TP 14066E

Burner Tests on Defective Thermal Protection Systems

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Department of Mechanical Engineering
Queen's University
Kingston, Ontario

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by

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16. Abstract

Certain railway tank-cars carrying dangerous goods are thermally protected from fire impingement by a layer of thermal insulation applied to the outside of the tank-car shell. This insulation is covered by a thin steel jacket. Over time, it is possible that the thermal insulation will sag, rip, degrade, or be crushed under the steel jacket. A technique to determine whether a tank has insulation deficiencies has been developed, but it is now necessary to determine which thermal deficiencies must be repaired.

The work reported here involved a series of fire tests using an upper quarter section of a tank-car to study fire heating of insulation defects. Twelve fire tests with constant, credible fire conditions were preformed on various insulation deficiencies. An infrared camera was used to measure the tank wall temperature. The thermal images were useful in determining the temperature profiles across the defects at different times and the transient temperature behaviour at different locations.

It was seen that proper thermal protection significantly reduces the heat transfer to the tank wall. Larger defect sizes result in higher peak wall temperatures. As the defect size gets larger, the peak temperature of the defect approaches the temperature that the wall would reach with no thermal protection at all. A square defect greater than 40 cm on a side should be considered very significant because, unlike smaller defects, there is little or no benefit from the surrounding protected material. The fire testing data agrees very well with previously conducted thermal modeling studies.

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16. Résumé

La paroi extérieure de certains wagons-citernes servant au transport des matières dangereuses comporte une couche d'isolant thermique destiné à protéger la citerne contre les flammes enveloppantes. Cet isolant est revêtu d'une enveloppe en acier de faible épaisseur. Avec le temps, l'isolant peut s'affaisser, se déchirer ou se détériorer autrement, ou, encore, être écrasé par l'enveloppe en acier. Une technique qui permet de déceler les défauts de l'isolant a été mise au point, mais la recherche doit en outre s'attacher à repérer les défauts de protection thermique qui nécessitent une intervention.

Les travaux faisant l'objet de ce rapport comprenaient une série d'essais auxquels a été soumis le quart supérieur de la section d'un wagon-citerne dans le but d'étudier le comportement au feu de zones présentant des défauts d'isolation. Douze essais ont été réalisés dans des conditions de feu constantes, avec différents défauts d'isolant. Les chercheurs ont employé une caméra infrarouge pour mesurer la température de la paroi de la citerne. Les images thermiques captées ont permis de déterminer les profils de température dans la zone des défauts à différents moments de même que les changements de température en différents points.

La recherche a révélé qu'une protection thermique adéquate réduit de manière significative le transfert thermique à la paroi de la citerne. Les défauts de grandes dimensions sont synonymes de température plus élevée à la paroi de la citerne. Plus le défaut est grand, plus la température maximale à cet endroit se rapproche de la température qu'atteindrait une paroi sans aucune protection thermique. Un défaut carré de plus de 40 cm de côté doit être considéré très grave parce que, contrairement aux petits défauts, le matériau de protection environnant apporte peu d'avantages, sinon aucun. Les données obtenues lors des essais au feu concordent effectivement avec les résultats d'études antérieures de modélisation des paramètres thermiques.

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Executive Summary

Certain rail tank-cars are covered with ceramic thermal protection and a steel jacket to protect them from fire engulfment in the case of an accident. The most common thermal protection configuration includes a 13 mm ceramic blanket of insulation protected by a 3 mm steel jacket. The Canadian General Standards Board (CGSB CAN/CGSB 43.147-2002) requires that the thermal protection system be able to protect the tank car from a 100 minute pool fire or a 30 minute torch fire.

If the thermal protection rips, is crushed, or slips out of position, it is possible that the thermal protection system will no longer meet the CGSB standard. With inadequate thermal protection, the tank-car shell can be thermally weakened to the point where it could rupture at internal pressures equal to or below the pressure relief valve setting.

An inspection technique has been developed to find thermal protection deficiencies on rail tank-cars, using an infrared thermal imager. This method has been shown to be effective for non-destructive inspection. It is not known when a specific defect is unacceptable and when a specific defect is acceptable from a safety standpoint. It is important that a guideline be developed to assess different thermal protection deficiencies. Fire test data is provided that will be useful in developing such a guideline.

A thermal computer model designed to study thermal protection defects on tank-cars is currently under development. The data from these fire tests is also useful in the validation of this thermal model.

The experimental apparatus used for the fire tests consisted of a quarter section tank-car model with a 16 mm thick steel wall. An array of nine propane utility burners was used to heat the tank wall and simulate a large hydrocarbon pool fire. To best simulate a typical pool fire, the burners were operated at a low pressure to give low-momentum, non-jetting flames, and the burner mixing tubes were plugged to starve the flames of air to give sooty, highly luminous flames. An infrared camera was used to measure the tank wall temperature. The thermal images were useful in determining the temperature profiles across the defects at different times and the transient temperature behaviour at specific locations.

Nine pre-test fire tests were run to develop a credible, repeatable fire condition. These tests were conducted with no thermal protection or steel jacket. The selected fire condition proved to be very repeatable and representative of a real pool fire scenario.

A total of 12 thermal protection deficiency fire tests were conducted in this study. In each test, identical fire conditions were used and only the thermal protection defect was changed. These tests all used a 3 mm steel jacket. The tests with thermal protection used 13 mm, ceramic insulation. Five different-sized square thermal protection defects were studied.

When the tank wall is exposed to the engulfing fire, the wall temperature is a function of the defect size. As the defect gets larger, the heat transfer, the temperature rise rate, and the maximum temperature of the tank wall in the defect area gets larger, as shown in Figure 1. For a defect smaller than 0.4 m, the surrounding thermal protection material provides a significant cooling effect for the defect area. For a defect larger than 0.4 m, the measured peak wall temperature at the centre of the defect is not affected significantly by the surrounding protected material. It can be seen from Figure 1 that defects larger than 40 cm gave about the same peak wall temperature as the case where only the steel jacket was present.

It is recommended that a thermal protection defect with average defect dimension of 40 cm or greater be considered to be a very significant defect.

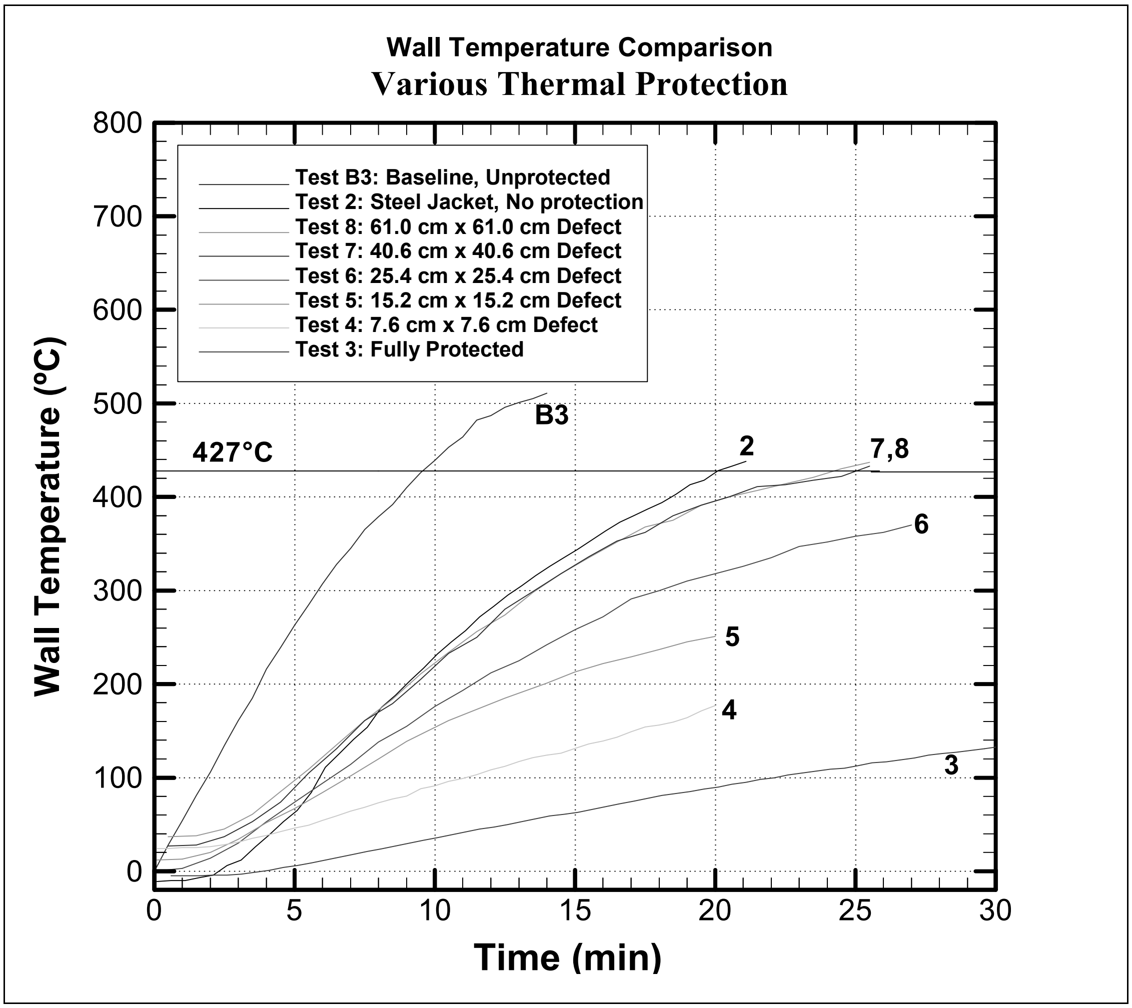

Figure 1: Wall Temperature versus Time for Various Defect Sizes

Sommaire

Certains wagons-citernes sont munis d'une protection thermique assurée par une doublure en céramique revêtue d'une enveloppe en acier, ensemble destiné à protéger la citerne contre un feu avec flammes enveloppantes susceptible de survenir lors d'un accident. Le système le plus couramment employé est une doublure en céramique de 13 mm d'épaisseur avec enveloppe en acier de 3 mm. Selon la norme CAN/CGSB 43.147-2002, de l'Office des normes générales du Canada (CGSB), le système doit être conçu pour fournir une protection suffisante à la citerne lorsqu'elle est soumise pendant 100 minutes à un feu de nappe de liquide inflammable, ou pendant 30 minutes à un jet enflammé.

Une protection thermique déchirée, écrasée ou déplacée risque de ne plus être conforme aux exigences de la norme CGSB. Sans protection thermique adéquate, la citerne, soumise à des pressions internes égales ou inférieures à la valeur de réglage de la soupape de sûreté, est susceptible de s'affaiblir jusqu'à rupture sous contrainte thermique.

Les chercheurs ont mis au point une technique d'inspection faisant appel à un imageur thermique infrarouge pour déceler les défauts de la protection thermique des wagons-citernes. Cette méthode d'essai non destructif s'est montrée efficace. Cependant, comme rien ne permet de déterminer si un défaut particulier est acceptable ou non du point de vue de la sécurité, on a fait valoir la nécessité d'élaborer une ligne directrice pour évaluer les différents défauts pouvant affecter la protection thermique. Les données issues des essais de comportement au feu serviront à élaborer la ligne directrice souhaitée.

À l'heure actuelle, on est à développer un modèle informatisé d'analyse thermique, conçu pour l'étude des défauts de protection thermique des wagons-citernes. Les données des essais au feu contribueront aussi à la validation de ce modèle de paramètres thermiques.

Le montage expérimental installé pour les essais de comportement au feu consistait en une maquette représentant un quart de section d'un wagon-citerne à paroi en acier de 16 mm d'épaisseur. Pour chauffer la paroi de la citerne, on a utilisé une rampe de neuf brûleurs utilitaires au propane pour usage général, simulant un important feu de nappe d'hydrocarbure. Pour plus de réalisme, les brûleurs fonctionnaient à basse pression, donnant des flammes à faible vélocité. De plus, les tubes de mélange ayant été obturés, les brûleurs étaient appauvris en air, produisant des flammes très lumineuses, avec dégagement de suie. Une caméra infrarouge mesurait la température de la paroi de la citerne. Les images thermiques ont été utiles pour déterminer les profils de température à des temps différents, à l'endroit des défauts, ainsi que les variations de température dans des zones spécifiques.

Neuf essais préliminaires ont été menés pour établir une condition de feu crédible, pouvant être reproduite. Ces essais se sont déroulés sans isolant thermique ni enveloppe extérieure en acier. La condition de feu retenue s'est avérée facile à répéter et simulait bien un feu de nappe de liquide.

L'étude a permis de réaliser un total de 12 essais de contrôle des défauts de protection thermique. Sauf pour ce qui est du type de défaut, qui pouvait changer, chaque essai

respe*ctait des conditions de feu identiques et portait sur une enveloppe extérieure en acier de 3 mm d'épaisseur. L'isolation thermique était assurée en l'occurrence par une doublure céramique de 13 mm d'épaisseur. L'étude a porté sur cinq défauts dans une zone carrée de dimensions différentes.

Lorsque la paroi est exposée à des flammes enveloppantes, sa température varie en fonction de la dimension du défaut. Comme l'illustre la figure 1, le transfert thermique, le taux d'élévation de température et la température maximale de la paroi dans la zone du défaut augmentent avec la dimension du défaut. Dans le cas d'un défaut inférieur à 0,4 m, le matériau de protection thermique qui l'entoure abaisse sensiblement la température de la zone du défaut. En revanche, si le défaut est plus grand que 0,4 m, le matériau de protection avoisinant n'a pas d'influence sensible sur la température maximale de la paroi. En examinant la figure 1, on constate que l'on obtenait plus ou moins la même température maximale de paroi dans le cas des défauts de plus de 40 cm que dans les situations où seule l'enveloppe en acier protégeait la citerne.

À la lumière de la recherche, il est recommandé qu'un défaut de dimension moyenne de 40 cm ou plus soit considéré comme un défaut très important.

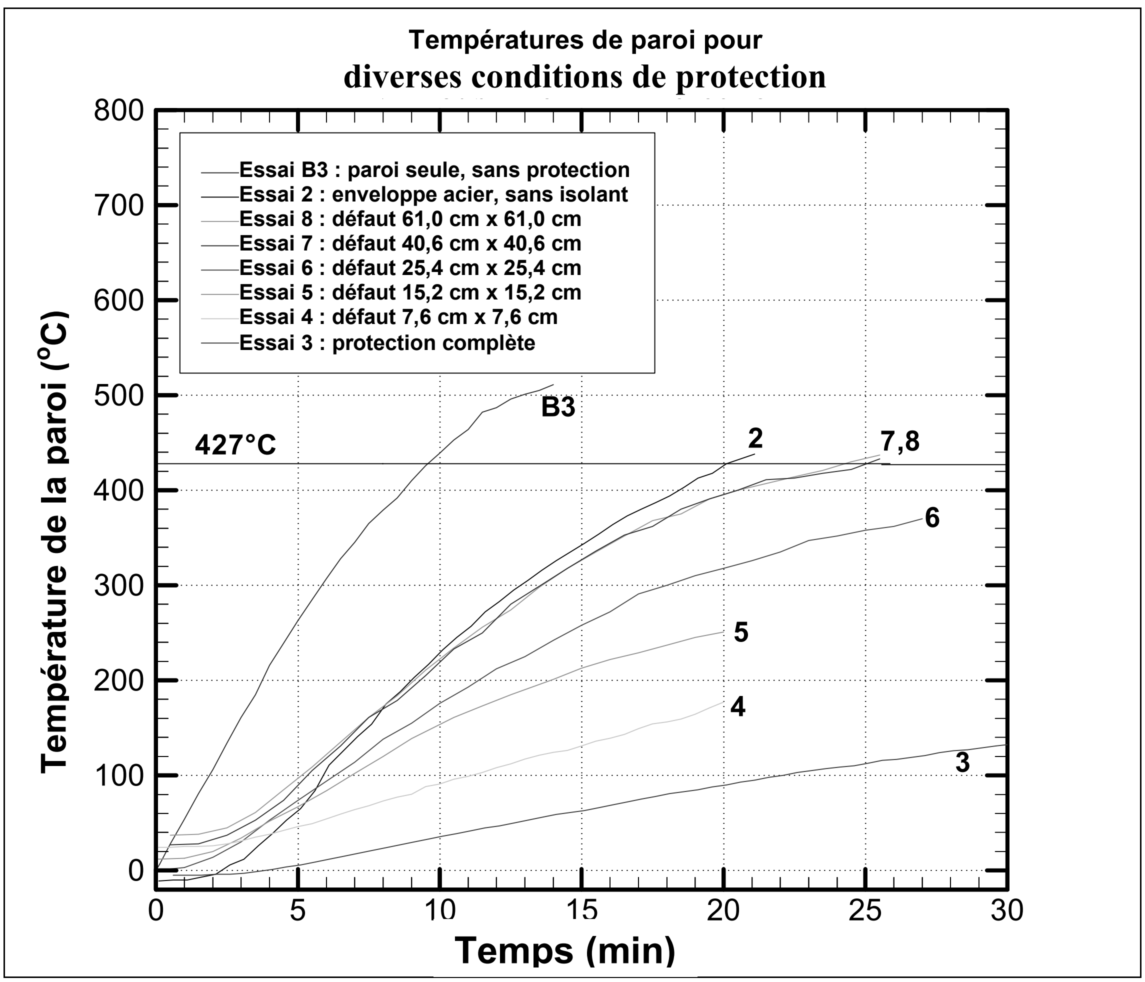

Figure 1 : Température de paroi en fonction du temps – défauts de dimensions variées

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1.0 Introduction

This report describes the results from a series of fire tests that were carried out by the Department of Mechanical Engineering, Queen's University in Kingston, Ontario, for the Transportation Development Centre and the Transport Dangerous Goods Directorate of Transport Canada. The experimental work was conducted to study heat transfer from a fire to a tank-car wall with a defective thermal protection system. It was completed in order to assess various defective thermal protection systems.

1.1 Background

In order for a railway tank-car to transport dangerous goods by rail, the Canadian General Standards Board Standard CAN/CGSB 43.147-2002 must be met according to the Transport Dangerous Goods Regulations. Sections 30.12 and 15.8 of the standard require that designated tank-cars are equipped with a thermal protection system. This thermal protection system must be able to protect the tank-car from a 100 minute engulfing pool fire or a 30 minute torch fire.

As verification of the performance standard mentioned above, tank manufacturers and owners use computer simulation software to conduct thermal analysis to assess the ability of a thermal protection system. The computer simulation program, Analysis of Fire Effects on Tank-Cars (AFFTAC) by Johnson (1998) outlines the required procedures to assess a given thermal protection system. This program in its current form cannot model the effects of thermal protection defects on tank-cars.

Most thermal protection systems include a ceramic 13 mm (0.5 in.) blanket of ceramic thermal insulation protected by a 3 mm (0.125 in.) steel jacket. As the thermal protection system on a tank gets older, it is possible that it will degrade. For example, the thermal protection provided by the insulation will be reduced if it is crushed or has slipped out of position, thereby allowing a higher heat flux to the tank shell.

This is of great concern in the case of fire impingement, because without adequate thermal protection, the tank shell can be thermally weakened to the point that it will rupture at internal pressures equal to or below the pressure relief valve (PRV) setting.

1.2 Objectives

The objective of this work was to experimentally measure the thermal response of a tank-car shell with a variety of defective thermal protection systems engulfed in fire to determine the temperature of the wall at the defect as a function of the defect size. The ultimate goal is to develop a guideline that states when an insulation deficiency leads to an unsatisfactory thermal protection system.

A secondary objective was to produce transient wall temperature data for different fire conditions and different thermal protection defects. This data is useful to get a better understanding of heat transfer from a fire to a tank wall, and to develop better thermal computer models. A thermal model must get the physics right to be an effective tool, and validation data is always helpful in getting the physics right.

2.0 Theory

This study attempts to add to the current state of knowledge by considering the effect of different types of thermal protection defects on heat transfer from an engulfing fire to a tank wall. It is the goal of this chapter to present necessary background theory.

2.1 Thermal Protection Systems

2.1.1 Benefits of Thermal Protection

The RAX 201 fire test (see Townsend, et al., 1974) showed that an unprotected tank-car could fail in an engulfing fire in about 24 minutes. A similar test of a thermally protected tank showed that the protected tank could survive approximately 100 minutes. For this reason many dangerous goods tank-cars are equipped with thermal protection systems.

2.1.2 Thermal Protection Defect Assessment

In the late 1960s and early 1970s, a sudden increase in the number of rail transportation accidents involving pressure liquefied gases resulted in a change in the Transport Dangerous Goods Regulations. The change required that designated tank-cars be equipped with thermal protection systems. In the late 1970s and early 1980s tanks were retrofitted with thermal protection, the most common system being a 13 mm (0.5 in.) blanket of ceramic fibre insulation covered by a 3 mm (0.125 in.) steel jacket.

Over time, thermally protected and thermally insulated rail tank-cars may develop insulation deficiencies due to continuous motion and vibration. A tank with unprotected areas is at higher risk of thermal rupture if exposed to severe fire.

To determine the severity of the thermal protection deficiency, an inspection technique involving thermography was developed by Birk and Cunningham (2000). Birk and Cunningham (2002) analyzed a large number of tanks in a random tank-car sample in the field to estimate the frequency and severity of deficiencies. Figure 1 shows that, as a tank-car gets older, the deficiency problem becomes more severe. Figure 2 and Figure 3 show images taken to assess a tank-car's thermal protection system. This method has been shown to be an effective method for non-destructive inspection, but a very important question still remains. What level of deficiency is acceptable from a safety standpoint?

If thermal insulation is not present in the annulus between the primary tank shell and the steel jacket, an engulfing fire or torch fire will heat the tank wall much more rapidly than when insulation is present. The steel jacket alone can provide some protection for the wall because it acts as a radiation shield, provided there is an air gap between the wall and the jacket. However, if the jacket is pressed hard against the wall then there is little or no protection.

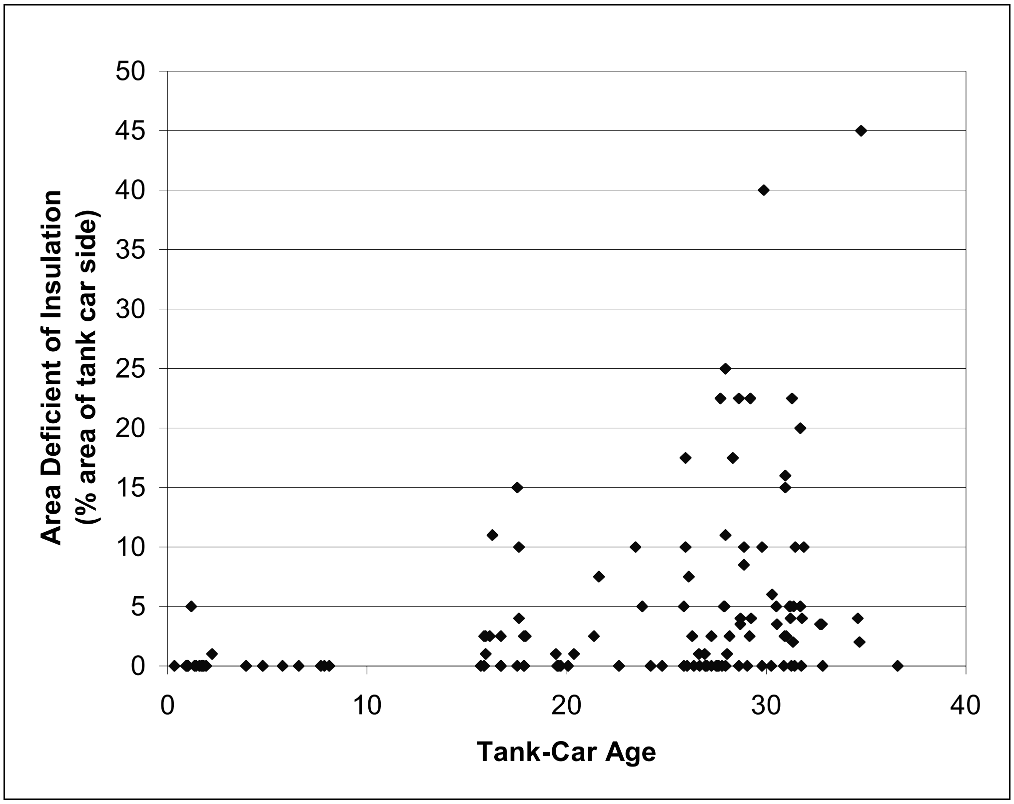


Figure 1: Defective Area on Tank Side versus Tank Age (Birk and Cunningham, 2002)

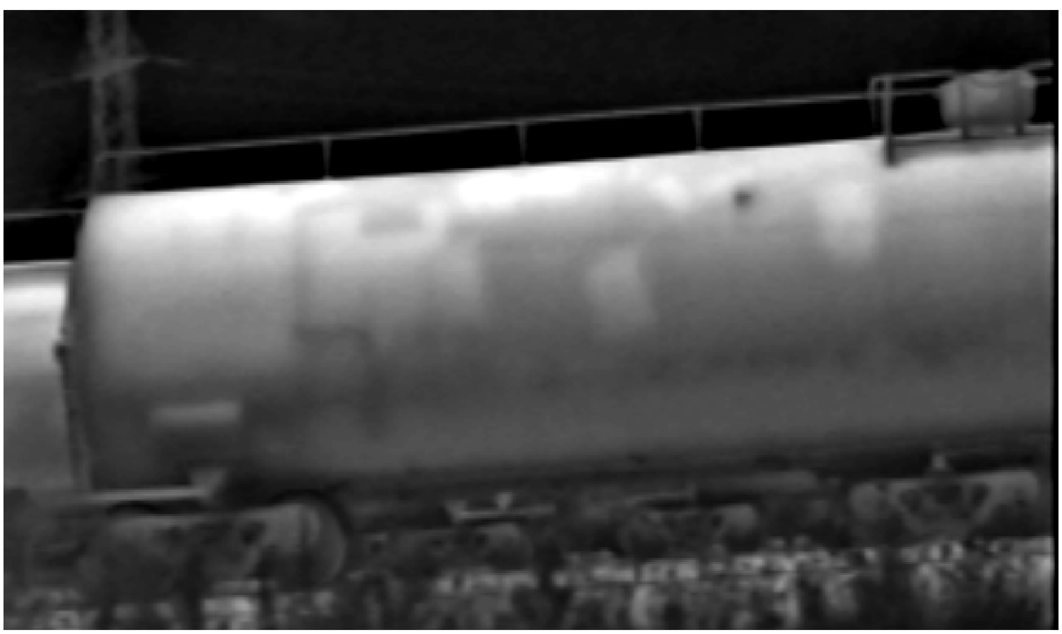


Figure 2: Tank-Car with Thermal Protection Deficiencies (Thermal Image)

Figure 3: Tank-Car with No Thermal Protection Deficiencies (Thermal Image)

If a defect is small then the surrounding protected tank wall will provide a cooling effect by thermal conduction for the unprotected area. Heat will naturally conduct, convect and radiate from the hot unprotected area to the cool protected areas. However, as this defect gets larger this effect becomes less significant.

It is very difficult to make these thermal protection systems perfect. It is reasonable to assume that there is some level of defect that is acceptable from a safety standpoint. The difficult part is defining the size and location of acceptable defects.

2.1.3 Thermal Computer Model

It was decided that a computer thermal model of the tank-car with thermal protection would be used to study the effects of different sized and differently located defects in a thermal protection system. The model currently being used is the tank thermal model IDA 2.0 (Insulation Defect Analyzer) based on a model developed by Birk and Cunningham (2002). This computer code is being modified so that it analyzes the full three-dimensional shape of the tank-car so that defects can be located anywhere on the tank surface.

The objective of this study is to provide heat transfer and wall temperature data for a tank wall with a deficient thermal protection system that is engulfed in fire. This data will be used for two things:

1. To assist in developing a guideline that states when a thermal protection deficiency is unacceptable.
2. To be used for validation of the thermal computer model IDA 2.0.

2.2 Tanks in Simulated Pool Fire

When assessing a thermal protection system, the test procedure outlined in the Canadian General Standards Board Standard CAN/CGSB 43.147-2002 must be used. This study focuses on pool fires. Some details from the standard should be mentioned at this point as the values given below will be referred to several times in the body of this report.

According to the standard, the pool-fire environment must have the following characteristics:

- A fire temperature of 871°C +/- 56°C must be used.
- The unprotected tank wall must indicate 427°C after 13 minutes +/- 1 minute.

Birk (2000) wrote a review of the AFFTAC thermal model in which he pointed out that the above standard is not consistent with published data. The required fire temperature is reasonable but the heat-up time for the tank wall is not consistent with an engulfing pool fire radiating as a blackbody. A simple 16 mm plate will heat up to 427°C in 6 to 8 minutes rather than the suggested 12 to 14 minutes. The 12 to 14 minute time came from the RAX 201 fire test of a non thermally protected tank-car (see Townsend et al., 1974). This discrepancy is due to differences between a tank-car filled partly with liquid and a simple steel plate with its back open to the surroundings. Since it is the heat flux that is important, the heat-up time will be ignored as long as the effective fire temperature is correct. For this reason, the testing conducted here has not applied the 13 minute heat-up rule.

3.0 Field Testing

This study involved exposing a tank wall with deficient thermal protection to a pool fire and measuring wall temperatures for various insulation deficiencies. The goal of this chapter is to briefly describe the experimental apparatus and field trials.

3.1 Test Layout and Apparatus

3.1.1 Site Location

The Centre for Advanced Gas Combustion Technology (CAGCT), located in the industrial region of Kingston, Ontario, was chosen as the location of the field trials. This facility was ideal because it has an outdoor concrete pad behind the building to allow for outdoor testing. Instrumentation cables were run into the building to the data acquisition computers.

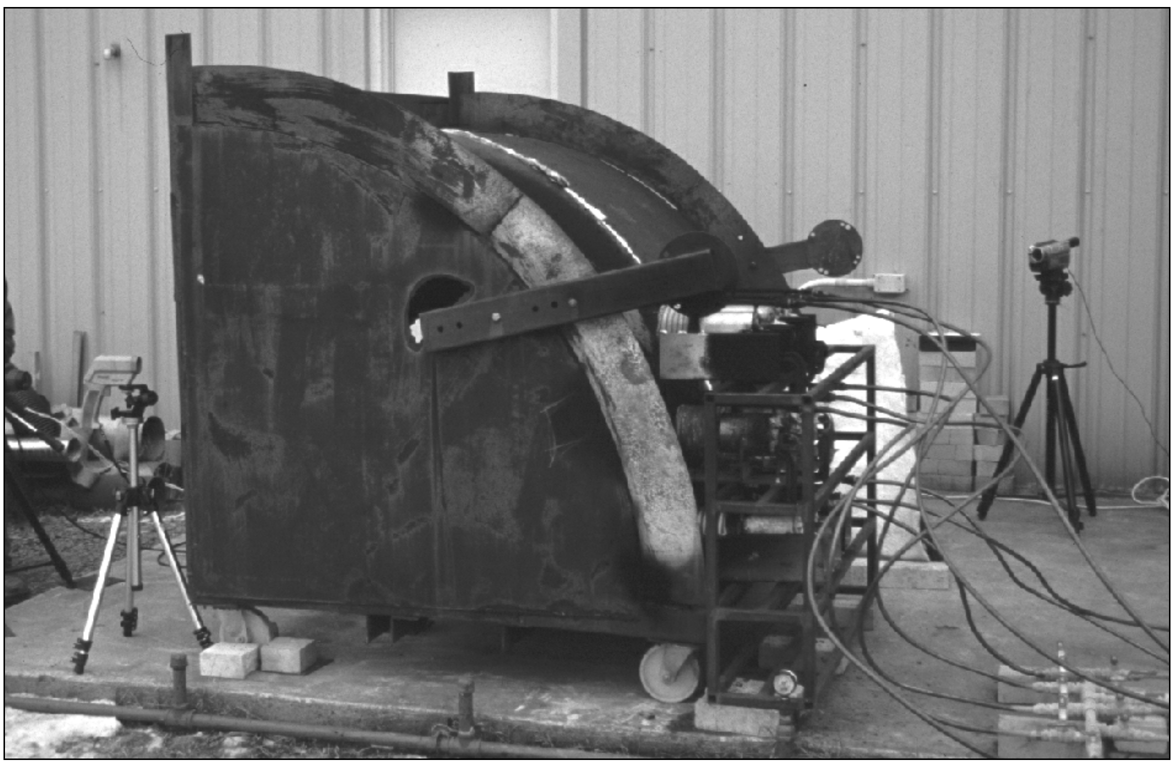


Figure 4: Test Apparatus Modeling Tank-Car Thermal Protection (1/4 Upper Section)

3.1.2 Test Apparatus

The apparatus, shown in Figure 4, was modified from a previous apparatus used by Birk and Cunningham (2000). It was originally designed to simulate a tank-car with:

- tank car curvature

- correct tank car wall thickness (16 mm)
- correct tank car wall material and thermal properties
- ability to include various configurations of thermal protection

The apparatus consisted of a 2.1 m long quarter section of a tank-car (provided by PROCOR, Oakville, Ontario). The primary wall is tank-car steel and has a thickness of 16 mm (5/8 in.) and a radius of curvature of approximately 1.5 m. The outer steel covering, or jacket, which can be seen in Figure 5, is plain carbon steel and has a thickness of 3 mm (1/8 in.).

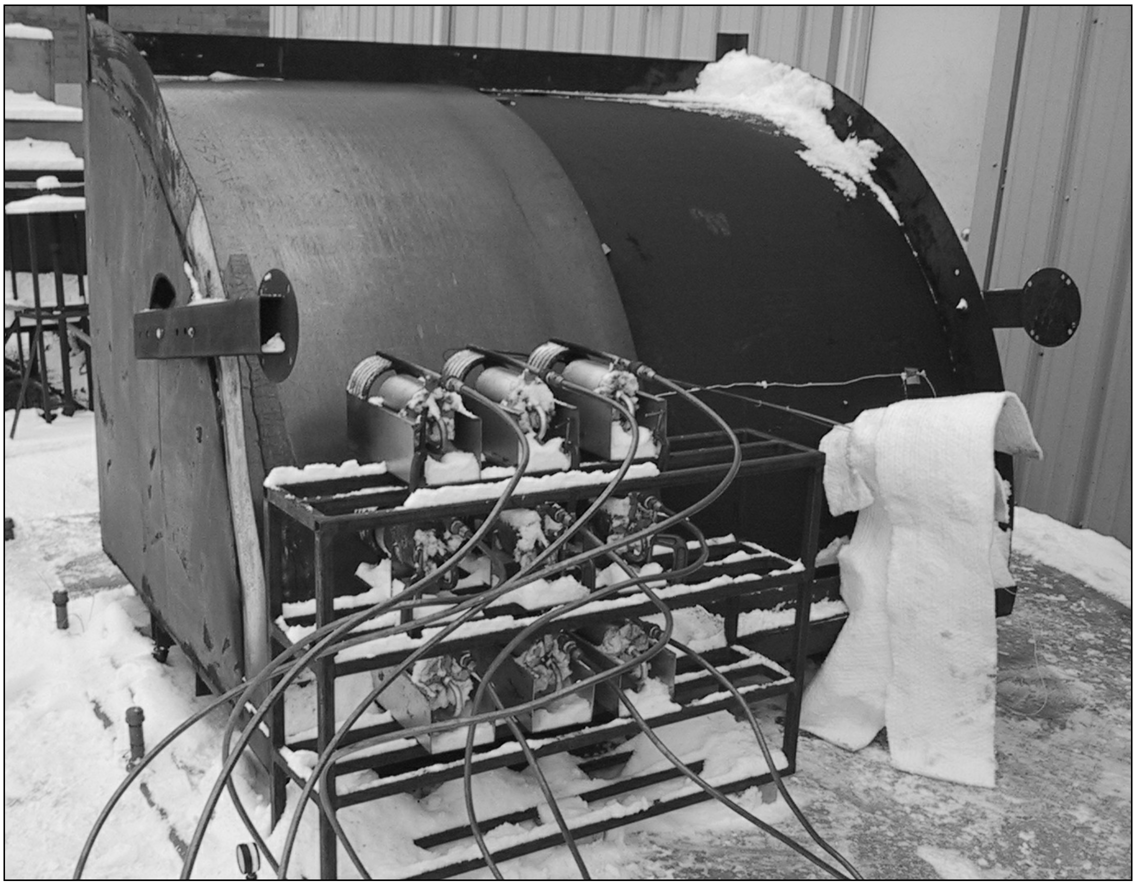


Figure 5: Front View of Test Apparatus Showing Steel Jacket (No Insulation)

A few modifications were made to the tank-car to prepare it for the current test series:

1. The front and back of the tank wall were painted flat black to give a consistent finish and high emissivity (e = 0.90-0.95).
2. The existing burner mounting system was removed and replaced with a burner rack, as can be seen in Figure 4 and Figure 5.
3. Part of the steel structure was cut away to expose the back wall and allow access for the thermal imager. This is shown in Figure 6.

