gpm/ft^2). Table 2 below

[6] NFPA 15 Standard for Water Spray Fixed Systems for Fire Protection, 2022

shows the five cases evaluated, showing the actual flow set and measured in the field and the equivalent flow density provided to the plate.

Table 2. Experiments parameters

Case Name	Water flow (gpm)	Flow density (gpm/ft^2)
0-0	0.0	0.00
005-10	0.5	0.06
01-10	1.0	0.11
02-10	2.0	0.22
03-10	3.0	0.33

6. Results

This section discusses the results of the testing and simulations performed during this analysis.

6.1 Fire & Heat Transfer Simulation

The simulations are described first as the performance analysis during the pool fire scenario, then the test results are discussed to determine any potential impact that the thermal conductivity may have on the simulation results, and the effect of cooling water during the emergency response activities.

6.1.1 Computational Modeling

This section describes the results obtained from the various computational models develop in execution of the research project. The first subsection discusses the fire modeling results followed by results obtained from the heat transfer and thermodynamics modeling.

6.1.1.1 Fire Modeling

The first model predicted a 6.5 kW/m^2 heat flux contour at 26.25 ft (8 m) from the tank car center, which is the maximum distance that an emergency responder would be able to approach the tank car due to the heat effect of the fire. It was expected that a responder with adequate cooling water could approach a little further, but from a risk perspective this value is generally accepted[7][8]. Figure 14 and Figure 15 below show the 6.5 kW/m^2 heat flux contour.

The atmospheric temperature was then estimated and compared with an approach criteria. An approach criteria is the minimum environmental conditions (temperature or heat flux) that fire responders (i.e., firefighters) can withstand to approach the flame. An approach criteria of 167°F (75°C) was considered. This value was chosen between values provided in NFPA 130[9], defined as 165°F for approximately 5 minutes to incapacitation without protection, and diverse European Fire Safety regulations[10],which is a tenability criteria for smoke temperature of 176°F. The NFPA 130 tenability criteria is defined without protection, and an allowance for a higher temperature was given by the protection provided by the first responder's structural firefighting gear. The simulation showed an approximate distance of 16 ft (5 m) from the tank car to the isothermal contour of 167°F measured at the ground level. However, the contour has an elevation that must be considered when evaluating the possible response approximation. Figure 16 shows the 167°F (75°C) isothermal contour.

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[7] Center for Chemical Process Safety, Fire Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities, 2003

[8] International Association of Oil & Gas Producers, Report No.434-14, Vulnerability of humans, 2010

[9] National Fire Protection Association, NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems, Annex B – Emergency Ventilation and Fire Risk, 2023

[10] B. Karlsson and J. G. Quintiere, Enclosure Fire Dynamics, CRC Press, Second Edition,

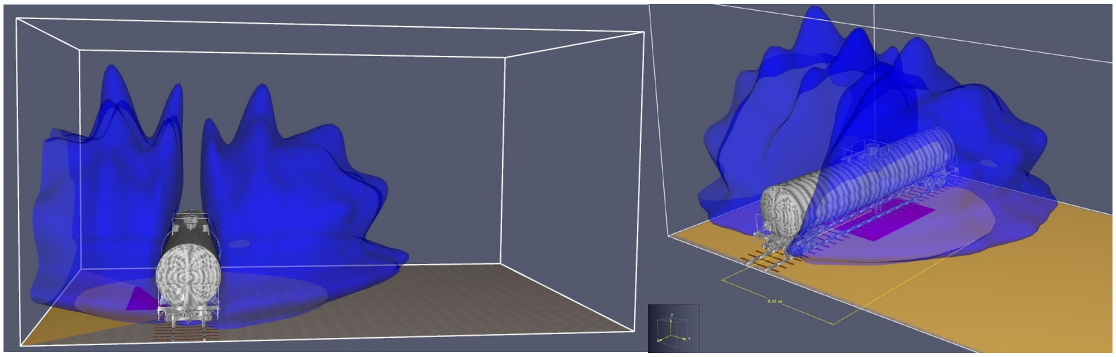

Figure 14. 6.5 kW/m^2 heat flux contour – side view and isometric

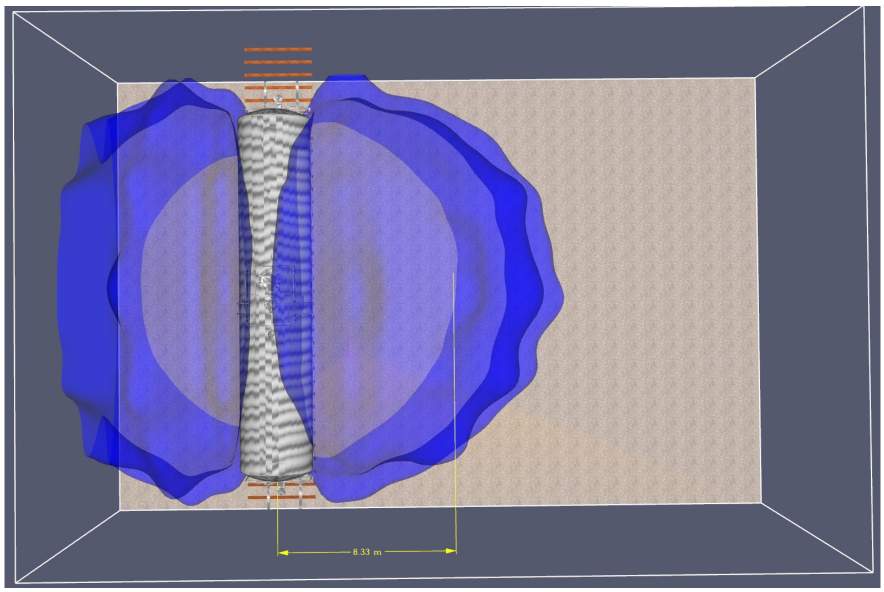

Figure 15. 6.5 kW/m^2 heat flux contour – top view

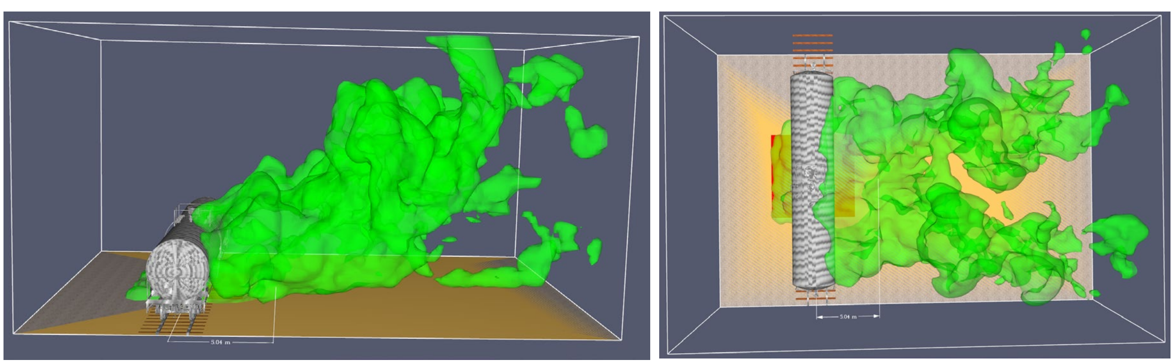

Figure 16. FDS 167°F isothermal contour

The second simulation predicted the tank car surface temperature and incident heat flux profile with their respective maximum values located below the ethanol pool. The simulation predicted a maximum value of approximately 300 kW/m^2 and 2,462°F (1,350°C) for the incident heat flux and surface temperature, respectively. This was an expected result as there was a direct flame impingement in this zone. Figure 17 and Figure 18 show the incident heat flux and surface temperature, respectively, from a bottom view. These maximum values were used as input for the exposed side in the heat transfer model.