4. Holes were drilled through the tank wall to allow either for the addition of 13 mm (0.5 in.) spacers or for clamping the steel jacket against the tank wall. Most tests required the 13 mm (0.5 in.) spacers to keep the jacket from crushing the 13 mm (0.5 in.) thick insulation. If the test required crushed insulation, however, the spacers were removed and the jacket was bolted to the tank wall.

Figure 6: Back of Tank Wall

3.1.3 Burners and Fuel Delivery

The objective of the burner system was to deliver heat in a uniform, repeatable manner, simulating a credible, large, hydrocarbon pool fire.

A 3 x 3 array of utility liquid propane burners, as shown in Figure 7, was used to simulate the pool fire. These burners are nominally rated at 586 kW (2 MBtu/hr) when the propane is supplied at 240 kPa (35 psi), but the propane pressure was regulated down to approximately 10 kPa (1.5 psi) to simulate a low momentum, non-torching fire. Pool fires are typically luminous and sooty, and so the burner mixing tubes were plugged with ceramic insulation to starve the flame of oxygen and to generate a more luminous, sooty flame.

Figure 8 shows a side view of the burner array. Notice how the distance between the burner and the tank wall is constant regardless of the burner row. This was done to ensure that the low-pressure flame would engulf the tank surface and not separate from the surface.

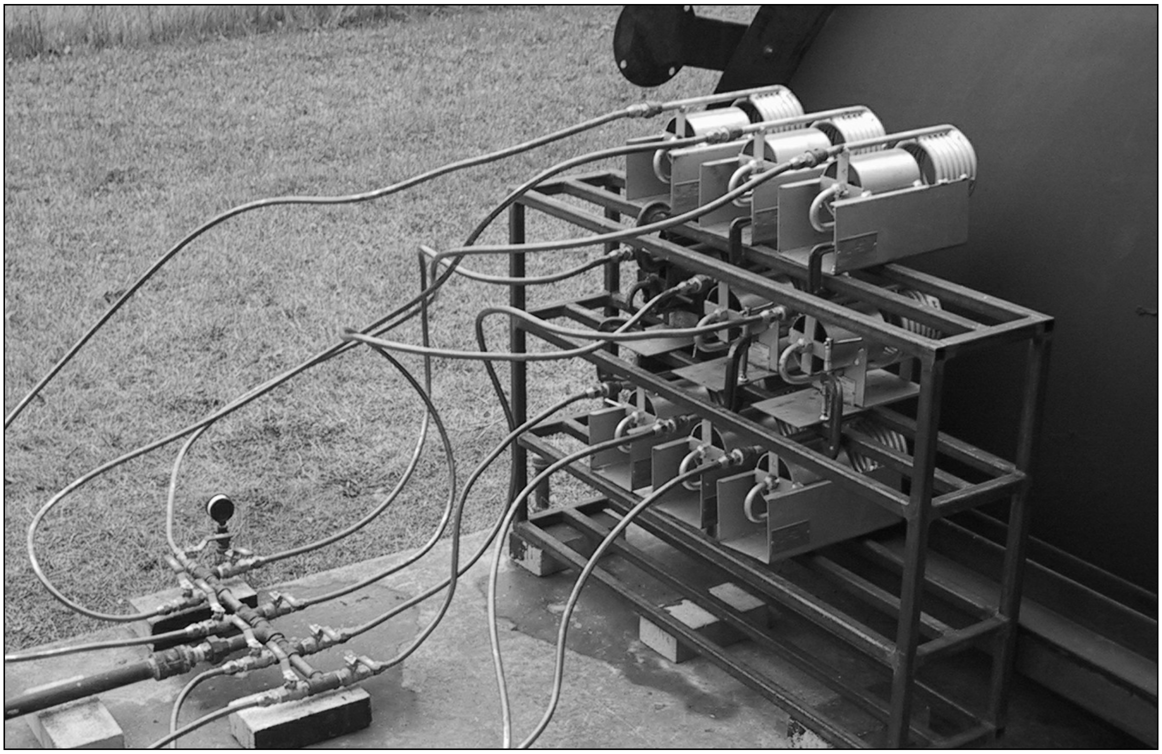


Figure 7: Burner Array and Fuel Manifold

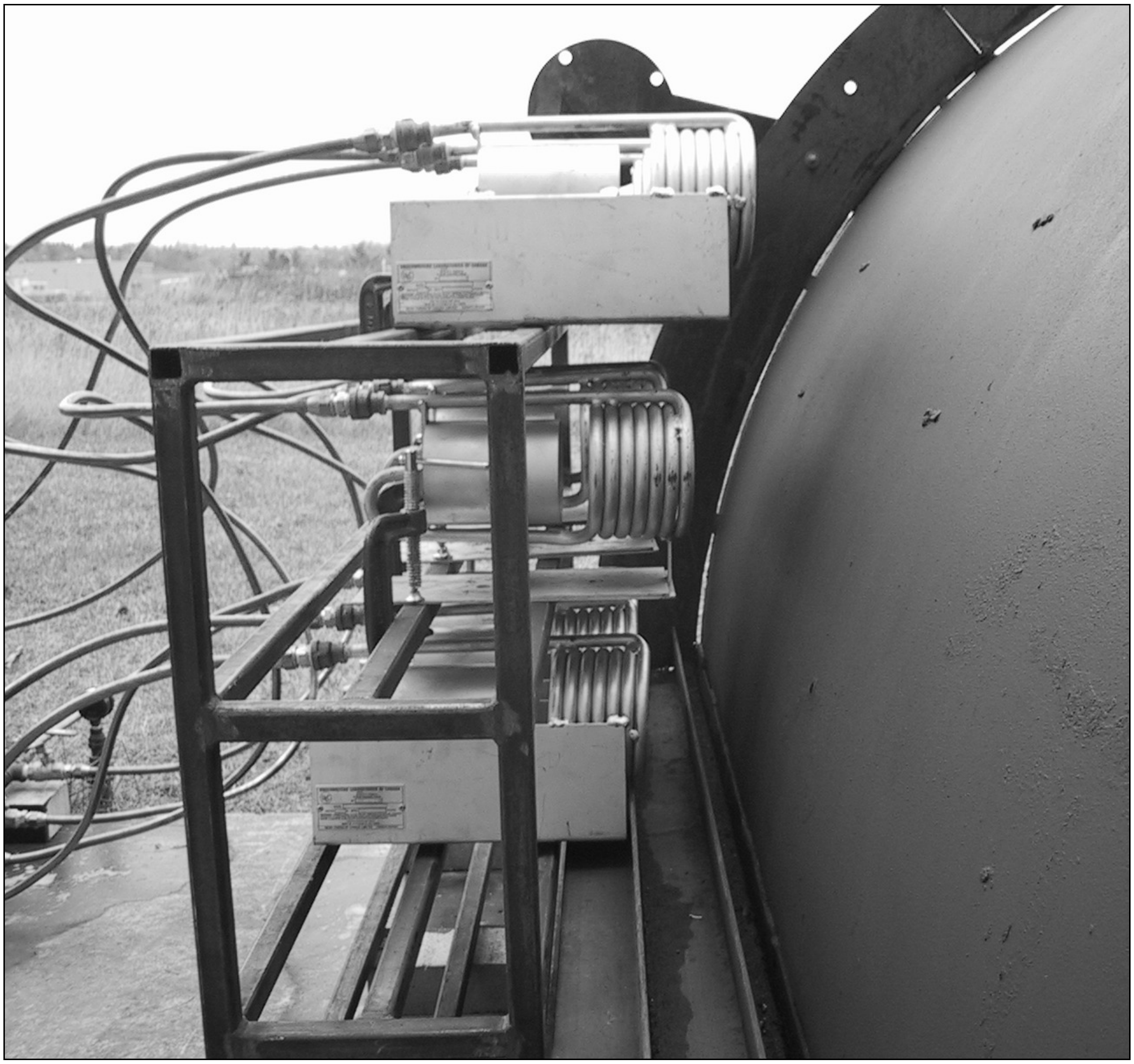


Figure 8: Side View of Burner Array

The liquid propane used to fuel the utility burners was stored in 45 kg (100 lb.) liquid-draw-off propane tanks. Figure 9 shows the path the propane must take as it travels from the tanks to the burners. As seen in Figure 9, the propane fuel delivery system includes from left to right:

- a pressure regulator
- a pressure gauge
- an electronic shut-off valve
- a manual shut-off ball valve
- two in-line pressure relief valves
- a one-input, nine-output manifold, with nine shut-off ball valves

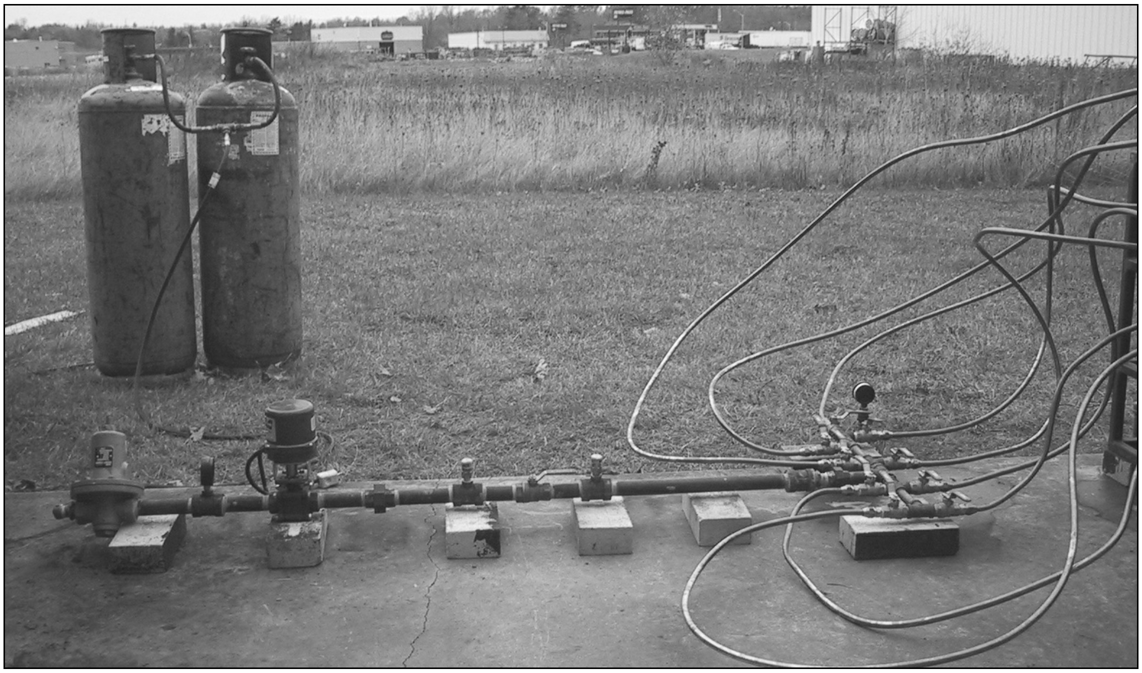


Figure 9: Propane Fuel Delivery System

3.1.4 Thermal Protection

The type and thickness of the thermal insulation used in this testing was the same as that found on actual tank-cars. The thermally protected configuration consisted of 13 mm (0.5 in.) of Fiberfrax ceramic insulation (72 kg/m^3 (4.5 lb/cu.ft.)) placed on top of the tank wall and covered with a 3 mm (1/8 in.) out steel shell. The spacing was maintained using spacers bolted to the tank wall.

3.2 Measurements and Instrumentation

The test instrumentation consisted of an infrared (IR) thermal imager, an infrared thermometer gun, two fire thermocouples, a wall thermocouple, and a fuel pressure gauge, as shown in Table 1.

Still photography and video photography were also used to collect data from the testing. A digital camera was used in each fire test to record the shape of the flame from several different locations.

Device	Purpose	Quantity
Fire Thermocouple	Measure flame temperature; Check for repeatable fire cond	2
IR Camera	248 x 239 pixel array thermal image; Show gradients on wall	1
IR Gun	Measure wall and fire temperature at one location	1
Wall Thermocouple	Verify temperature measurements from IR devices	1
Fuel Pressure Gauge	Measure pressure of fuel delivered to array of burners	1

Table 1: Instrumentation List

Figure 10: IR Camera (FLIR ThermaCAM SC 1000) and IR Thermometer (Raytek MX4)

Data acquisition was accomplished using two different computers. A Pentium P3-550 computer was used for data acquisition for the thermocouple data. The thermocouple data was recorded at a rate of 10 samples per second. A Pentium 166 notebook computer was used for data acquisition for the IR camera data. A thermal image was recorded every 15 seconds. Data from the fuel pressure gauge and the IR thermometer gun were recorded in a lab notebook.

3.2.1 Wall Temperature Measurements

The wall temperatures were measured with three different methods:

1. One unsheathed, 24 gauge, type K thermocouple was mounted on the back unheated surface of the tank wall in the centre of the region where defects were positioned (see Figure 6). This thermocouple is shown in Figure 11. The thermocouple junction was ball peened onto the wall and held in place using high-temperature cement.

2. A Raytek MX4 infrared (IR) thermometer was also used to measure the temperature. This device worked by simply aiming the device and pulling a trigger. The measured temperature was displayed on the instrument screen. In this test program, the IR thermometer gun was always pointed at the same location next to the thermocouple mounting. The IR thermometer gun requires a preset surface emissivity. Using the

thermocouple reading and adjusting the set emissivity, it was found that an emissivity of 0.95 best matched the tank wall surface.

3. A FLIR ThermaCAM SC 1000 infrared camera was also used in some of the fire tests. It outputted a 248 by 239 pixel thermal image and was most useful in tests with large temperature gradients. This was best seen in tests with defects cut out of the insulation.

The IR devices can be seen in Figure 10. For more information on how thermography works, the reader is referred to work by Birk and Cunningham (1998) or to any heat transfer or radiation text.

Figure 12 shows a sample plot from one of the tests. It shows the maximum wall temperature versus time using all three measuring methods. The temperature data from the thermocouple, IR thermometer, and IR camera are in excellent agreement.

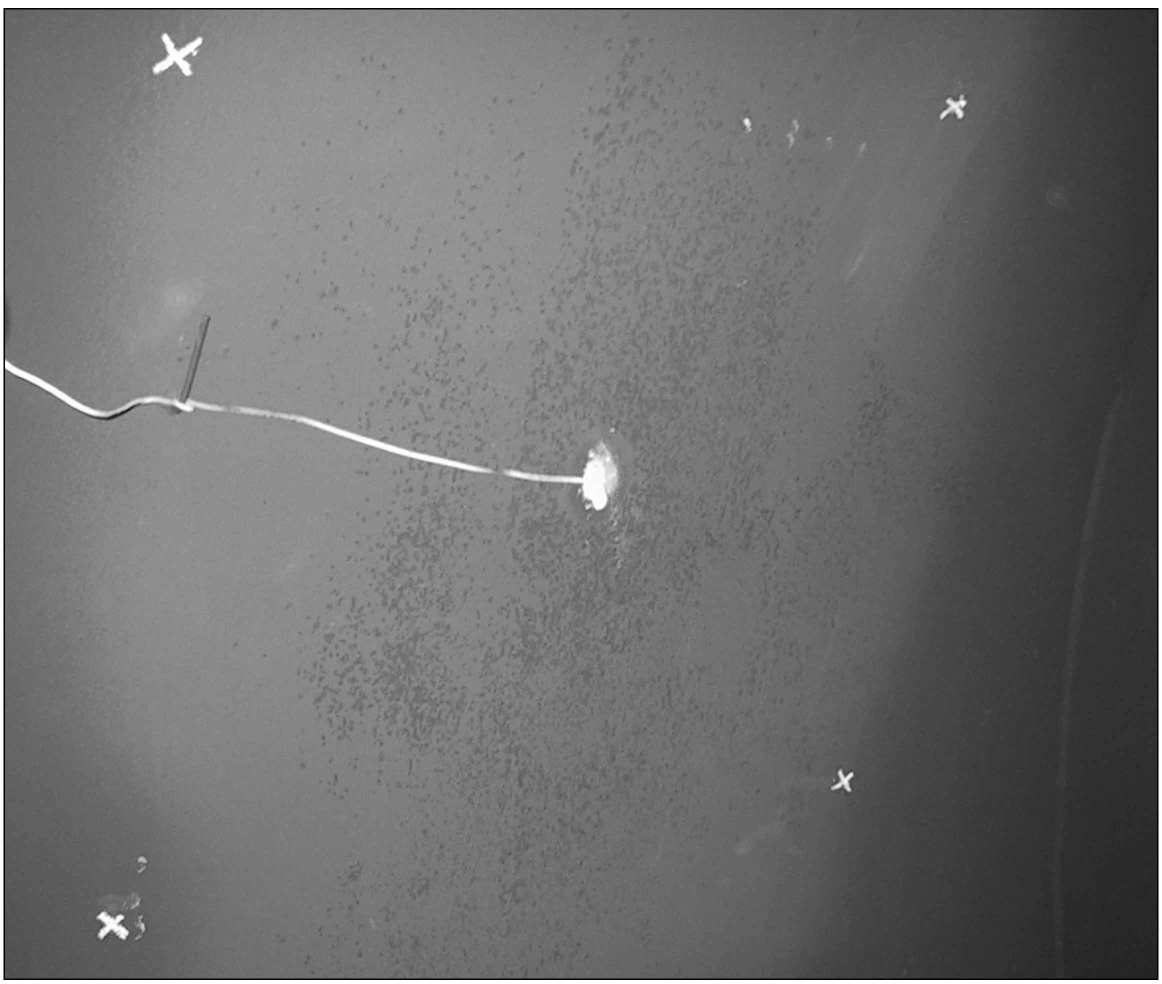


Figure 11: Wall Thermocouple

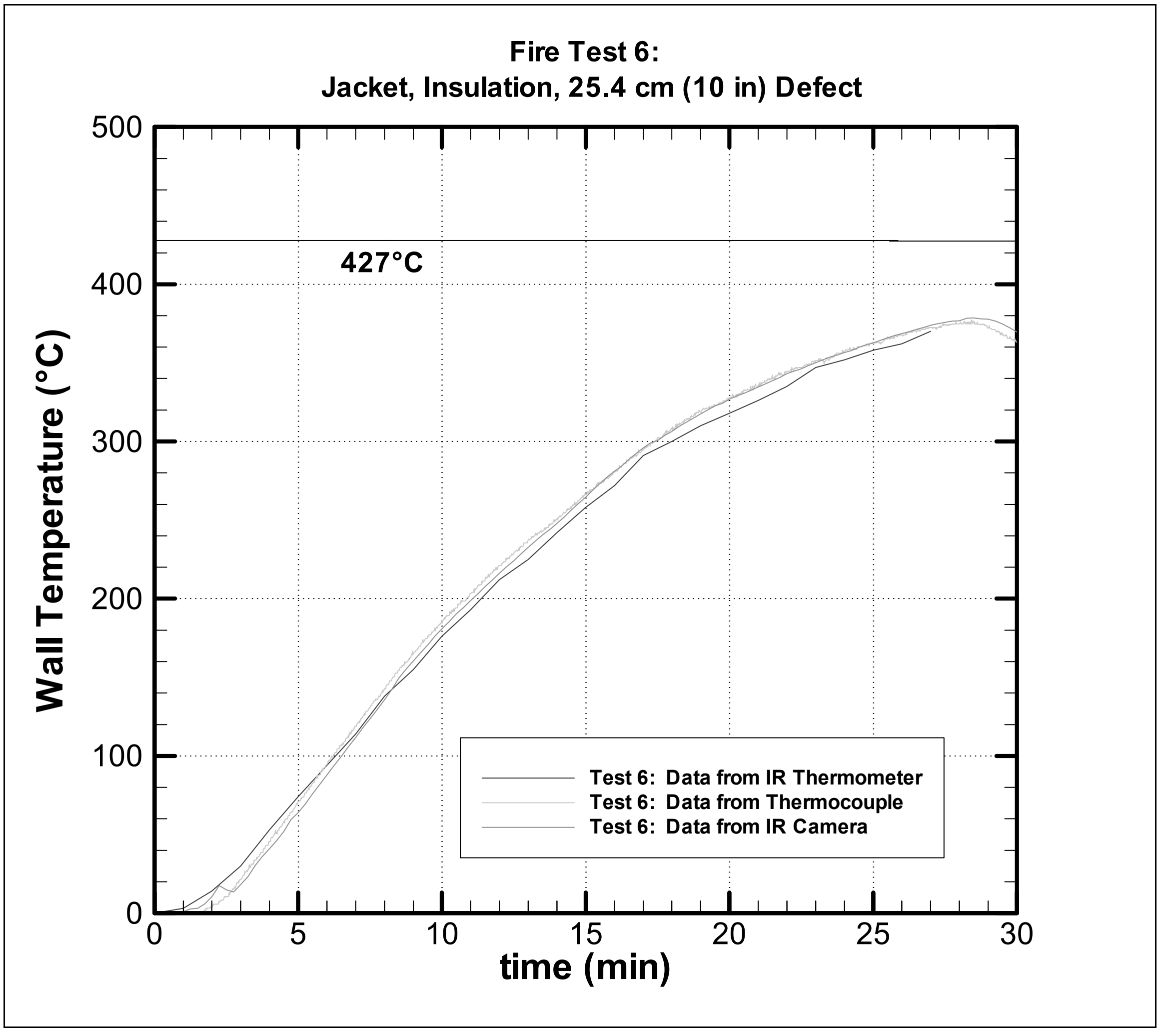


Figure 12: Maximum Wall Temperatures from Fire Test 6

3.2.2 Fire Temperature Measurements

Accurate measurements of the fire temperature were important for two reasons. First of all, good measurements of each test were required to prove that the fire conditions from test to test were similar. Secondly, good fire measurements were required to prove that the fire conditions were credible pool-fire like conditions. The Canadian General Standards Board Standard CAN/CGSB 43.147-2002 requires that when testing a thermal protection system in a pool fire, the fire must have an effective blackbody temperature between 816 and 927°C (1500 and 1700°F).

The fire temperatures were measured in two different ways:

1. The flame temperature was measured using two stainless steel, sheathed, type K thermocouples. One fire thermocouple had a sheathing diameter of 1.75 mm while the other had a sheathing diameter of 6.5 mm. The large thermocouple was used because of its rigidity and its ability to measure from a consistent location. The

smaller thermocouple was used because of its small thermal inertia and quick response to temperature chances. These two fire thermocouples were used primarily to check for consistent fire conditions. The thermocouples were placed deep enough into the fire to minimize conduction and radiation errors.

2. The blackbody flame temperature was measured using the Raytek MX4 infrared thermometer. To determine the blackbody temperature, the measurements taken with the IR thermometer assumed a fire emissivity of ε=1.0. The blackbody temperature is of interest because it is generally accepted in the literature that a large engulfing fire radiates as a blackbody (Drysdale, 1998). The approximate blackbody temperatures for the fire tests must all lie in the range between 816 and 927°C, as required by the standard.

The data from the two thermocouples in one of the tests is given in Figure 13. The darker line represents the measurement from the small thermocouple. Notice that it has quicker response and more sudden changes due to its small thermal inertia. The light line represents the larger thermocouple. It has a more sluggish response.

The difference between the readings is due to thermocouple errors. To minimize conduction error, the thermocouples were located several centimetres into the flame to minimize the temperature gradient at the tip. Because of the nature of fire, thermal gradients were present and conduction errors occurred. The thermocouples were also inserted deeper into the fire to minimize the radiation errors. Because the flames were not totally opaque, there was radiation exchange between the probe and the environment, and radiation errors still occurred. The large probe obviously has a larger surface and cross-sectional area and thus was more affected by radiation and conduction errors. The large thermocouple thus gave a lower temperature. See Appendix A for further details on radiation error.

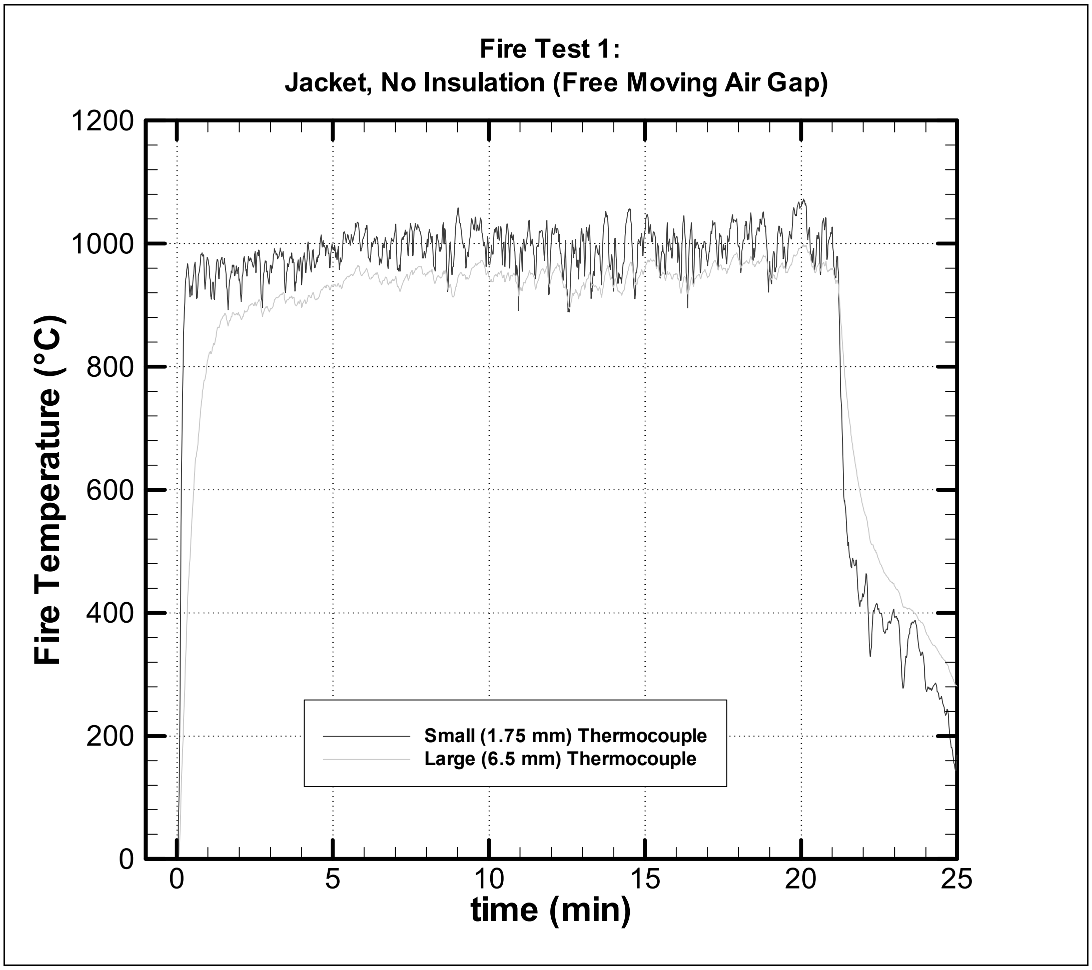


Figure 13: Fire Temperature from Fire Test 1

3.3 Test Matrix

The fire tests performed can be separated into three different groups:

1. Exploratory Fire Tests (Pre-tests)
2. Baseline Fire Condition Tests
3. Thermal Protection Deficiency Tests

3.3.1 Exploratory Fire Tests

The primary purpose of the initial pre-tests was to develop a credible pool fire. This pool fire must be able to be repeated for all later tests.

In this test series, all tests used the array of nine utility burners described in section 3.1.3. No thermal protection (insulation or steel jacket) was used. The size of the burner nozzles, the fuel pressure, and air/fuel mixing characteristics were varied to get an understanding of each parameter's role in the fire conditions.

Two different fuel nozzles were used. The nominal nozzles that come with the 586 kW (2 MBTU/hr) burners have 3 holes, 2.7 mm in diameter. Smaller capacity nozzles containing 3 holes, 2.0 mm in diameter, were also available.

Two different air/fuel mixing characteristics were also used. In some cases the burner's mixing tube was blocked with the Fiberfrax insulation and in other cases there was no blockage. Starving the flame of air dramatically increased the flame's luminance.

Finally, two different fuel supply pressures were used, as indicated in Table 2. Both pressures were near the lower limit of the system. Table 2 gives a summary of the input parameters for the six pre-tests performed. The table also shows some of the results of the testing. This will be discussed more in the next chapter.

	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Date	Nov 14	Nov 19	Nov 20	Nov 20	Nov 21	Nov 21
Number of Burners	9	9	9	9	9	9
Nozzle Size	Large	Large	Large	Small	Small	Small
Fuel Pressure	2-3 psi	2-3 psi	1-2 psi	1-2 psi	1-2 psi	2-3 psi
Plugged Mixing Tubes	Yes	Yes	Yes	Yes	No	No
Steel Jacket?	No	No	No	No	No	No
Insulation?	No	No	No	No	No	No
Ambient Temp (°C)	9	6	10	10	6	6
Initial Heat Rate (°C/min)	57	62	53	46	27	52
Time to 427°C (from 0°C)	7.8 min	7.3 min	9.3 min	11.7 min	19.1 min	9.0 min
Approx Blackbody Fire Temp (°C)		840	820	780	540	750

Table 2: Summary of Exploratory Tests

After the completion of the six pre-tests, it was decided that the heat-up rate in Tests P3 and P2 were the most representative of a large engulfing hydrocarbon pool fire. (See Chapter 4 for more detail and the plotted results.) Test P3 was repeated to check the repeatability of this baseline fire condition.

3.3.2 Baseline Fire Tests

The first baseline fire test (Test B1) was intended to be a repeat of P2 simply to get a better feeling for test repeatability. The last two baseline fire tests, Test B2 and Test B3, were intended to repeat the selected fire condition, Test P3. As will be shown in Chapter 4, the fire conditions were very repeatable.

Table 3 shows a summary of the baseline fire tests.

	B1	B2	B3
Date	Nov 25	Nov 25	Nov 27
Number of Burners	9	9	9
Nozzle Size	Large	Large	Large
Fuel Pressure	2-3 psi	1-2 psi	1-2 psi
Plugged Mixing Tubes	Yes	Yes	Yes
Steel Jacket?	No	No	No
Insulation?	No	No	No
Ambient Temperature (°C)	1	1	-4
Compare to Test:	P2	P3	P3
Initial Heat Rate (°C/min)	61	51	53
Time to 427°C (from 0°C)	7.0 min	9.4 min	9.5 min
Approx. Blackbody Fire Temp (°C)	850	860	840

Table 3: Summary of Baseline Fire Tests

3.3.3 Thermal Protection Deficiency Fire Tests

The last series of fire tests involved thermal protection deficiencies. All 12 tests in this test series used the steel jacket and used the fire conditions from Test P3.

The 12 fire tests are listed below and summarized in Table 4.

1. Jacket, No Insulation (Free Moving Air Gap)
2. Jacket, No Insulation (Sealed Air Gap)
3. Jacket, Insulation, No Defect
4. Jacket, Insulation, 7.6 cm (3 in.) Defect
5. Jacket, Insulation, 15.2 cm (6 in.) Defect
6. Jacket, Insulation, 25.4 cm (10 in.) Defect
7. Jacket, Insulation, 40.6 cm (16 in.) Defect
8. Jacket, Insulation, 61.0 cm (24 in.) Defect
9. Jacket Pressed Against Wall, No Insulation
10. Jacket Pressed Against Wall, Crushed Insulation
11. Jacket Pressed Against Wall, Crushed Insulation, 25.4 cm (10 in.) Defect
12. Jacket Clamped Against Wall, No Insulation

In Test 1, the air gap between the jacket and the wall was not sealed around the edges and the air in the deficient region was allowed to be freely exchanged with atmospheric air. As expected, this decreased the heat transfer from the fire to the tank wall. In the remaining tests completed with no insulation, the air gaps were all sealed around the edges with thin strips of insulation to stop free circulation of the air in the gap. This increased the heat flux from the fire to the wall. Figure 14 shows a test with no insulation, except for enough insulation to seal the air space edges.

In the first eight tests, the steel jacket was supported by 13 mm (0.5 in.) spacers around the perimeter of the jacket. These spacers were removed for the last four tests. Removing the spacers allowed for simulating pressed or clamped jacket conditions.

In pressed jacket tests, the jacket was bolted to the tank wall around the jacket perimeter. This allowed the jacket and the wall to come into contact in several locations and left a very thin air gap for the no insulation test (Test 9). Figure 14 shows this sort of set-up. The set-up was identical in the clamped jacket test (Test 12), except vice-grips were used to clamp the jacket to the tank wall near the thermocouple position. Figure 15 shows the clamp positioned on the tank viewed from the back wall.

Test	Date	Ambient Temp (°C)	Jacket	Insulation	Other	Initial Heat Rate (°C/min)
1	Dec 2	-6	Yes	No	Open Air Gap	24.1
2	Dec 3	-13	Yes	No	Sealed Air Gap	25.2
3	Dec 4	-9	Yes	Yes	No Defect	5.3
4	Dec 9	-12	Yes	Yes	7.6 cm Defect	9.9
5	Dec 9	-10	Yes	Yes	15.2 cm Defect	17.7
6	Dec 10	0	Yes	Yes	25.4 cm Defect	21.4
7	Dec 10	0	Yes	Yes	40.6 cm Defect	23.4
8	Dec 11	0	Yes	Yes	61.0 cm Defect	23.4
9	Dec 11	0	Pressed	No	Sealed Air Gap	25.4
10	Dec 12	0	Pressed	Crushed	No Defect	6.4
11	Dec 12	0	Pressed	Crushed	25.4 cm Defect	23.2
12	Dec 13	-2	Clamped	No	Sealed Air Gap	26.7

Table 4: Summary of Insulation Deficiency Fire Tests

Tests 10 and 11 used a piece of crushed insulation. The nominally 13 mm thick insulation was crushed down to approximately 6 mm. After the crushed insulation was placed on the tank, the steel jacket was again bolted to the tank wall.

Tests 4, 5, 6, 7, 8, and 11 were run with a square defect cut out of the insulation. The size of the defect listed in Table 4 indicates the length of one side of the square defect. The defect was positioned so that the thermocouple was in the centre of the defect. Figure 16 shows the 15.2 cm defect before the jacket was placed over it.

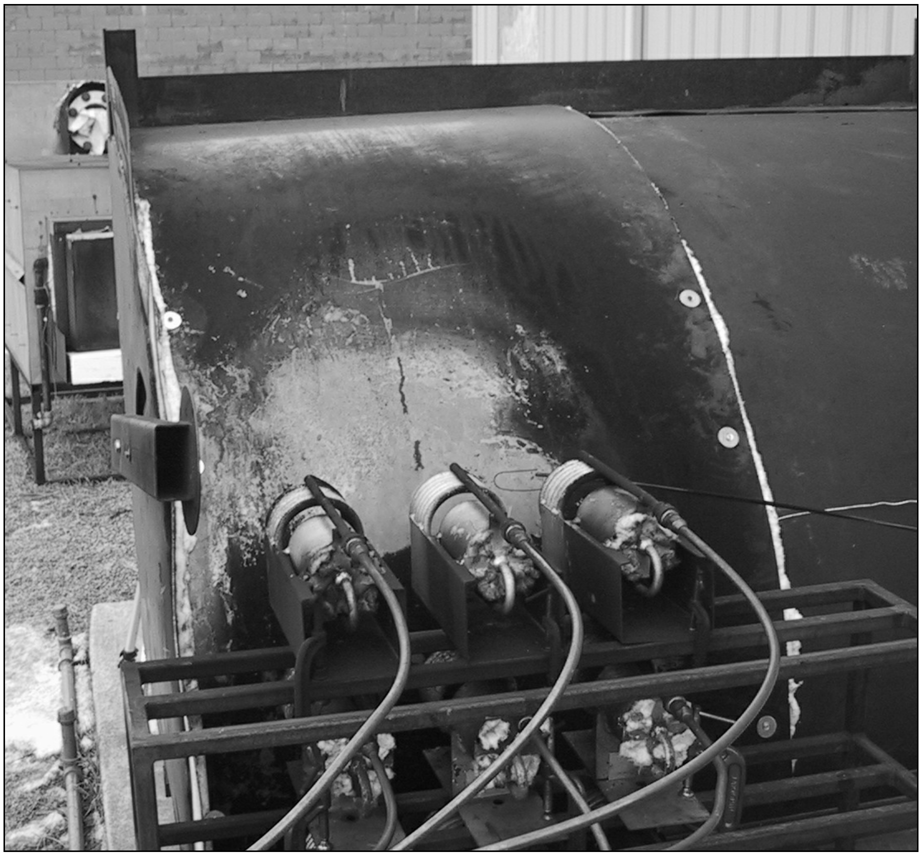


Figure 14: Pressed Jacket, No Insulation, Sealed Air Space (Test 9)

Figure 15: Back Side of Clamped Wall – Clamped at Thermocouple Location (Test 12)

Figure 16: 15.2 cm Defect, Jacket Removed (Test 5)

3.4 Test Procedure

The procedure used for the fire tests was very simple. The appropriate defect was set up, the burners were ignited, and the measuring devices recorded temperatures. The tests were stopped after approximately 25 minutes.

Appendix B describes the procedure in more detail. Appendix B also gives some checklists that were used in the field. These checklists give more information about the test sequence.

4.0 Validation of Fire Conditions

This chapter discusses the preliminary tests performed to ensure credibility and repeatability of the fire conditions. Six tests were performed to find the best fire conditions for the testing and three tests were performed to test the repeatability. This chapter discusses the results from these nine tests. Table 5 gives a brief summary of the tests while Appendix C presents a more comprehensive compilation of the pre-test results.

4.1 Fire Condition Requirements

For optimal results from this study, the fire conditions must be both repeatable and credible.

1. Repeatable. The fire must be able to heat an engulfed tank wall at a repeatable rate from test to test, assuming no change in the thermal protection of the tank wall. This simply requires keeping input parameters such as fuel pressure and the effect of wind constant.

2. Credible. The fire conditions must be representative of fires that a tank-car might see in a real accident situation. Therefore, the fire should simulate a large engulfing, hydrocarbon pool fire. To represent a real pool fire, the testing fire condition must:

- be highly luminous, sooty, and optically thick
- fully engulf the tank in the test area
- have gentle, low-momentum, non-jetting flames
- transfer heat primarily by radiation

4.2 Pre-test Fire Tests

4.2.1 General Observations on the Fire Conditions

Figure 17 through Figure 19 show images from the testing. Figure 17 shows a flame from the front view. Notice that the flame is quite opaque. The fire thermocouples enter the image from the right, but because of the optically thick flame, the tip of the thermocouple cannot be seen. The region of the wall that is directly in front of the array of burners is almost completely engulfed in fire. Figure 18 shows the side view of the fire engulfment. Notice that the flame engulfs the surface well. In this image, there are parts of the flame that are transparent, but again, most of the flame is opaque. Figure 19 shows a close up of the swirling fire. Table 5 gives a summary of the fire conditions. The average flame temperature given in the table is that measured with a thermocouple. The blackbody temperature given in the table is the theoretical blackbody temperature of a fire that would give the same heat flux as the test fire. The test fire was not truly black (i.e. $\varepsilon < 1$) and therefore the blackbody temperature is less than the fire temperature. As the fire becomes less luminous, the difference between flame temperature and blackbody temperature becomes larger.

Test	Date	Defect	Initial Heat Rate (°C/min)	Avg Flame Temp (°C)	Approx Blackbody Fire (°C)
P1	Nov 14	No Protection	57	--	--
P2	Nov 19	No Protection	62	1042	840
P3	Nov 20	No Protection	53	981	820
P4	Nov 20	No Protection	46	949	780
P5	Nov 21	No Protection	27	504	540
P6	Nov 21	No Protection	52	1080	750
B1	Nov 25	No Protection	61	1030	850
B2	Nov 25	No Protection	51	1008	860
B3	Nov 27	No Protection	53	959	840

Table 5: Summary of Pre-test Fire Test Results

Figure 17: Front View of Fire Engulfment

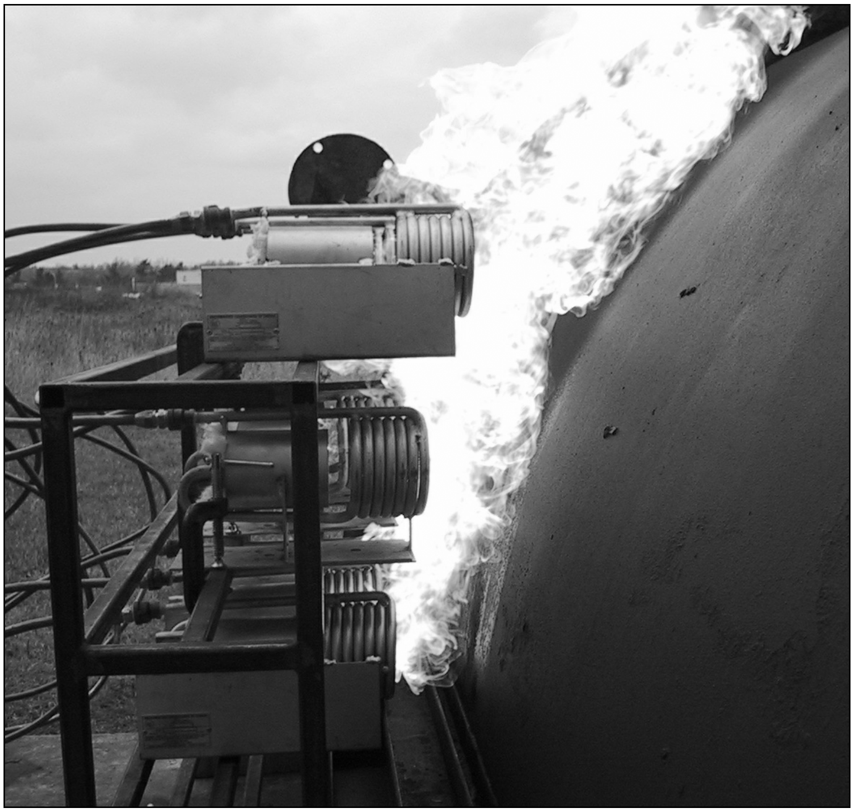


Figure 18: Side View of Fire Engulfment (Test P1)

Figure 19: Close Up of Sooty, Luminous Flame

The flames were typically quite sooty, leaving a fine black coating on the tank jacket during the tests. Black specks of soot were common in the plume. In many cases, the distinctive smell of unburned hydrocarbons was present.

4.2.2 Effect of Various Parameters

The first nine fire tests performed (Tests P1-P6 and Tests B1-B3) were completed with no thermal protection. Thus the difference in wall temperature curves is due solely to the difference in fire conditions.

Several parameters were varied throughout the pre-test fire tests, which allowed for an interesting variety in fires. The data presented in Table 5, Figure 20 and Figure 21 shows the effect of the different parameters. Figure 20 and Figure 21 show the same trends, because without thermal protection, a higher fire temperature will result in better heat transfer and higher wall temperatures.

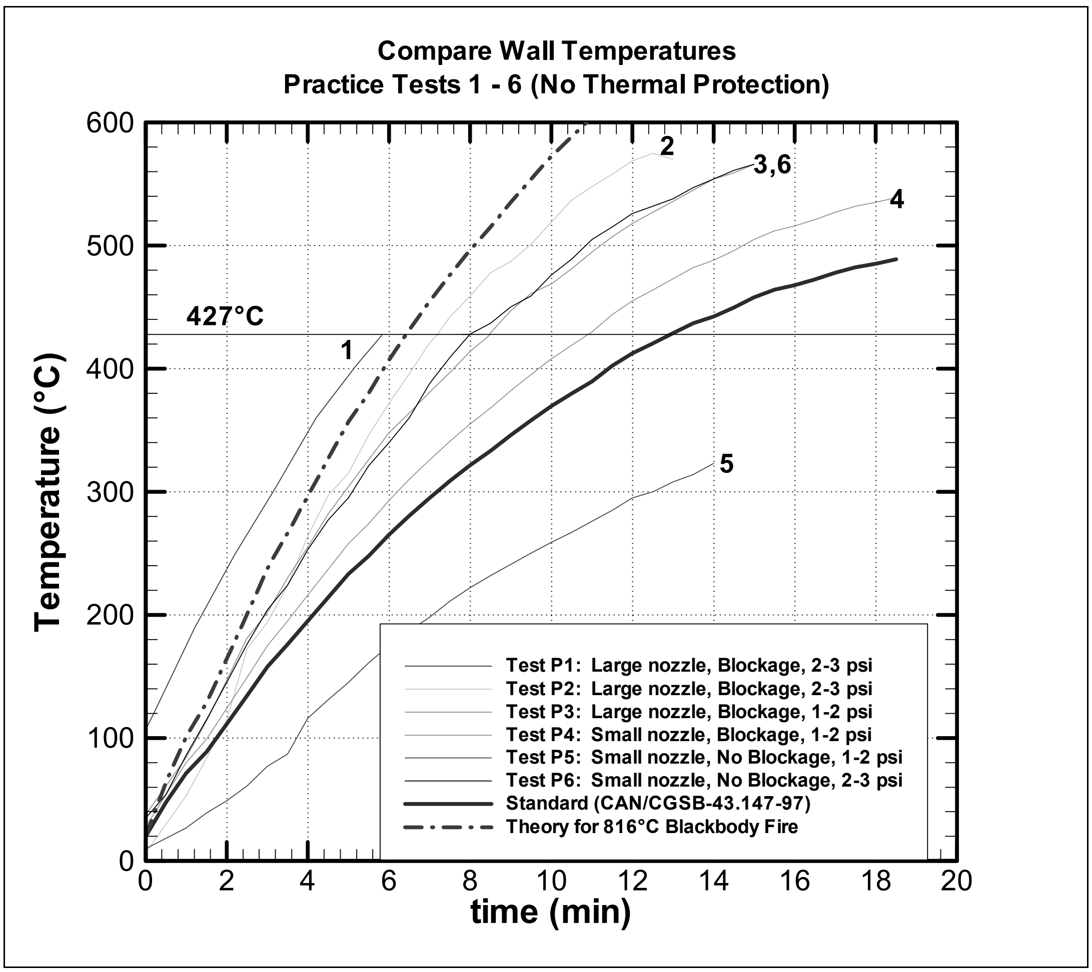


Figure 20: Wall Temperature from Pre-test Fire Tests

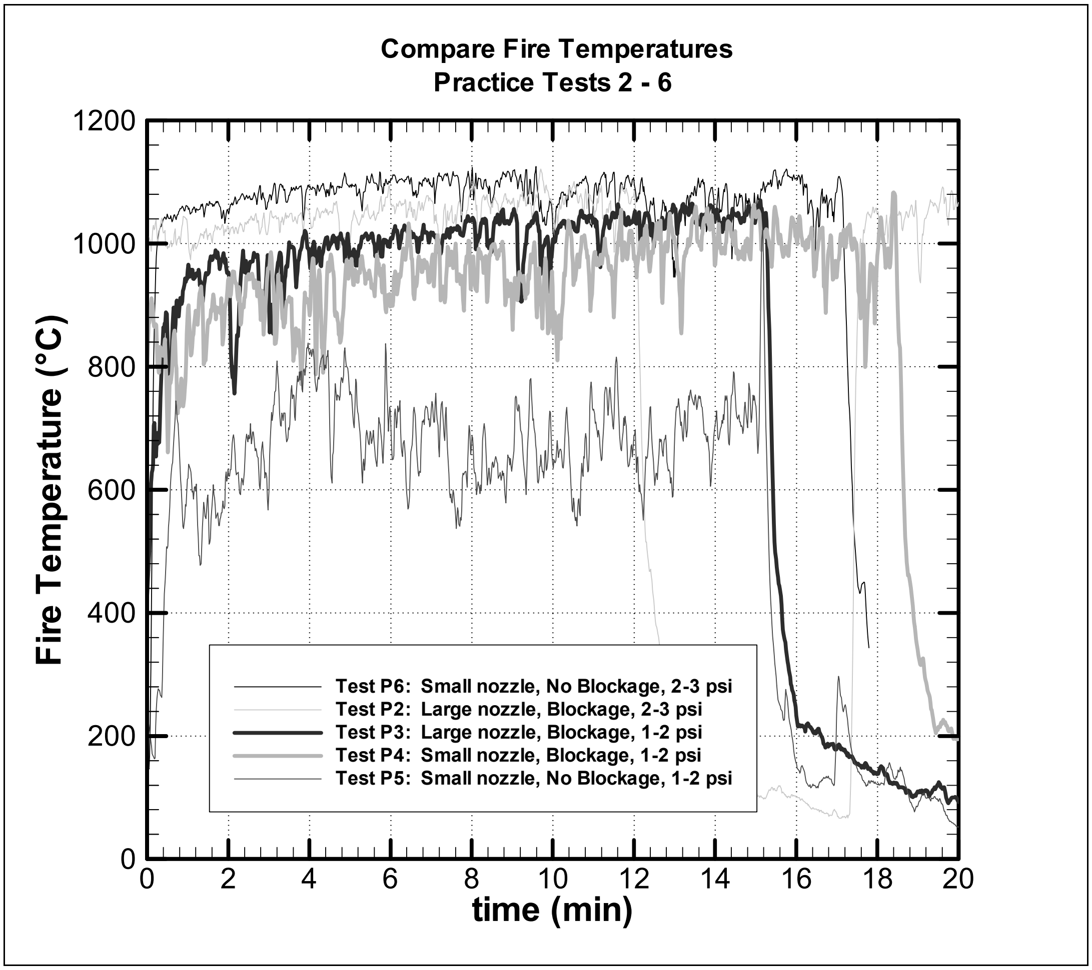


Figure 21: Fire Temperatures from Pre-test Fire Tests

Tests 1 and 2 (blocked mixing tube, large nozzle, approximately 20 kPa (2-3 psi) fuel pressure) had the highest initial heating rate. Reducing the fuel pressure to approximately 10 kPa (1-2 psi) reduced the heating rate of Test 3, as seen in Figure 20. Switching to the smaller nozzles in Test 4 further reduced the heating rate. Unblocking the mixing tube in Test 5 significantly reduced the heating rate. The final test, Test 6, had an increased pressure and the heating rate again increased.

Comparing Tests P3 and P4 shows the effect of the different nozzles. When the original nozzles were replaced with smaller nozzles, the result was a smaller, more compact, more uniform flame. This is an intuitive result because the smaller nozzles result in a lower fuel flow rate. This leads to a cooler flame, less heat transfer, and a cooler wall, as seen in Figure 20.

The first three tests were performed with plugged mixing tubes, as described in the previous chapter. Plugging the mixing tube starves the flame of air and this produces a dirty, sooty flame that is highly luminous and strongly radiating. There was a dramatic difference when a test was performed without the ceramic insulation plugging the tubes, as seen by comparing Tests P4 and P5. The better mixing of fuel and air allowed for a more transparent, less sooty flame and this reduced the thermal radiation from the flame. The thermocouple tip was actually visible through the flame. Also, because the flame was better mixed, it needed less time for the fuel to burn and thus was a more compact flame. The pungent smell of unburned hydrocarbons and the radiant heat from the clearer flame was also significantly less with better mixing. Heat transfer from the better-mixed flame is dominated more by convection and less by radiation. This is seen by comparing the approximate blackbody fire temperatures: 780°C when the tubes are plugged and 540°C when the tubes are open (Table 5). Plugging the mixing tube results in a more radiative fire and a higher heat rate. Plugging the mixing tubes created a highly luminous, sooty fire, as desired to simulate a pool fire.

Increasing the fuel pressure also made a visible difference in the flame. A higher fuel pressure resulted in a visibly and audibly stronger jet of flames from the burners. The higher fuel pressure also resulted in better mixing, more visible swirling, and higher turbulence. An increase in the fuel pressure results in a higher burning rate and higher temperatures, as seen by comparing Test P2 and Test P3, and Test P5 and Test P6. The stronger jet was undesirable as the desired fire was to be a low convective, non-jetting fire.

4.3 Credible Fire Conditions

The fire condition in Test P3, as shown in Figure 20, was used for the main fire tests. This fire condition was selected because it best met all of the requirements mentioned in section 4.1.

- It used plugged mixing tubes, which led to a luminous, sooty flame, as required.
- It used a very low pressure, which led to a gentle, non-jetting, low convection flame, as required, while still fully engulfing the test region, as shown in Figure 17 and Figure 18.
- It used the large nozzles to give an increased heating rate, closer to the heating rate anticipated by an actual fire as predicted with heat transfer theory (see Figure 20).

The CAN/CGSB-43.147-2002 standard requires that the blackbody fire temperature be in the range between 816 and 927°C. Table 5 shows that the blackbody temperature in Test P3 falls in that range.

The thick line in Figure 20 shows a heat-up rate that would meet the CAN/CGSB-43.147-2002 standards discussed in Section 2.2. The heat-up rate in Test P3 is higher than what the standard allows for an unprotected tank. This was explained in section 2.2.

4.4 Repeatable Fire Conditions

The fire conditions had to be repeatable, as well as credible. Figure 22 and Figure 23 can be used to prove the fire's repeatability.

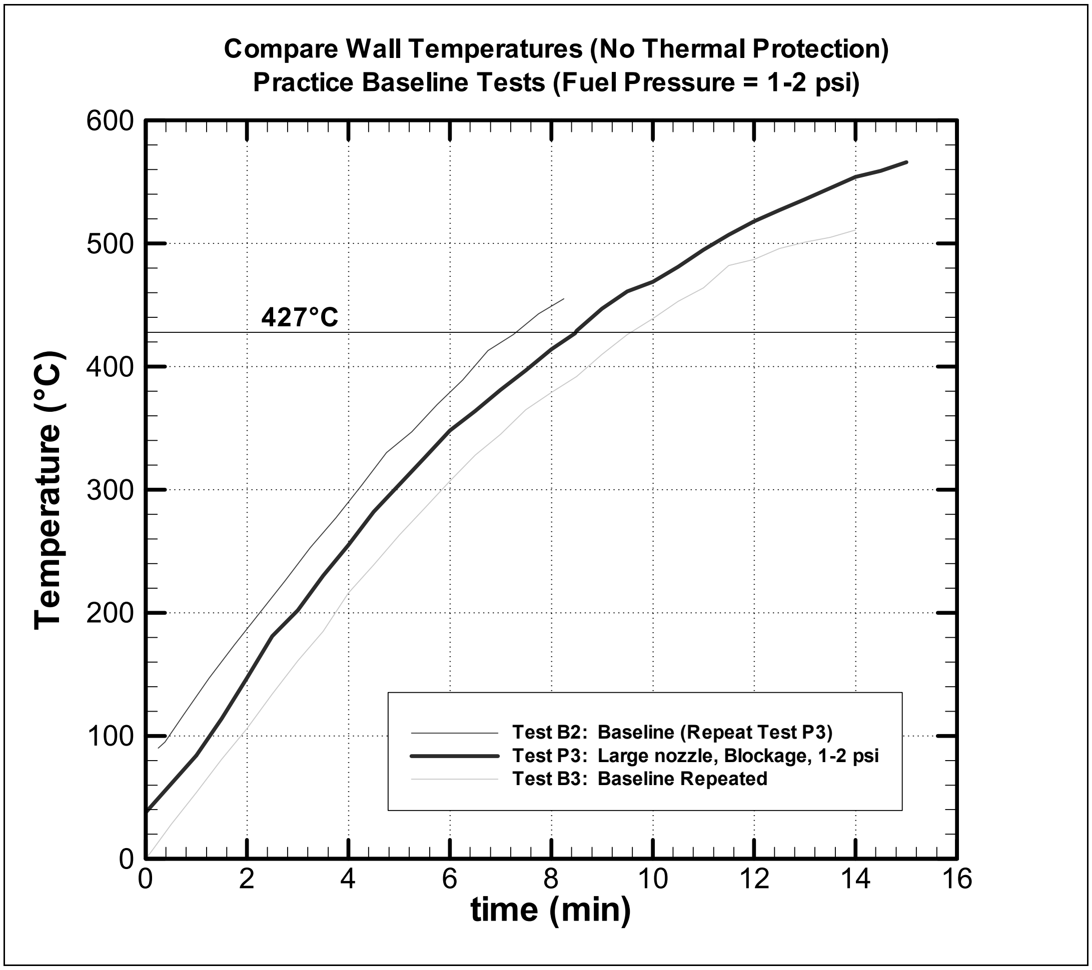


Figure 22: Baseline Tests to Check for Repeatability

The three baseline tests were designed to test the fire's repeatability. Figure 22 shows the wall temperature for Test P3 and the two tests that were designated to be a repeat of Test P3. As desired, the three curves are almost identical, except for the initial starting temperature.

The wall temperatures for the insulation defect tests cannot be used to show repeatable fire conditions because of the different thermal protection systems. Figure 23, however, shows the fire temperatures for the first five fire tests. This plot shows that the fires are indeed repeatable.

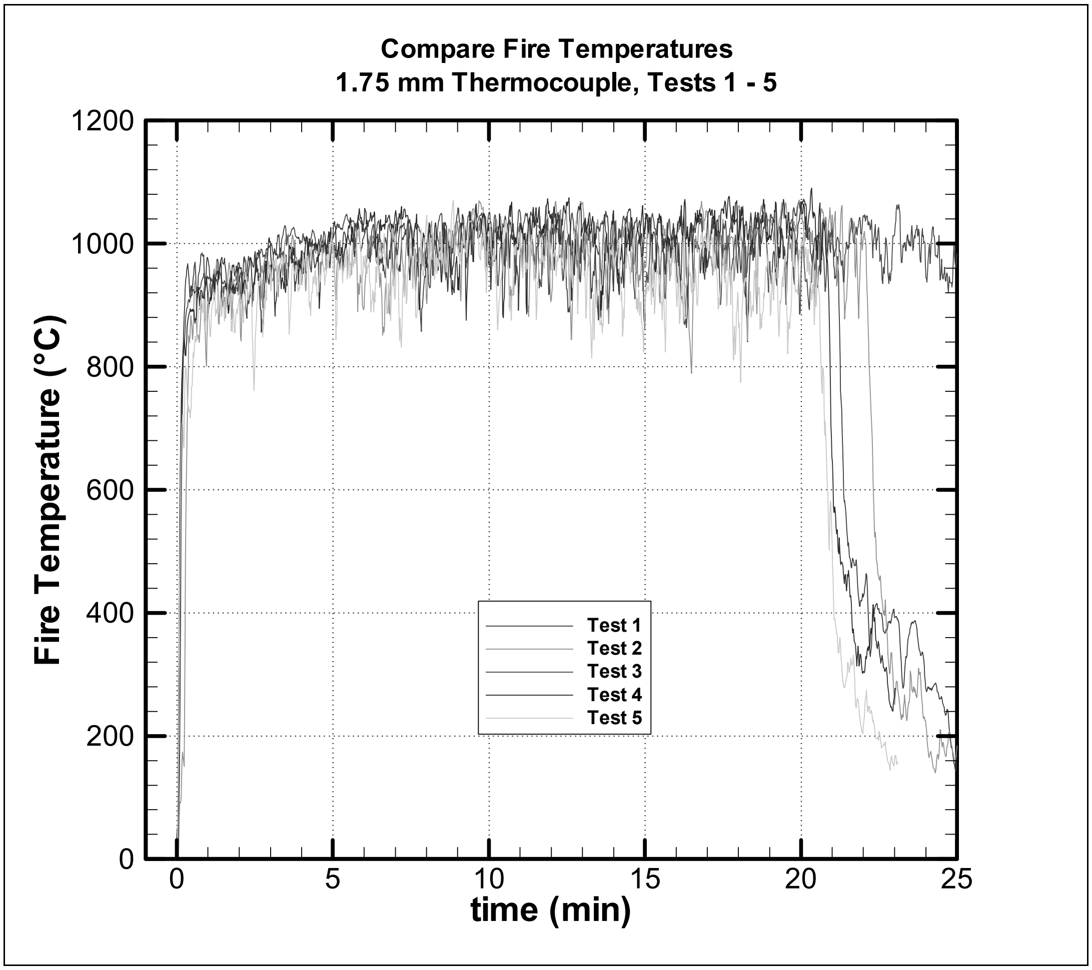


Figure 23: Repeatable Fire Temperatures in Main Fire Tests

5.0 Thermal Protection Deficiency Tests

This chapter presents and analyzes the data from the twelve thermal protection deficiency tests. Table 6 summarizes the data from these tests, while Appendix C presents a more comprehensive compilation of the data.

Test	Date	Defect	Initial Heat Rate (°C/min)	Avg Flame Temp (°C)	Approx. Blackbody Fire (°C)
B3	Nov 27	No Protection	53	959	840
1	Dec 2	No Insulation	24	982	870
2	Dec 3	No Insulation	25	984	880
3	Dec 4	Insulation	5	1003	830
4	Dec 9	7.6 cm Defect	10	997	840
5	Dec 9	15.2 cm Defect	18	944	850
6	Dec 10	25.4 cm Defect	21	1000	880
7	Dec 10	40.6 cm Defect	23	987	840
8	Dec 11	61.0 cm Defect	23	964	830
9	Dec 11	Pressed Jacket	25	1043	890
10	Dec 12	Crushed Insulation	6	948	830
11	Dec 12	Crushed Defect	23	952	870
12	Dec 13	Clamped Jacket	27	991	850

Table 6: Summary of Insulation Deficiency Fire Test Results

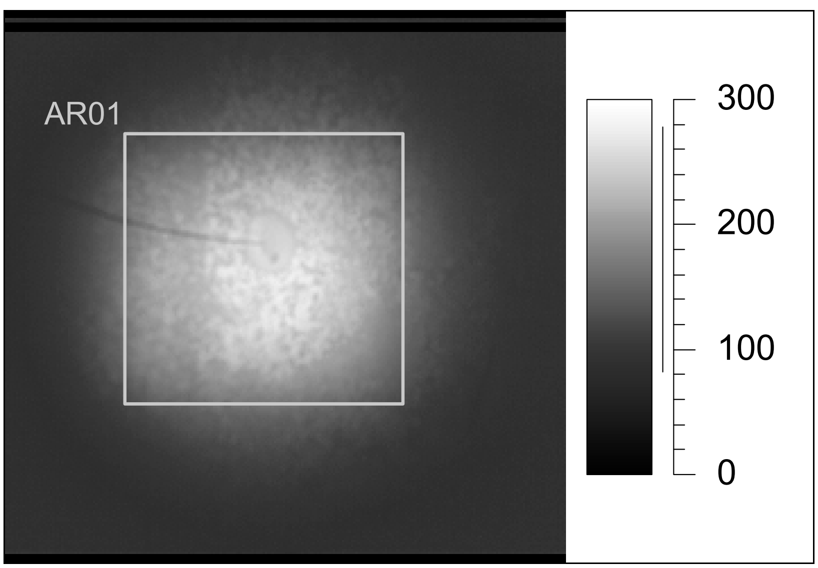


Figure 24: Thermal Image of Tank Wall with an Insulation Defect (15 min into Test 6)

5.1 Thermal Protection Deficiency Test -- Wall Temperature Data

The twelve main tests were all performed with identical fire conditions. Since the fire conditions were all the same for the deficiency tests, the wall temperature data only differed due to the different deficiencies. Thus the temperature data is useful in comparing thermal protection systems.

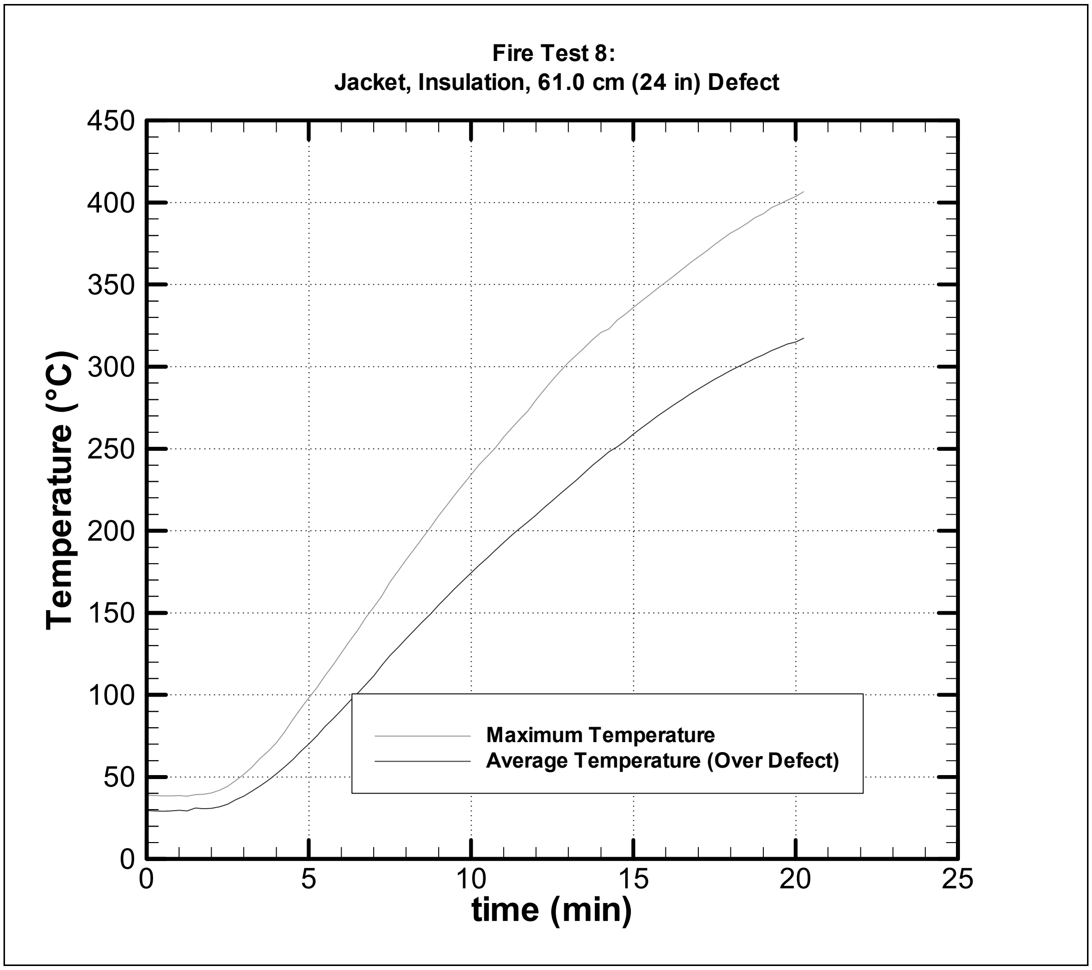


Figure 25: Maximum and Average Temperature in Defect Area for Test 8

In the tests with square defects cut out of the insulation, the thermal image data was very useful in studying not only the temperature rise with time, but also the temperature gradients across the defect. Figure 24 shows a thermal image taken during Test 6, the test with a square 25.4 cm defect. The relative size of the defect is shown in the image. Also notice evidence of the thermocouple in the centre of the image.

There is much data stored in the thermal images. Figure 25 and Figure 26 show IR image data plotted in two different ways. Figure 25 shows the maximum and average temperature in the defect region versus time for Test 8. The more uniformly the temperature is distributed over the defect, the closer the average will be to the maximum. Notice in the figure that as time goes on, the difference between the maximum plot and the average plot gets larger. This suggests that there are greater temperature gradients across the defect as time increases.

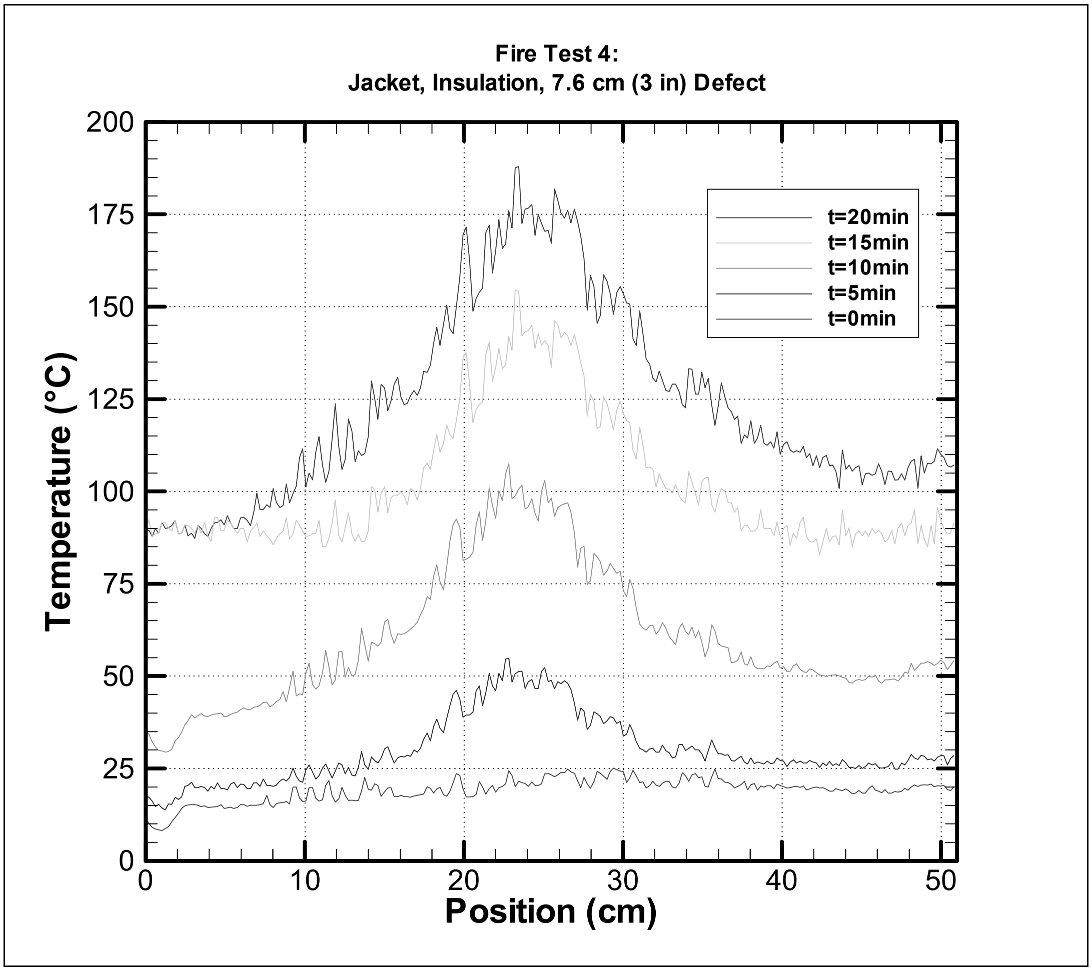


Figure 26: Temperature Profile Across Defect at Various Times During Test 4

Figure 26 shows temperature profiles across the defect at various times during Fire Test 4. As time goes on, the maximum temperature gets higher and the temperature gradients get larger. It is anticipated that if the fire test were allowed to continue, the peak temperature would eventually reach equilibrium and level off, and the gradients would decrease as the "hot spot" gets wider.

5.2 Thermal Protection Deficiencies

As mentioned previously, twelve fire tests were performed with a variety of thermal protection deficiencies. The following discussion considers all the different deficiencies.

5.2.1 Air Gap

If there is a very large defect the steel jacket will still provide some thermal protection (i.e. radiation shield effect reduces heat flux by about half). Table 7 shows that the initial heat rate to the tank shell is approximately doubled if the steel jacket covering is removed.