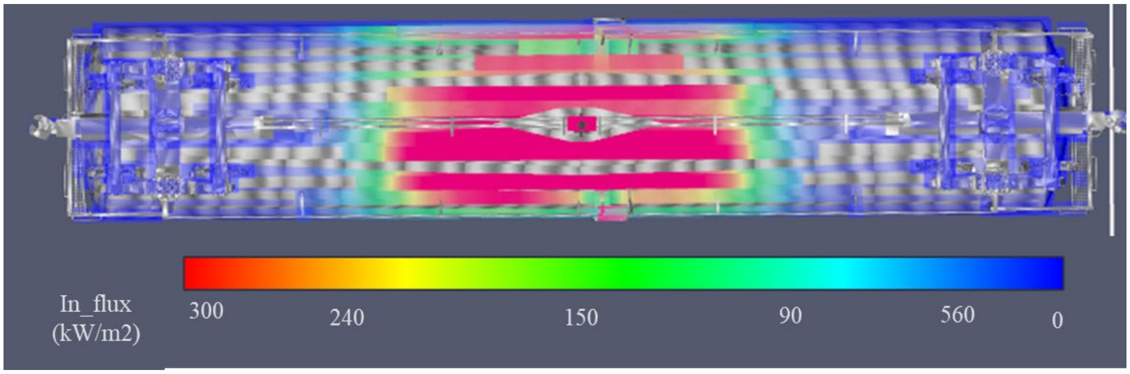

Figure 17. Incident heat flux

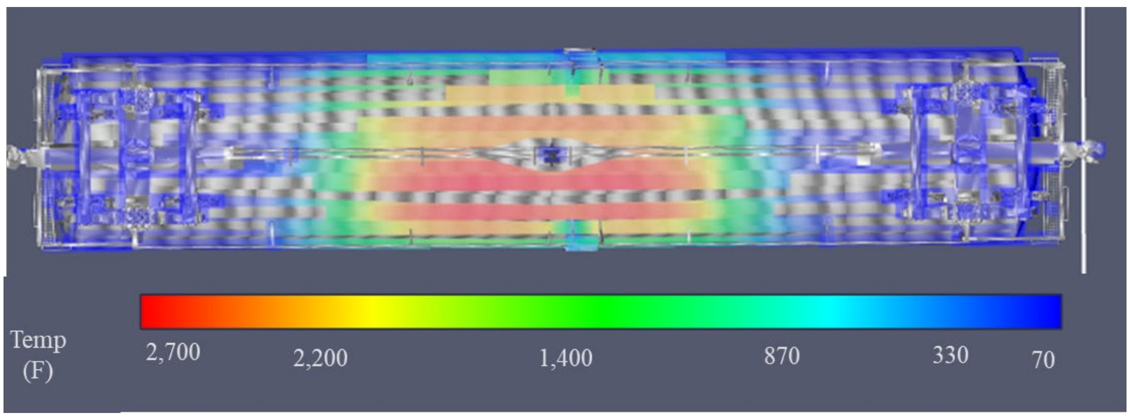

Figure 18. Surface temperature

6.1.1.2 Heat Transfer Modeling

The heat transfer model was applied to two cases: one with the thermal conductivity values of FyreWrap and insulation corresponding to ambient temperature as provided by vendor datasheets,[11] and another with a higher thermal conductivity (i.e., κ value) corresponding to elevated temperature. The higher-temperature value for the insulation was taken from Jannot et al,[12] whose data for Quartzel® felt generally agree with the KwikFlex® insulation data[13] provided by the vendor but are available at higher temperatures. The team used the value corresponding to the highest temperature reported (500°C). Since high-temperature data is not available for FyreWrap, and its thermal conductivity at room temperature is like that of the insulation, the team assumed that its thermal conductivity at higher temperatures would be equal to the other insulation (i.e., KwikFlex). These values are summarized in Table 3 below.

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[11] Unifrax I LLC. FyreWrap Tank Car Blanket, Product Information Sheet. Published online 2015.

[12] Y. Jannot, J. Meulemans, V. Schick, M. Capp, and I. Bargain. (2020). A Comparative Fluxmetric (CFM) Method for Apparent Thermal Conductivity Measurement of Insulating Materials at High Temperature, International Journal of Thermophysics.

[13] Knauf Insulation, Inc., KwikFlex® Pipe & Tank Insulation Data Sheet, 2021.

Table 3. Values of thermal conductivity for the thermal protection materials

	Thermal Conductivity (W/m K)	
	KwikFlex Insulation	**FyreWrap**
Ambient Temperature (25ºC)	0.035	0.03
High Temperature (500ºC)	0.273	0.273

The heat transfer model yielded significantly different predictions for the two cases of thermal conductivity. The thermal wave caused by the fire propagated more slowly when the thermal conductivity used was that of ambient temperature, as shown in Figure 19 below. With ambient-temperature κ values, a steady temperature profile took about 40 minutes to develop, while for the high-temperature κ values it only took 5 minutes. Additionally, the heat fluxes differed markedly between the two cases, as seen in Figure 20. Ambient κ values produced a steady-state heat flux of 390 W/m^2, while elevated κ values yielded 3,100 W/m^2. This order-of-magnitude separation in heat flux predictions results from the order-of-magnitude difference in thermal conductivity values used for the analysis, and it points to a significant potential error that can occur in fire protection analyses if thermal properties under fire conditions are assumed to be equal to those at ambient conditions. It also underscores the need to obtain more accurate estimates of thermal conductivity for the actual temperatures of the fire scenario in question, as the elevated temperature (500°C) at which κ was estimated above is still far lower than the maximum surface temperature predicted via FDS (1350°C) or even the average temperature in the thermal protection system (~700°C, assuming a linear temperature profile).

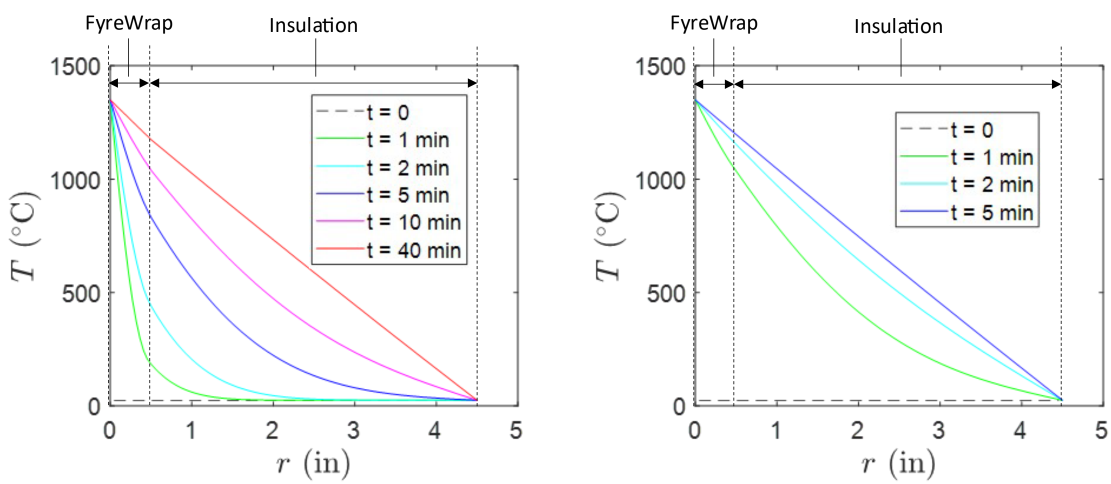


Figure 19. Temperature profiles for values of thermal conductivity values corresponding to (a) ambient temperature and (b) elevated temperatures

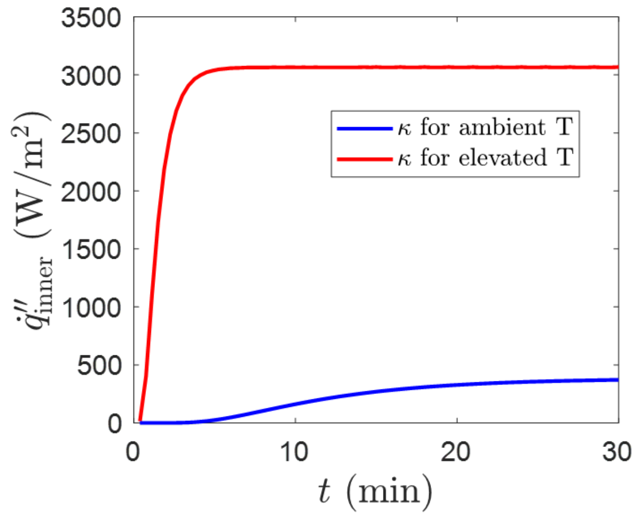


Figure 20. Heat flux to the ethanol contained in a car vs. time, for conductivity at different temperatures

The steady-state heat flux through the insulation for the high-κ case, although higher than the low-κ case, is nevertheless significantly reduced in comparison to the case of unprotected steel, as shown in Table 4. Specifically, the thermal protection dropped the flux by about two orders of magnitude compared with the bare steel case, for which the flux into the liquid was expected to be essentially the same as the heat flux from the fire. Furthermore, upon assuming the surface area exposed to this flux and the mass of ethanol in the tank car, the team estimated the temperature rise rate that the ethanol would experience in the two scenarios. These heating rates are also reported in Table 4 and exhibit the same separation of two orders of magnitude. The safety benefit of using the thermal protection system is hence quite clear.

Table 4. Heating rates with and without thermal protections for high-κ

Case	Heat flux (kW/m^2)	T increase of ethanol* (°F/hr)
Steel w/ protection	3.17	1.24
Steel w/o protection	228	90

6.1.1.3 Thermodynamics Modeling

A thermodynamic model for the tank car and its ethanol contents was next used to translate the heat fluxes from Table 4 into pressures in the tank car, which allowed researchers to evaluate the potential for catastrophic failure. Figure 21 below shows the thermodynamic response, including temperature, pressure, and liquid volume fraction in the tank car for the case of a tank that is initially 80 percent full of liquid.

As seen in the uninsulated case from Figure 21, early heating brings about a mild pressure increase and volumetric expansion of the liquid up until the boiling point of the liquid is reached. At this point, the liquid volume fraction starts to drop as boiling occurs, and the pressure correspondingly begins to increase significantly. This scenario represents boiling overpressure, the first possible mode of tank overpressure. With the addition of thermal protection, however, the boiling point was not reached during the simulated time window (i.e., 1 hour, as the emergency response team would be on site after this timeframe), and so the steep rise in pressure associated with boiling was avoided. Thus, the thermal protection system reduces the possibility of catastrophic failure significantly.