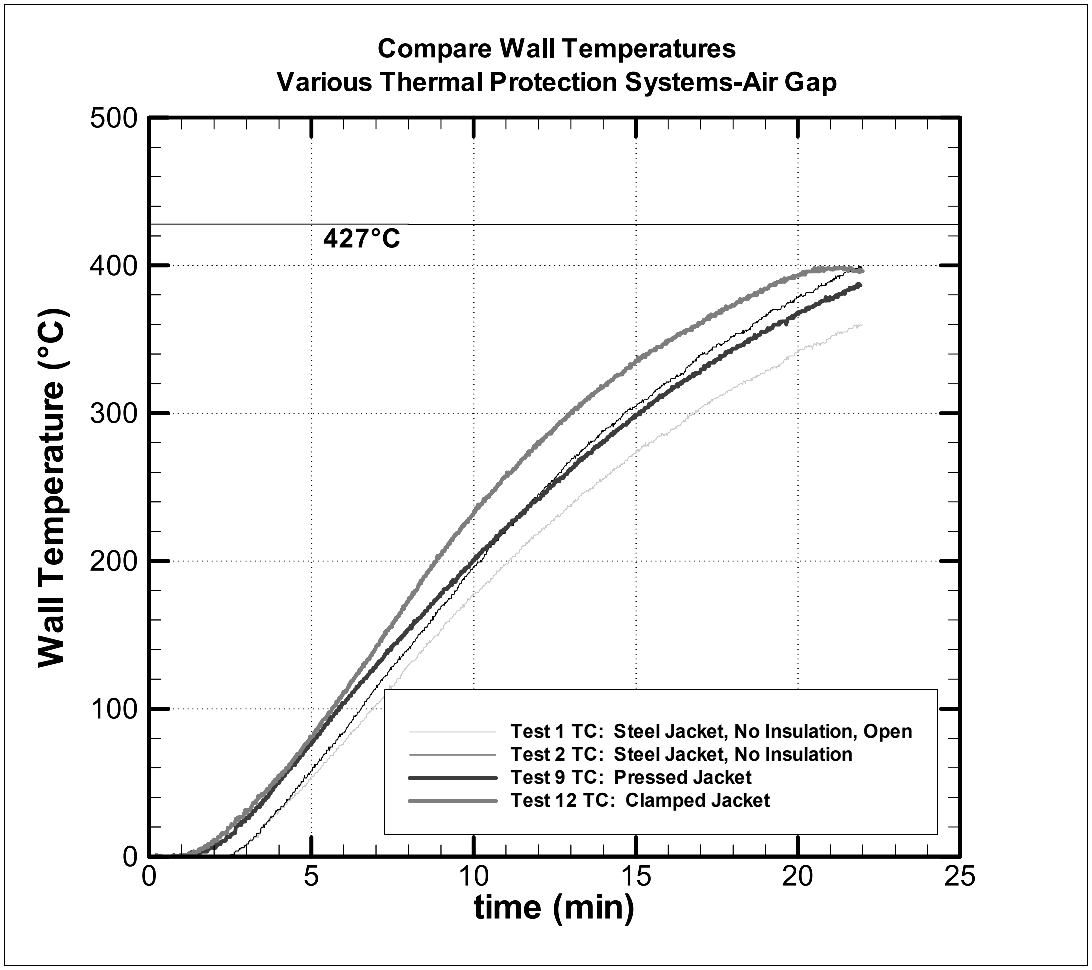


Figure 27: The Effect of Various Different Air Gaps

Test	Description	Initial Heat Rate (°C/min)
B3	No Protection	53
1	13 mm Air Gap, Open Air Gap	24
2	13 mm Air Gap, Sealed Air Gap	25
7	40.6 cm Defect	23
8	61.0 cm Defect	23
9	Pressed Jacket	25
12	Clamped Jacket	27

Table 7: Heating Rate for Tests with No Insulation

Figure 27 shows the wall temperature versus time plots for the four tests completed without insulation. Several interesting results can be seen in this plot:

- Compare Test 1 and Test 2. Preventing the air in the air gap from being exchanged with fresh, atmospheric air makes a significant difference in heat transfer from the fire to the tank wall. After 20 minutes in the fire, the test wall with the sealed air gap was over 40°C warmer than the test with the open-air gap.
- Compare Test 2, Test 9, and Test 12. Pressing the steel jacket against the tank wall improves the heat transfer from the fire to the wall. In this data, this is only a small difference, but if a larger force were applied, this could be significant. Similarly, clamping the jacket to the tank wall gives a slightly higher heat rate than the pressed jacket, but again the difference is small. Again, a much larger clamping force could make the difference in heat transfer very significant.

These results can be seen clearly in Table 7.

5.2.2 Defect Size

The size of the insulation defect affects the total heat transfer and maximum temperature of the tank wall. Figure 28 shows the peak (centre) temperature versus time for various defects tested. It should be clear that as the defect gets larger the temperature rise rate gets larger. Table 8 shows this same data in tabular form.

Notice that curves for the larger defects (40.6 cm and 61.0 cm) are very close to the curve for no insulation as all. This is the identical conclusion made earlier in Birk and Cunningham's Field Inspection Manual (1999).

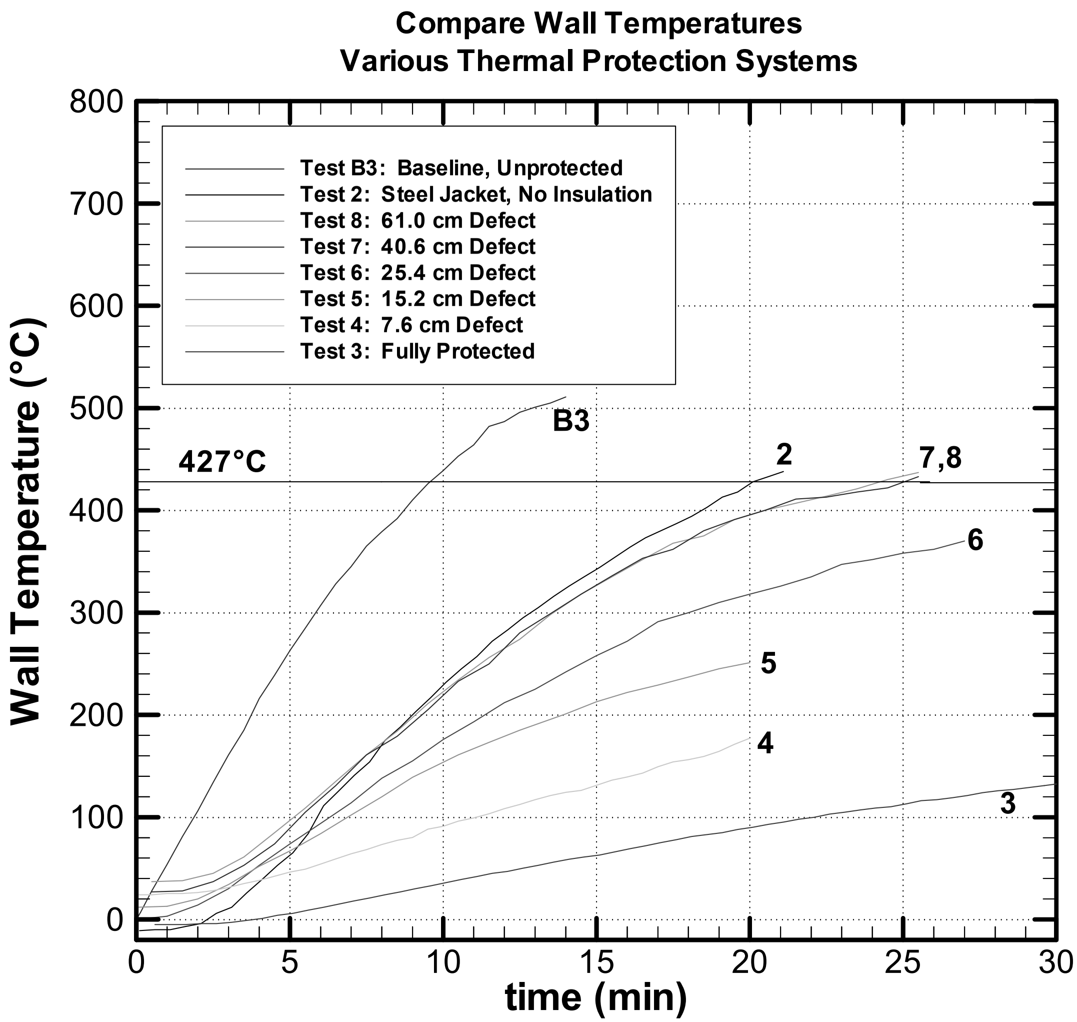


Figure 28: Wall Temperature versus Time for Various Defect Sizes

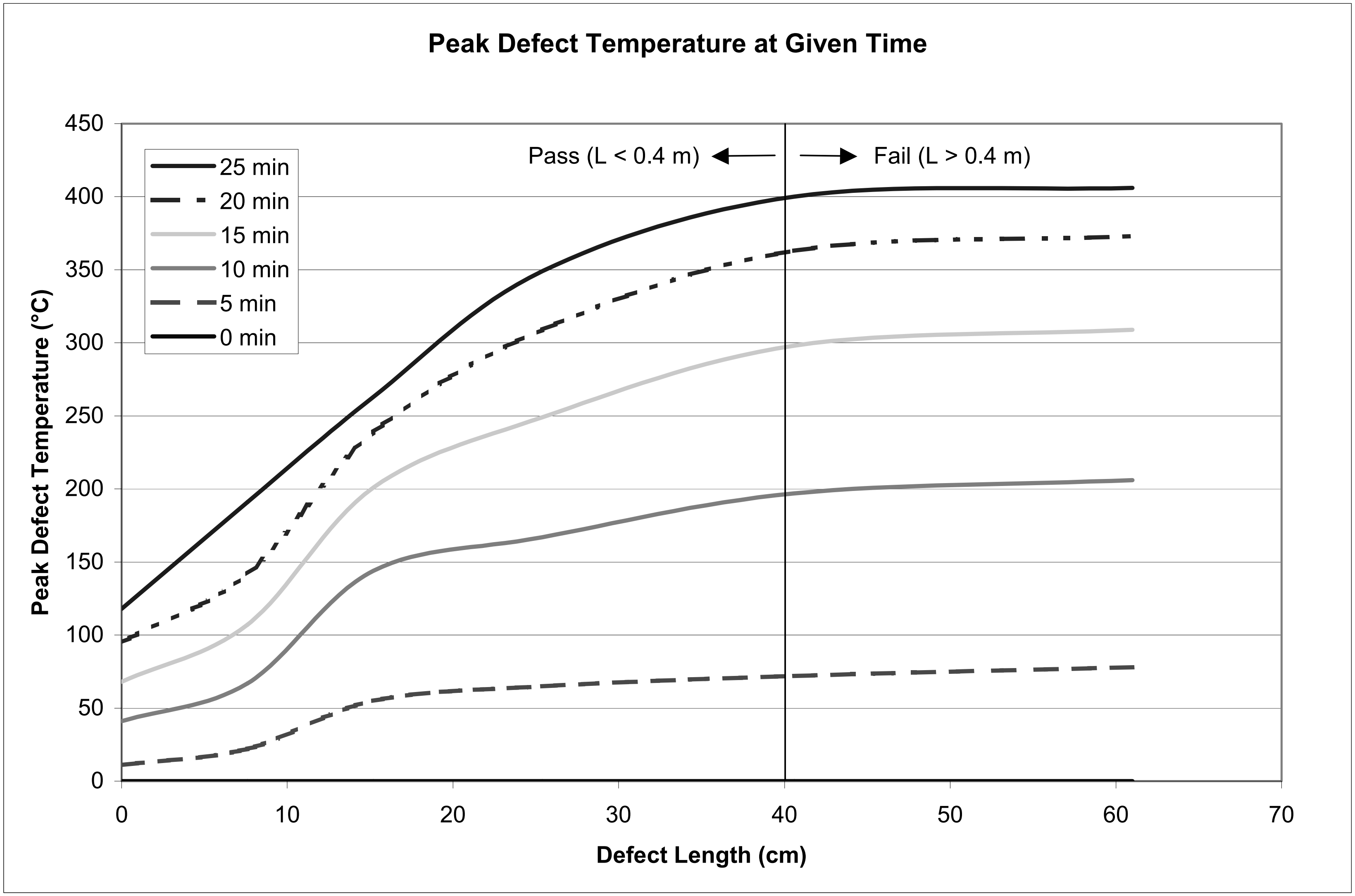


Figure 29: Peak Defect Temperature at Given Time

Figure 29 shows how at a fixed time, the peak temperature changes with defect length. This plot again shows that 40 cm is the transition defect size. A defect smaller than 40 cm means that the surrounding protected material reduces the peak wall temperature, while a defect greater than 40 cm means there is little or no benefit from the surrounding material as far as peak wall temperature is concerned.

Test	Description	Initial Heat Rate (°C/min) Peak T
3	Full Sheet of Insulation	5
4	7.6 cm Defect	10
5	15.2 cm Defect	18
6	25.4 cm Defect	21
7	40.6 cm Defect	23
8	61.0 cm Defect	23
2	No Insulation	25

Table 8: Heating Rate for Tests with a Square Defect

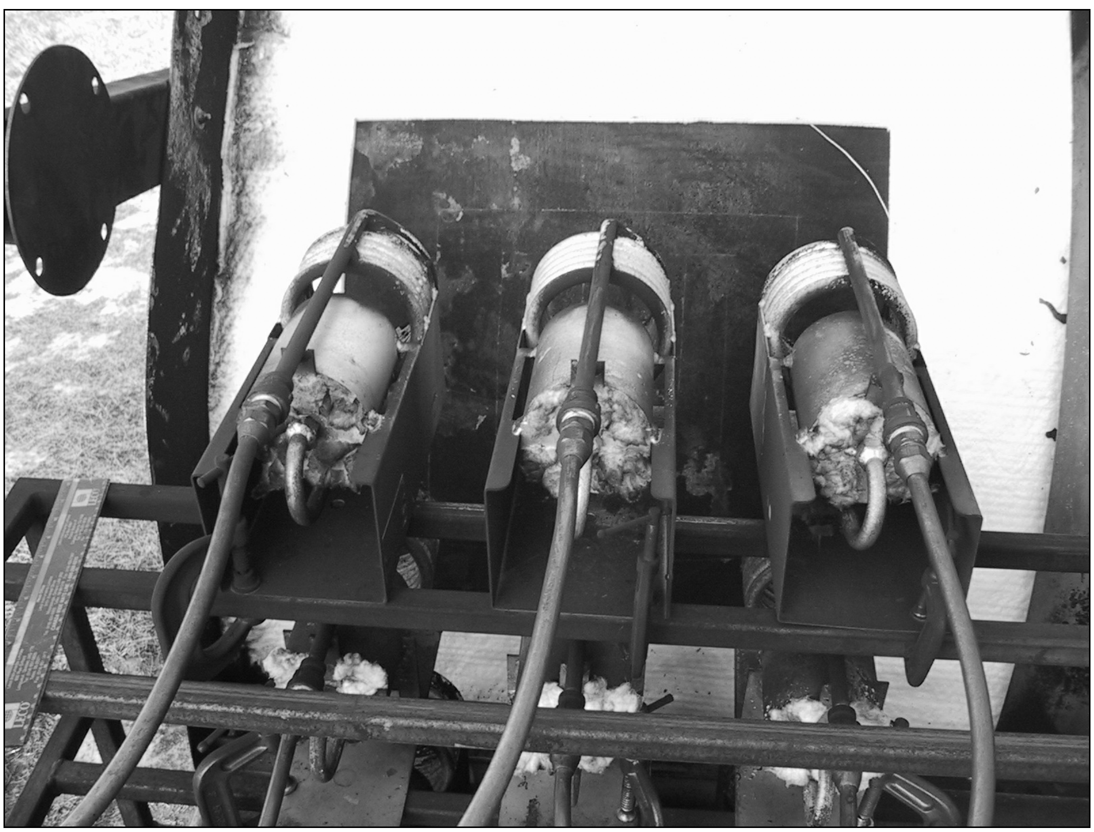


Figure 30: 61.0 cm Defect, Jacket Removed for Photo (Test 8)

The shape of the temperature profile also differs with defect size, as shown in Figure 31. Not only is the peak temperature higher with a larger defect, but the range of temperatures (max-min) is higher as well. This suggests that the difference between the maximum and average temperature will get greater as the defect increases in size.

Figure 31 shows a plot of the non-dimensional temperature profiles at 20 minutes. Notice that the non-dimensional width of the "hot spot" is consistent through all the tests at 20 minutes. Also notice that, as the defect gets larger, the profiles start looking identical. As suggested earlier, at a certain size of defect, the size no longer matters very much. This size has been shown to be about 0.4 m.

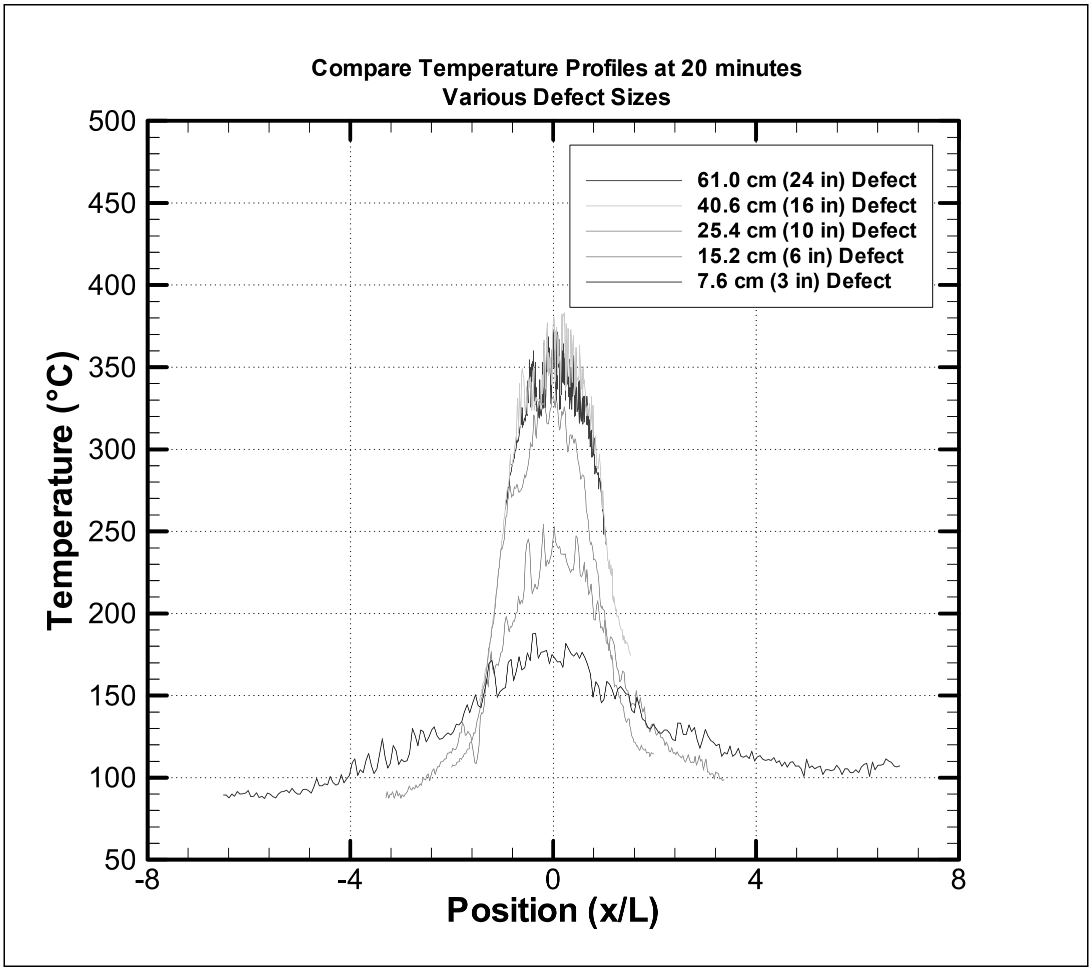


Figure 31: Various Non-dimensional Temperature Profiles at 20 minutes (L=half length of defect)

5.2.3 Crushed Insulation

The final thermal protection system deficiency examined in this study was crushed insulation. The 13 mm thick insulation was crushed to 6 mm and the sheet of insulation was covered with the steel jacket and tightly bolted into place. Table 9 and Figure 32 show the effect of crushed insulation. Tests 3 and 6 were performed with 13 mm thick insulation while the insulation used in Tests 10 and 11 was approximately 6 mm thick.

We must note here that it was not possible to apply a uniform crushing force with the apparatus and, as a result, the data shown here must be taken with caution. By crushing the insulation to 50 percent of its original thickness we would expect a near doubling of the conductance and heat transfer. This was not seen and may be due to our inability to crush the insulation uniformly.

In an actual tank-car, severe crushing is possible and this is expected to have a significant effect on heat transfer.

Test	Description	Initial Heat Rate (°C/min)
3	Full Sheet of Insulation	5
10	Crushed Insulation	6
6	25.4 cm Defect	21
11	25.4 cm Defect (Crushed)	23

Table 9: Heating Rate for Tests with Crushed Insulation

Table 9 and Figure 32 indicate that crushed insulation does not protect as well as uncrushed insulation, but the difference is small in our tests.

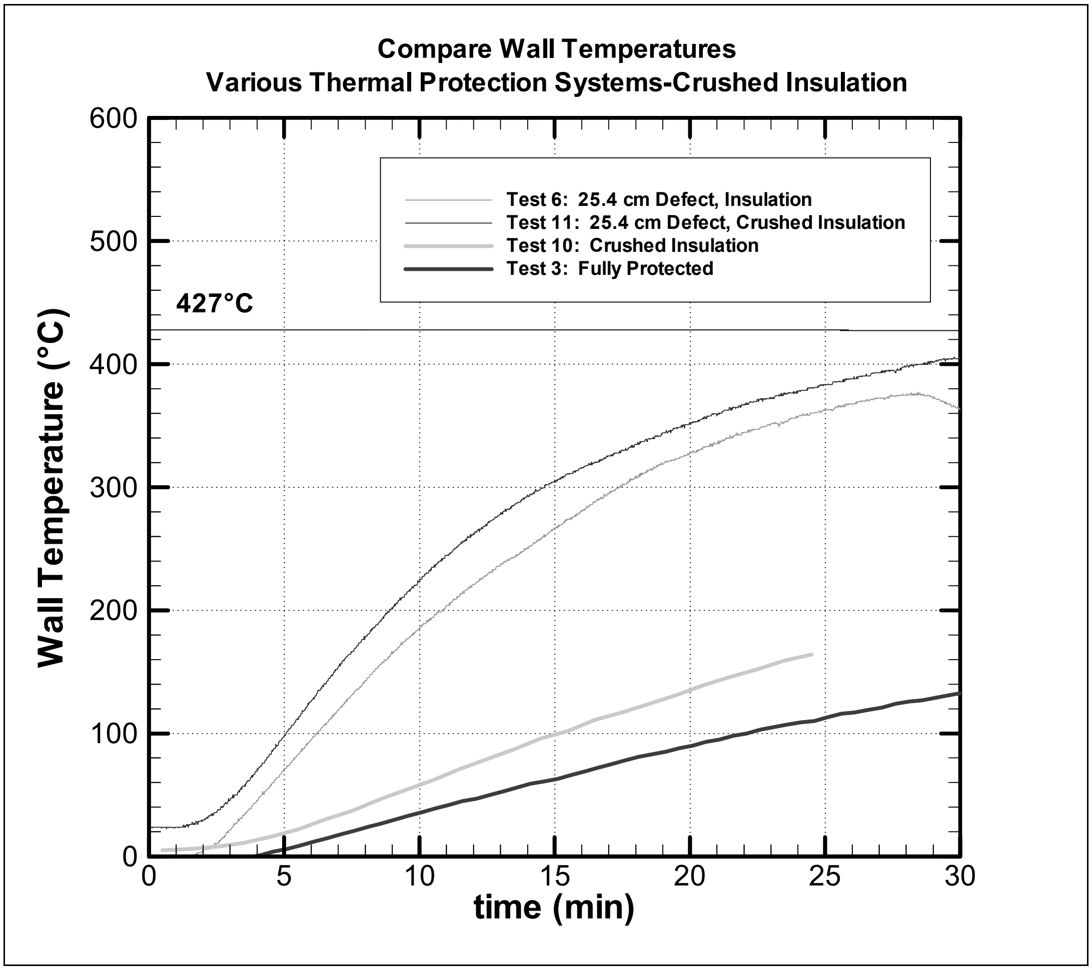


Figure 32: Wall Temperatures for Tests with Crushed Insulation

6.0 Conclusions and Recommendations

The ultimate goal of these fire tests was to collect temperature data and to better understand the heat transfer from an engulfing pool fire to a protected tank wall for different deficient thermal protection systems. This chapter summarizes the findings and discusses relevant areas that still need to be studied.

6.1 Conclusions

A total of 12 different thermal protection deficiency fire tests were performed. The following conclusions can be made about these tests:

- A credible fire condition was developed during the pre-tests. When applied to the wall of the unprotected tank mock-up, the initial wall heat rate was approximately 53°C/min and would rise to 427°C in approximately 8 to 9.5 minutes. The approximate blackbody fire temperature varied from about 830 to 890°C, which satisfies the CGSB standard (816 – 927°C). This does not agree with the 13 minute heat-up time required by the CGSB standard.
- The fire conditions used were repeatable. In three practice tests (Tests P3, B2, and B3) that were designed to be identical, the initial heating rate varied by only 2°C/min (53, 51, and 53°C/min).
- Using only the steel jacket with an air gap provides thermal protection as it behaves as an effective radiation shield. In these tests, the jacket cuts the wall heating rate to approximately half of an unprotected wall (29°C/min vs. 53°C/min). The air gap between the wall and the jacket is necessary for this performance.
- Thermally protecting the tank wall with a steel jacket and a blanket of 13 mm ceramic insulation provided excellent thermal protection. In these tests, the fully protected tank reduces the wall heating rate to approximately one tenth of an unprotected wall (5°C/min vs. 53°C/min).
- A steel jacket with no insulation provided better protection if the jacket is not pressed or clamped to the primary wall.
- Larger defect sizes result in higher average and peak wall temperatures in the area of the defect.
- As defects get larger, the peak temperature in the defect area approaches the wall temperature the wall would reach with only a steel jacket present (i.e. no thermal insulation). The transition defect length appears to be about 40 cm. If the defect is smaller than 40 cm, the peak temperature is reduced by the surrounding protected material. If the defect is larger than 40 cm, there is little or no benefit from the surrounding material as far as peak temperature is concerned.
- Non-dimensional temperature profiles for the larger 61.0 cm and 40.6 cm defect are very similar.
- Crushed insulation under the steel jacket reduces the effectiveness of the thermal protection.

The results from this work are in good agreement with the thermal analysis reports of Birk and Cunningham (2000).

6.2 Recommendations

The following recommendations are made:

- From a heat transfer standpoint, a square thermal defect greater than 40 cm side length should be considered significant.
- Data from this study should be used to validate thermal models.
- Data from this study should be used to assist in the development of a field test manual that determines what level of thermal deficiency is acceptable from an enforcement standpoint. This guide should be used in conjunction with method highlighted by Birk and Cunningham (1999): *Thermographic Inspection of Tank-Car Insulation: Field Test Manual (TP13517E).*

6.3 Future Work

The results of this study should be compared with thermal model predictions of tank insulation defects.

This study was not able to address certain questions with high confidence. Further testing should be conducted to study:

- severe crushing of insulation
- hard contact between jacket and wall

References

Birk, A.M., Cunningham, M.H., *Thermographic Inspection of Tank-Car Thermal Insulation*, Transport Canada, Transportation Development Centre, TP 13203E, March 1998.

Birk, A.M., Cunningham, M.H., *Tank-Car Insulation Defect Assessment Criteria: Thermal Analysis of Defects*, Transport Canada, Transportation Development Centre, TP 13518E, October 1999.

Birk, A.M., Cunningham, M.H., *Thermographic Inspection of Tank-Car Insulation: Field Test Manual*, Transport Canada, Transportation Development Centre, TP 13517E, October 1999.

Birk, A.M., *Review of AFFTAC Thermal Model*, Transport Canada, Transportation Development Centre, TP 13539E, January 2000.

Birk, A.M., Cunningham, M.H., "Thermographic Inspection of Rail-Car Thermal Insulation", *Journal of Pressure Vessel Technology*, ASME, Vol 122, November 2000.

Birk, A.M., Cunningham, M.H., *On the Inspection and Assessment of Defects in Tank-Car Thermal Protection Systems*, International Symposium on Protection of Dangerous Goods Tanks & Cylinders in Fire, Transport Canada, Transport Dangerous Goods Directorate, October 22-23, 2002.

Drysdale, D., *An Introduction to Fire Dynamics*, 2nd Edition, John Wiley & Sons, 1998.

Johnson, M.R., *Tank Car Thermal Analysis -- Volume II Technical Documentation Report for Analysis Program, (AFFTAC)*, DOT/FRA/ORD-98/09B, 1998.

National Standard of Canada, *Construction and Maintenance of Tank Car Tanks and Selection and Use of Tank Car Tanks, Portable Tanks and Rail Cars for the Transportation of Dangerous Goods by Rail*, CAN/CGSB-43.147-2002, 2002.

Townsend, W., Anderson, C., Zook, J., Cowgill, G., *Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled with LPG Subjected to a Fire Environment*, US DOT Report No. FRA-OR&D 75-32, Washington, 1974.

Appendix A. Thermocouple Error Calculations

The following computer model predicts the thermocouple error in various conditions. It allows the user to vary:

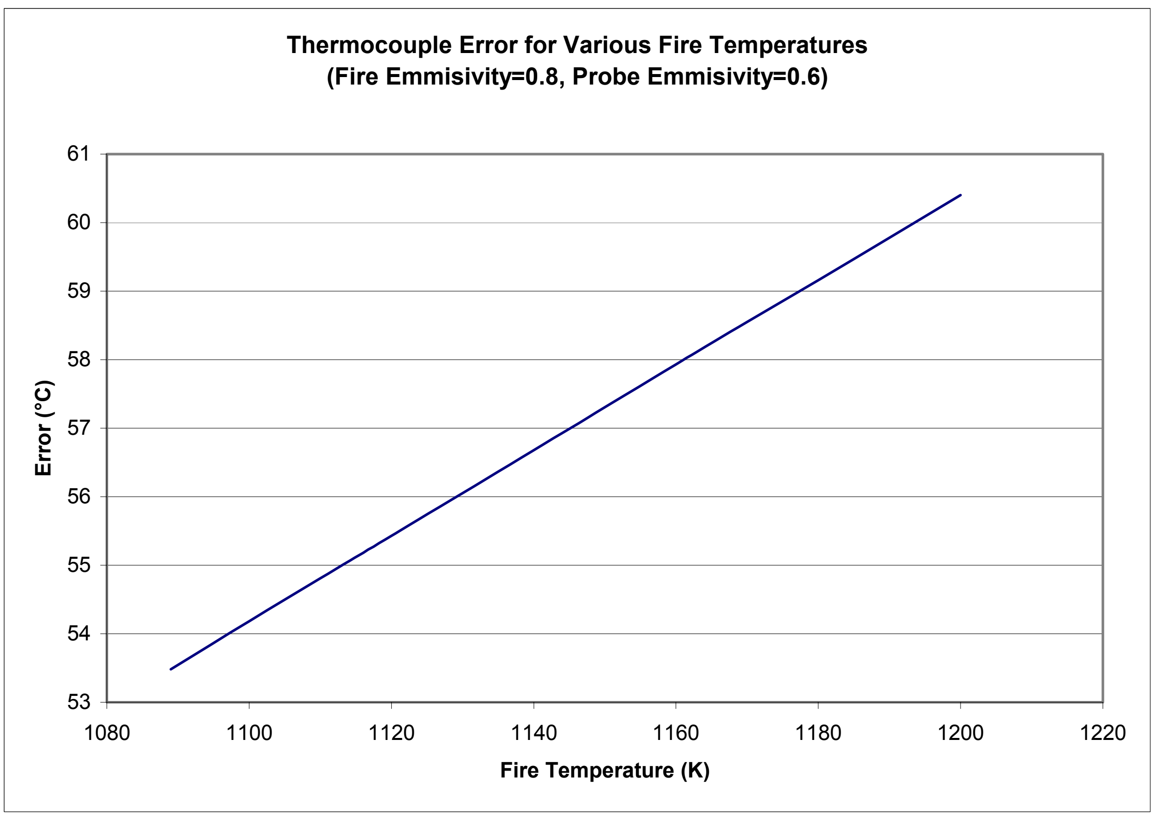
- Fire emmisivity
- Fire temperature
- Thermocouple emmisivity
- Ambient temperature
- Convective heat transfer coefficient

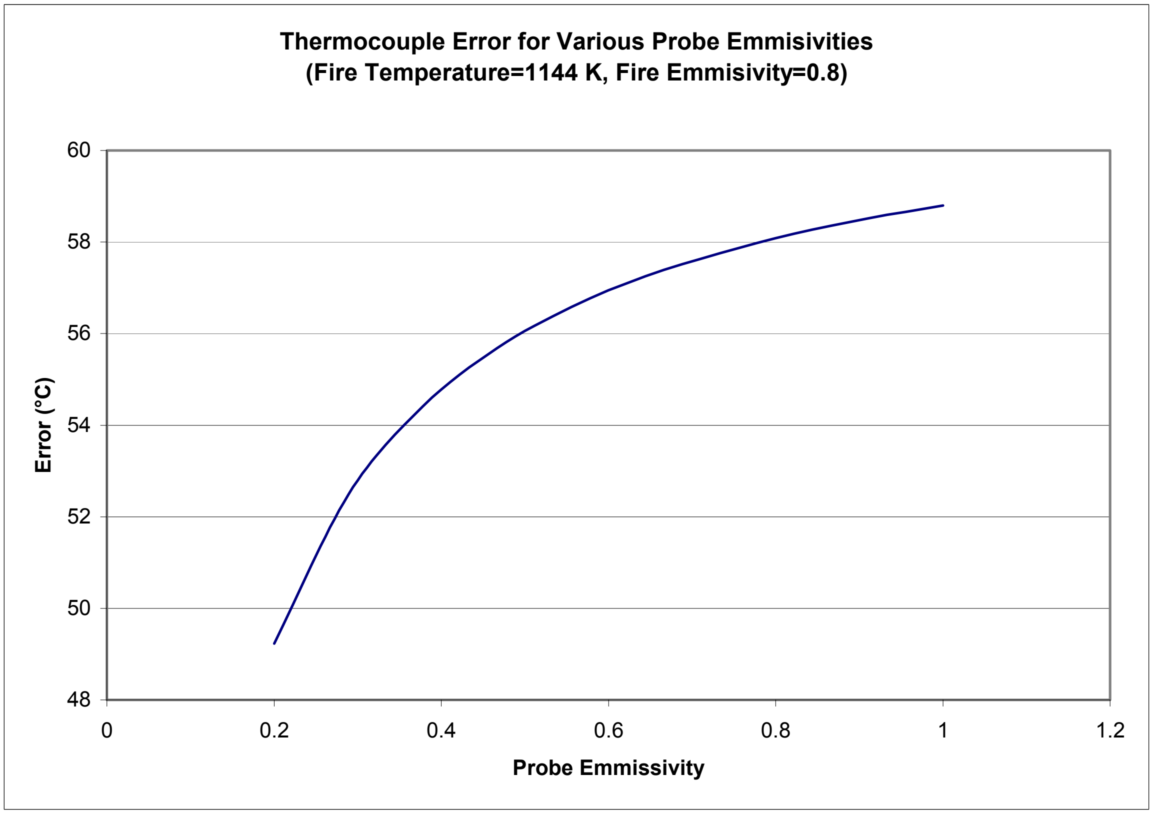
From the results in the Table and Figures below, it is estimated that the thermocouple radiation error is between 25 and 50°C.

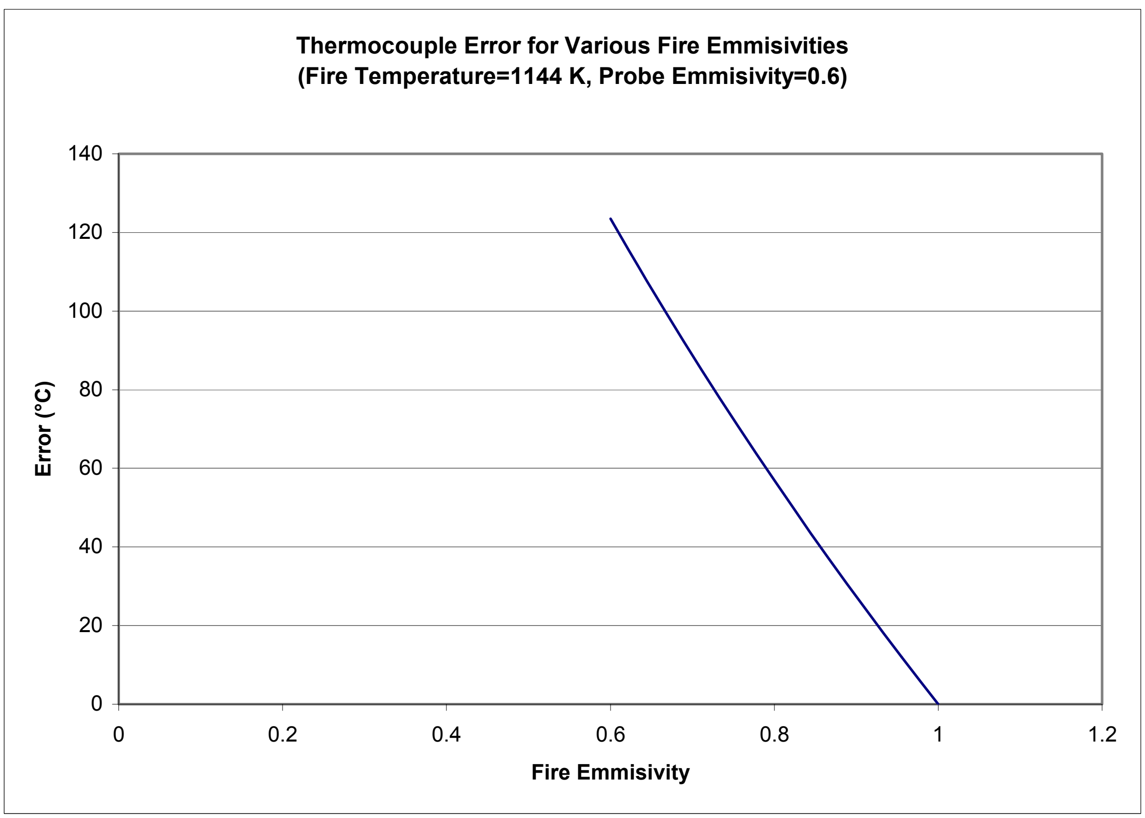
```
Thermocouple in Fire.EES
{Thermocouple in Fire
Jonathan VanderSteen
November 18, 2002}

{Inputs}

emm_f=0.8               {Emmissivty of the Fire}
T_f=871+273             {Temperature of the Fire}

emm_p=0.6               {Emmisivity of the Probe}
{T_p}                   {Temperature of the Probe}

T_amb=273               {Temperature of the Environment}

h=15                    {Convective Heat Transfer Coefficient}


{Program}

sigma=5.67E-8

Q_in = h*(T_f-T_p) + emm_p*(1-emm_f)*sigma*T_amb^4 + emm_p*emm_f*sigma*T_f^4

Q_out = emm_p*sigma*T_p^4

Q_in=Q_out

deltaT=T_f-T_p
```

Fire Emmisivity	Probe Emmisivity	Fire Temperature (K)	Probe Temperature (K)	Error (°C)
0.8	0.2	1144	1095	49.2
0.8	0.6	1144	1087	56.9
0.8	1.0	1144	1085	58.8
0.8	0.6	1200	1140	60.4
0.8	0.6	1089	1036	53.5
1.0	0.6	1144	1144	0.0
1.0	0.2	1144	1144	0.0
0.9	0.2	1089	1067	22.1
0.9	0.6	1144	1117	27.5
0.9	0.6	1200	1171	29.1

Thermocouple Radiation Error for Various Inputs




Thermocouple Error for Various Probe Emmisivities
(Fire Temperature=1144 K, Fire Emmisivity=0.8)
Error (°C)
60
58
56
54
52
50
48
0
0.2
0.4
0.6
0.8
1
1.2
Probe Emmissivity


Thermocouple Error for Various Fire Emmisivities
(Fire Temperature=1144 K, Probe Emmisivity=0.6)
Error (°C)
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
Fire Emmisivity

Appendix B. Field Check Lists and Procedure Sheet

- Test Procedure
- Trial Testing Data Sheet
- Testing Procedure Checklist

Test Procedure:

1. Field/Rig Set up

- The tank, burners stand, and array of 9 burners were located.
- The burner mixing tubes were plugged with insulation.
- The fire extinguisher was positioned in a convenient location.
- Depending on the specific test, spacers, clamp, insulation, insulation defect, and jacket were properly set up.
- The fire thermocouples were positioned between the jacket and the burners.
- The wall and fire thermocouples were plugged into the data acquisition system.
- The infrared thermometer gun was positioned and properly aimed at the location right beside the wall thermocouple. Emissivity was set at 0.95 for the back wall.
- The infrared camera was positioned and wired into the data acquisition computer.
- The IR camera was turned on to give enough time for the camera's internal cooler to ensure proper operating temperature at the time of testing.