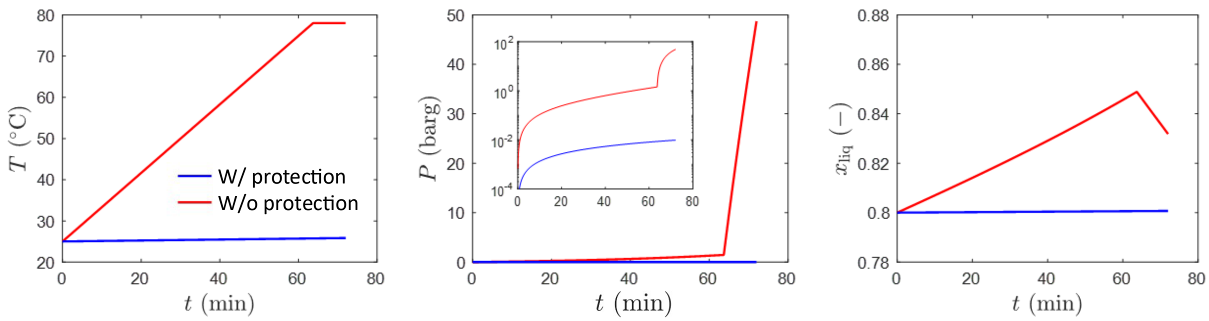


Figure 21. The thermodynamic response of the tank's ethanol contents – namely, its (a) temperature, (b) pressure, and (c) liquid volume fraction vs. time. In this scenario, the tank is initially 80% full of liquid

Liquid expansion overpressure, another mode of overpressure, is demonstrated in Figure 22, which similarly shows the temperature, pressure, and liquid fraction for the case of a tank that is initially 95 percent full of liquid. In this scenario, boiling does not occur, as a catastrophic pressure rise is encountered at a temperature below the boiling point. This pressure spike is caused by thermal expansion of the liquid to the point that the liquid fully fills the tank. Again, as in the case of boiling overpressure, the addition of thermal protection significantly reduced the pressure rise and therefore the possibility of vessel rupture.

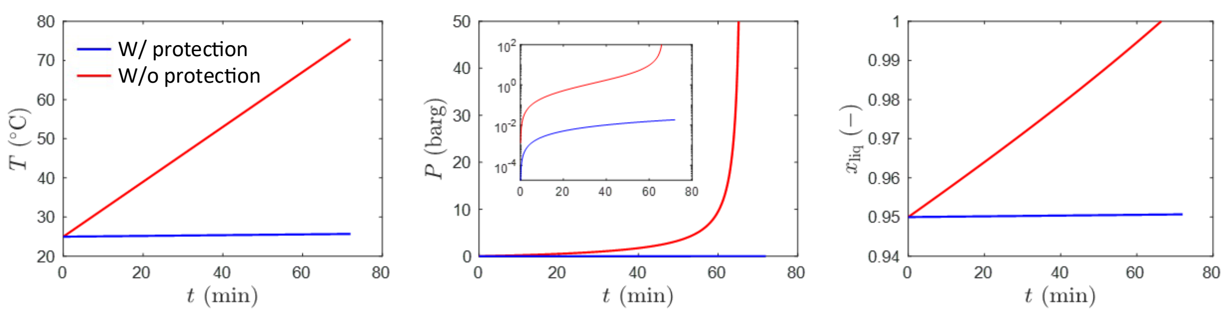


Figure 22. The thermodynamic response of the tank's ethanol contents – namely, its (a) temperature, (b) pressure, and (c) liquid volume fraction vs. time; in this scenario, the tank is initially 95% full of liquid

6.1.2 Experimental Testing

This section describes the experimental testing conducted in conjunction with the modeling effort.

6.1.2.1 Thermal Conductivity

This experimental test followed the experimental setup explained in Section 4.2.1 to evaluate the thermal conductivity temperature dependency at elevated temperatures for the materials used in the thermal protection system. Each insulation material was tested independently.

For FyreWrap, the experimental setup used four layers of the material, and the experiment was run until the steady state profile was reached. Figure 23 and Figure 24 show the experimental setup before and during testing, respectively. Figure 25 and Figure 26 show the temperature measured on the hot and cold side, respectively, during one of the tests. For the four layers of material, this steady state was reached after 30 minutes of fire exposure.