2. Thermocouple Data Acquisition

- The data acquisition box and computer were powered up.
- The labview data acquisition program (DAQII.vi) was loaded up.
- The proper file name and directory (depending on test number) was programmed into the software.
- The program was set up to start outputting thermocouple measurements to the screen.

3. IR Data Acquisition

- The data acquisition laptop computer was powered up.
- The TheramCAM software was loaded up.
- The software was connected to the camera.
- The object parameters, such as ambient temperature and wall emissivity (0.95) were set in software.
- The proper temperature scale and range was set up. (The camera always started in Range 1 and moved through all the ranges up to Range 4 during the tests.)
- The recording conditions, such as file names and sampling frequency, was stored in the software.
- The IR Camera was properly focused.
- The IR Camera was properly located.

4. Final Check Before Test.

- The notebook, pen, igniter, stopwatch, and digital camera were placed in a convenient location.
- The ambient and initial temperatures were recorded.
- The thermocouple and infrared data acquisition systems were triggered to start recording.
- Propane was ignited manually and all the valves were opened.

5. During Test

- The temperature measured with the IR gun was recorded in the notebook once every 30 seconds.
- The pressure gauge was monitored and the pressure regulator was adjusted accordingly.
- The pressure reading was recorded.
- Digital pictures were taken of the flame from three different locations around the apparatus.
- The IR camera was switched from Range 1 to Range 2 before the maximum temperature reached 50°C.
- The IR camera was switched from Range 2 to Range 3 before the maximum temperature reached 150°C.
- The IR camera was switched from Range 3 to Range 4 before the maximum temperature reached 320°C.
- The flame filter was placed on the IR camera before the maximum temperature reached 450°C.
- The IR thermometer gun was removed from the tripod and used to measure the fire temperature. The set emissivity was changed to 1.0, assuming a black fire.
- The test was stopped after approximately 25 minutes and the temperature rise rate started to slow down.

Trial Testing Data Sheet

Test: ______________________

Date: ______________________

Fuel Pressure: [   ] psi

Number of Burners: [   ] -->

Premix Tube
Blocked?
Yes / No

Burner Array

time	Temperature (°C)	
(min:sec)	Wall	Fire
0		

Ignition Time:

Valve Shut Off Time:

Time to 427°C:

Comments:

Testing Procedure – Burner Tests
Test Number/Date:________________________

Rig/Set Up

- □ Remove Tarp
- □ Check Burner Locations
- □ Check Insulation plugging mixing tube
- □ Bring out fire extinguisher
- □ Set up spaces, clamp, insulation, jacket
- □ Bring out thermocouple tripod
- □ Bring out tripod insulation
- □ Hook up Thermocouples
- □ Bring out IR gun tripod
- □ Set up and aim IR gun
- □ Bring out IR camera tripod
- □ Connect all camera wires
- □ Turn camera on

Thermocouple Data Acquisition

- □ Power to Data Acquisition Box
- □ Power up desk top
- □ Load up DAQ program
- □ Set file name and directory
- □ Start measurements

IR Data Acquisition

- □ Power up laptop
- □ Load up ThermaCAM software and open session
- □ Connect to Camera
- □ Get camera image
- □ Object Parameter settings (emissivity, temp, etc)
- □ Set scale (0-600), Range (1), and Lock
- □ Recording Conditions and Saving Files

IR Camera

- □ Put Camera in Range 1
- □ Focus Camera
- □ Check settings such as emmissivity on Camera
- □ Check and Calibrate Camera location

Final Check before test

- □ Get Binder, Pen, Ignitor, and Stopwatch Set up
- □ Call Assistant/Digital Camera
- □ Start Thermocouple DAQ
- □ Start IR DAQ
- □ Record Initial Temperature
- □ Ignite Propane

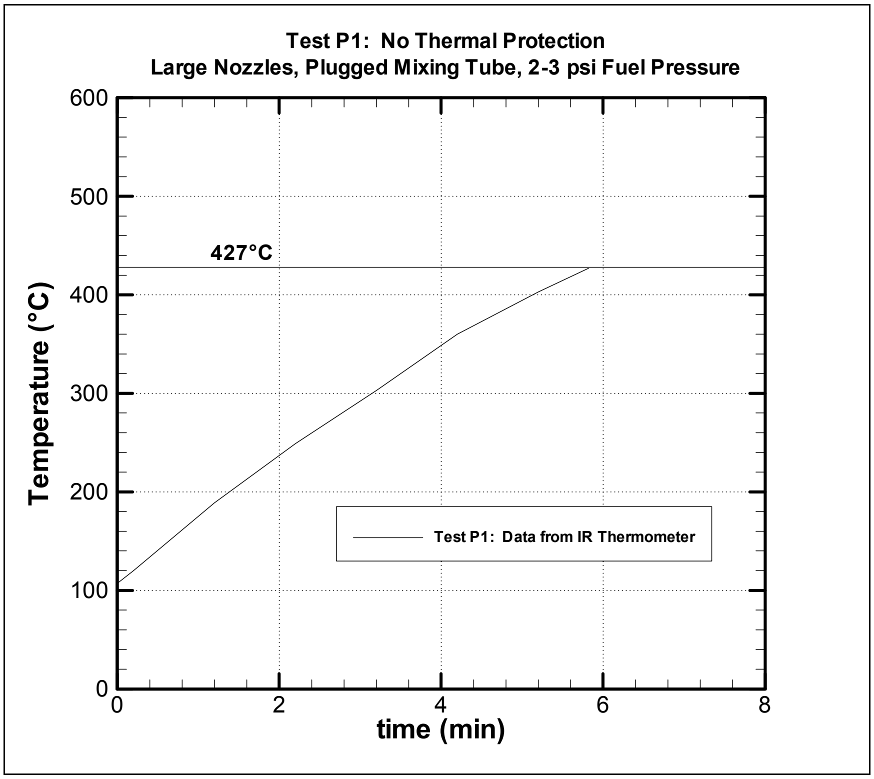
Comments:

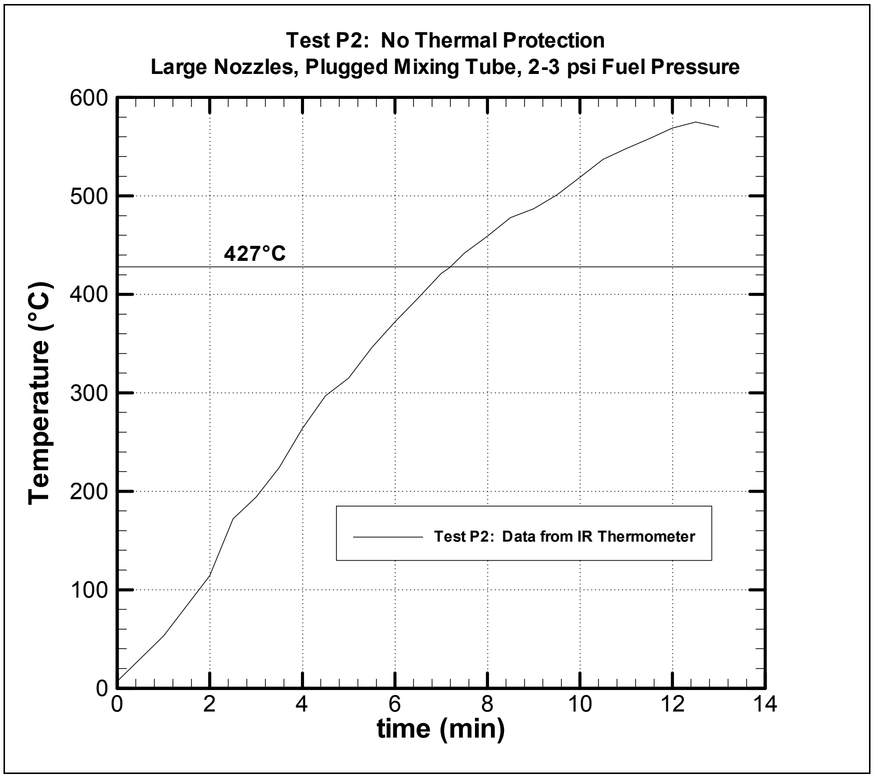
-Start in Range 1
-1→2 at 50°C
-2→3 at 150°C
-3→4 at 320°C
-4→lens at 450°C

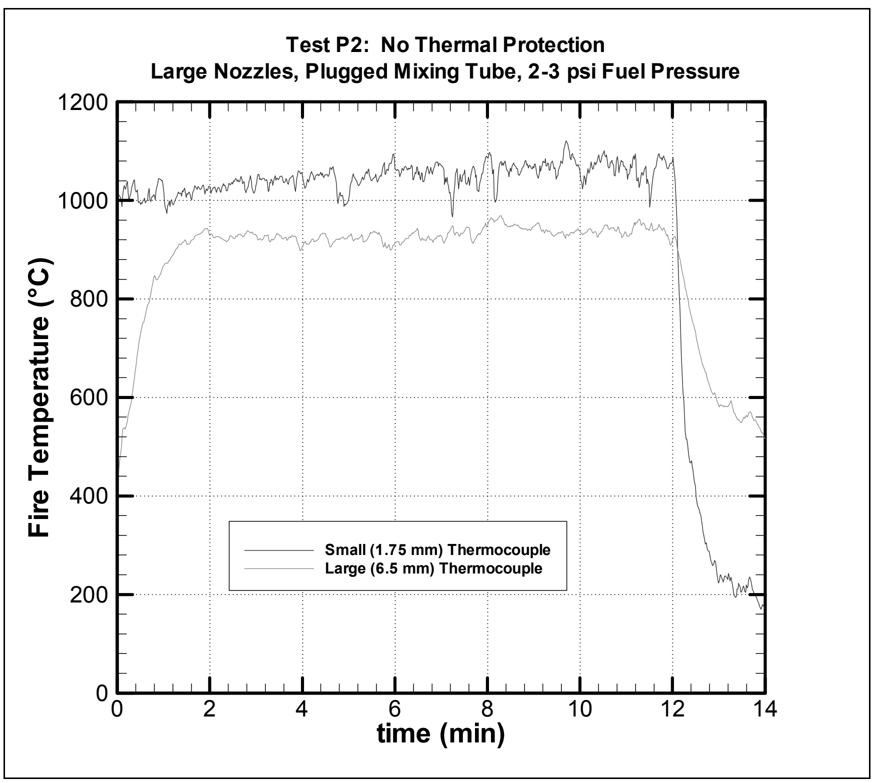
emm = ___________

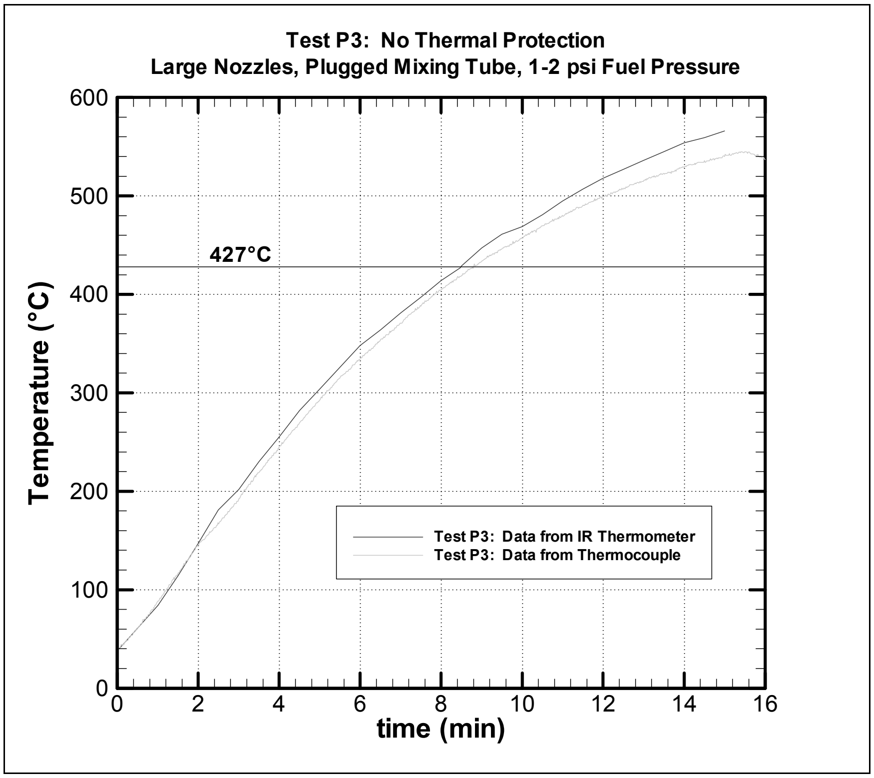
amb Temp = _______

Appendix C. Additional Data Plots




Test P2: No Thermal Protection
Large Nozzles, Plugged Mixing Tube, 2-3 psi Fuel Pressure
427°C
Test P2: Data from IR Thermometer
Temperature (°C)
time (min)
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14


Test P2: No Thermal Protection
Large Nozzles, Plugged Mixing Tube, 2-3 psi Fuel Pressure
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
Fire Temperature (°C)
time (min)
0
200
400
600
800
1000
1200
0
2
4
6
8
10
12
14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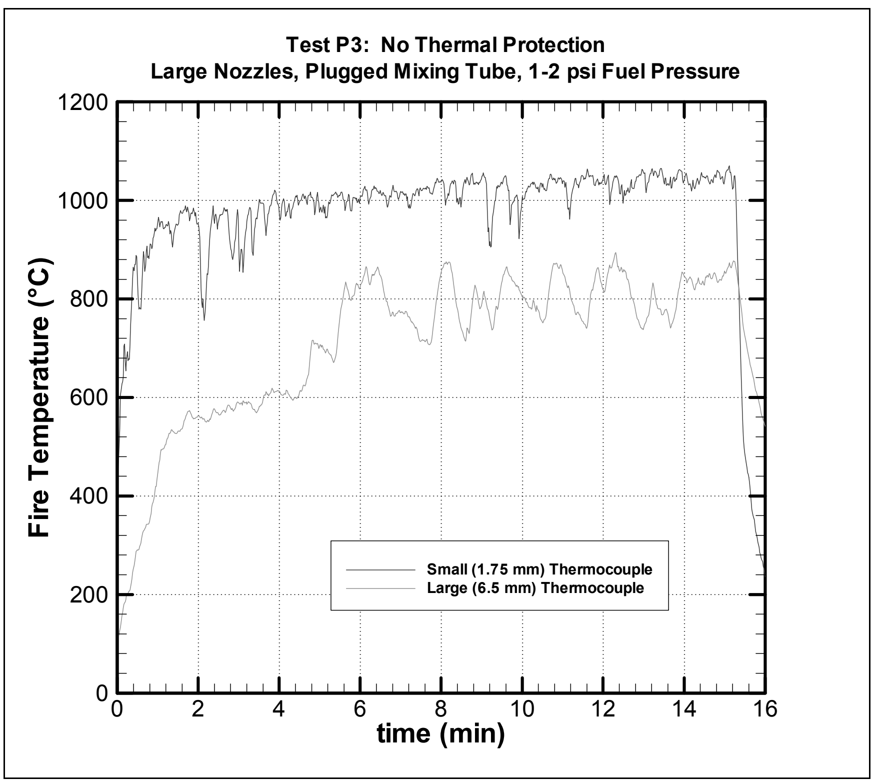
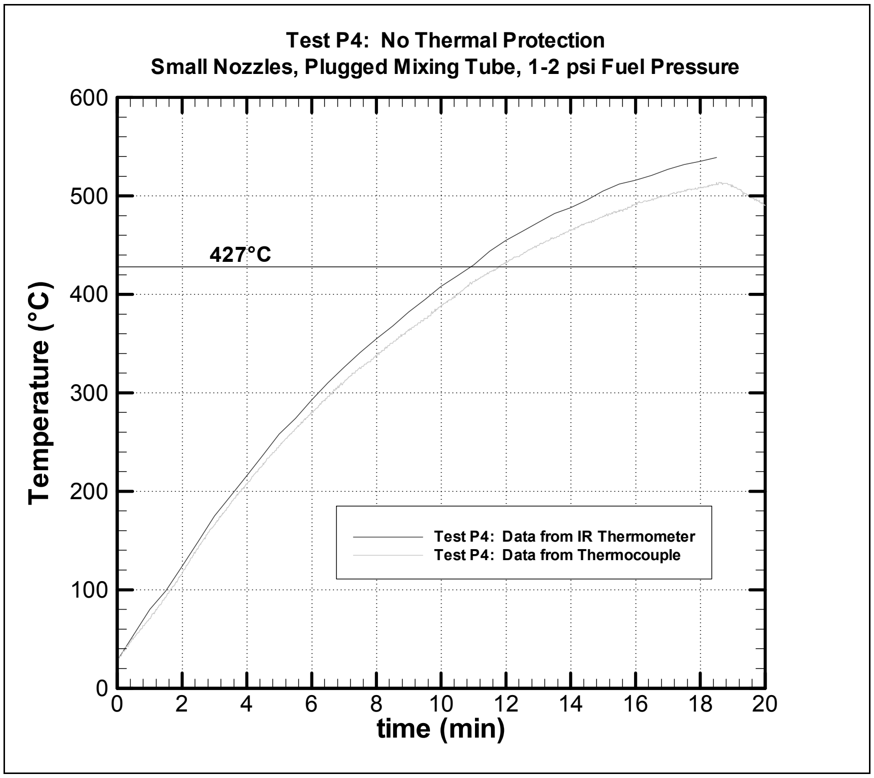
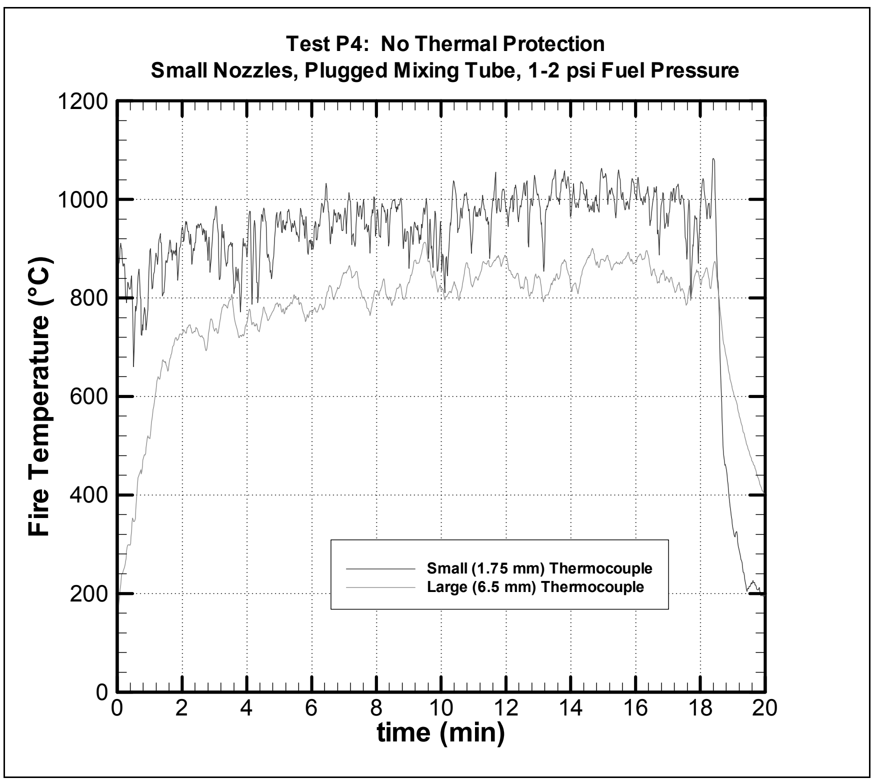
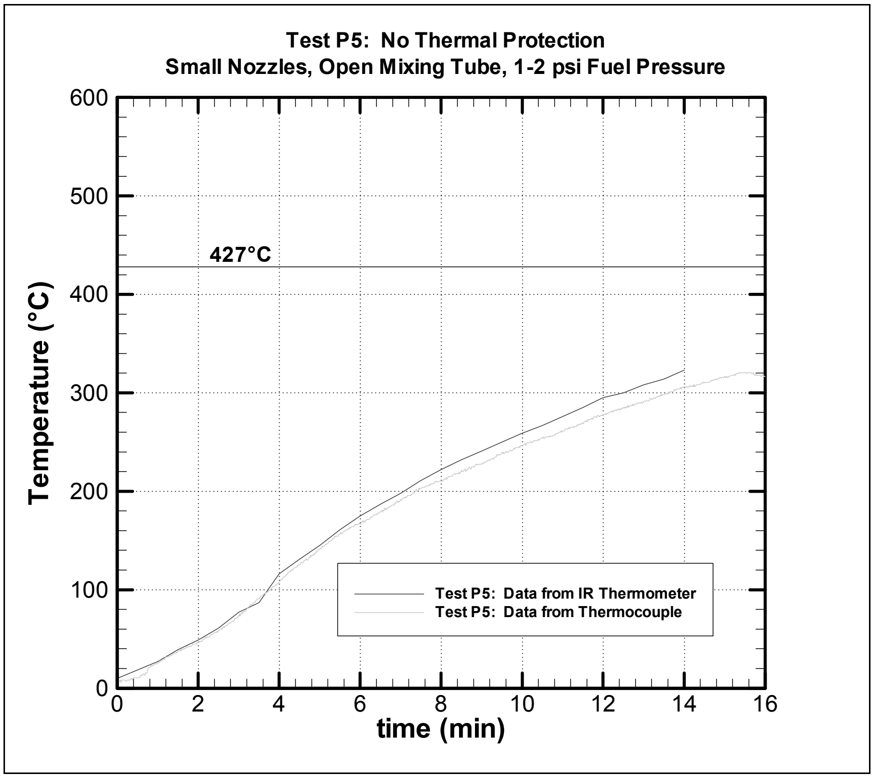
Large Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
427°C
Temperature (°C)
time (min)
Test P3: Data from IR Thermometer
Test P3: Data from Thermocouple
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16


Test P3: No Thermal Protection
Large Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
2
4
6
8
10
12
14
16


Test P4: No Thermal Protection
Small Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
Temperature (°C)
time (min)
427°C
Test P4: Data from IR Thermometer
Test P4: Data from Thermocouple
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16
18
20


Test P4: No Thermal Protection
Small Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
2
4
6
8
10
12
14
16
18
20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Small Nozzles, Open Mixing Tube, 1-2 psi Fuel Pressure
427°C
Temperature (°C)
time (min)
Test P5: Data from IR Thermometer
Test P5: Data from Thermocouple
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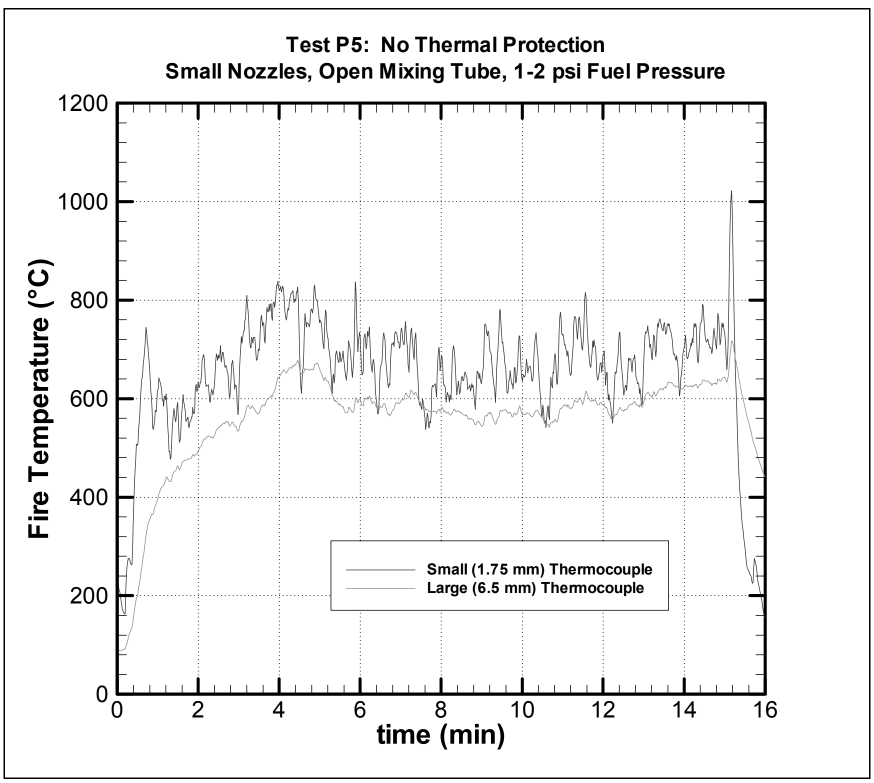
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16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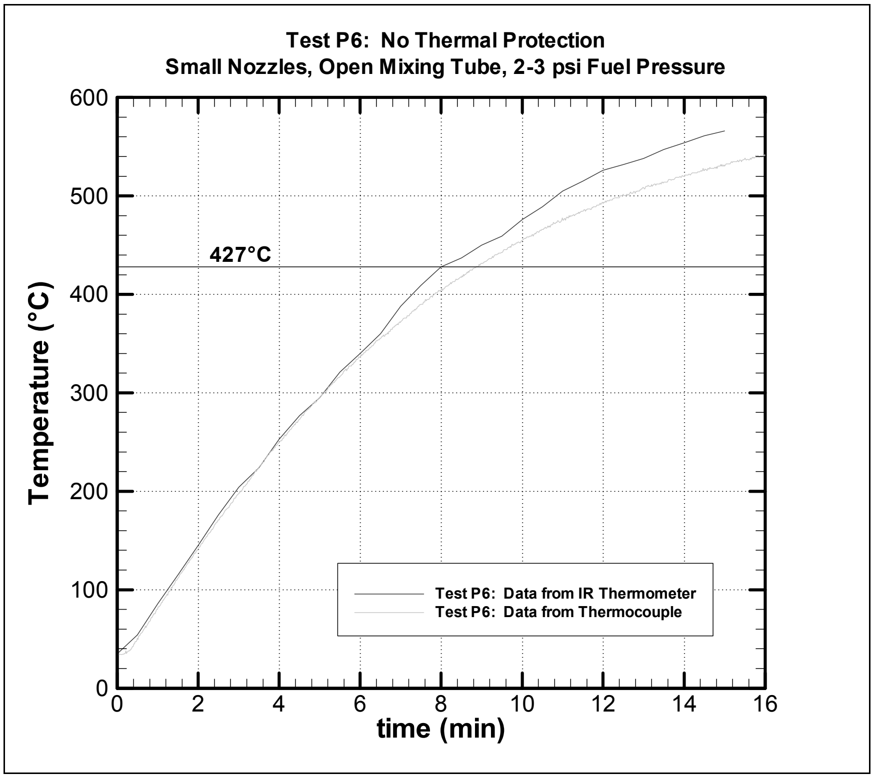
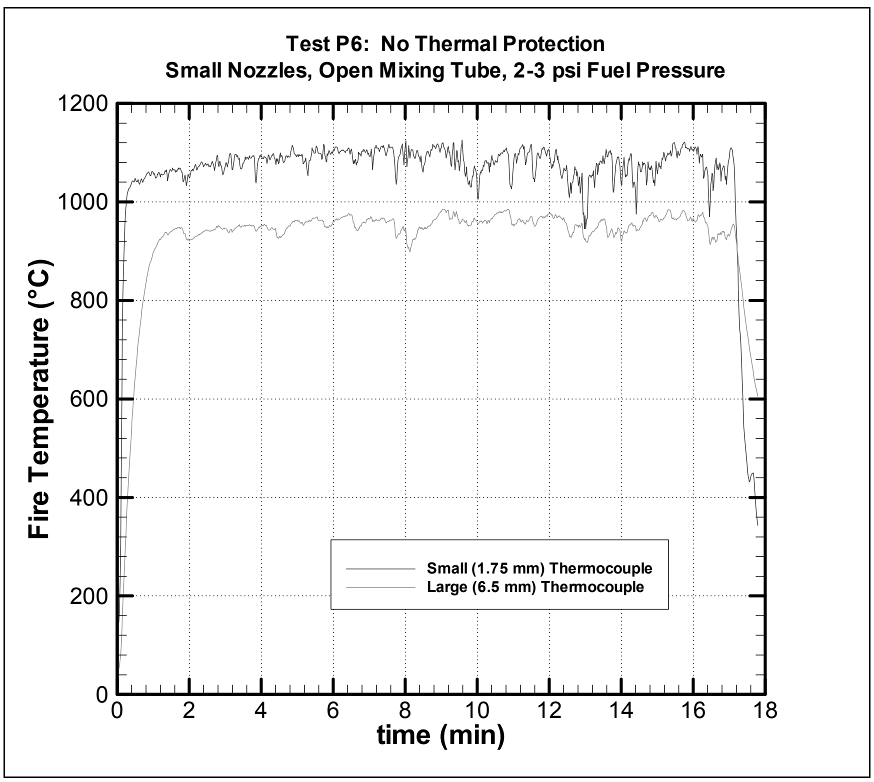
Small Nozzles, Open Mixing Tube, 1-2 psi Fuel Pressure
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
2
4
6
8
10
12
14
16


Test P6: No Thermal Protection
Small Nozzles, Open Mixing Tube, 2-3 psi Fuel Pressure
Temperature (°C)
time (min)
427°C
Test P6: Data from IR Thermometer
Test P6: Data from Thermocouple
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16


Test P6: No Thermal Protection
Small Nozzles, Open Mixing Tube, 2-3 psi Fuel Pressure
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
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1200
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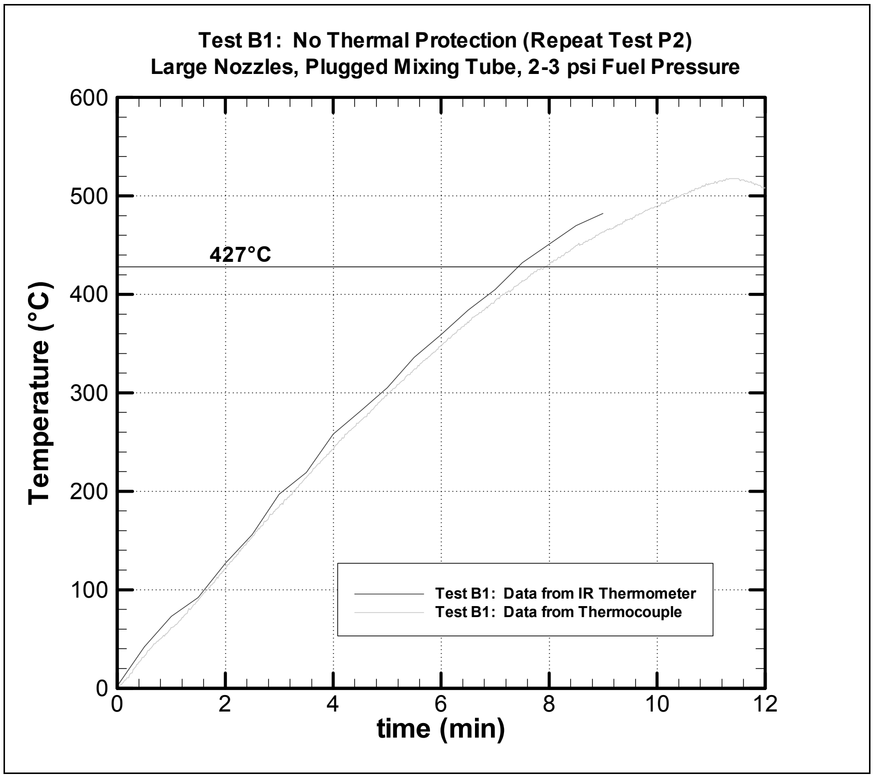
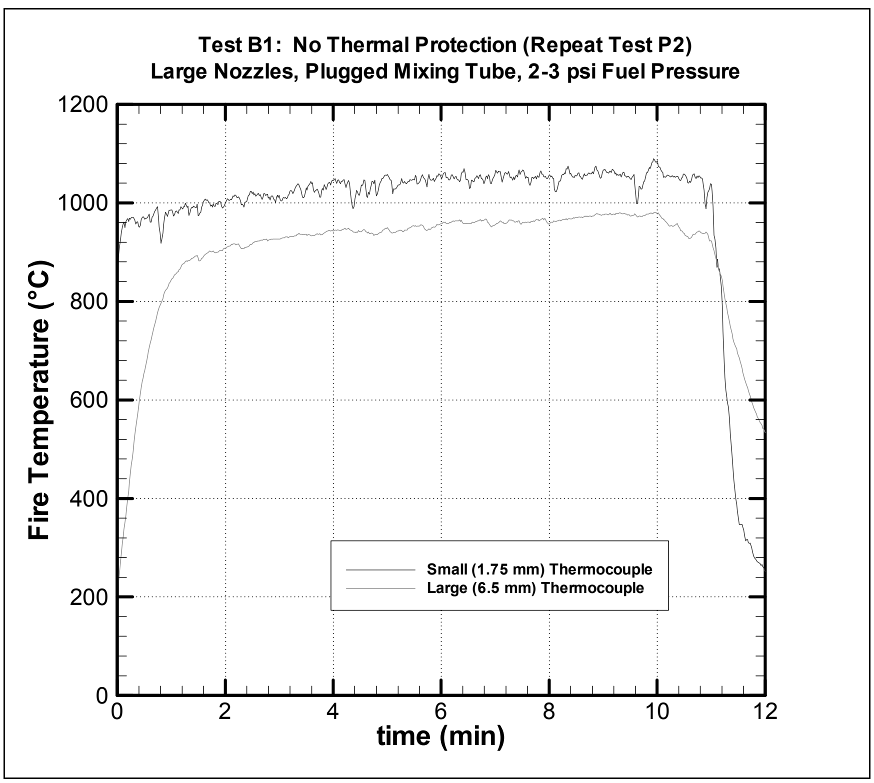
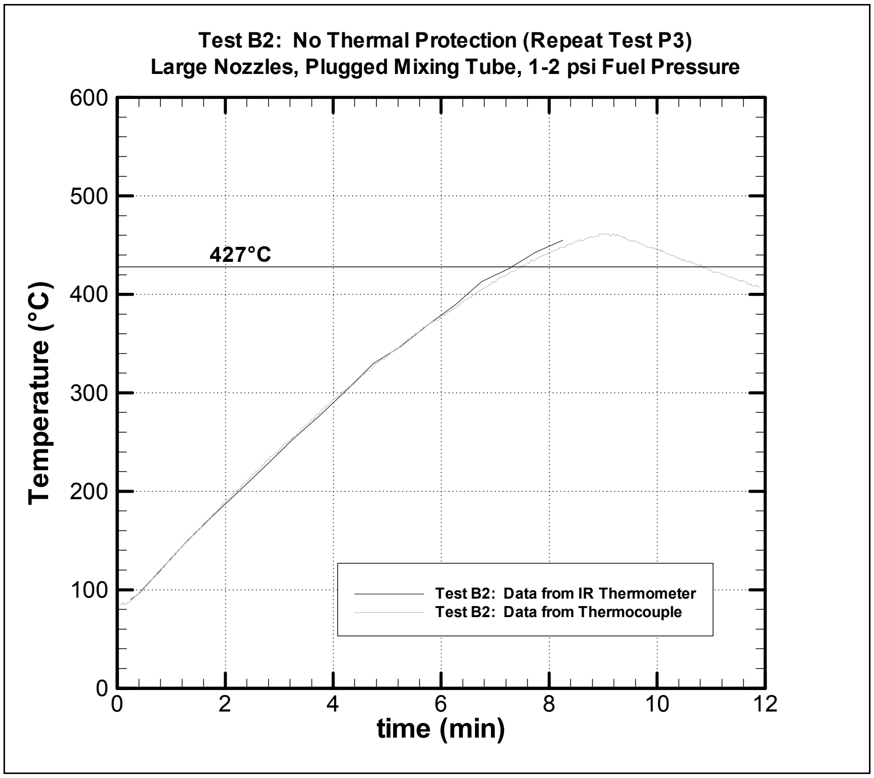
10
12
14
16
18


Test B1: No Thermal Protection (Repeat Test P2)
Large Nozzles, Plugged Mixing Tube, 2-3 psi Fuel Pressure
427°C
Temperature (°C)
time (min)
0
100
200
300
400
500
600
0
2
4
6
8
10
12
Test B1: Data from IR Thermometer
Test B1: Data from Thermocouple


Test B1: No Thermal Protection (Repeat Test P2)
Large Nozzles, Plugged Mixing Tube, 2-3 psi Fuel Pressure
Fire Temperature (°C)
time (min)
0
200
400
600
800
1000
1200
0
2
4
6
8
10
12
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple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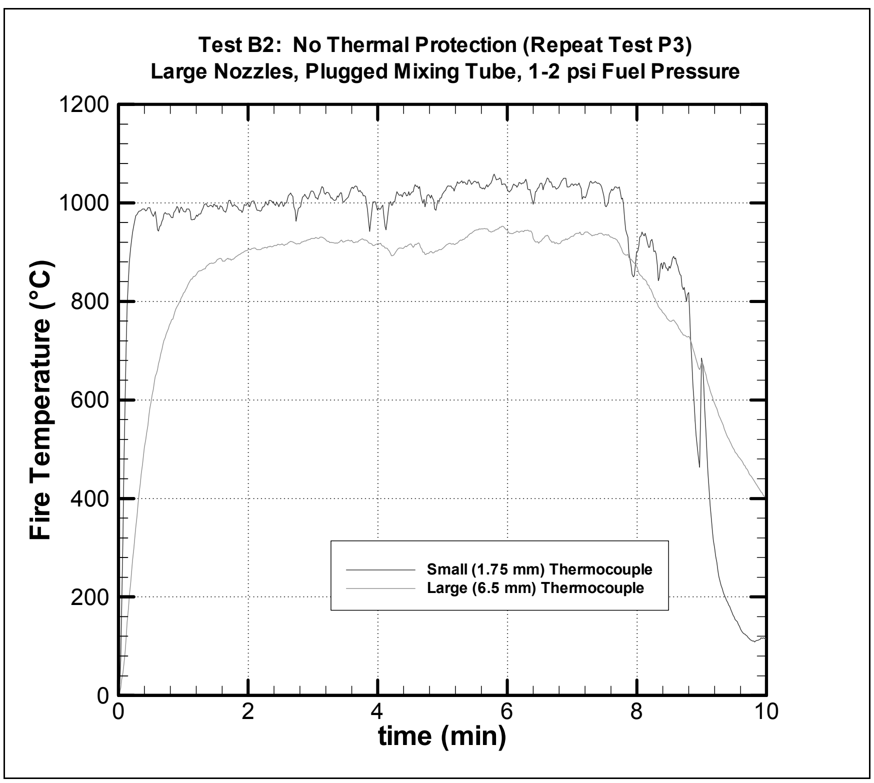
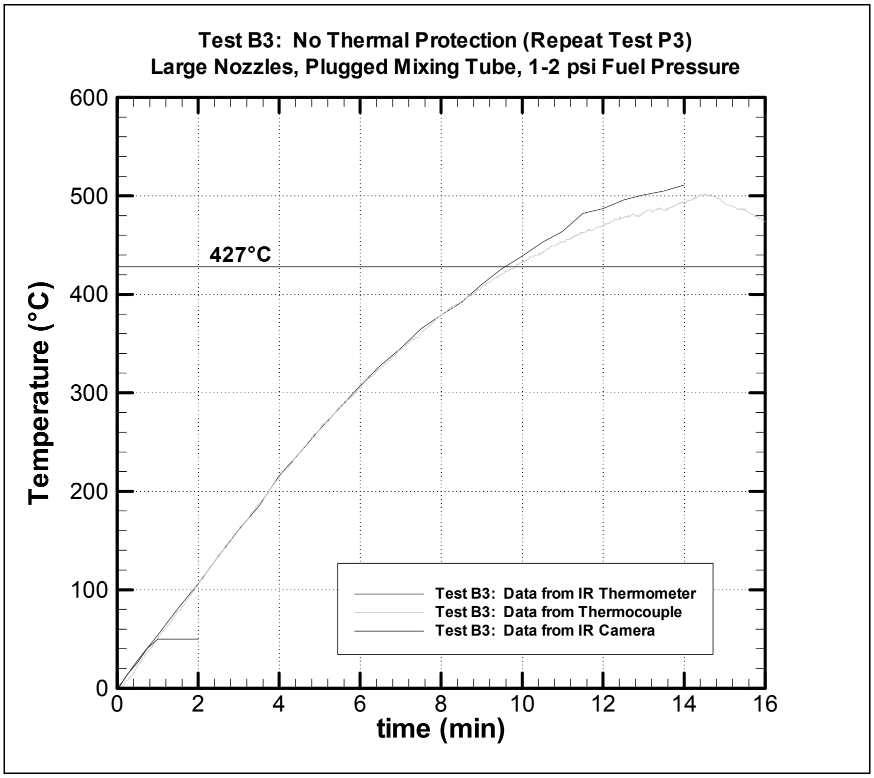
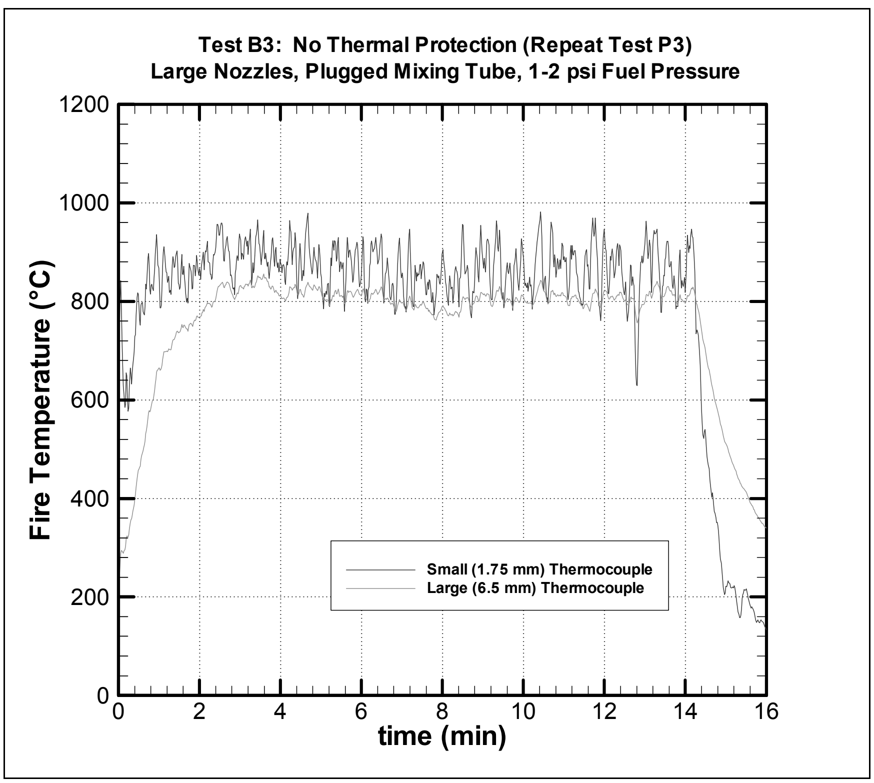
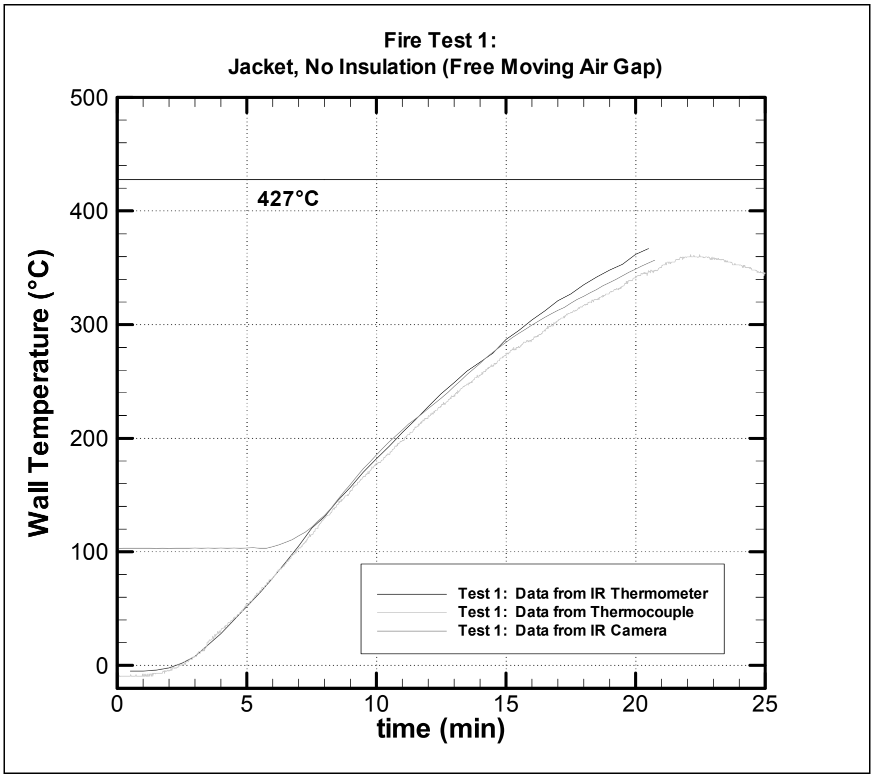
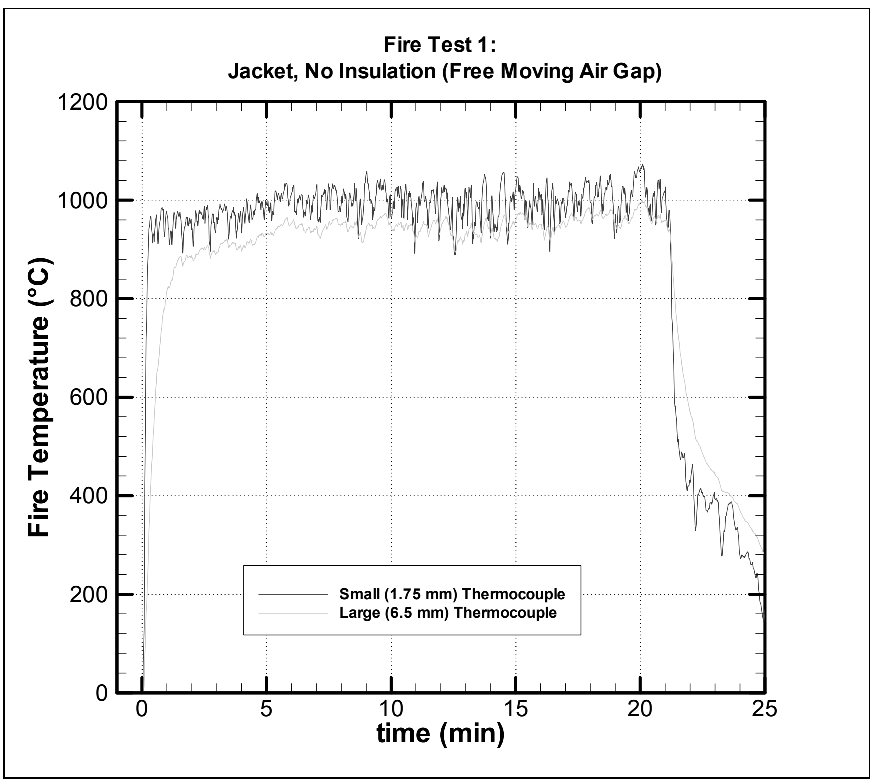
Large Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
427°C
Temperature (°C)
time (min)
Test B2: Data from IR Thermometer
Test B2: Data from Thermocouple
0
100
200
300
400
500
600
0
2
4
6
8
10
12

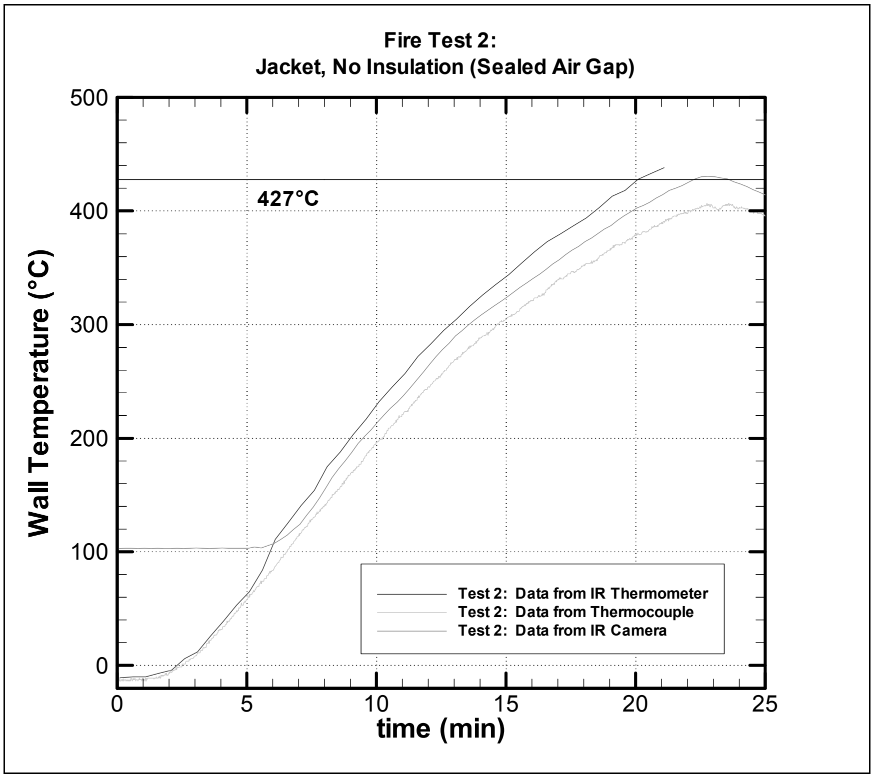

Test B2: No Thermal Protection (Repeat Test P3)
Large Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
2
4
6
8
10

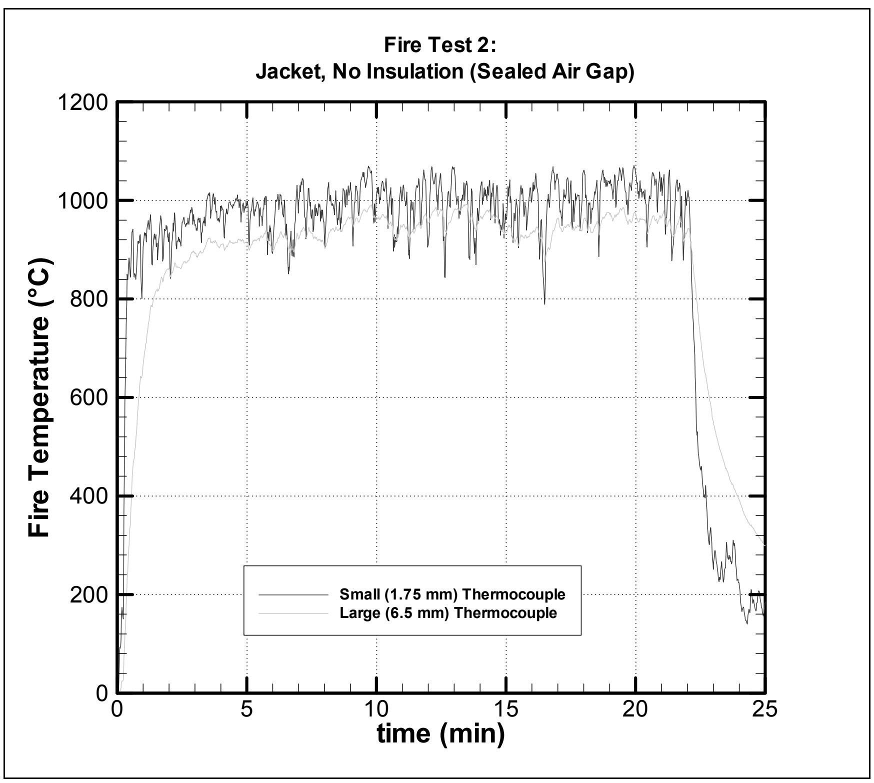

Test B3: No Thermal Protection (Repeat Test P3)
Large Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
Temperature (°C)
time (min)
427°C
Test B3: Data from IR Thermometer
Test B3: Data from Thermocouple
Test B3: Data from IR Camera
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16

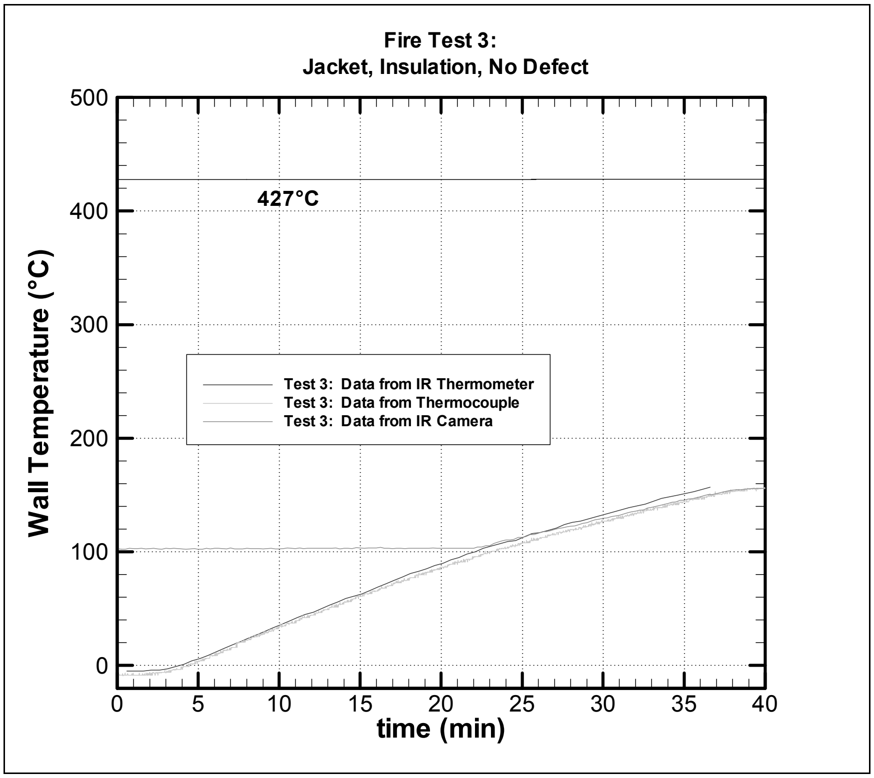

Test B3: No Thermal Protection (Repeat Test P3)
Large Nozzles, Plugged Mixing Tube, 1-2 psi Fuel Pressure
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
2
4
6
8
10
12
14
16


Fire Test 1:
Jacket, No Insulation (Free Moving Air Gap)
Wall Temperature (°C)
time (min)
427°C
Test 1: Data from IR Thermometer
Test 1: Data from Thermocouple
Test 1: Data from IR Camera
0
100
200
300
400
500
0
5
10
15
20
25

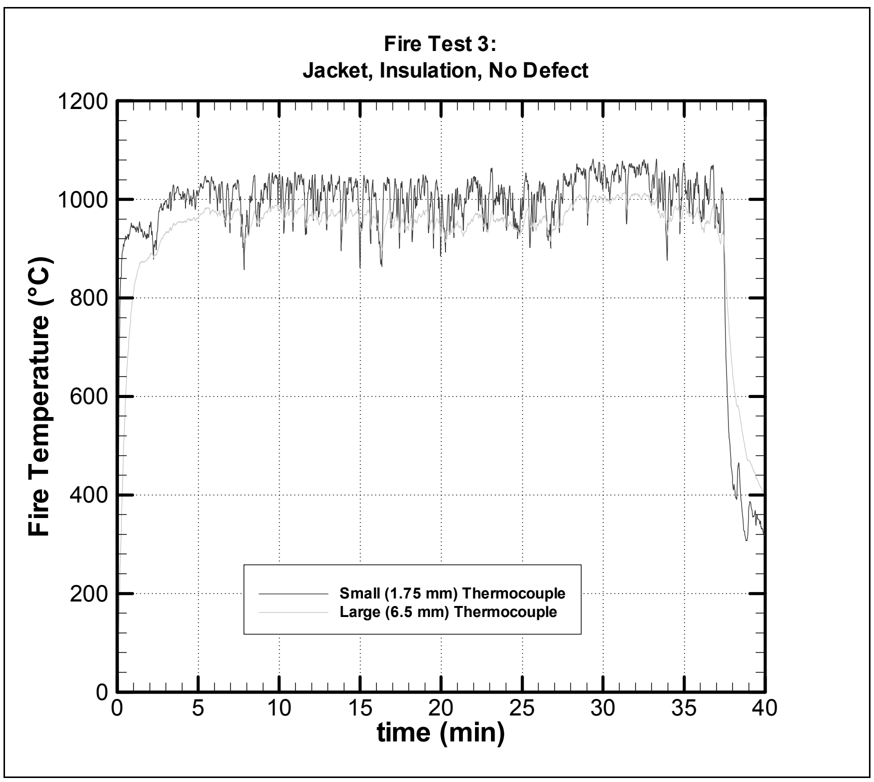

Fire Test 1:
Jacket, No Insulation (Free Moving Air Gap)
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
5
10
15
20
25


Fire Test 2:
Jacket, No Insulation (Sealed Air Gap)
Wall Temperature (°C)
time (min)
427°C
0
100
200
300
400
500
0
5
10
15
20
25
Test 2: Data from IR Thermometer
Test 2: Data from Thermocouple
Test 2: Data from IR Camera

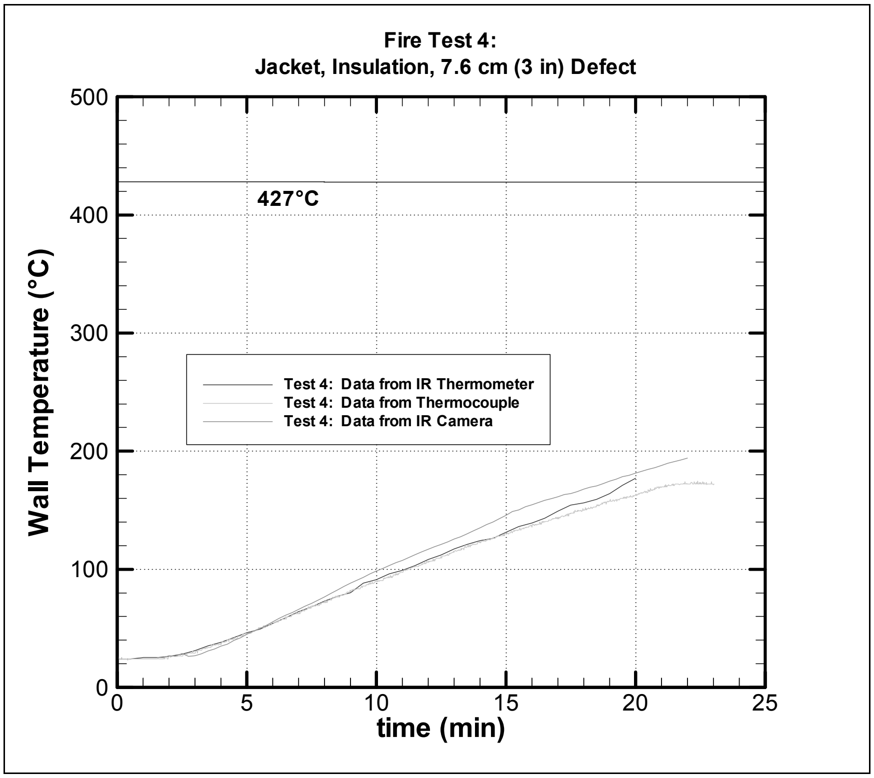

Fire Test 2:
Jacket, No Insulation (Sealed Air Gap)
Fire Temperature (°C)
time (min)
0
200
400
600
800
1000
1200
0
5
10
15
20
25
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple

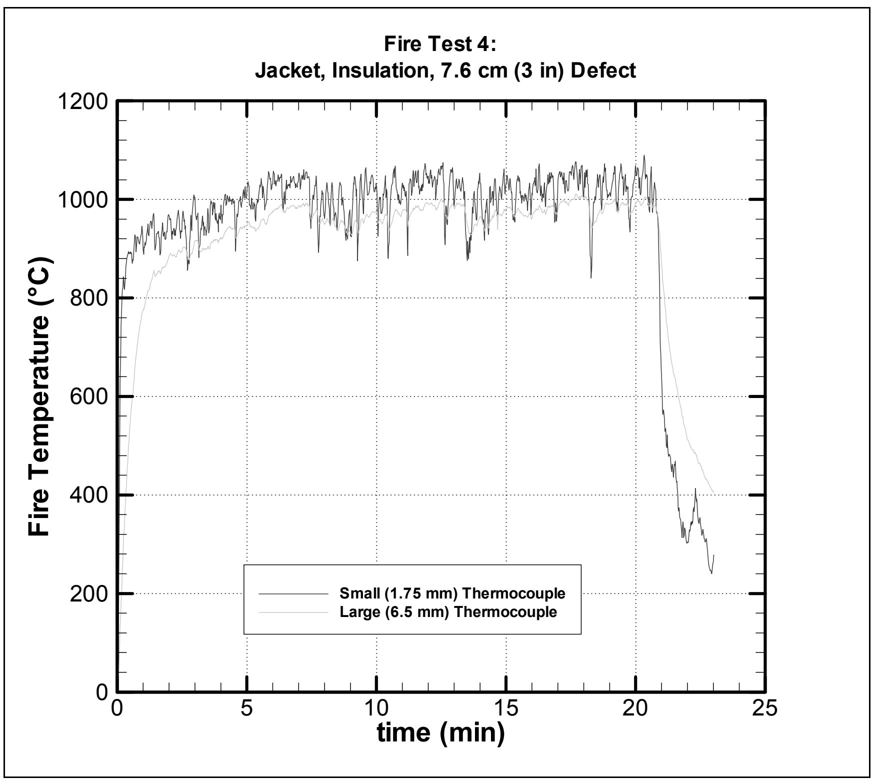


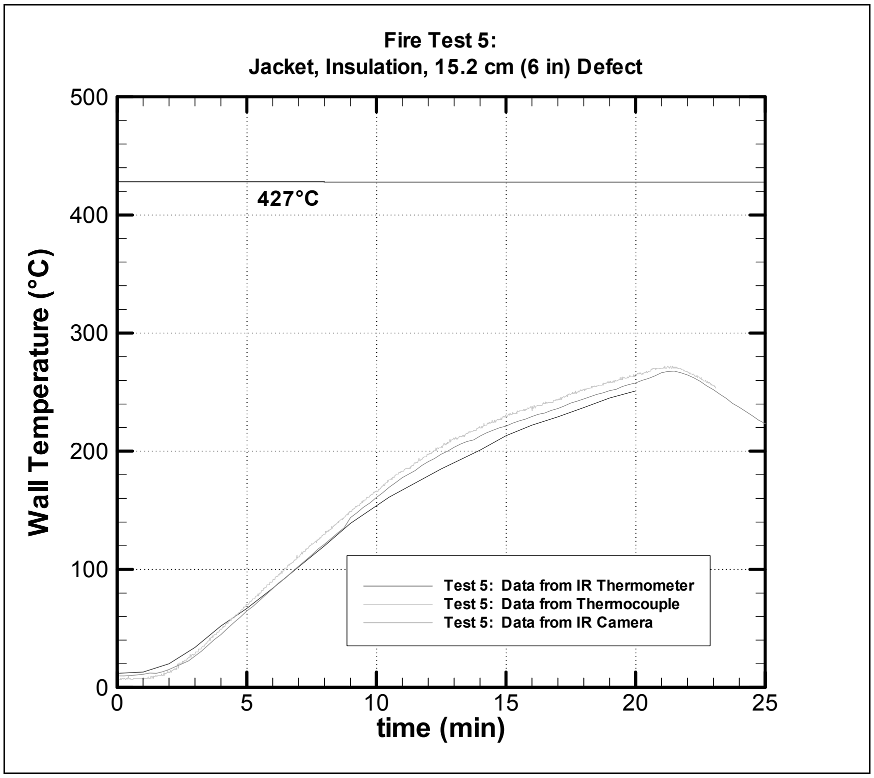
Fire Test 3:
Jacket, Insulation, No Defect
Wall Temperature (°C)
time (min)
427°C
Test 3: Data from IR Thermometer
Test 3: Data from Thermocouple
Test 3: Data from IR Camera
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40



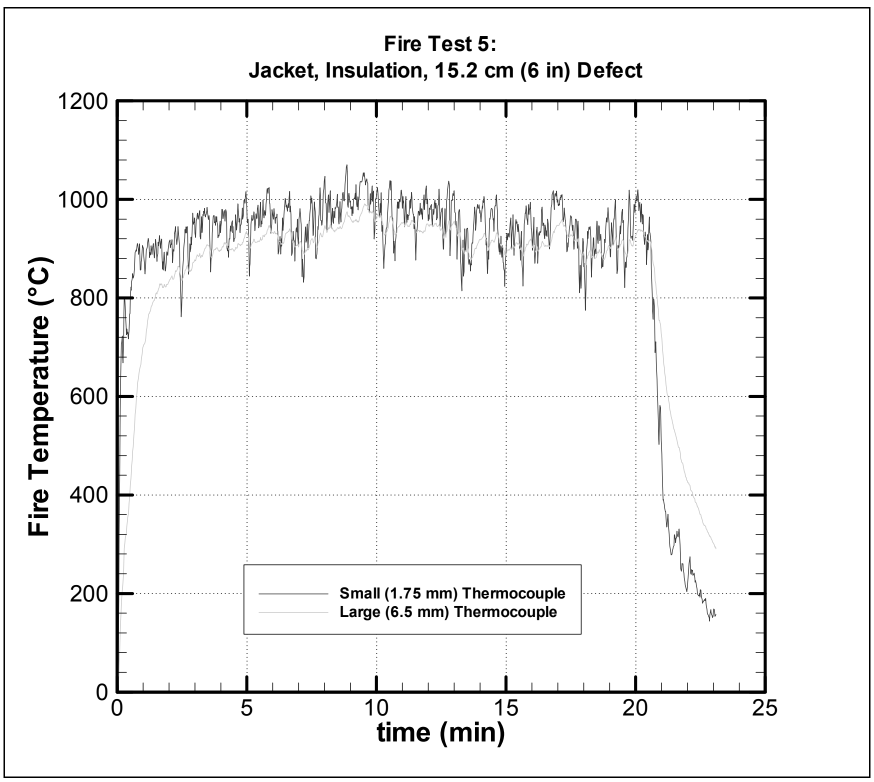
Fire Test 3:
Jacket, Insulation, No Defect
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
40


Fire Test 4:
Jacket, Insulation, 7.6 cm (3 in) Defect
427°C
Test 4: Data from IR Thermometer
Test 4: Data from Thermocouple
Test 4: Data from IR Camera
Wall Temperature (°C)
time (min)
0
100
200
300
400
500
0
5
10
15
20
25

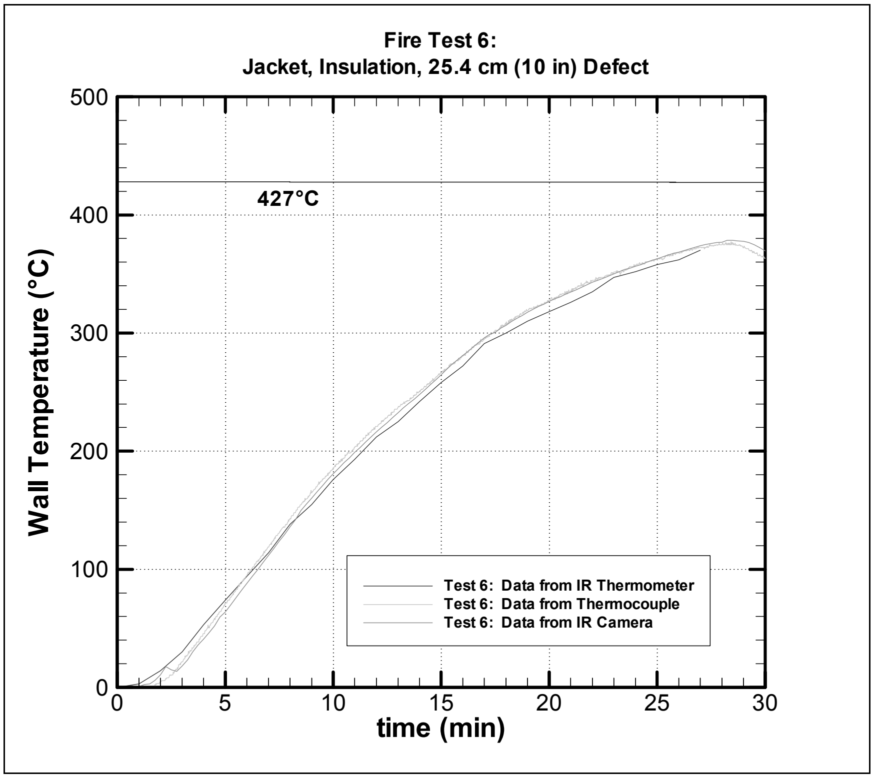

Fire Test 4:
Jacket, Insulation, 7.6 cm (3 in) Defect
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
Fire Temperature (°C)
time (min)
0
200
400
600
800
1000
1200
0
5
10
15
20
25