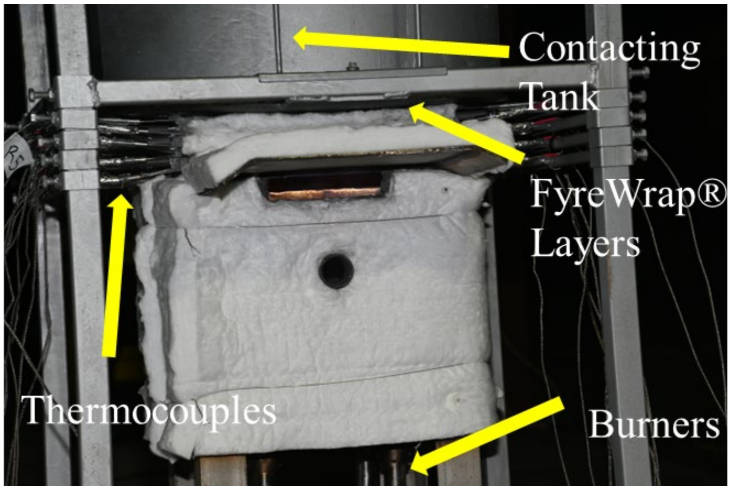


Figure 23. Thermal conductivity experimental setup before testing

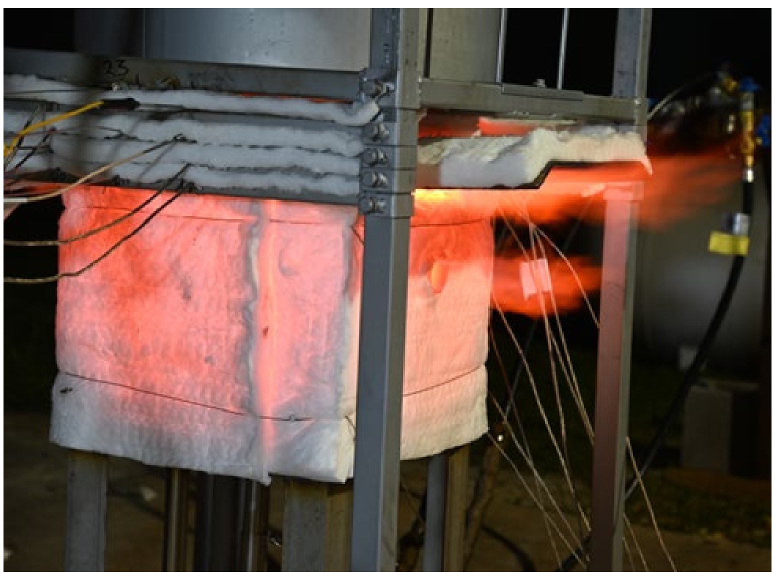


Figure 24. Thermal conductivity experimental setup during test

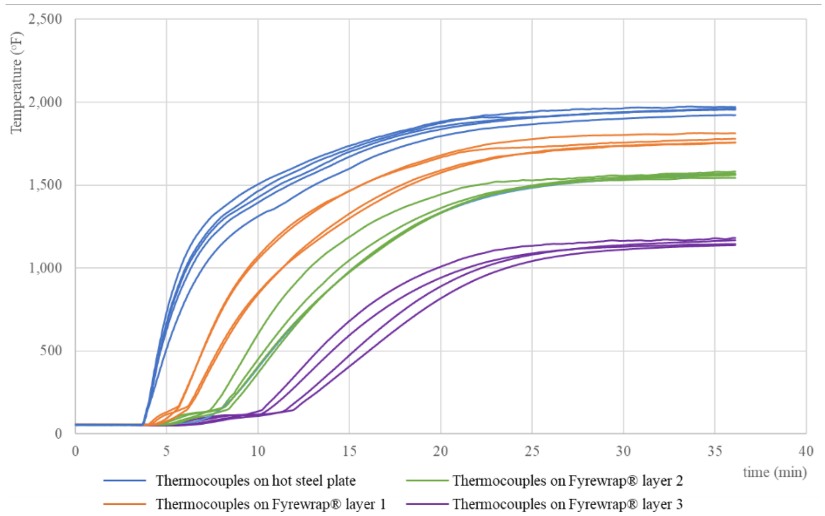


Figure 25. Measured temperatures on the hot side

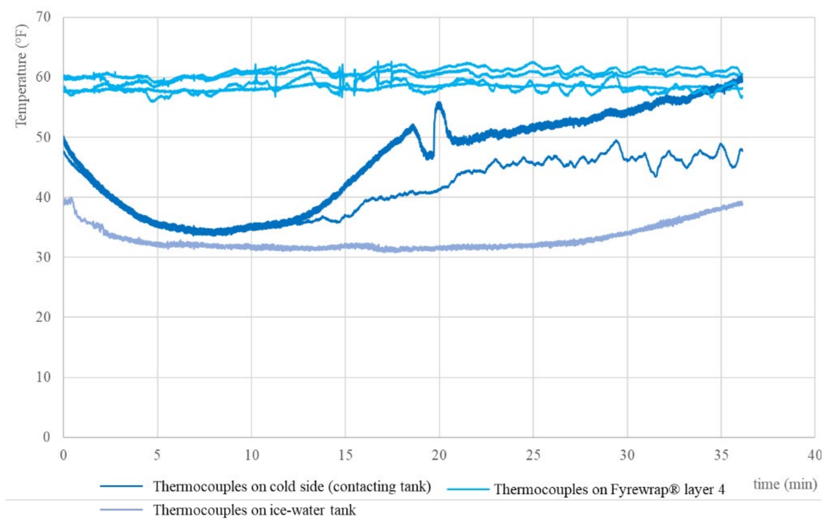


Figure 26. Measured temperatures on the cold side

The temperature data measured during the tests allowed team members to estimate the temperature profile within the FyreWrap layers. Figure 27 shows this steady state temperature profile in comparison with that corresponding to the previously assumed constant thermal conductivity. Unlike for the constant-κ case, the experimental temperature profile exhibited curvature, indicating that the thermal conductivity was indeed changing with temperature. This profile provided a heat flux of approximately 2 kW/m^2 through the four layers, thus showing qualitatively the insulation capacity of the material, considering that the total combined capacity of the four burners, divided by the plate area, yielded an approximate maximum heat flux of 2,460 kW/m^2. These values indicate that the heat transferred into the rail car's interior under steady state conditions was only 0.08 percent of the provided heat.

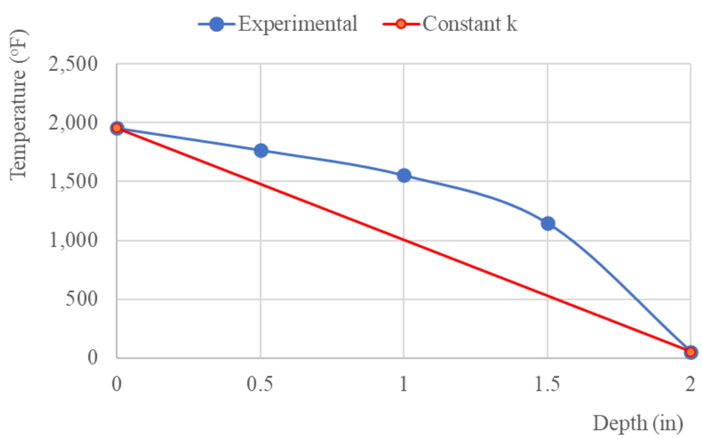


Figure 27. Steady state temperature profile

The same analysis was performed four times to ensure good statistics. The data for each experiment in conjunction with the known thermal conductivity value at room temperature specified in the product data sheet allowed the team to estimate the thermal conductivity curve against temperature for each experiment.

Figure 28 shows the FyreWrap thermal conductivity against temperature for each experiment alongside a curve fit. The fitted expression is $\kappa_{\text{FyreWrap}} = aT^5 + bT$, where a = 9.53e-17 W/m/K^6 and b = 1.06e-4 W/m/K^2.

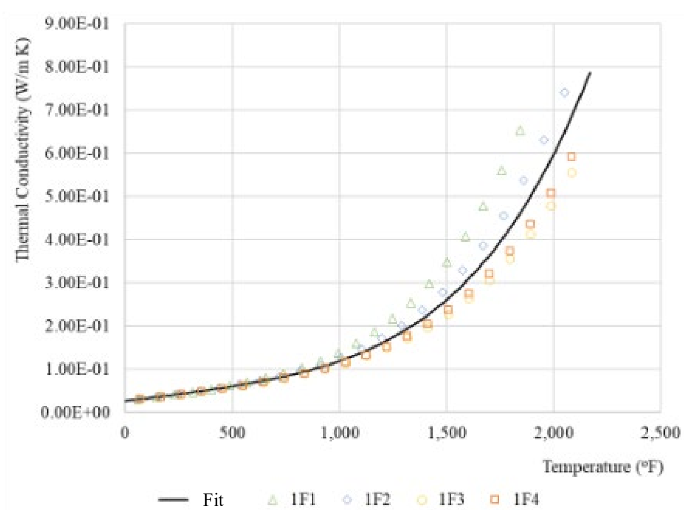


Figure 28. FyreWrap thermal conductivity temperature dependency

A similar test was performed for the KwikFlex fiberglass, but the experiment exceeded the material's melting point before achieving steady state conditions, making it impossible to use the data collected from this test. Therefore, it is recommended as future work to perform a similar test with one layer of FyreWrap to prevent fiberglass melting. In lieu of that data, the team used the following expression, fitted to the data from Jannot et al., for any heat transfer calculations involving the fiberglass insulation: $\kappa_{\text{fiberglass}} = cT^4 + dT$, where c = 5.69e-13 W/m/K^5 and d = 1.06e-4 W/m/K^2.

6.2 Effect of Cooling Water

This section describes the experiments conducted by the research team to evaluate the effects of cooling water during the emergency response activities to reduce heat transfer to the commodity inside the tank car.

6.2.1 Cooling Water Experiments

The purposes of this test were 1) to evaluate the system performance when it is exposed to a more realistic fire by exposing the thermal protection system to an actual pool fire and 2) to evaluate the system behavior when cooling water is added.

This test followed the setup explained in Section 5.1. As indicated in Figure 11, the thermocouples were classified as 'protected' (i.e., protected from the fire by thermal protection) or 'unprotected' (i.e., sitting between the steel plate and the FyreWrap and therefore not protected by the thermal protection system). Figure 29 and Figure 30 show the pool fire during one of the experiments before and after activating the cooling water, respectively.

Figure 29. Ethanol pool fire experiment before activating cooling water

Figure 30. Ethanol pool fire experiment after activating cooling water

The measured temperature data show that the unprotected-side temperature reduced its temperature quickly after the cooling water was activated. Figure 31 shows the unprotected-side temperature measured for the 3 gpm case. This graph shows a rapid decrease in temperature 10 minutes after ignition, coincident with the cooling water activation time. This observation corroborates the effectiveness of cooling water as a firefighting strategy in uninsulated vessels.

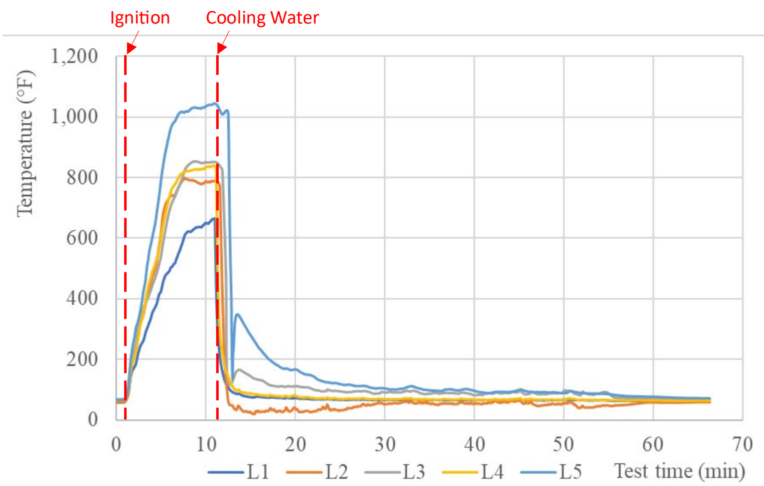


Figure 31. Unprotected side temperature measured for the 3-gpm case with 10 minutes delay

Conversely, the protected side showed a constant and somewhat elevated temperature after cooling water was activated. This observation was expected because thermal protection is an insulation system where the materials not only reduce the heat input but also prevent already-transferred heat from escaping the system. The temperature dependence of the thermal conductivity likely plays a role in this effect; prior to cooling water activation, the thermal conductivity of the FyreWrap near the hot plate was high and thus facilitated heat entry, but thereafter the cooling water lowered the thermal conductivity and impeded heat escape.

Figure 32 shows the protected side temperature measured for the 3 gpm case for 5 test runs.

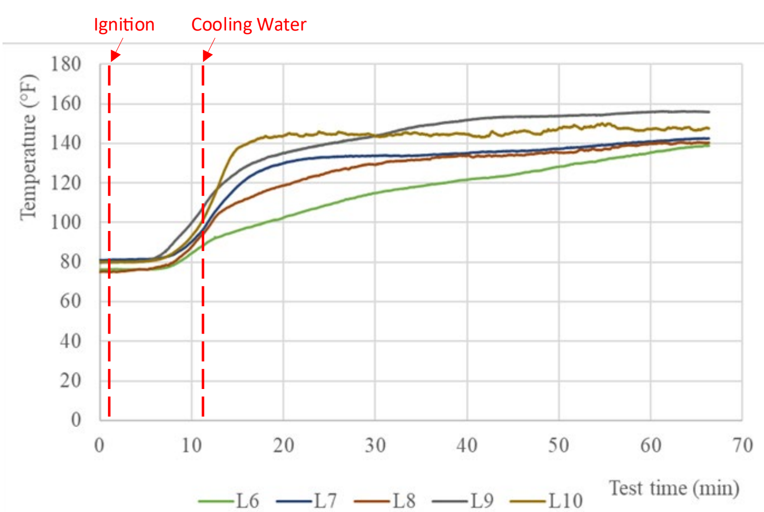


Figure 32. Protected side temperature measured for the 3-gpm case with 10 minutes delay

By comparing Figure 31 and Figure 32, researchers observed an offset in the time at which the system started heating up. While the unprotected side started heating up at 20 minutes (i.e., when ignition occurred), the protected side started heating up approximately 5 minutes later. A similar delay in thermal response was observed after the cooling water was activated, with the difference that the protected side maintained the temperature instead of decaying, as observed in the unprotected side. This contrast indicates that the cooling water prevents further heating of the tank car but does not actually provide cooling to its contents (i.e., the ethanol).

Figure 33 below shows the average temperature change for both the protected and unprotected side. This change was calculated as the difference between the maximum and minimum temperatures measured by a given thermocouple over time, and the average was then calculated by taking the mean change across all thermocouples on a given side. For cases with cooling water flow, the minimum temperature was measured, the average cool down time measured is presented in Figure 34. For the no-flow case (i.e., 0 gpm of cooling water) the minimum is the ambient temperature before ignition. As indicated previously, the unprotected side showed a larger temperature difference because the cooling water was cooling the steel plate. The protected side showed a smaller temperature difference because the cooling water only prevented more heating but did not remove heat that already passed through the insulation. The unprotected curve is indicative of the cooling water effectiveness and the protected curve is indicative of the thermal protection system effectiveness. One important observation in this graph is that the same temperature difference was reached when the flow was below the flow density required by the NFPA (i.e., 0.25 gpm/ft^2). This result suggests that lower flows may still be effective in mitigating catastrophic failure in DOT 117 tank cars.

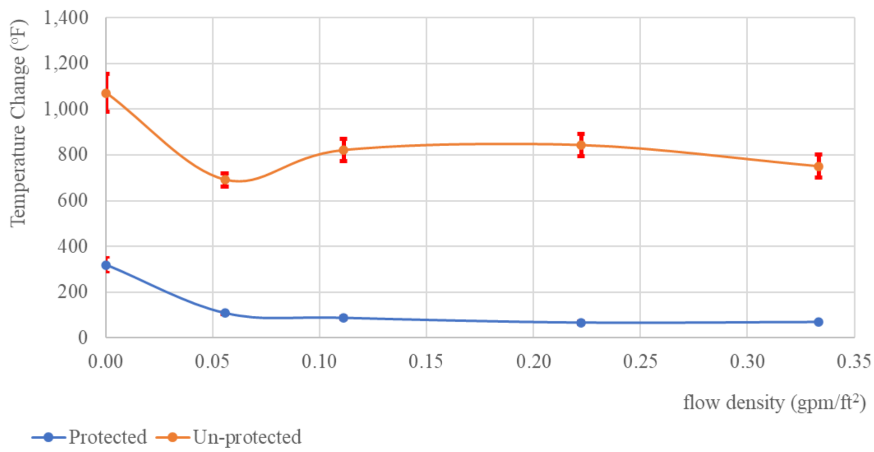


Figure 33. Temperature changes on the protected and unprotected side versus cooling water flow density

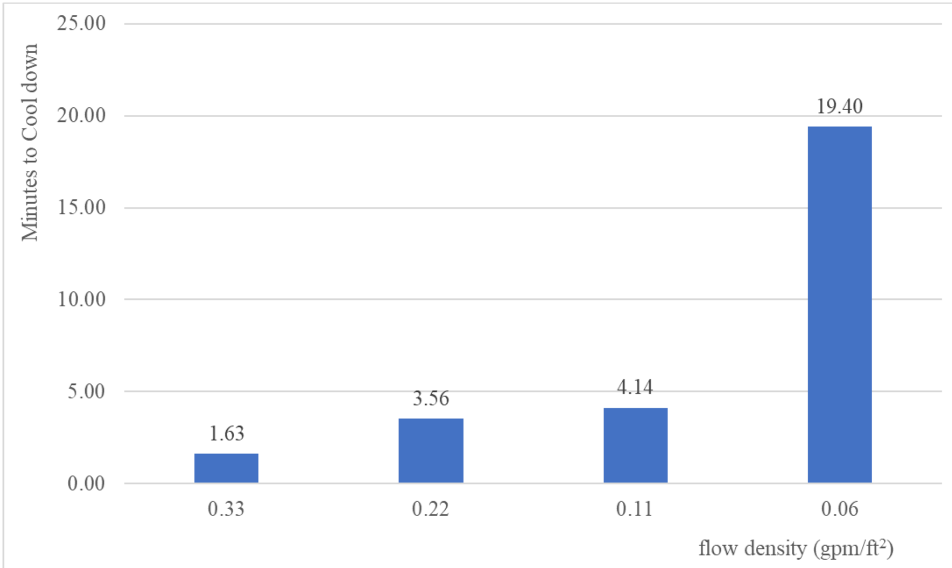


Figure 34. Average time taken to cool down the unexposed side for each cooling water flow density case

7. Conclusion

Considering the simulation and experiments performed during this project, the research team made the following conclusions:

The thermal protection system significantly reduces the pool fire impact, adequately protecting the DOT-117 rail car for at least 1 hour of fire exposure. This result gives the fire responders at least one hour to arrive, deploy, and provide cooling water to the exposed rail cars. Researchers used one hour as the time scope for this project, but the results show that, most likely, the protection would extend for more time. Nevertheless, with this analysis, the exact protection time cannot be specified.

FyreWrap thermal conductivity increases with temperature, with its value at fire temperatures being one order of magnitude higher than the value reported in the product specification. KwikFlex insulation likely exhibits a similar trend. Hence, researchers must be careful to use appropriate thermal conductivity values when performing thermal calculations of the DOT-117 tank car thermal protection system. This thermal conductivity increase allows the ingress of higher heat than expected at higher temperatures (i.e., fire exposure); therefore, any decisions taken considering the specified thermal conductivity would have an uncertainty related to this deviation. However, given the isolation layer depth, the thermal protection system still functions adequately as a passive system against heat ingress from fire exposure.

Cooling water effectively stops heat from entering the tank car; however, it does not remove heat that has already passed into the thermal protection prior to starting the water flow. In that regard, many first responders believe that cooling water is actually cooling its content, but in reality, it is only stopping more heat ingress. It is important to include this result in the first responder's training to guarantee their understanding of the thermal protection system functionality during an emergency.

Cooling water flows below values recommended by NFPA (i.e., 0.25 gpm/ft^2) may still provide adequate cooling and prevent heat transfer through the thermal protection system. This result shows that the most important aspect of the response strategy is to provide water on the tank car surface, not necessarily at high volume, but enough to stop heat ingress. This result also validates the safety factor typically used by NFPA in their standards, showing that the flow recommended by them is adequate for fire cooling.

Appendix A.
Model Assumption Register

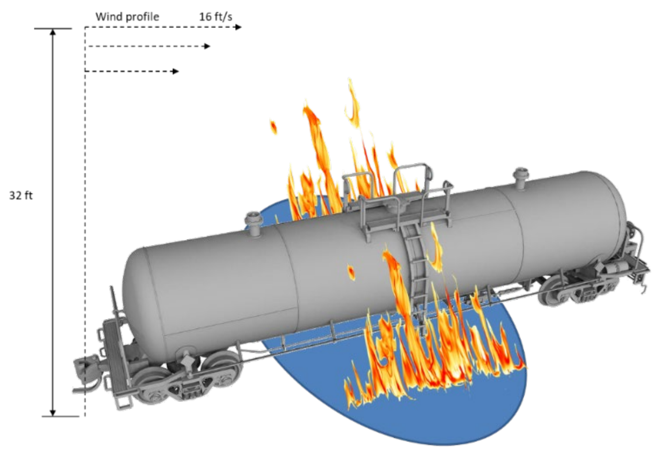
This Appendix provides the assumptions that was used during the fire simulation. The following sections and tables document these assumptions indicating:

- A general assumption description
- Significance or Likely effects on the study
- Justification for the assumption

1. Fire Scenario

The purpose of the research is to evaluate the thermal impacts of a DOT-117 tank car exposed to a hydrocarbon pool fire. There could be many factors that influence the specific fire scenario, and the intent of the research is not to vary all these parameters; rather, it is to show that a particular scenario can be evaluated by including generic factors.