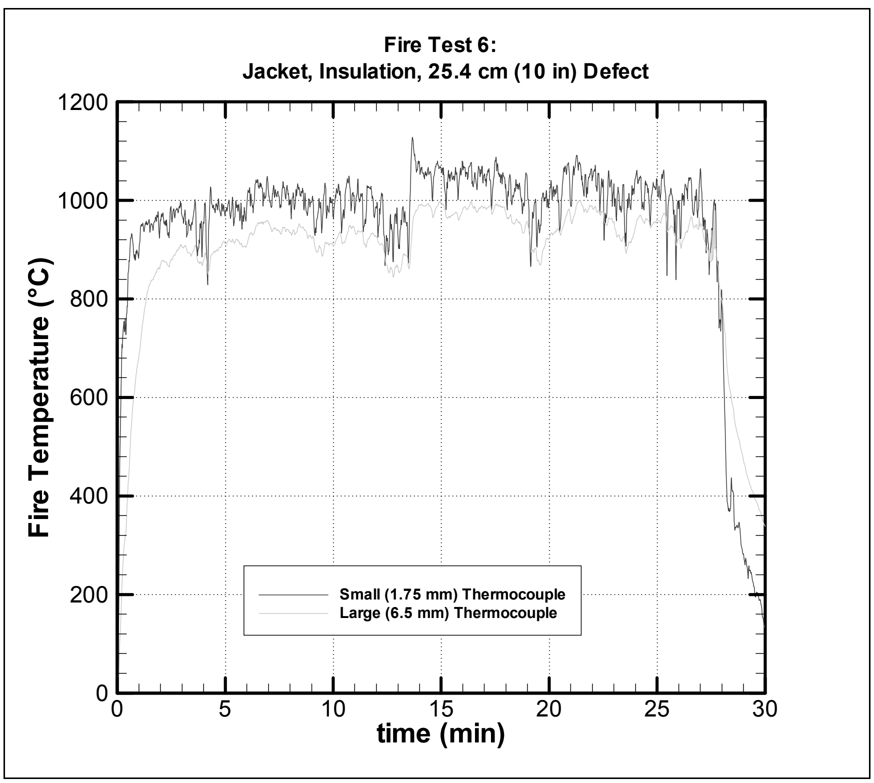


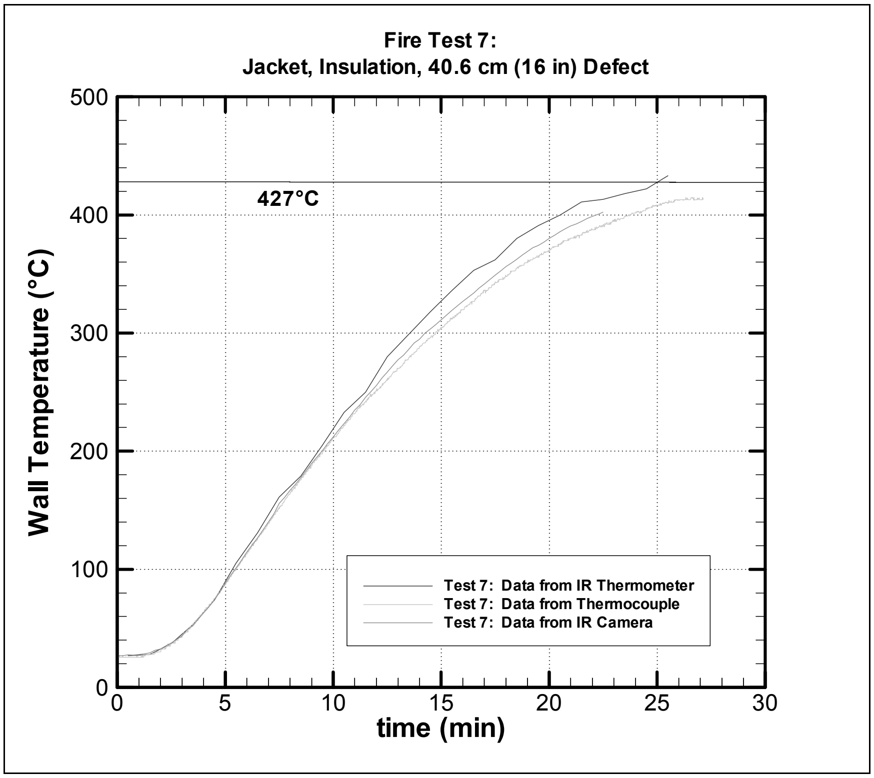
Fire Test 5:
Jacket, Insulation, 15.2 cm (6 in) Defect
Wall Temperature (°C)
time (min)
427°C
Test 5: Data from IR Thermometer
Test 5: Data from Thermocouple
Test 5: Data from IR Camera

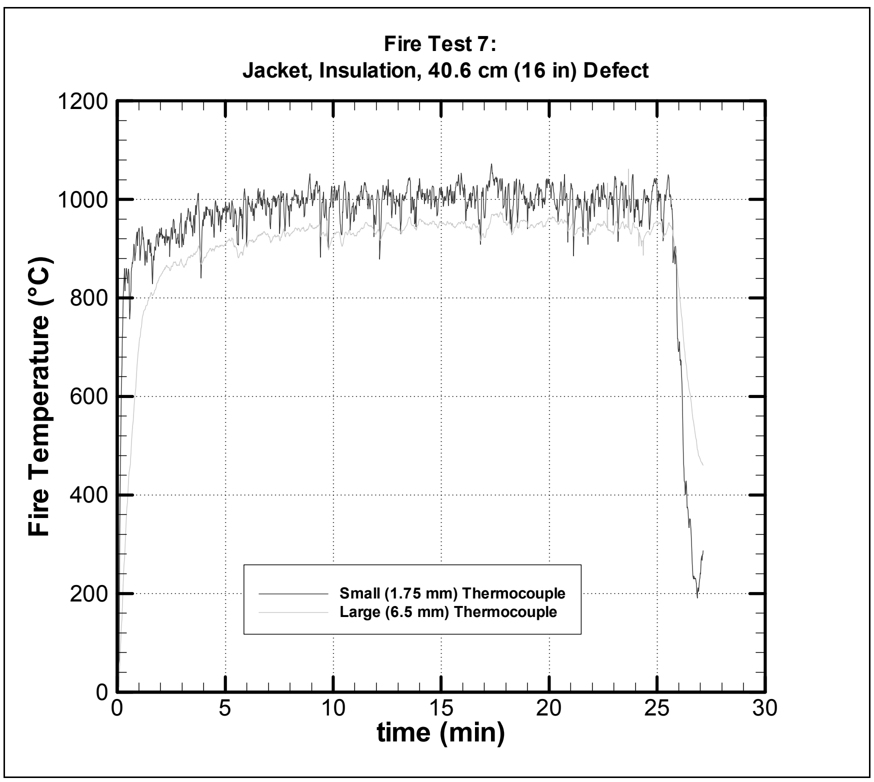


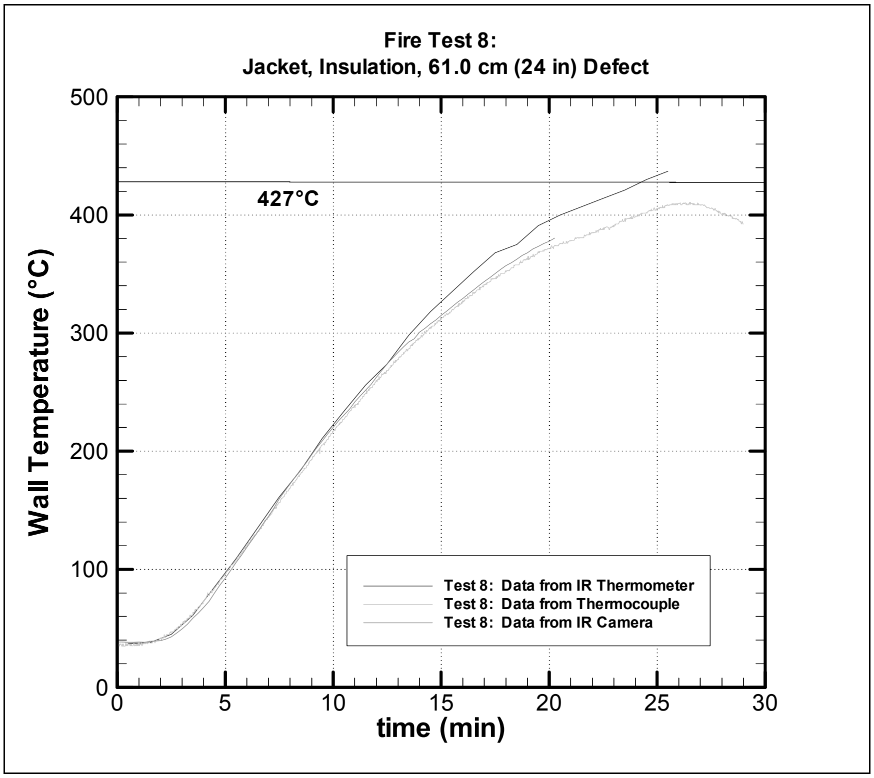
Fire Test 5:
Jacket, Insulation, 15.2 cm (6 in) Defect
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple

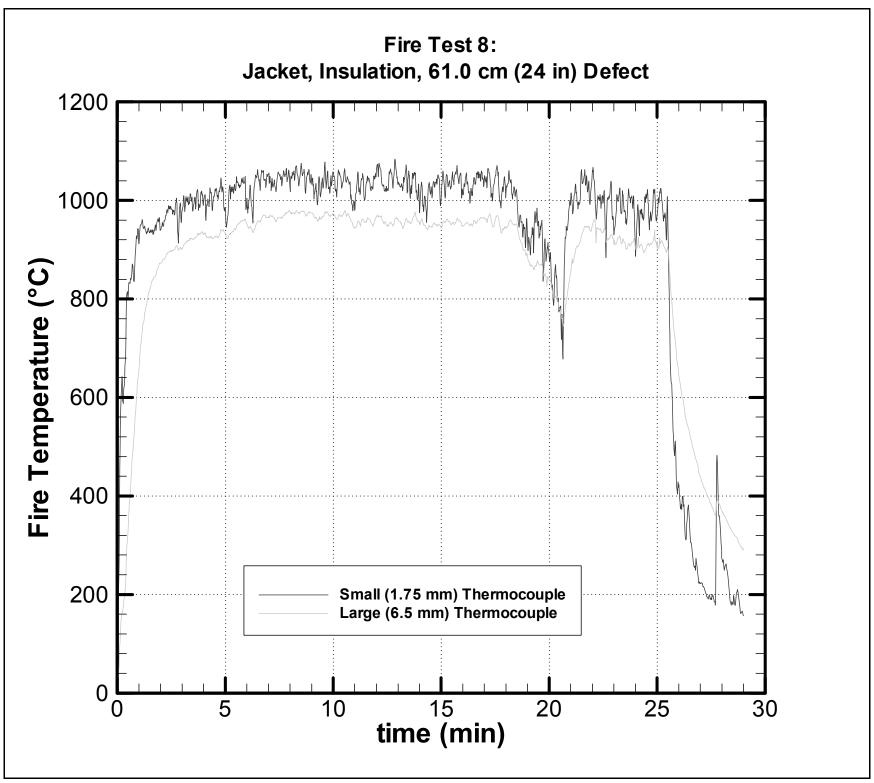

Fire Test 6:
Jacket, Insulation, 25.4 cm (10 in) Defect
Wall Temperature (°C)
time (min)
427°C
Test 6: Data from IR Thermometer
Test 6: Data from Thermocouple
Test 6: Data from IR Camera
0
100
200
300
400
500
0
5
10
15
20
25
30

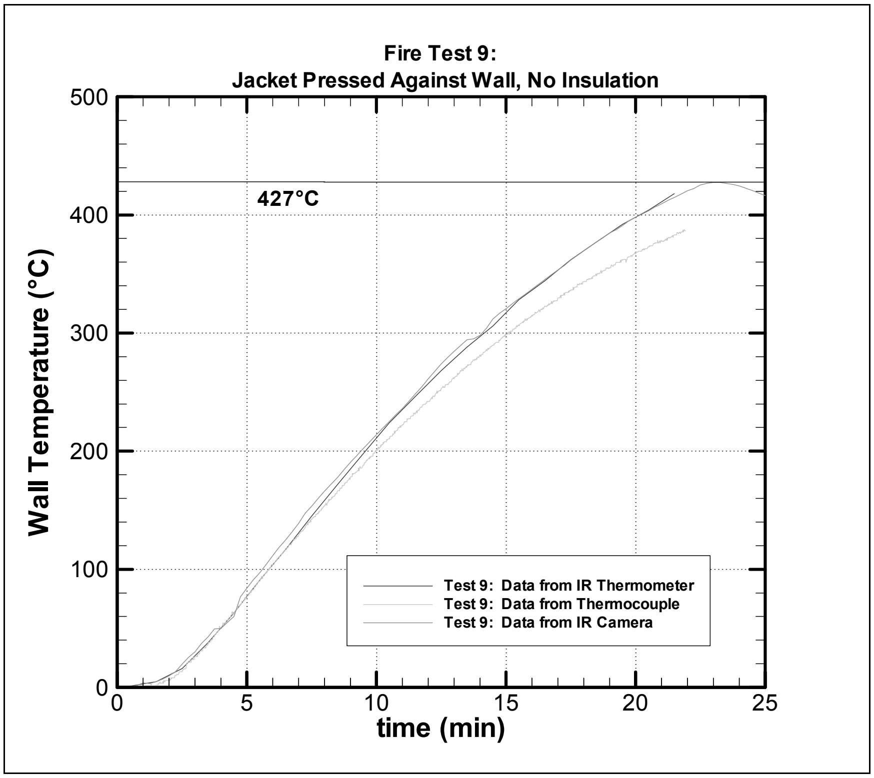

Fire Test 6:
Jacket, Insulation, 25.4 cm (10 in) Defect
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
5
10
15
20
25
30

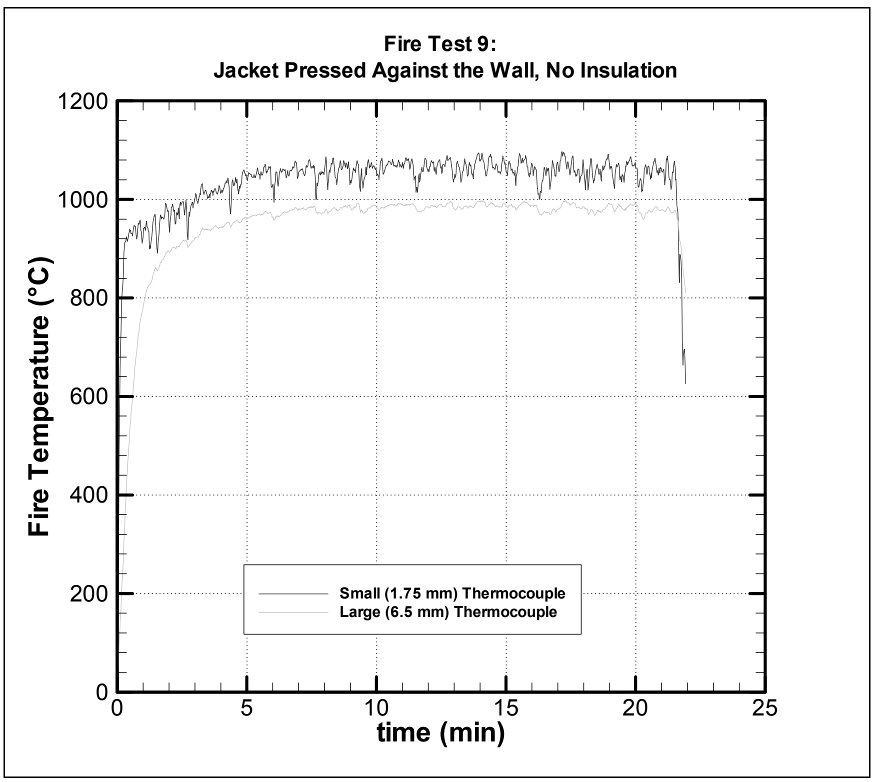

Fire Test 7:
Jacket, Insulation, 40.6 cm (16 in) Defect
427°C
Wall Temperature (°C)
time (min)
Test 7: Data from IR Thermometer
Test 7: Data from Thermocouple
Test 7: Data from IR Camera
0
100
200
300
400
500
0
5
10
15
20
25
30

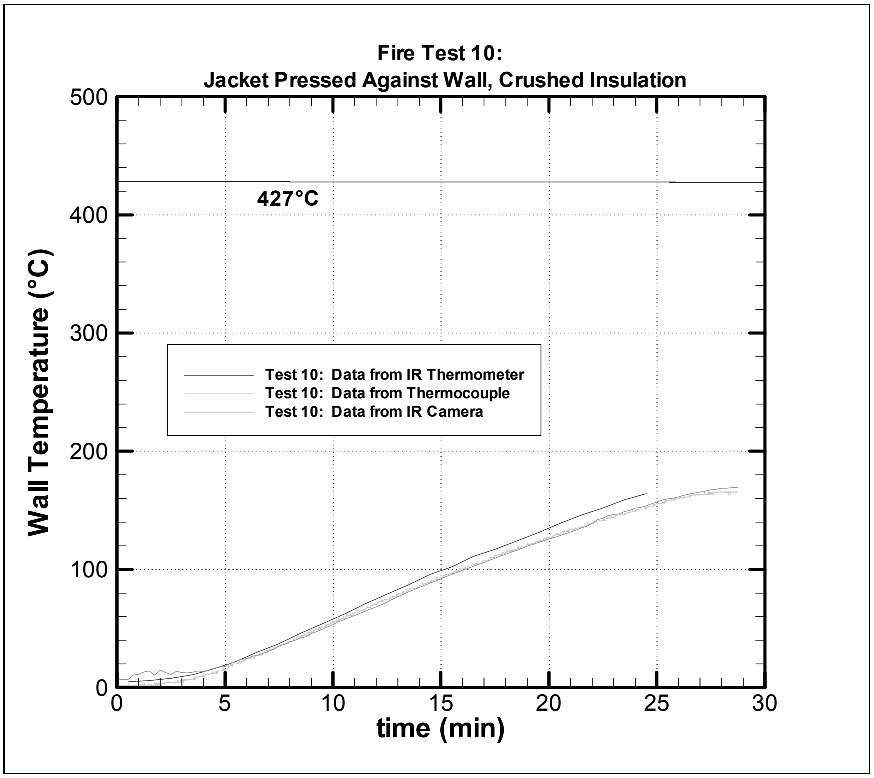

Fire Test 7:
Jacket, Insulation, 40.6 cm (16 in) Defect
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
5
10
15
20
25
30

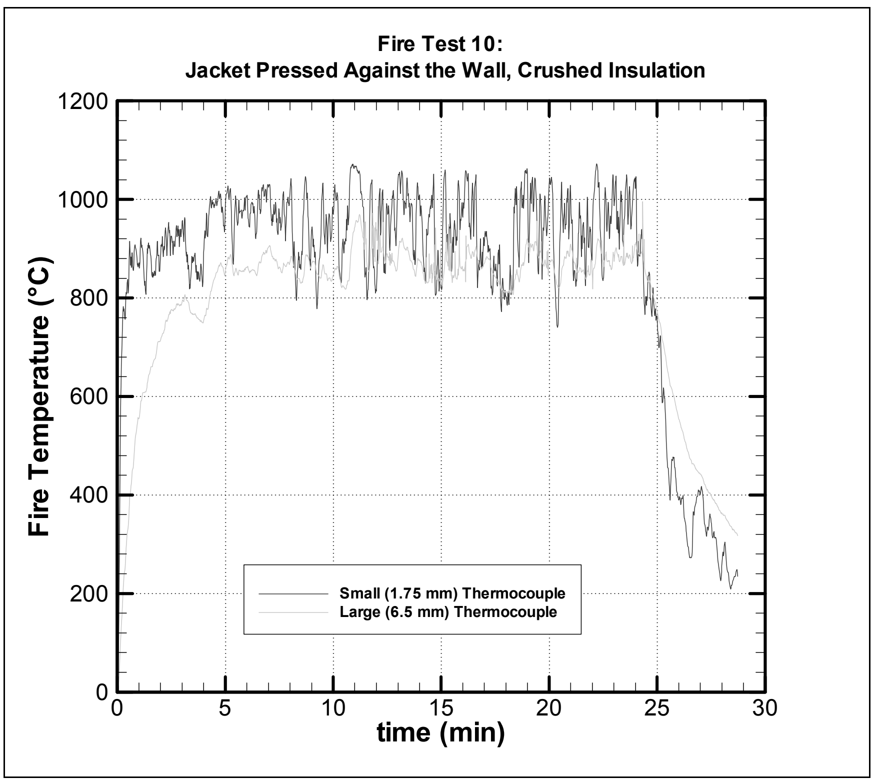

Fire Test 8:
Jacket, Insulation, 61.0 cm (24 in) Defect
Wall Temperature (°C)
time (min)
427°C
Test 8: Data from IR Thermometer
Test 8: Data from Thermocouple
Test 8: Data from IR Camera
0
100
200
300
400
500
0
5
10
15
20
25
30

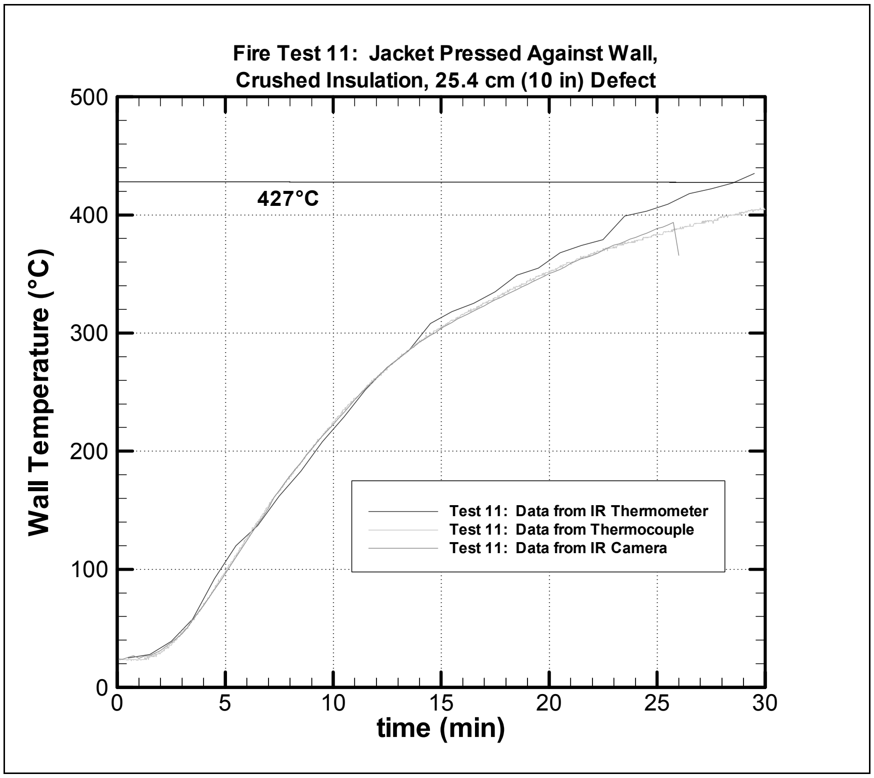

Fire Test 8:
Jacket, Insulation, 61.0 cm (24 in) Defect
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
0
200
400
600
800
1000
1200
0
5
10
15
20
25
30

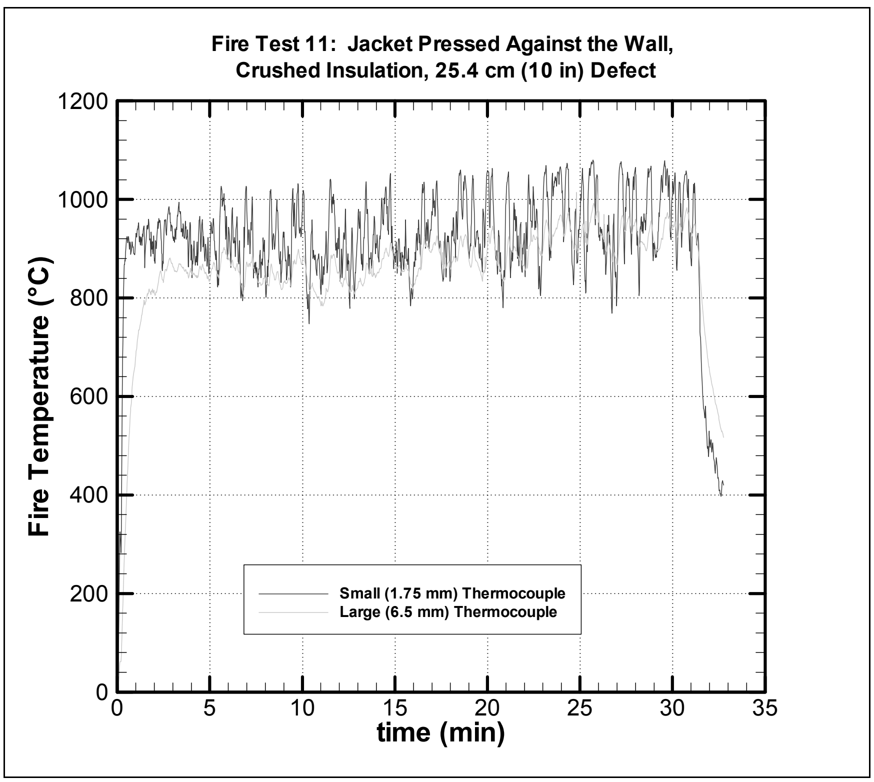

Fire Test 9:
Jacket Pressed Against Wall, No Insulation
427°C
Wall Temperature (°C)
time (min)
Test 9: Data from IR Thermometer
Test 9: Data from Thermocouple
Test 9: Data from IR Camera

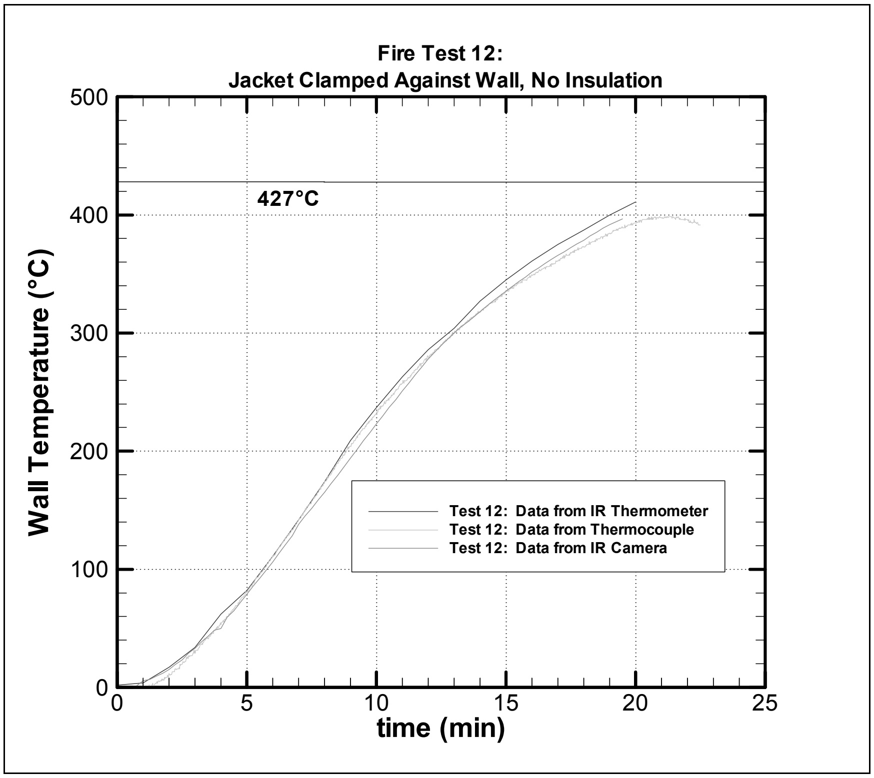

Fire Test 9:
Jacket Pressed Against the Wall, No Insulation
Fire Temperature (°C)
time (min)
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple

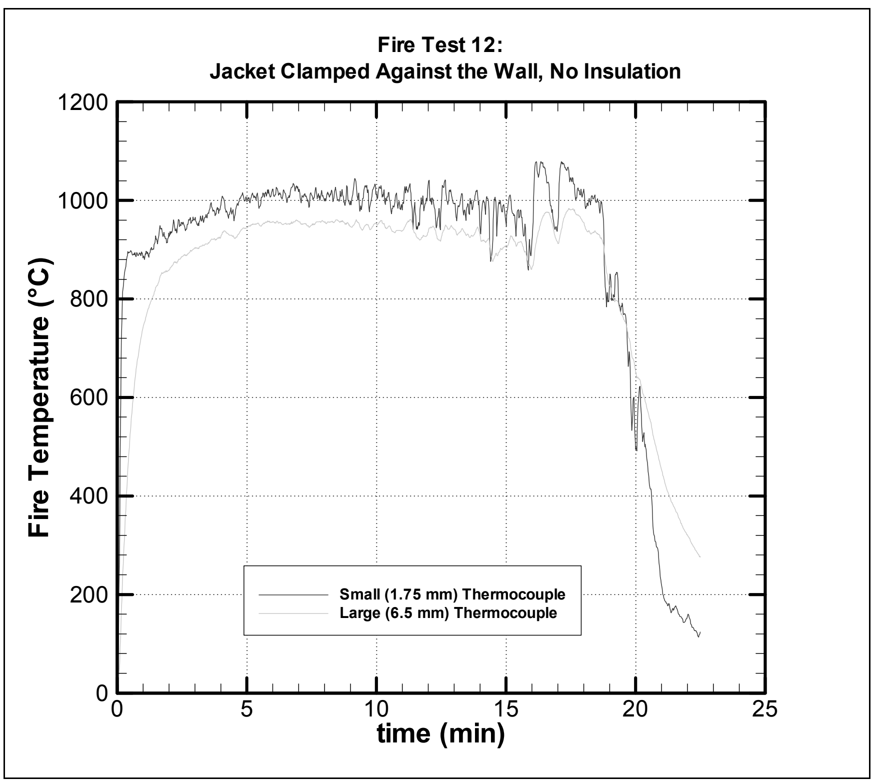

Fire Test 10:
Jacket Pressed Against Wall, Crushed Insulation
427°C
Test 10: Data from IR Thermometer
Test 10: Data from Thermocouple
Test 10: Data from IR Camera
Wall Temperature (°C)
time (min)
0
100
200
300
400
500
0
5
10
15
20
25
30

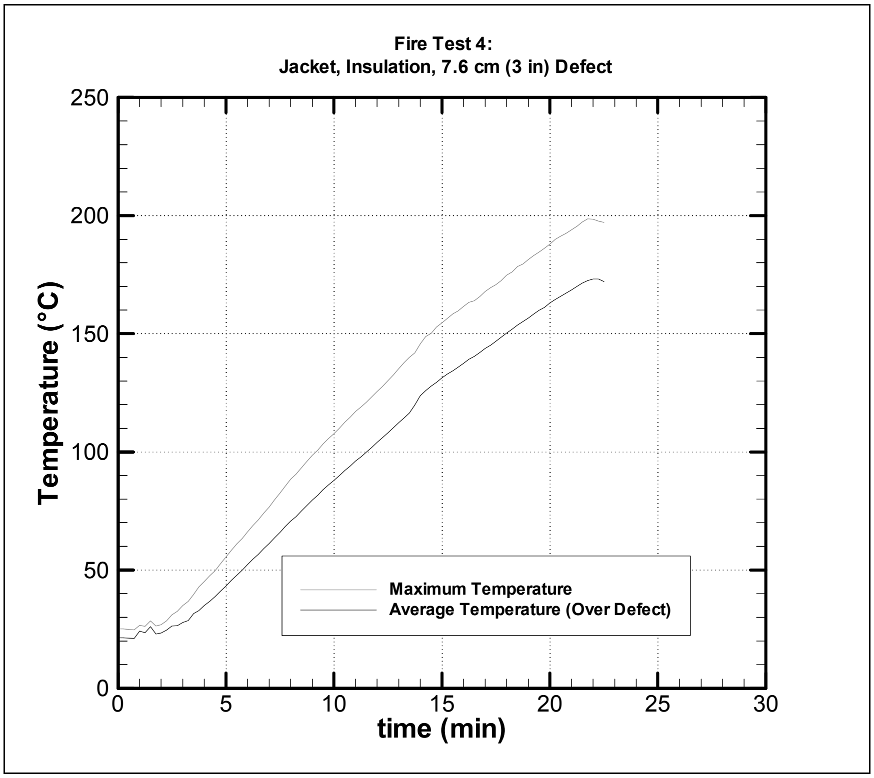

Fire Test 10:
Jacket Pressed Against the Wall, Crushed Insulation
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
Fire Temperature (°C)
time (min)
0
200
400
600
800
1000
1200
0
5
10
15
20
25
30

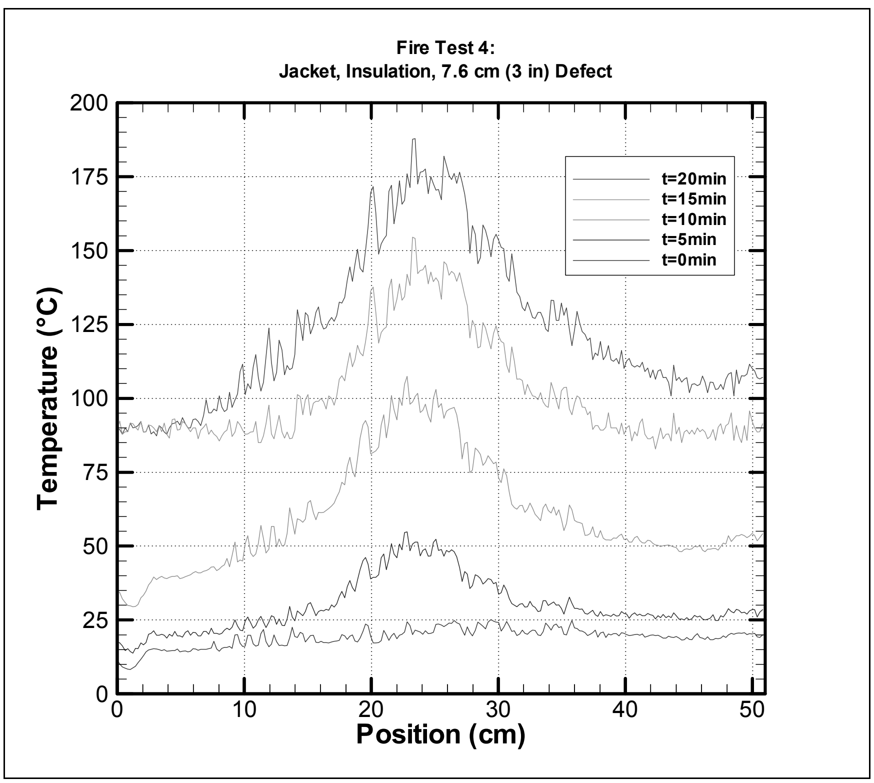

Fire Test 11: Jacket Pressed Against Wall,
Crushed Insulation, 25.4 cm (10 in) Defect
427°C
Test 11: Data from IR Thermometer
Test 11: Data from Thermocouple
Test 11: Data from IR Camera
Wall Temperature (°C)
time (min)
0
100
200
300
400
500
0
5
10
15
20
25
30

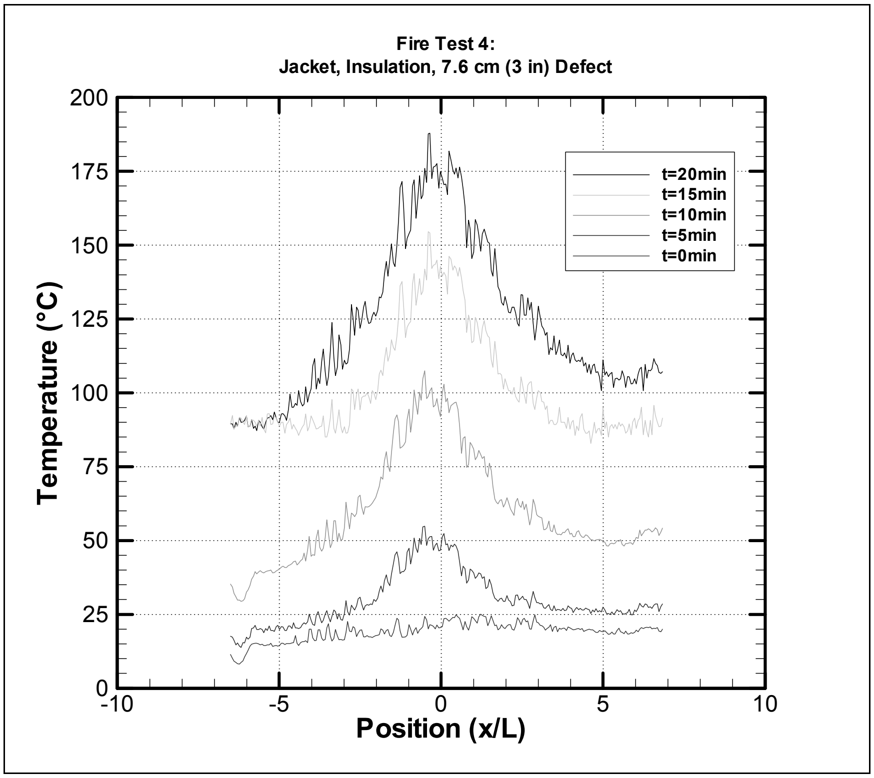

Fire Test 11: Jacket Pressed Against the Wall,
Crushed Insulation, 25.4 cm (10 in) Defect
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple
Fire Temperature (°C)
time (min)
0
200
400
600
800
1000
1200
0
5
10
15
20
25
30
35

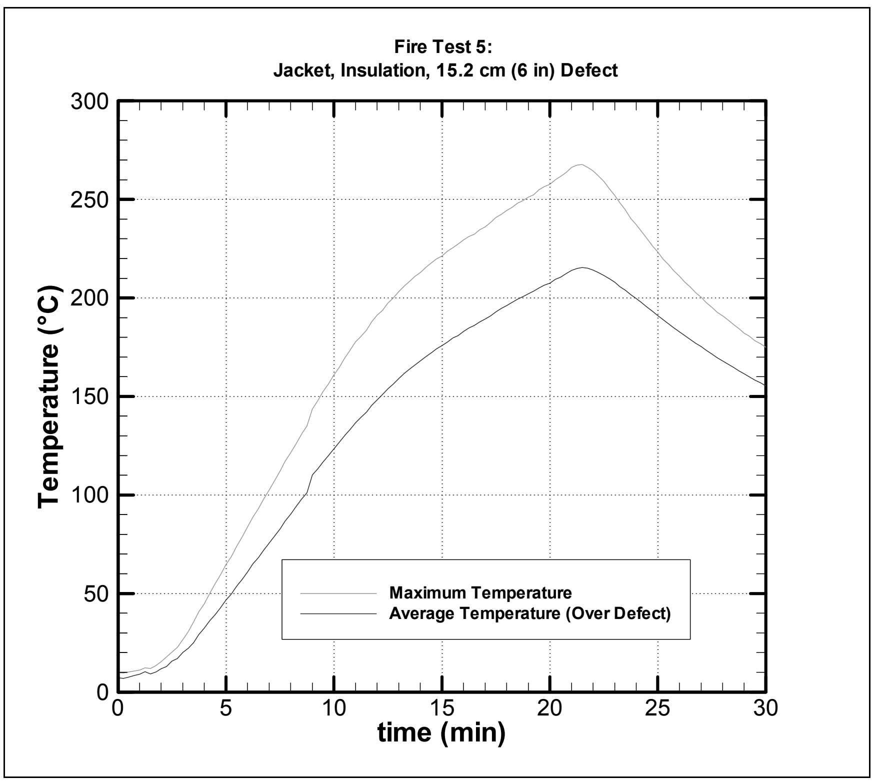

Fire Test 12:
Jacket Clamped Against Wall, No Insulation
427°C
Wall Temperature (°C)
time (min)
0
100
200
300
400
500
0
5
10
15
20
25
Test 12: Data from IR Thermometer
Test 12: Data from Thermocouple
Test 12: Data from IR Camera

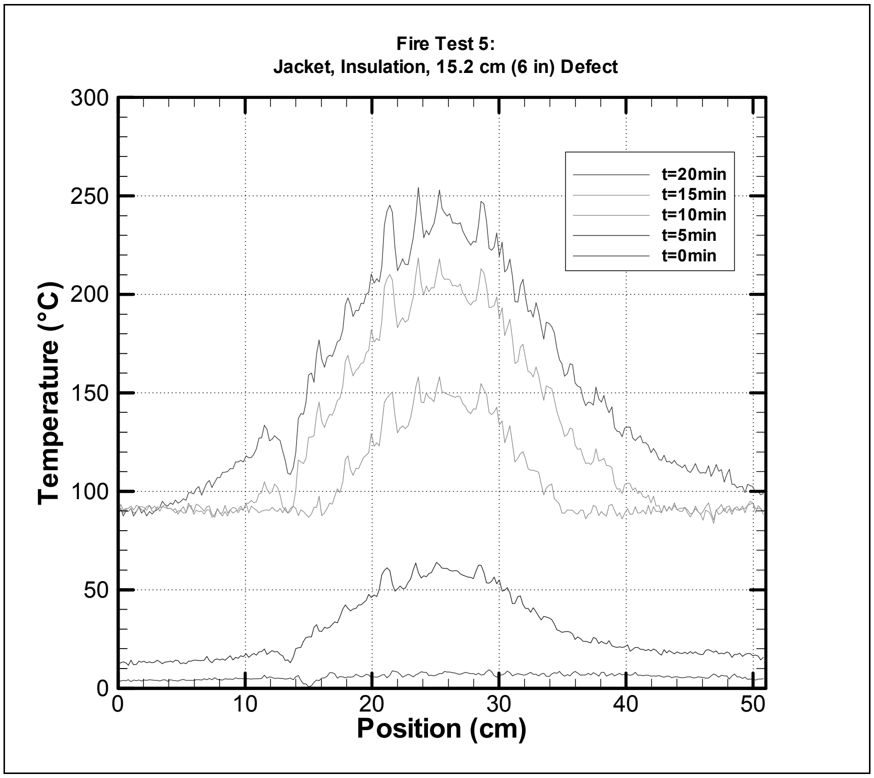

Fire Test 12:
Jacket Clamped Against the Wall, No Insulation
Fire Temperature (°C)
time (min)
0
200
400
600
800
1000
1200
0
5
10
15
20
25
Small (1.75 mm) Thermocouple
Large (6.5 mm) Thermocouple

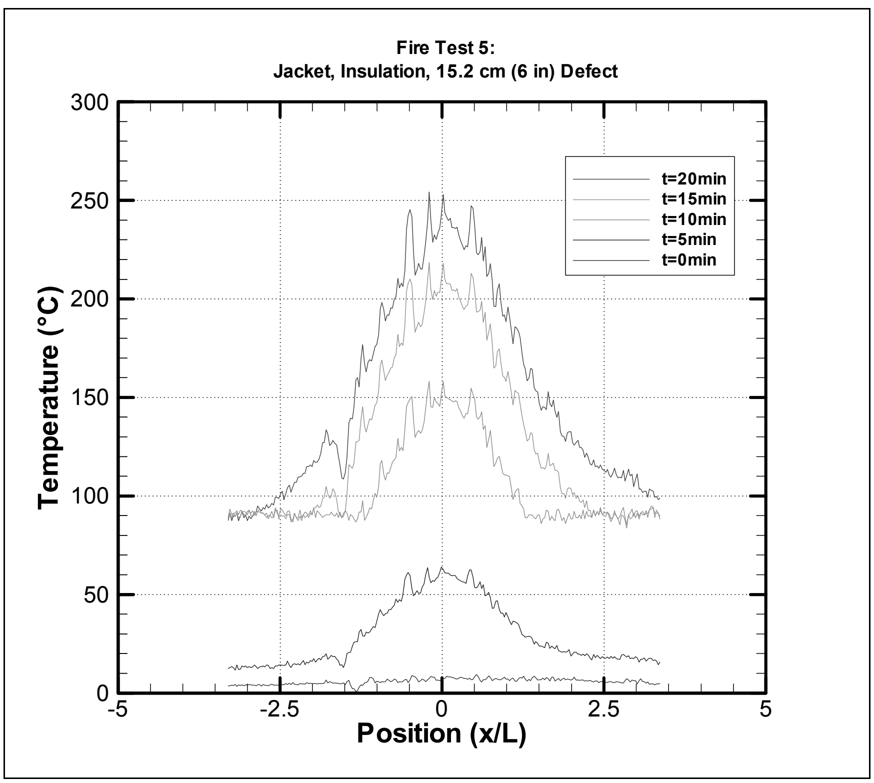

Fire Test 4:
Jacket, Insulation, 7.6 cm (3 in) Defect
Temperature (°C)
time (min)
Maximum Temperature
Average Temperature (Over Defect)
0
50
100
150
200
250
0
5
10
15
20
25
30

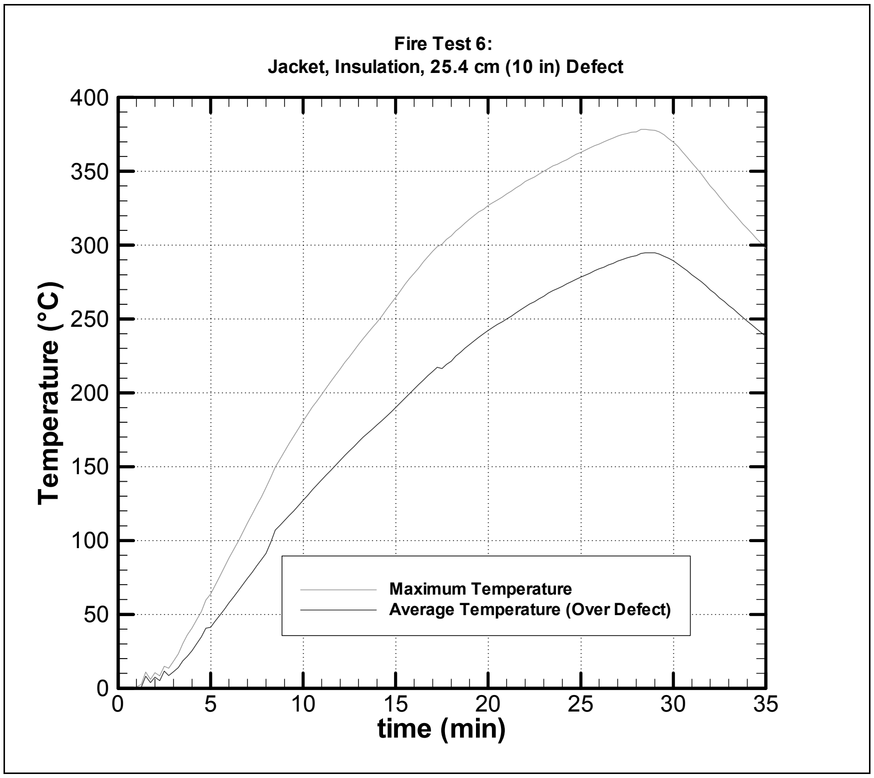

Fire Test 4:
Jacket, Insulation, 7.6 cm (3 in) Defect
Temperature (°C)
Position (cm)
t=20min
t=15min
t=10min
t=5min
t=0min
0
25
50
75
100
125
150
175
200
0
10
20
30
40
50

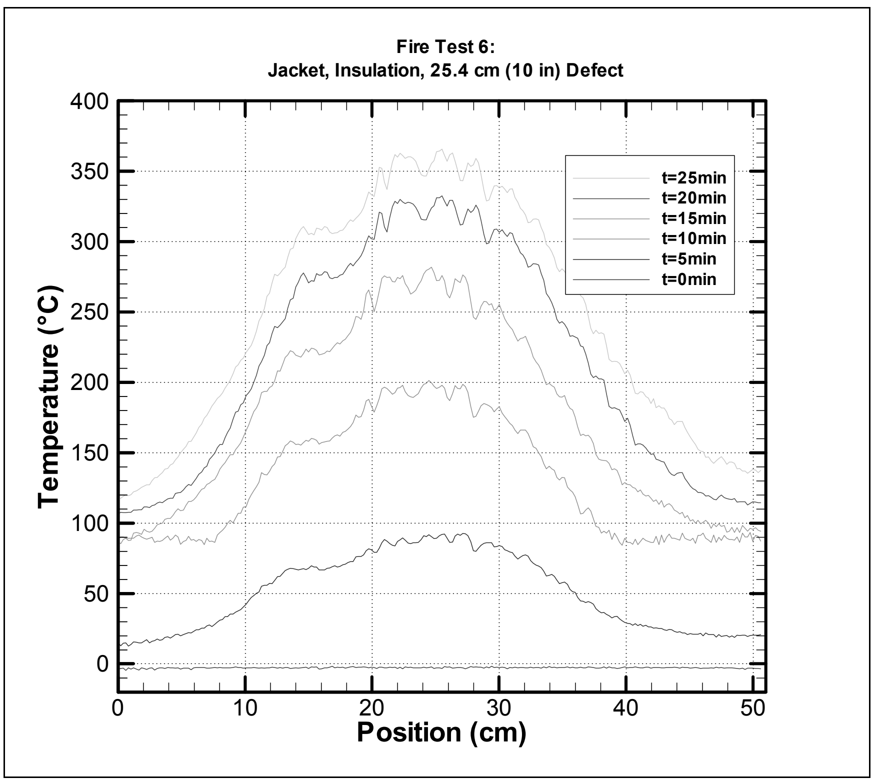

Fire Test 4:
Jacket, Insulation, 7.6 cm (3 in) Defect
Temperature (°C)
Position (x/L)
t=20min
t=15min
t=10min
t=5min
t=0min
200
175
150
125
100
75
50
25
0
-10
-5
0
5
10

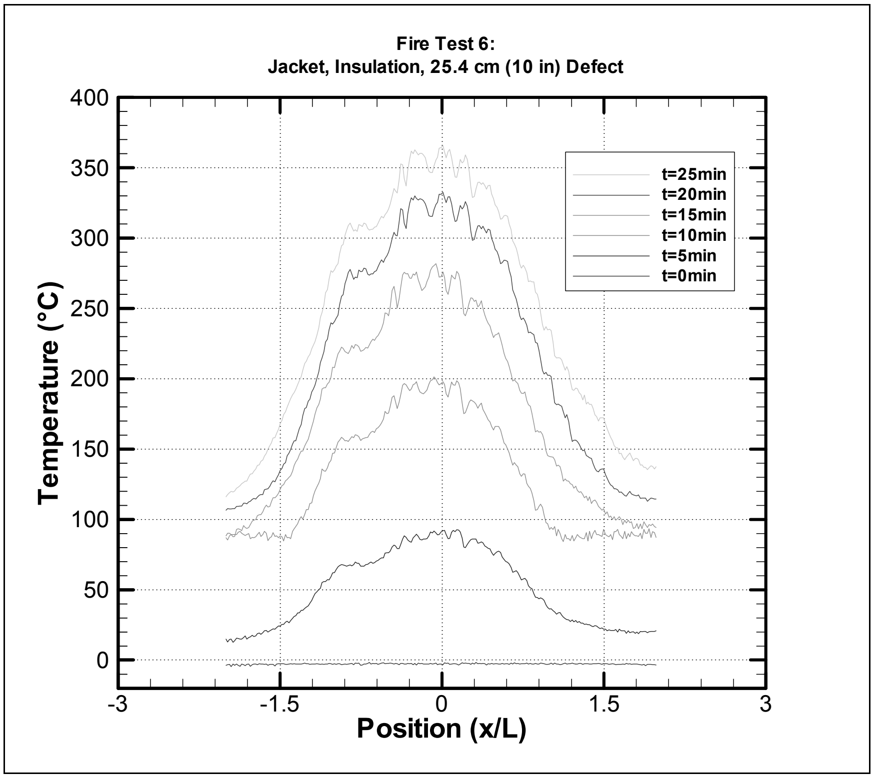

Fire Test 5:
Jacket, Insulation, 15.2 cm (6 in) Defect
Temperature (°C)
time (min)
Maximum Temperature
Average Temperature (Over Defect)
300
250
200
150
100
50
0
0
5
10
15
20
25
30

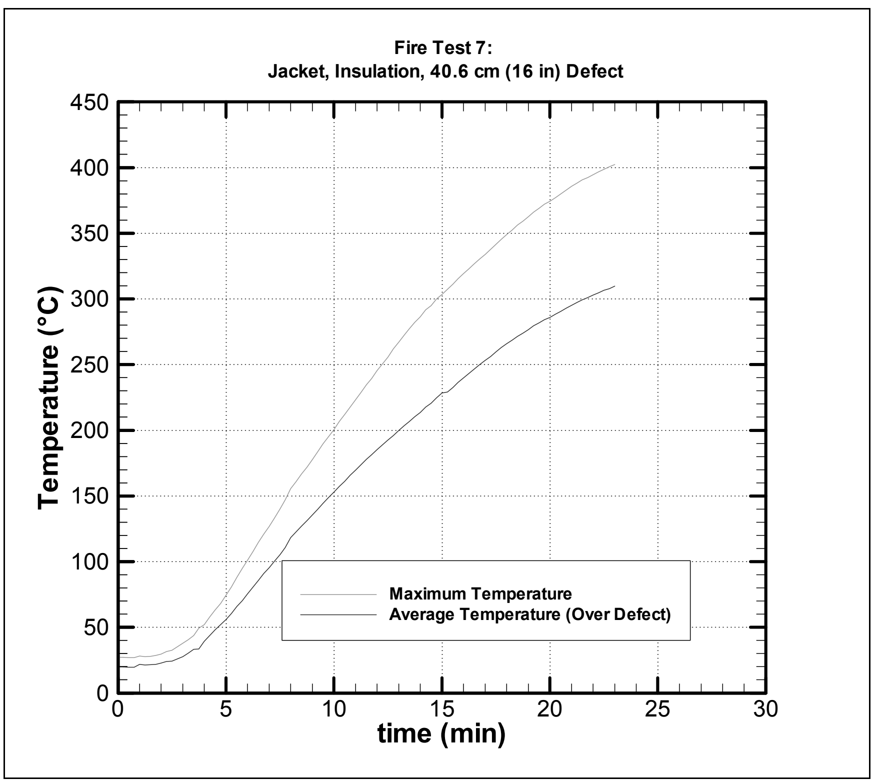

Fire Test 5:
Jacket, Insulation, 15.2 cm (6 in) Defect
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (cm)
0
50
100
150
200
250
300
0
10
20
30
40
50

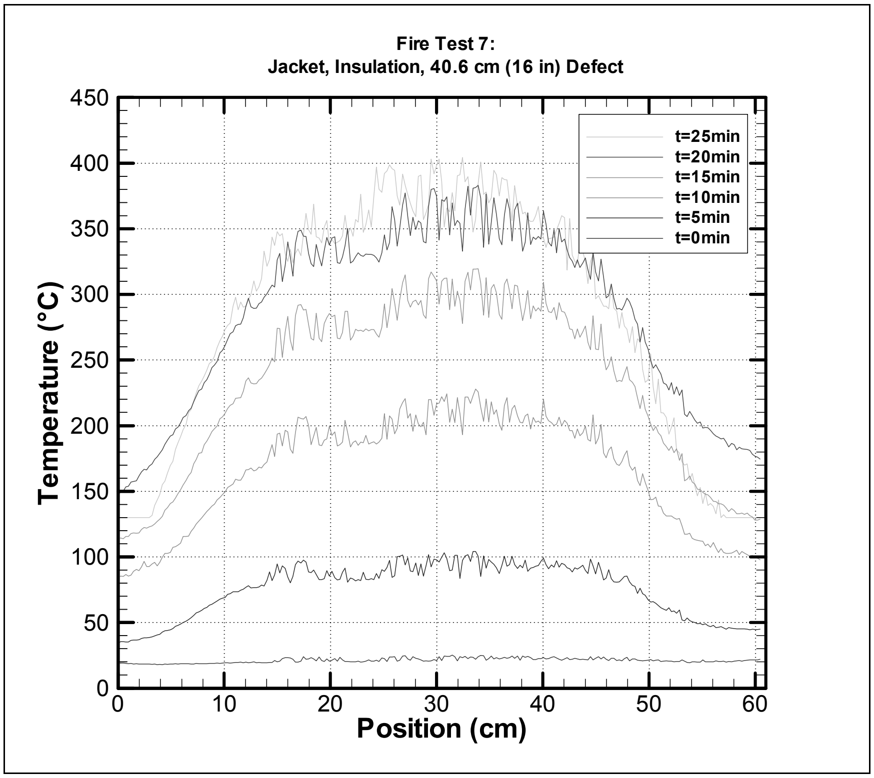

Fire Test 5:
Jacket, Insulation, 15.2 cm (6 in) Defect
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (x/L)
0
50
100
150
200
250
300
-5
-2.5
0
2.5
5

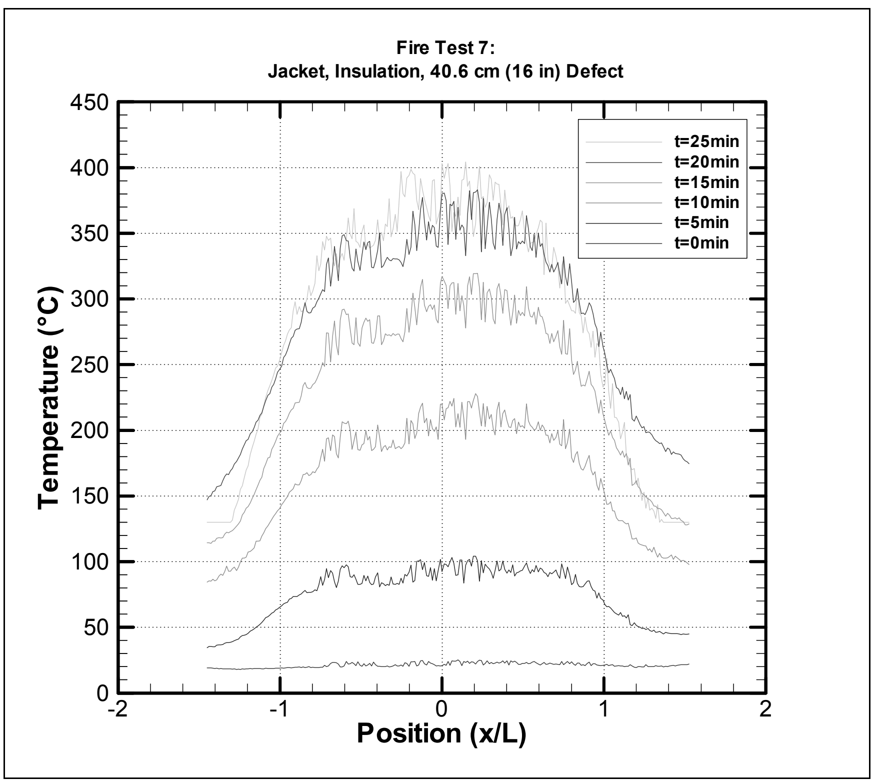

Fire Test 6:
Jacket, Insulation, 25.4 cm (10 in) Defect
Temperature (°C)
time (min)
Maximum Temperature
Average Temperature (Over Defect)
0
50
100
150
200
250
300
350
400
0
5
10
15
20
25
30
35

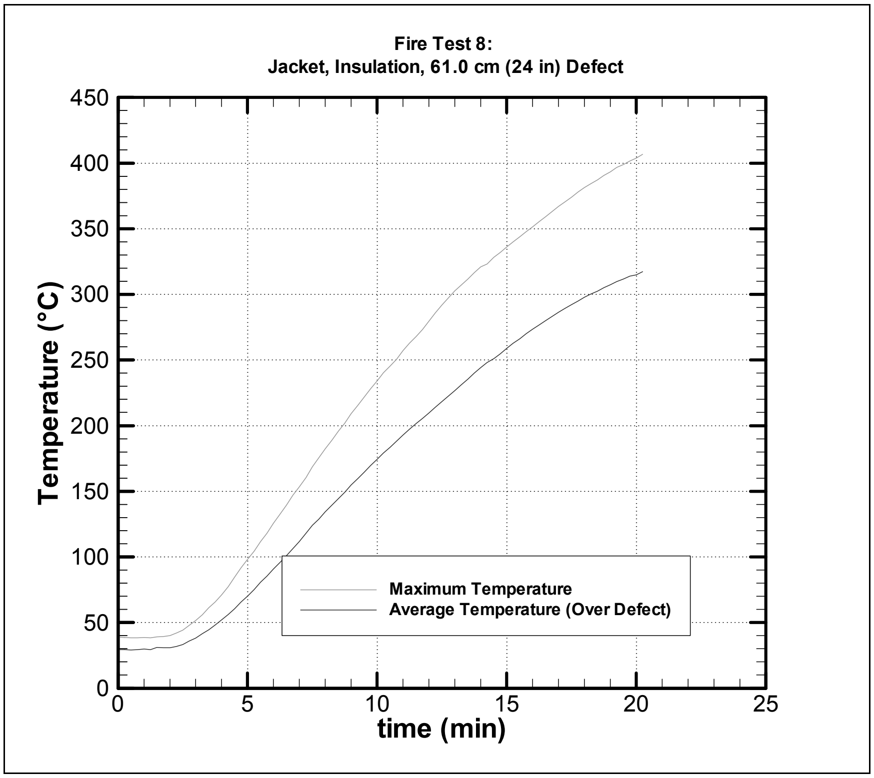

Fire Test 6:
Jacket, Insulation, 25.4 cm (10 in) Defect
Temperature (°C)
Position (cm)
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
0
50
100
150
200
250
300
350
400
0
10
20
30
40
50

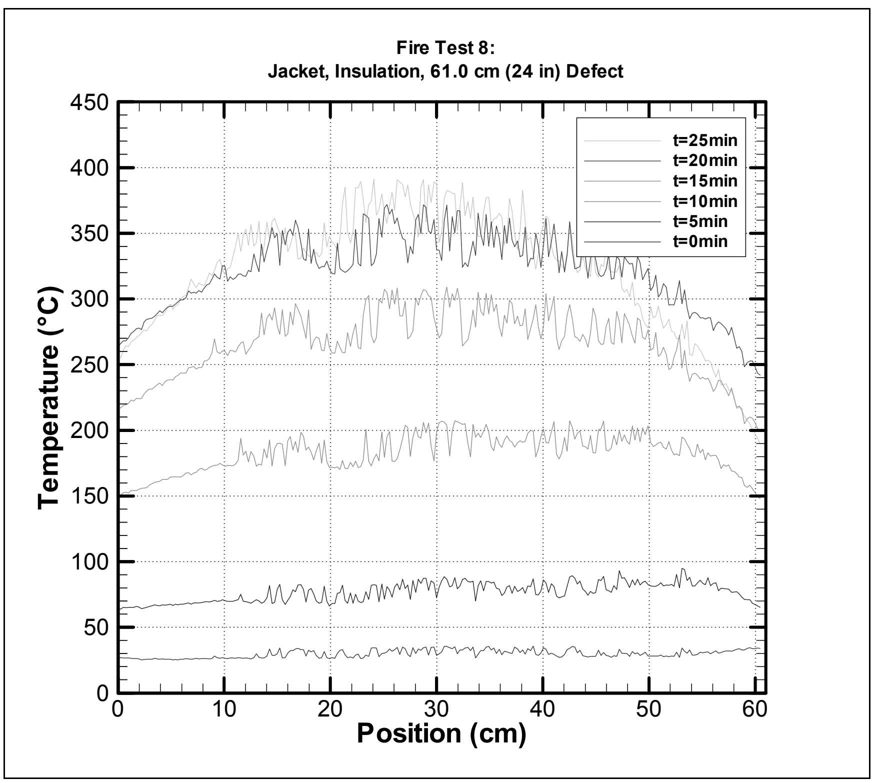

Fire Test 6:
Jacket, Insulation, 25.4 cm (10 in) Defect
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (x/L)
400
350
300
250
200
150
100
50
0
-3
-1.5
0
1.5
3

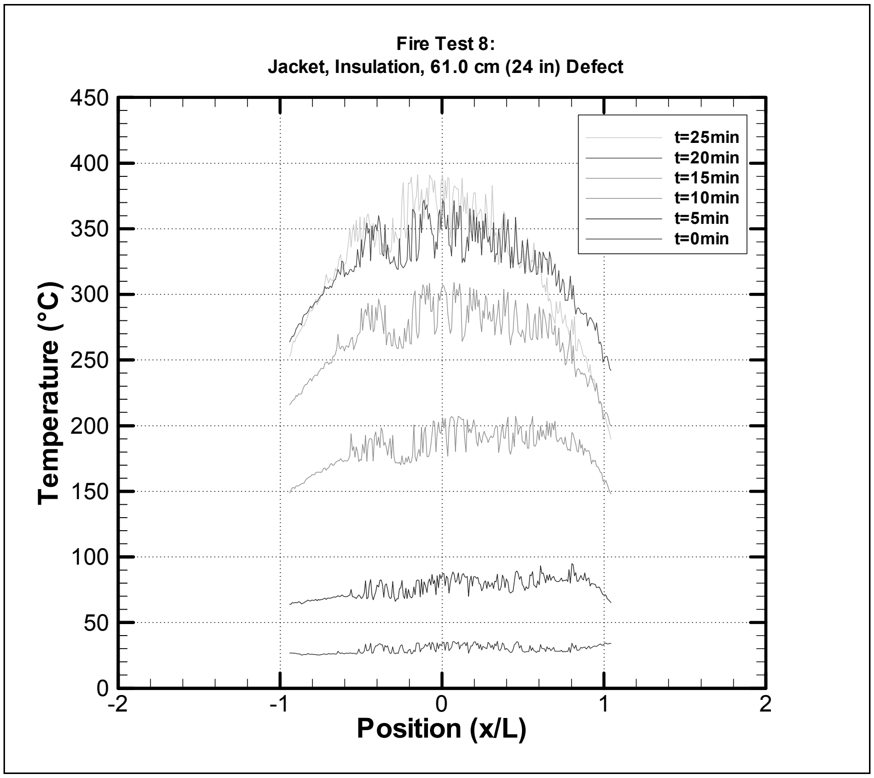

Fire Test 7:
Jacket, Insulation, 40.6 cm (16 in) Defect
Maximum Temperature
Average Temperature (Over Defect)
Temperature (°C)
time (min)
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30

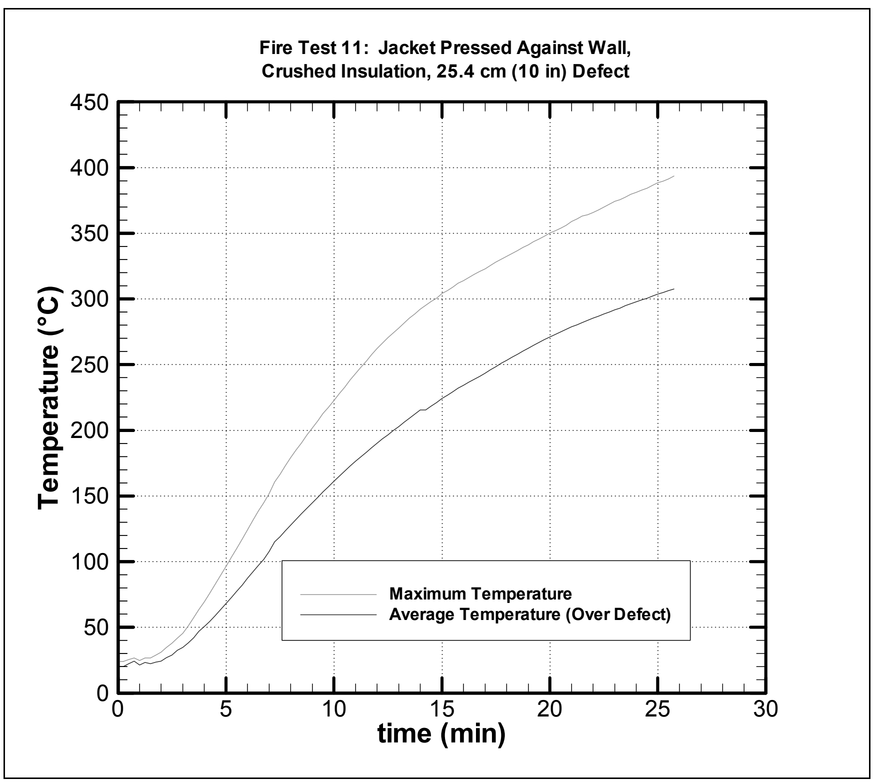

Fire Test 7:
Jacket, Insulation, 40.6 cm (16 in) Defect
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (cm)
0
50
100
150
200
250
300
350
400
450
0
10
20
30
40
50
60

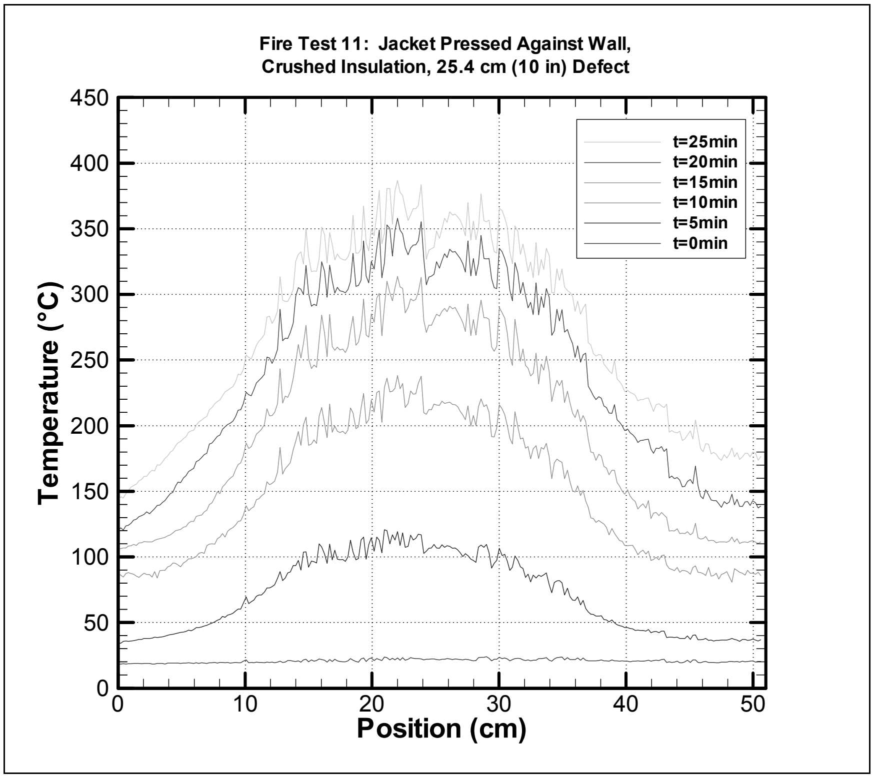

Fire Test 7:
Jacket, Insulation, 40.6 cm (16 in) Defect
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (x/L)
0
50
100
150
200
250
300
350
400
450
-2
-1
0
1
2

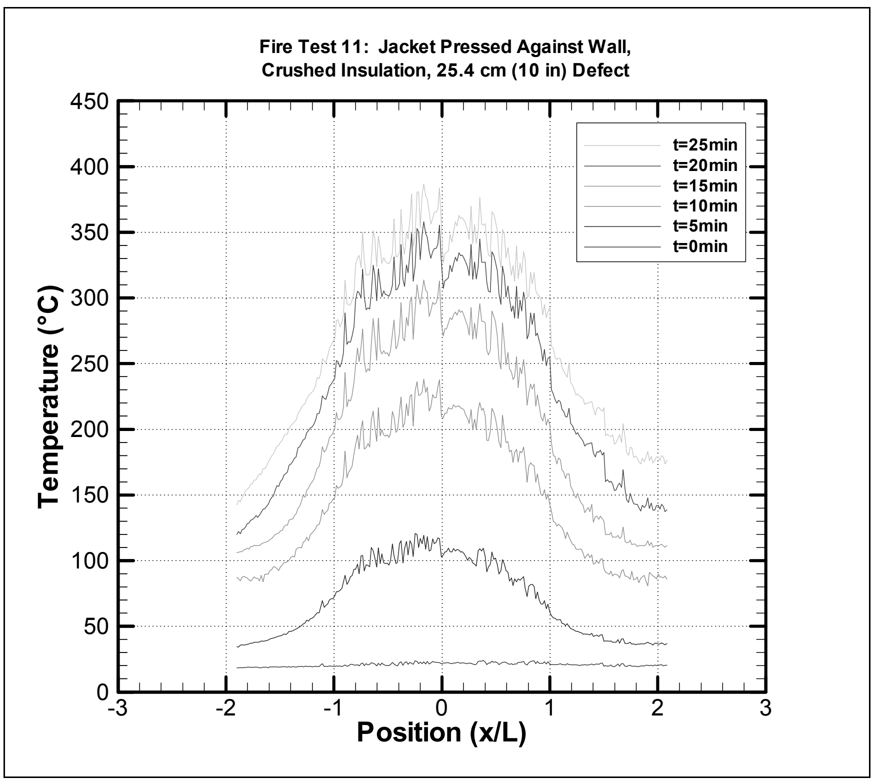

Fire Test 8:
Jacket, Insulation, 61.0 cm (24 in) Defect
Temperature (°C)
time (min)
Maximum Temperature
Average Temperature (Over Defect)
0
50
100
150
200
250
300
350
400
450
0
5
10
15
20
25


Fire Test 8:
Jacket, Insulation, 61.0 cm (24 in) Defect
Temperature (°C)
Position (cm)
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
0
50
100
150
200
250
300
350
400
450
0
10
20
30
40
50
60


Fire Test 8:
Jacket, Insulation, 61.0 cm (24 in) Defect
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (x/L)
0
50
100
150
200
250
300
350
400
450
-2
-1
0
1
2


Fire Test 11: Jacket Pressed Against Wall,
Crushed Insulation, 25.4 cm (10 in) Defect
Maximum Temperature
Average Temperature (Over Defect)
Temperature (°C)
time (min)
0
50
100
150
200
250
300
350
400
450
0
5
10
15
20
25
30


Fire Test 11: Jacket Pressed Against Wall,
Crushed Insulation, 25.4 cm (10 in) Defect
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (cm)
0
50
100
150
200
250
300
350
400
450
0
10
20
30
40
50


Fire Test 11: Jacket Pressed Against Wall,
Crushed Insulation, 25.4 cm (10 in) Defect
t=25min
t=20min
t=15min
t=10min
t=5min
t=0min
Temperature (°C)
Position (x/L)
0
50
100
150
200
250
300
350
400
450
-3
-2
-1
0
1
2
3