The modeled fire scenario will consist of an ethanol pool fire beneath the tank car with average ambient winds. The wind profile to be modeled will utilize a speed of 16 ft/s [5 m/s] measured at a height of 32 ft [10 m], and a stable atmospheric condition. The tank car model will be located on a level section of rail track, with no surrounding objects such as structures, vegetation, or geological formations.



For evaluating the effect of fire responders applying cooling water to the tank car, the same parameters are considered with the addition of a prescribed water spray toward the rail car.

Significance/Likely Effects on Study

Given the many variables for the scenario to be analyzed, the chosen scenario can result in many different effects within the tank car. However, for the purpose of simplifying the analysis, a single scenario which utilizes generic rail conditions and average values will be considered.

Justification for Use of Assumptions

There are many variations that can be used but considering all possible variations would be unpracticable as many simulations would need to be performed. To simplify the analysis, this study assumed a single scenario as a demonstrative mean of the simulation possibilities.

2. Terrain and Soil

The terrain to be modeled will be considered flat, with no change in elevation. The material directly beneath the rail car will be modeled as typical compacted ballast – a 20-inch-deep layer of porous media consisting of a mixture between the ballast material and air with a 35 percent void volume.

The thermophysical properties to be assumed for the ballast are:

Parameter	Value
Density	110 lb/ft^3 [1,762 kg/m^3]
Thermal Conductivity	15.7 BTU-in/hr-ft^2-°F [2.26 W/m-K]
Heat Capacity	0.27 BTU/lb-°F [1.129 kJ/kg-K]

References:

AREMA 2016 Manual for Railway Engineering – Part 2 – Ballast

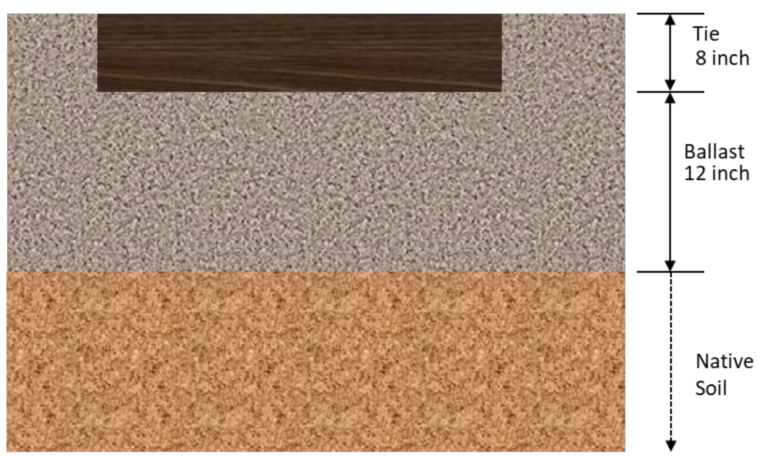
Sussmann, T.R. et al, J. Transport. Res. Board, 2289, 87-94, 2012.

O.B. Andersland, Geotechnical Engineering for Cold Regions, McGraw-Hill Inc., 1978.

Beneath this ballast layer, a generic native soil will be modeled having the following average thermophysical properties:

Parameter	Value
Density	110 lb/ft^3 [1,762 kg/m^3]
Thermal Conductivity	13.2 BTU-in/hr-ft^2-°F [1.90 W/m-K]
Heat Capacity	0.19 BTU/lb-°F [0.7946 kJ/kg-K]

3. Flat Terrain and Soil



References:

AREMA 2016 Manual for Railway Engineering

O.B. Andersland, Geotechnical Engineering for Cold Regions, McGraw-Hill Inc., 1978.

Significance/Likely Effects on Study

The thermal properties of the soil and ballast interact with the heat produced by the hydrocarbon pool fire, contributing to the heat profile. The ground would absorb and reflect some heat participating in the heat transfer phenomena.

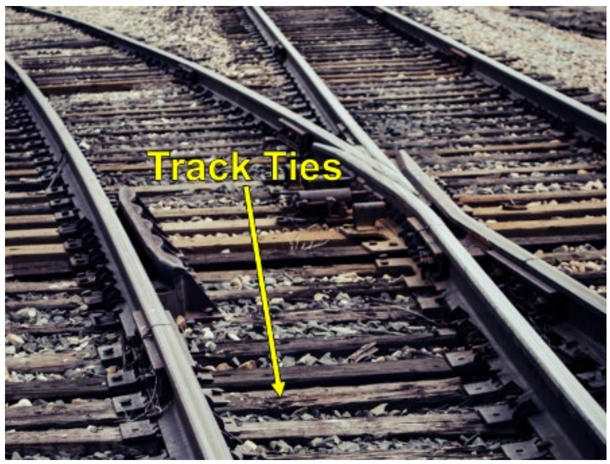
Justification for Use of Assumption

The terrain will participate in the overall heat transfer by absorbing and reflecting some of the heat generated by the pool fire. Many fire simulations only consider an inert ground, but to provide a realistic simulation, the thermal effects of soil and ballast need to be included.

4. Ties

Railroad Track Ties

Railroad track ties are rectangular supports for the rails in the tracks.



These ties can be made of different materials. For the purposes of this research, the ties will be modeled as oak wood. While the reflection and absorption of heat by the wood ties will be modeled, the combustion (i.e., burning) of the ties will not be considered. The thermophysical properties to be assumed for the wood ties are:

Parameter	Value
Density	43.7 lb/ft^3 [700 kg/m^3]
Thermal Conductivity	1.36 BTU-in/hr-ft^2-°F [0.196 W/m-K]
Heat Capacity	0.359 BTU/lb-°F [1.5 kJ/kg-K]

References:

Anton TenWolde, J. Dobbin McNatt, Lorraine Krahn, "Thermal Properties of Wood and Wood Products for use in Buildings", Oak Ridge National Laboratory publication # 87-21697/1, DOE/USDA-21697/1

William Simpson and Anton TenWolde, "Physical Properties and Moisture Relations of Wood", Wood Handbook Chapter 3

J.D. MacLean, "Thermal Conductivity of Wood", Heating, Piping, and Air Conditioning, Vol. 13, No. 6, pp. 380-391

Significance/Likely Effects on Study

The wood ties would interact with the heat produced by the pool fire. The amount of heat generated by burning the wooden ties would be relatively insignificant in relation to the heat produced by the hydrocarbon pool fire; therefore, ignoring this variable would not significantly impact the results of the analysis.

Justification for Use of Assumption

The presence of wood ties would interact with the heat produced by the hydrocarbon pool fire, contributing to the overall heat profile. Introducing heat production and mass loss by burning the ties would introduce a complexity in the model that will increase the run time and a source of potential mathematical error. Therefore, it is better to simplify the model by removing the pyrolysis model of the simulation.

5. Materials

Rail Car and Railroad Track Material

Rail tank car and railroad track will be modeled as typical carbon steel with the following thermophysical properties:

Parameter	Value
Density	489.4 lb/ft^3 [7,840 kg/m^3]
Thermal Conductivity	347 BTU-in/hr-ft^2-ºF [50 W/m-K]
Heat Capacity	0.113 BTU/lb-ºF [0.473 kJ/kg-K]

References:

2012 AREMA Manual for Railway Engineering Chapter 4, Figures 4-1-1 through 4-1-7

ASM Ready Reference – Thermal Properties of Metals, ASM International, Materials Park, OH, 2002.

The radiation heat transfer effects of the rail car paint coating will be ignored, with its reflectance modeled as a black body.

Significance/Likely Effects on Study

The rail tank car and tracks receive most of the heat, as they are in direct contact with the flame in a pool fire scenario. Correct values for these properties and materials need to be assumed to predict the heat transfer and resulting temperature profiles more accurately.

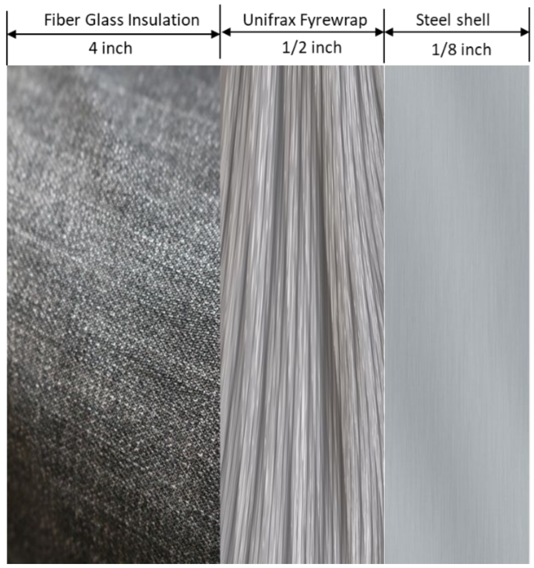
Justification for Use of Assumption

- Acceptable references for the steel thermal parameters values.
- There is no reliable reference for the reflectance of a painted steel surface during a fire, as most of the references identified by ESi are for uncoated steel or coated steel at standard atmospheric conditions (i.e., room temperature). Therefore, there is no confidence on the radiation behavior during high temperature conditions as a fire. For that reason, the materials are assumed to behave as a black body.
- There is an uncertainty on how the rail tank car coating will behave when exposed to a fire. Experience has indicated that this will become fouled, burn, and eventually be

removed by the fire. Therefore, due to this uncertainty and to simplify the model, the coating was excluded from the simulation.

6. Rail Car Thermal Protection System

Rail tank car thermal protection system assumed for the model consists of half inch thick Unifrax Fyrewrap, four-inch-thick fiber glass insulation, and 11-gauge ($^1/_8$ inch thick) steel jacket.



The Unifrax Fyrewrap and typical fiber glass insulation have the following thermophysical properties:

Unifrax Fyrewrap	
Parameter	**Value**
Density	4.5 lb/ft^3 [72.08 kg/m^3]
Thermal Conductivity	0.2083 BTU-in/hr-ft^2-°F [0.03 W/m-K]
Heat Capacity	0.239 BTU/lb-°F [1 kJ/kg-K]

Fiber Glass	
Parameter	**Value**
Density	0.75 lb/ft^3 [12.01 kg/m^3]
Thermal Conductivity	0.24 BTU-in/hr-ft^2-°F [0.035 W/m-K]
Heat Capacity	0.202 BTU/lb-°F [0.8444 kJ/kg-K]

References:

DOT / PHMSA List of Thermal Protection Systems Excepted from Test Verification

UniFrax FyreWrap® Elite® Blanket Product Information Sheet (https://www.unifrax.com/wp-content/uploads/2018/08/C-1541.pdf)

UniFrax FyreWrap® Tank Car Blanket Product Information Sheet (https://www.unifrax.com/wp-content/uploads/2018/08/C-1448.pdf*

Knauf KwikFlex Pipe & Tank Insulation Data Sheet (https://res.cloudinary.com/knauf-insulation/image/upload/v1578610840/knauf%20insulation/kwik%20flex%20pipe%20%20and%20%20tank/literature/knauf-kwikflex-pipe-and-tank-data-sheet.pdf

J.G. Hust, J.E. Callanan, S.A.Sullivan, "Specific Heat of Insulations", Thermal Conductivity 19, D.W. Yarbrough, Ed., Plenum, NY, 1988, pp. 533-550

Significance/Likely Effects on Study

The rail tank car receives most of the heat during a pool fire scenario, as it is in direct contact with the flame. The tank cars modeled have a thermal protection system that minimizes and slows heat transfer to the material inside the tank car. The thermophysical properties for the thermal protection have a significant effect on the heat transfer that occurs and the resulting temperature profiles.

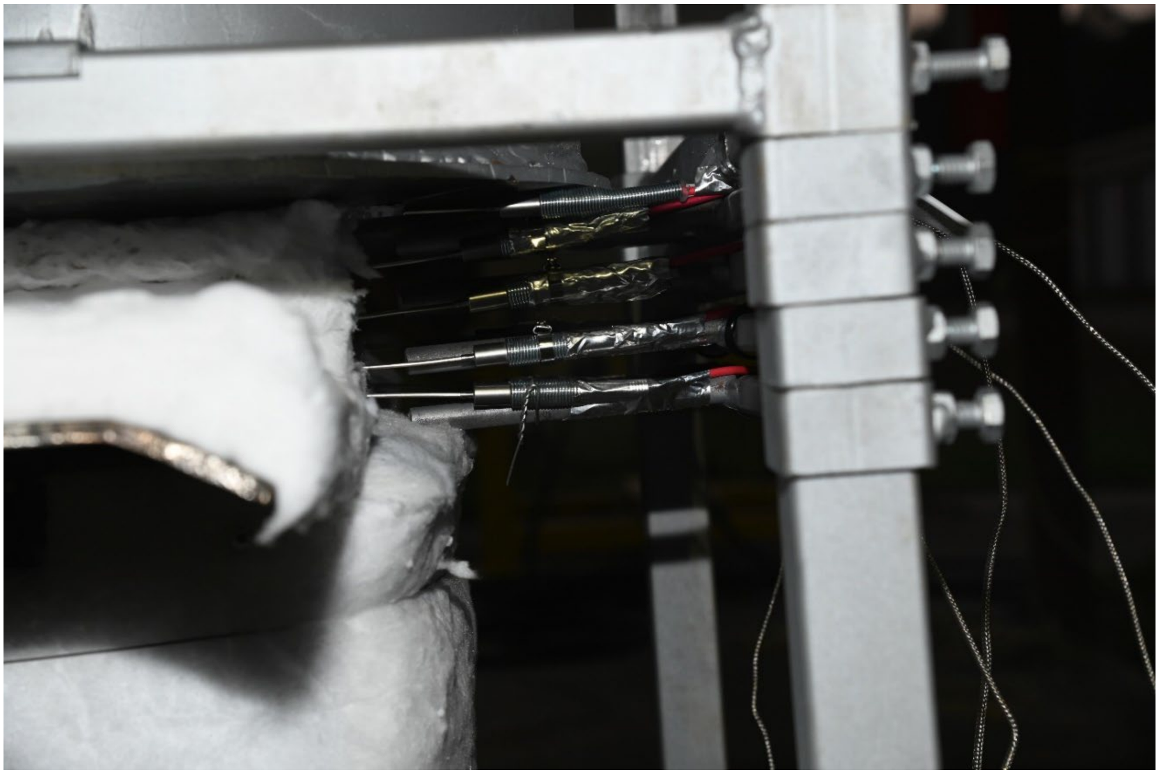
Justification for Use of Assumption

As the hazard values need to be adequately characterized to accurately model the heat transfer and resulting temperature profiles, appropriate thermophysical properties from product manufacturer data and other industry references for the thermal protection system components will be utilized.

Appendix B.
Experimental Test Photos

Thermal Conductivity Test

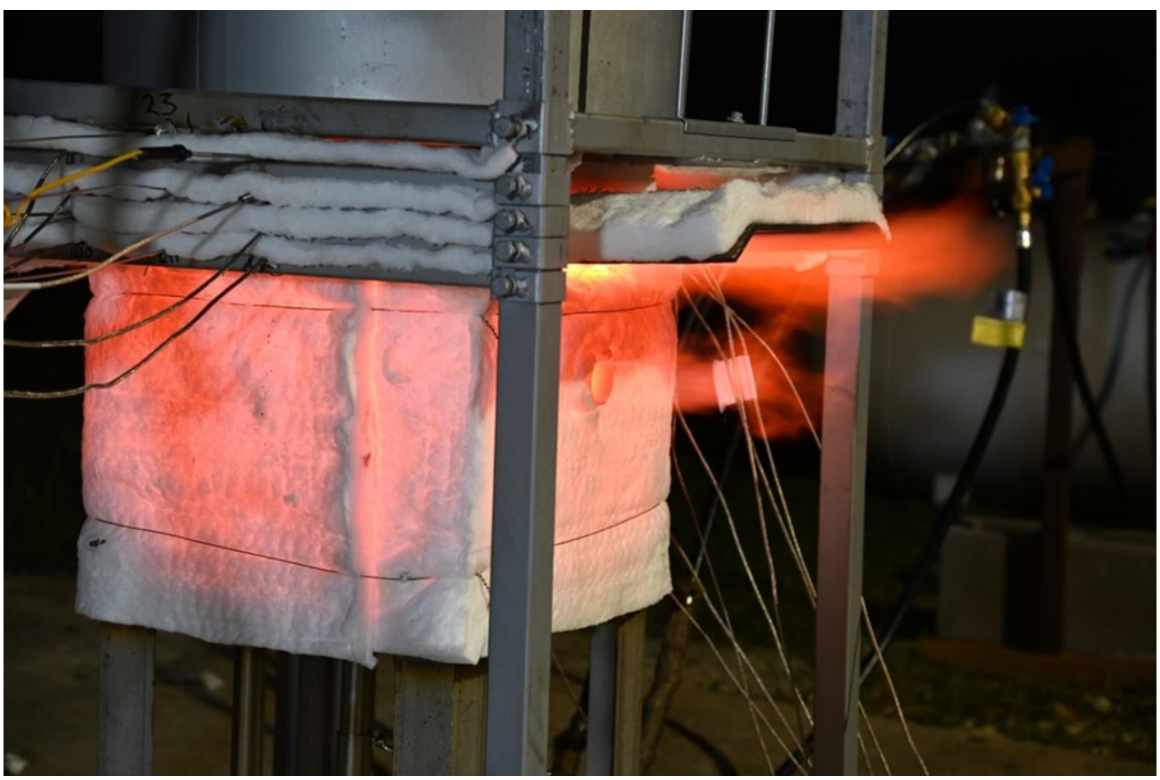
Thermal conductivity test apparatus



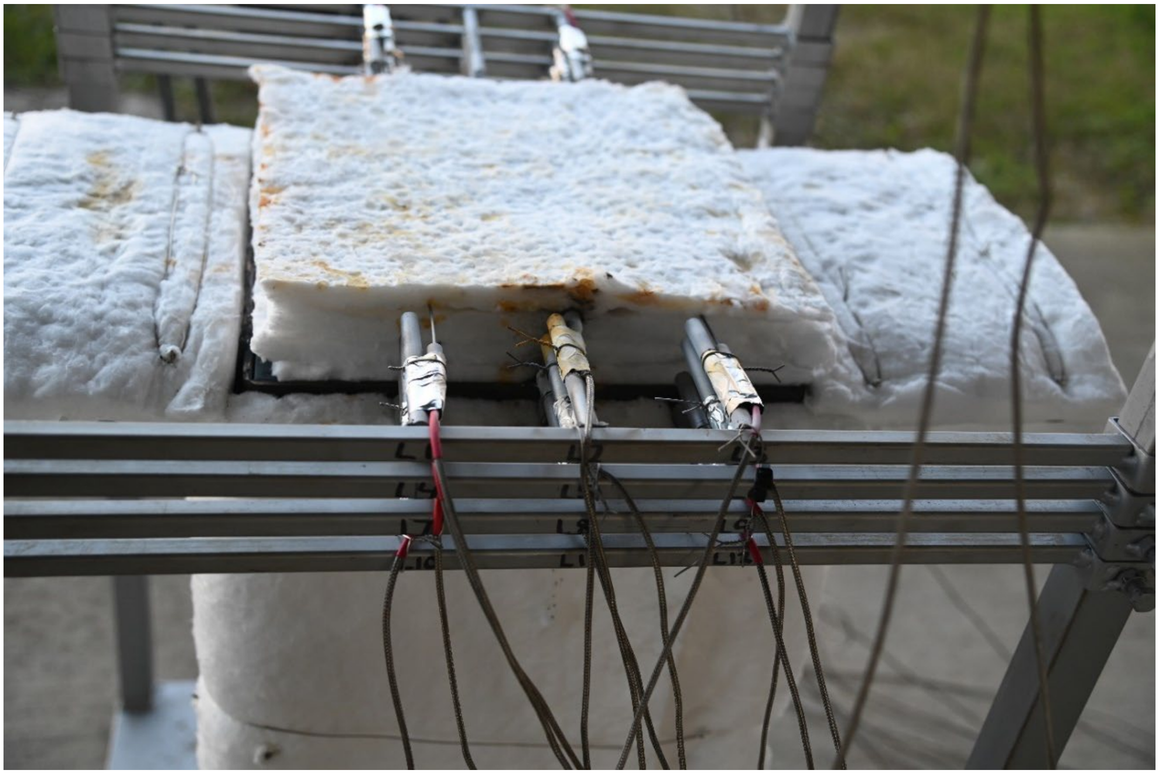
Thermocouple detail in thermal conductivity test apparatus

Insulation layer detail in thermal conductivity test

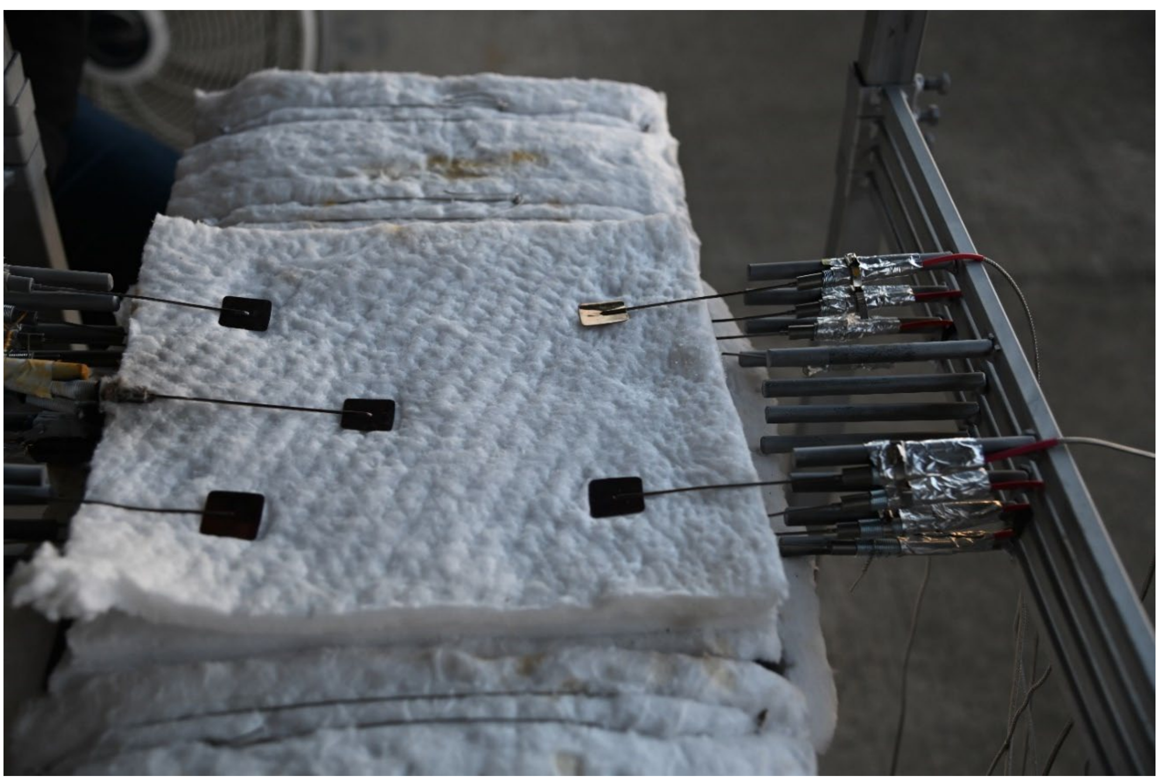
Thermal conductivity test initiation



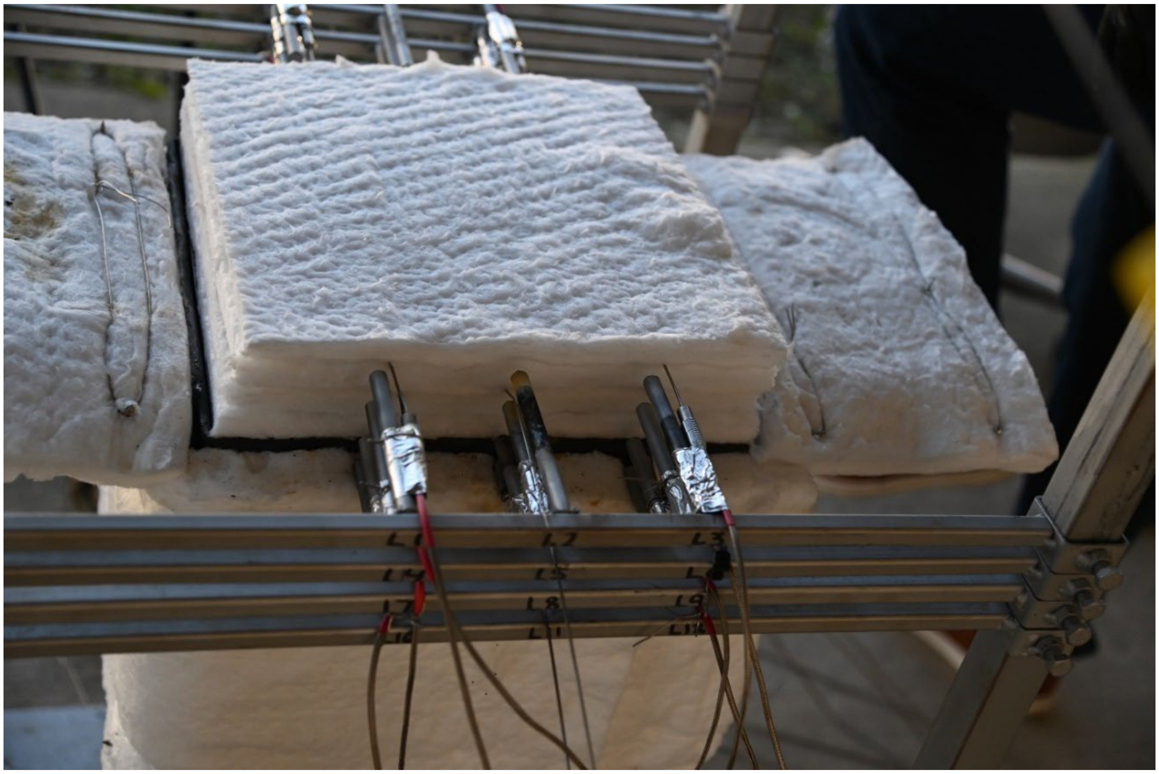
During the thermal conductivity test



Thermocouples and layers after the thermal conductivity test



Thermocouples in the middle layer after the thermal conductivity test



General arrangement of insulation layers and thermocouples

Cooling Water Experiment

Pool fire test apparatus – front

Pool fire test apparatus – back (protected side)

Pool fire test

Pool fire test before cooling water

Pool fire test – activating cooling water

Pool fire test – cooling water

Abbreviations and Acronyms

ACRONYM	**DEFINITION**
CFD	Computational Fluid Dynamics
FRA	Federal Railroad Administration
FDS	Fire Dynamic Simulator
HAZMAT	Hazardous Materials
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology