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Effects of Fire Damage on the Structural Properties of Steel Bridge Elements

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16. Abstract
It is well known that fire can cause severe damage to steel bridges. There are documented cases where fire has directly led to the collapse or significant sagging of a steel bridge. However, when the damage is less severe, the effects of the fire, if any, are not so clear. Evaluation techniques that can be performed easily in the field, but still provide uniform and meaningful information for this situation are lacking. The objective of this research is to develop simple yet effective guidelines for assessing the potential level of damage sustained during a fire when there are no obvious signs of distress (i.e., sagging, collapse). The guidelines are intended to be used by inspectors and engineers in the field immediately following the fire event to provide general insight into the potential influence the fire may have had on the material properties of the bridge steel, based on the visual appearance of the steel.

A unique testing method is reported in which flange and web sections from a bridge girder are tested in real fire scenarios. The test setup allows for the examination of differences in outcomes due to a variety of paint coatings on the steel, thickness of steel, temperature and duration of fire exposure. Each test is photographed at certain stages that would be seen at a fire affected-bridge. These photographs can then be compared to actual bridge damage and an estimate of surface temperature attained. Following each fire test, material properties may be determined and compared to virgin or unexposed steel and AASHTO specifications to establish whether the material properties have changed or if the material is below minimum standards. Since the test setup and procedures are well defined, the test method can be standardized so that additional data can be collected in a consistent manner and incorporated into the guidelines in the future.

This report, and more specifically the inspection guide provided in Chapter 7, provides a much-needed tool for the inspection and evaluation of steel bridge members exposed to fires where obvious physical damage has not occurred. It will allow uniform and quick initial determination on a bridge's serviceability after undergoing fire exposures.

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EXECUTIVE SUMMARY

It is well known that fire can cause severe damage to steel bridges. There are documented cases where fire has directly led to the collapse or significant sagging of a steel bridge. In such cases, the bridges are closed and require major repair if not complete rebuilding. However, when the damage is less severe, the effects of the fire, if any, are not so clear. In these cases, DOT engineers and inspectors are pressed to determine, sometimes onsite, if the bridge can be reopened to traffic. Evaluation techniques that can be performed easily in the field, but still provide uniform and meaningful information for this situation are lacking.

Even when there is limited apparent damage, prior to reopening the bridge, the owner will close the bridge for an indefinite period of time to obtain material samples for testing to determine if the material properties still meet AASHTO specifications. This procedure can take time and severely impact the economy of surrounding municipalities due to bridge closure and result in other greater roadway hazards due to rerouting of traffic. As stated, when a bridge is visually distorted, the recommendations of what must be done to repair the bridge may be intuitive. However, when no apparent deformations are visible, the course of action is unclear. Therefore, the objective of this research is to develop simple yet effective guidelines for assessing the potential level of damage sustained during a fire when there are no obvious signs of distress (i.e., sagging, collapse). The guidelines are intended to be used by inspectors and engineers in the field immediately following the fire event to provide general insight into the potential influence the fire may have had on the material properties of the bridge steel, based on the visual appearance of the steel.

A unique testing method has been developed that allows researchers to take flange and web sections from a bridge girder and test them in real fire scenarios. The test setup allows researchers to examine the differences in outcomes due to a variety of paint coatings on the steel, thickness of steel, temperature and duration of fire exposure. Since the test setup and procedures are well defined, the test method can be standardized so that additional data can be collected in a consistent manner by any researcher and incorporated in the guidelines over time.

Following each test, material properties may be determined and compared to virgin or unexposed steel and AASHTO specifications to establish if the material properties have changed or if the material is below minimum standards. Each specific test is photographed at certain stages that would be seen at a bridge in the field after being involved in a fire. These photographs can then be compared to actual bridge damage and an estimate of surface temperature could be attained. The inspection guide would then give average values for the reduction or increase of tensile strength and toughness for a particular bridge.

This report, and more specifically the inspection guide, provides a much-needed tool for the inspection and evaluation of steel bridge members exposed to fires where obvious physical damage has not occurred. It will allow uniform and quick initial determination on a bridge’s serviceability after undergoing fire exposures.

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1.0 INTRODUCTION

Steel bridges are occasionally subjected to fire events due to accidents or explosions of vehicles containing flammable materials. Significant bridge fire events have occurred in the recent past. For example:

(i) In Hazel Park, Michigan on July 15, 2009 an out of control car caused a tanker, carrying 13000 gallons of gas and 4000 gallons of diesel fuel, to strike an overpass on I-75. Intense heat and an explosion caused the overpass to collapse within 30 minutes of exposure to approximately 2300°F (1260^{o}C) in temperature (Kodur et al. 2010).

(ii) In Oakland, California on April 29, 2007 a tanker that was traveling too fast overturned, dumping 8600 gallons of gasoline and causing an intense fire on I-880. Collapse occurred after 22 minutes of sustained fire loading. It is believed that temperatures during the fire reached 2000°F (1100°C). Softening of bolts in the connections and the girders caused large deformations resulting in the deck pulling off of its supports (Kodur et al. 2010).

(iii) In Birmingham, Alabama on July 5, 2002 a car crashed into a tanker that was carrying 9000 gallons of fuel. This caused an explosion with fire temperatures exceeding 2000°F (1100°C). The resulting damage included seven to ten foot deflections of girders as well as damage to the deck (Hancock et al. 2008).

(iv) In Indianapolis, Indiana on Oct. 22, 2009, a truck hauling a trailer of liquefied propane lost control and crashed beneath the east- and westbound bridges carrying mainline I-465 traffic over a ramp carrying traffic from I-69. As a result of the fire, the steel superstructure was subjected to extreme temperatures. The duration of these temperatures could not be established accurately. The authors were involved with the post-fire evaluation of this bridge. Material coupons and samples were taken from the fire-exposed and unexposed portions of the steel bridge. The experimental evaluations indicated no major differences between the material properties with or without fire exposure damage (Marcu et al. 2011).

2.0 BACKGROUND

Limited research has been conducted on the fire behavior and post-fire evaluation of steel bridges. Kodur et al. (2010) and Astaneh-Asl et al. (2009) are two studies which include case studies of bridges that have been exposed to fires, discuss ways to prevent fires and better ways of designing against failure during fire exposures, and express the need for further research in the area of post-fire inspection, evaluation, and fire resistant design.

Kodur et al. (2010) cite a study conducted by the New York State Department of Transportation in combination with 17 other states. They reported 1746 bridge failures collectively with a majority of the failures being caused by flooding. They also showed that about three times the number of bridges collapsed because of fire as opposed to seismic issues. Battelle et al. (2001) estimated that annually $139 million in damage is caused by accidents with either fire or explosions occurring during transit. This illustrates the importance of the current research and findings to the bridge engineering and inspection community.

Astaneh-Asl et al. (2009) discuss the effects of elevated temperatures due to fire on the material properties of steel bridges. As shown in Figure 2.1, the tensile yield strength of the steel decreases gradually up to 500^{o}C (932^{o}F). It is reduced to about 50% of its nominal yield strength at 600^{o}C (1112^{o}F). This essentially eliminates any factor of safety, which is usually between 1.5 and 2.0 for bridge calculations. The steel yield strength decreases more rapidly for temperatures greater than 500^{o}C (932^{o}F), and failure may be inevitable if temperatures keep increasing while the loading is sustained.

Astaneh-Asl et al. (2009) also discuss the effects of elevated temperatures due to fire on the material properties of concrete. Concrete undergoes cracking, spalling, and experiences a decrease in stiffness and strength as the temperature increases. Concrete has low thermal conductivity, which allows it to undergo heating for longer durations before the temperature increases significantly and damage occurs. As shown in Figure 2.2, the concrete compressive strength starts decreasing rapidly after its temperature reaches approximately 400°C (750°F). At temperatures of around 500^{o}C (932^{o}F), the concrete compressive strength is reduced to 50% of its nominal strength.

Figure 2.3 shows the reduction in the tensile strength of high strength low alloy (HSLA) reinforcing steel and prestressing steel with elevated temperatures. As shown, the tensile strength of prestressing steel reduces steadily for temperatures greater than 300°C (570°F), and the tensile strength of HSLA bars reduces steadily for temperatures greater than 400°C (750°F). Figure 2.4 shows the reduction in the tensile strength of high strength bolt and weld material at elevated temperatures. As shown, these strengths reduce gradually up to 400°C (750°F), and then reduce more rapidly and steadily for temperatures greater than 400°C (750°F).

Figure 2.5 shows reduction in modulus with increase in temperature. As shown, the modulus reduces gradually up to 400°C (750°F), and then reduces more rapidly for temperatures greater than 400°C (750°F).

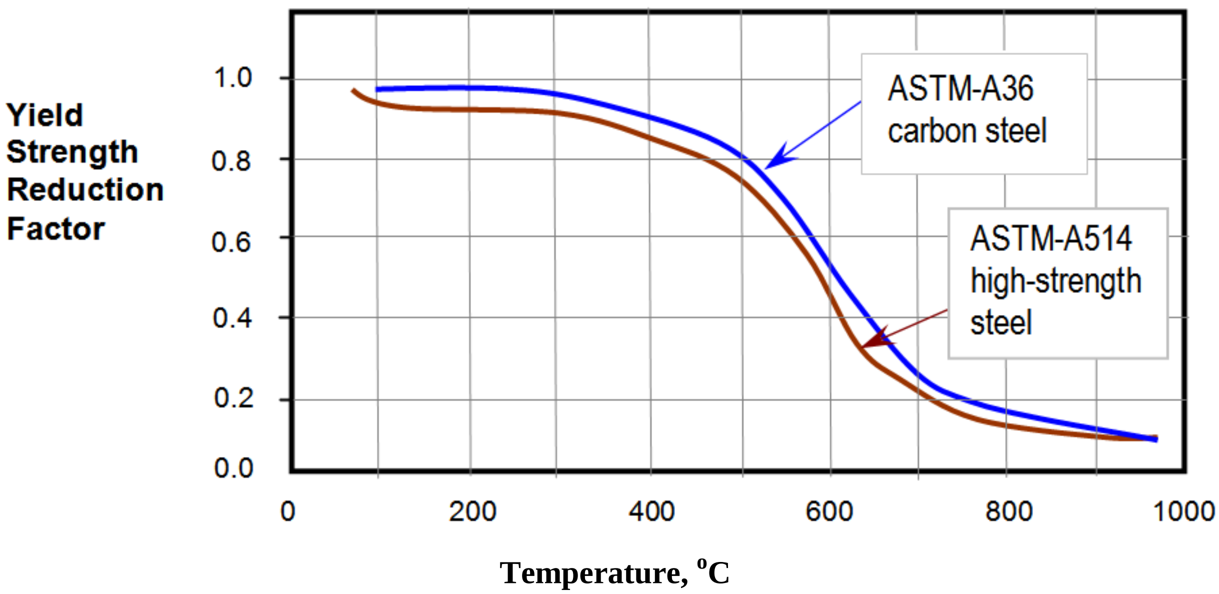


Figure 2.1. Reduction of steel yield strength with temperature (Astaneh-Asl et al. 2009)

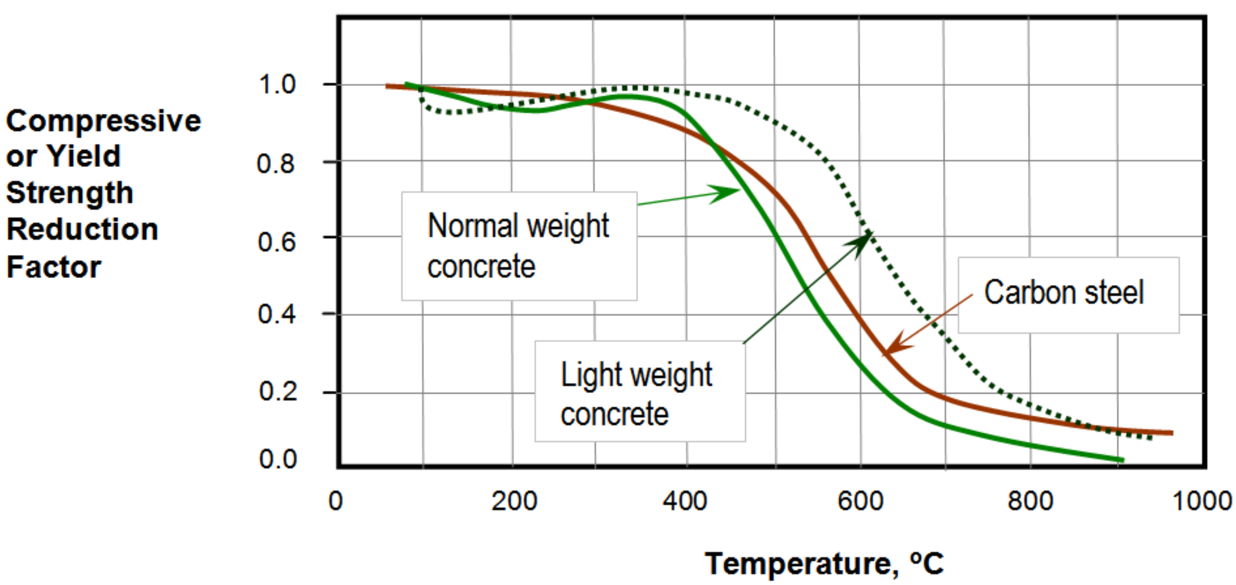


Figure 2.2. Reduction in concrete compressive strength with temperature (Astaneh-Asl et al. 2009)

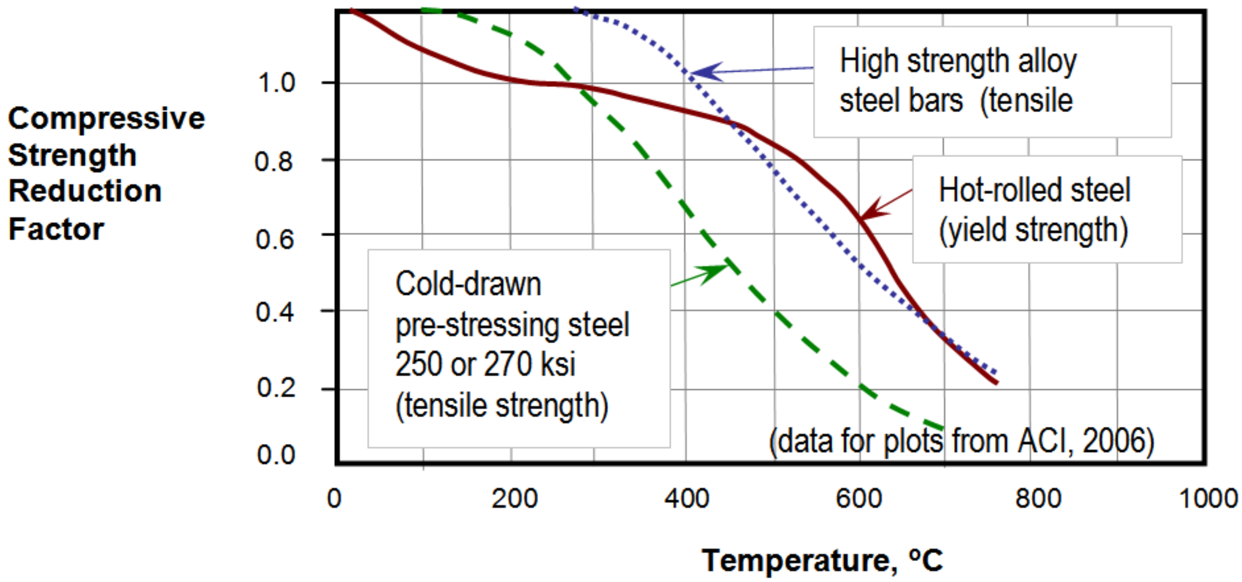


Figure 2.3. Reduction in strength of prestressing steel and high strength alloy bars with temperature (Astaneh-Asl et al. 2009)

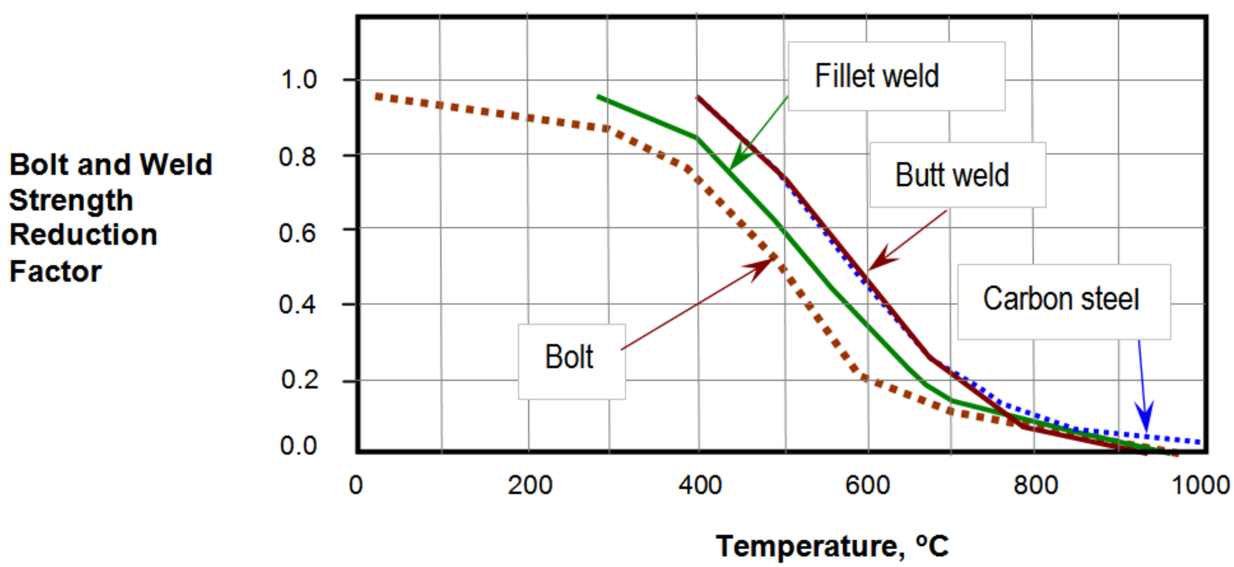


Figure 2.4. Reduction in strength of bolts, welds, reinforcing bars with temperature (Astaneh-Asl et al. 2009)

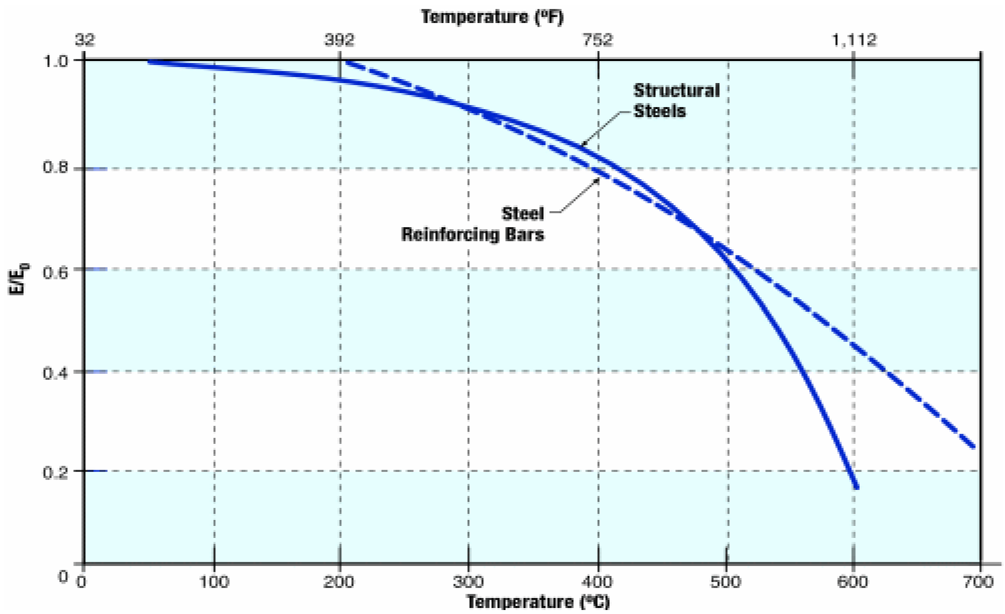


Figure 2.5. Reduction in modulus of steel with respect to temperature (SFPE 2000).

Astaneh-Asl et al. (2009) indicate that the extent of fire hazard or risk can be assessed for every bridge. These risks can be used to develop different categories of fire protection including: (i) no fire protection, (ii) active protection, and (iii) passive fire protection. The most common types of passive fire protection are panel systems, formed in place systems, spray applied materials (insulators), intumescent coatings, and use of fire resistant steel. It is important to note that the current *AASHTO LRFD Bridge Design Specification* (5^{th} edition, 2010) does not have specific fire resistance requirements, design guidelines, or assessment and repair strategies for bridges exposed to fire.

Kodur et al. (2010) suggest that bridges should be designed according to a performance-based design approach. Each bridge should be assessed for hazards based on the probability of occurrence of fire considering both life safety and property protection. They suggest using the building fire safety design strategy for bridges since there are no mathematical models for bridge exposure.

Both Kodur et al. (2010) and Astaneh-Asl et al. (2009) identify the need for post-fire inspection and evaluation of bridges. It is relatively easy to inspect bridges that have distortions of several feet and require elements (for example, beams or diaphragms etc.) to be replaced. However, it is much more difficult to perform post-fire evaluation of bridges that have been exposed to fire exposures but have not sustained large deformations. There is a clear need for post-fire evaluation techniques to evaluate the structural integrity and material properties of bridges exposed to fires but having minimal distortions and fire induced deformations since the condition of the bridge is not obvious (i.e., no visible damage).

The following four steps are recommended for post-fire assessment (Kodur et al. 2010):

1. *On-site Inspection*: A quick visual inspection of the bridge elements exposed to fire such as piers, girders, decks and bearings. Member deformations and material discoloration may indicate the extent of damage caused by fire loading. In concrete sections (such as girders and decks), problems may include cracks, spalling, and surface cover delaminations. Steel members exposed to fire may exhibit buckling, lateral drift, bending, and distortion when exposed to high temperatures.
2. *Residual strength tests*: Concrete cores obtained from damaged bridge elements can be used to determine their compressive strength. Also, petrographic analysis can be performed on the concrete cores to assess the level of microcracking caused by high temperatures, which influences the performance and durability of concrete. Material strength tests should be conducted on coupons taken from fire exposed steel shapes.
3. *Loading Rate Analysis*: The undamaged areas of the bridges should be analyzed to evaluate the secondary effects of distortions and deterioration of material properties in the fire exposed areas. The shear and flexural strengths of the fire exposed deck and girders should be evaluated based on field inspection reports and fire exposure.
4. *Repair Strategies*: After the post-fire damage assessment is completed, relevant repair strategies should be implemented. Research may be necessary to develop proper repair strategies. Moderately damaged members may be repaired, while severely damaged ones should be replaced.

3.0 PROBLEM STATEMENT, RESEARCH OBJECTIVES, and METHODOLOGY

State highway agencies (for example, Pennsylvania Department of Transportation (PennDOT), Indiana Department of Transportation (INDOT), etc.) must occasionally perform post-fire inspections and evaluations of steel bridges exposed to fires. This poses a significant challenge for bridge inspectors because there are rarely any accurate measurements of temperatures, time duration of fire, sustained loading etc. available during or following the event. The bridge inspectors have very little information available on site, and even less research-based or even experience-based knowledge to draw upon to make decisions regarding the structural integrity and material properties of the fire exposed bridge and its elements.

To assist in the decision making process, the objectives of this research are to develop simple but experimental research-based inspection or evaluation tools that can be used to:

(i) Aid the visual inspection of steel bridges and aid in the estimation of the temperatures, durations, and damage endured by the bridge elements during the event.

(ii) Aid in the estimation of the mechanical properties of the steel bridge elements that are exposed to fire based on the temperatures and fire durations estimated from the visual inspection.

(iii) Provide guidance to assist with the decision process regarding the integrity of steel bridges exposed to fire based on the visual inspection and estimated mechanical properties.

The paint coating system used for steel bridge elements is an important parameter in this research. The focus of this report is on the effects of fire exposure on steel bridge elements with old paint coating systems and also with new paint coating systems endorsed by Bulletin 15 issued by the PennDOT.

The research objectives were achieved by conducting controlled fire exposure tests on steel bridge elements with PennDOT endorsed paint coating systems as follows.

- The steel bridge elements (plates) with paint coatings were exposed to fires using a specially designed jet flame setup with a sooting fuel type (e.g., ethylene). Two different paint coating systems (Acrolon and Carbothane) were considered in the tests. Additionally, some steel plates from actual steel bridges (decommissioned by PennDOT and as well as coated specimens provided to the researchers) were also evaluated.
- The fire exposures were controlled by adjusting the distance from the steel plate to the jet nozzle to achieve different fire temperatures (800, 1000, and 1200 ^{o}F (427, 538, and 649 ^{o}C)) and exposure durations (20 – 40 minutes) on the steel plates. The steel plate temperatures were measured using thermocouples attached to the surfaces.
- After fire exposure, the steel plates were hand brushed with a wire brush (to remove coating debris) and then washed clean. Photographs were taken of both sides of the steel plates: (a) before fire exposure, (b) after fire exposure, (c) after brushing, and (d) after washing. These photographs were used to develop the visual inspection guide for steel bridge elements exposed to fires.
- Material coupons were fabricated from the steel plates, and uniaxial tension tests (ASTM E8/AASHTO T68), Charpy V-notch (CVN) fracture toughness tests (ASTM E23/AASHTO T266), and surface hardness tests (ASTM E18/AASTHO T80) were conducted according to applicable ASTM standards to determine the post-fire yield strength, tensile strength, elastic modulus, elongation at rupture, fracture toughness, and surface hardness of the steels. These material properties will be used to develop guidelines for evaluating steel bridge elements exposed to fires.

4.0 EXPERIMENTAL INVESTIGATIONS

4.1 Test Setup

The controlled fire exposure tests were conducted at Zukrow Laboratory, which is an indoor fire testing laboratory at Purdue University in West Lafayette, Indiana. A steel frame superstructure with a flame jet setup within the fixture was used to apply controlled fire exposure to the steel bridge elements (plates). A photograph of the flame jet setup in Zukrow laboratory is shown in

Figure 4.1. At the top of the setup is an exhaust fan that discharges the soot and smoke from flame safely to the outside of the laboratory.

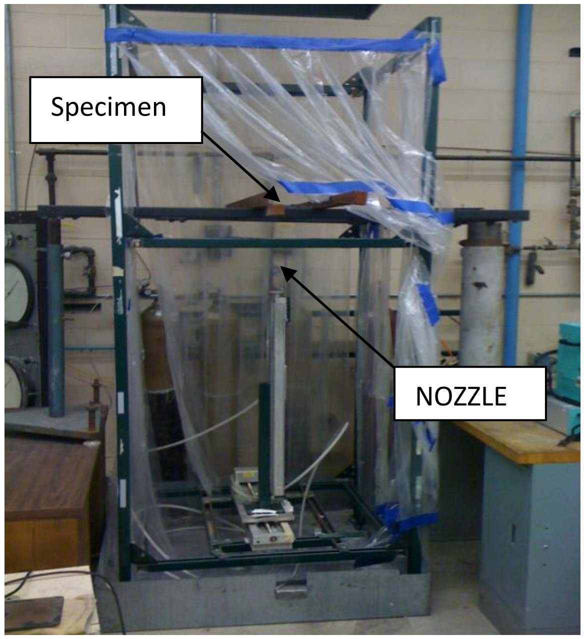


Figure 4.1. Photograph of jet flame test set up.

The flame jet consisted of an 8 mm nozzle connected to an adjustable meter, which allowed calibrated mass flow rates to be achieved. Ethylene gas (C_2H_4) was used to simulate the fire exposure. This is a sooting fuel with adiabatic flame temperature of 2900°C (5252°F). This temperature assumes a pre-mixed flame and no heat loss. However, in the tests there was heat loss to the specimen and cooling from the ambient surroundings, which was also representative of real bridge fire exposures.

The ethylene fuel was not mixed with air until it exited the nozzle. The flow rate was initially set at 30 mg/s and adjusted with time depending upon the desired temperature. The steel plate specimens were suspended over the flame jet using four fixed tabs, one at each corner of the specimen. The nozzle was attached to a screw jack, which allowed it to traverse along three axes. The steel plate specimens were 10 x 10 in. squares cut from either plate stock or out of web and flange materials provided by PennDOT as described in the following sub-section.

4.2 Test Matrix

The complete test matrix consisted of steel plate specimens that were taken from the flanges and web materials of decommissioned steel bridges or ASTM A709(ASTM A709) plate stock as follows:

1. PennDOT had provided a pallet of beam sections from a steel bridge that had been exposed to a real fire event. It included sections that had been directly exposed to the fire and those

that were away from the fire (unexposed). The beam sections had ¾ in. thick flanges and ½ in. thick webs with an indeterminate paint coating on them.

2. PennDOT also provided a pallet of steel beam sections from a decommissioned steel bridge of an age similar to that described in 1 (above) that had never been exposed to a fire. The beam sections had ½ in. thick flanges and ½ in. thick webs with an indeterminate paint coating on them.
3. As part of this research ½ in. thick and 1 in. thick A709 plate stock was obtained. Plates with the same thickness (½ in. or 1 in.) came from the same heat. A suite of ½ in. thick and 1 in. thick specimens with *Acrolon* paint coating for existing steels were prepared. This paint coating system is described below.
4. A suite of ½ in. thick and 1 in. thick A709 steel plate specimens with *Carbothane* paint coating systems for new steels were also prepared. This paint coating system is also described below.

PennDOT has a list of currently approved coatings in Bulletin 15 for *existing* and *new* structural steels. All steels are required to be coated with three-coat zinc-rich paint systems. Existing steels can be coated with systems from both Carboline Company and Sherwin Williams Company. However, new steels can be coated only with systems from the Carboline Company.

- For existing steels, Sherwin Williams' *Acrolon* coating consists of a primer coat of ZincClad III HS, Macropoxy 646 intermediate coat, and Acrolon 218 HS top coat. This ends up rusty red in color.
- For new steels, the inorganic zinc coating system (*Carbothane*) from Carboline Company must be used. The first coat is Carbozinc 11 HS, followed by an intermediate Carboguard 893 coat, and a finish coat of Carbothane 133. This ends up steel blue in color

Table 4.2 presents the test matrix for the experimental investigations. The Specimen ID consists of the origin of the steel, a letter and a number identifier, and the test condition of the plate. The table consists of 4 parts. The first part is the set of plate specimens made from the beam sections that had been exposed to a real fire event. Four beam sections (PennDOT 1, 2, 3, and 4) were provided, of which PennDOT 1 and 4 were exposed to the fire event, and PennDOT 2 and 3 were not exposed to the fire event.

- As shown in Table 4.2, specimens were made from the ¾ in. thick flanges and ½ in. thick webs of the burned (PennDOT 1 and 4) beam sections, and the corresponding control specimens were made from ¾ in. thick flanges and ½ in. thick webs of the unburned (PennDOT 2) section. These plate specimens were used only to conduct material tests, and were not exposed to controlled fires using the flame jet setup.
- As shown in Table 4.2, plate specimens were also made from the ¾ in. thick flanges and ½ in. thick webs of the unburned (PennDOT 3) beam section that was not exposed to the fire event. These included a control specimen, and two specimens that were exposed to controlled fires using the flame jet setup to surface temperatures of 800 and 1200 ^{o}F.

The second part is the set of plate specimens made from the beam sections from the decommissioned steel bridge that had never been exposed to a fire. The beam section (PennDOT 5) had ½ in. thick webs and ½ in. thick flanges. As shown in Table 4.2, three plate specimens were made from both the ½ in. thick flanges and the ½ in. think web. These included a control specimen, and two specimens that were exposed to controlled fires using the flame jet setup to surface temperatures of 800 and 1200 ^{o}F.

The third part is the set of plate specimens made from ½ in. thick and 1 in. thick A709 plate stock with the Sherwin-Williams' *Acrolon* paint coating for existing steels (rusty red in color). As shown in Table 4.2, a total of five specimens each were tested for the two plate thicknesses (1/2 in. and 1 in.). These included: (i) control specimen (that was not heated), (ii) three specimens that were exposed to controlled fires using the flame jet setup to achieve surface temperatures of 800, 1000, 1200 ^{o}F, and (iii) one specimen that was exposed to an uncontrolled fire using the flame jet setup, which resulted in 1200 ^{o}F surface temperature also.

The fourth part is the set of plate specimens made from ½ in. thick and 1 in. thick A709 plate stock with the Carboline's *Carbothane* paint coating for new steels (steel blue in color). As shown in Table 4.2, a total of four ½ in. thick plate specimens were tested. These included: (i) control specimen (that was not heated), (ii) two specimens that were exposed to controlled fires using the flame jet setup to achieve surface temperatures of 1000 and 1200 ^{o}F, and (iii) one specimen that was exposed to an uncontrolled fire resulting in 1200 ^{o}F surface temperature also. A total of three 1 in. thick plate specimens were tested. These included two specimens that were exposed to controlled fires using the flame jet setup to achieve surface temperatures of 1000 and 1200 ^{o}F, and (iii) one specimen that was exposed to an uncontrolled fire resulting in 1200 ^{o}F surface temperature also.

Typical surface temperature-time curves resulting from the heating are shown in Section 5. Generally, heated specimens were brought to their target temperatures and this was maintained for 20 minutes. The "uncontrolled" specimens were exposed to unrestricted heating for 40 minutes.

Thus, the parameters included in the experimental investigations are: (i) effects of real fire events on material properties, (ii) plate thickness, (iii) coating type, (iv) surface temperature achieved, and (v) duration of fire.

Table 4.2. Test Matrix

Part	Specimen ID	Origin	Type or Temperature	Description
1	Penn DOT 2 AA (27) Control	PennDOT 2	Control Specimen	½ in. thick web Material tests only
1	Penn DOT 1 Y (25) Burned	PennDOT 1	Burned Specimen	½ in. thick burned web Material tests only
1	Penn DOT 4 EE (31) Burned	PennDOT 4	Burned Specimen	½ in. thick burned web Material tests only
1	Penn DOT 2 BB (28) Control	PennDOT 2	Control Specimen	¾ in. thick flange Material tests only
1	Penn DOT 1 Z (26) Burned	PennDOT 1	Burned Specimen	¾ in. thick burned flange Material tests only
1	Penn DOT 4 FF (32) Burned	PennDOT 4	Burned Specimen	¾ in. thick burned flange Material tests only
1	Penn DOT 3 CC (29) Control	PennDOT 3	Control Specimen	½ in. thick web Material tests only
1	Penn DOT 3 S (19) 800 F	PennDOT 3	800 F	½ in. thick web Flame jet and material tests
1	Penn DOT 3 T (20) 1200 F	PennDOT 3	1200 F	½ in. thick web Flame jet and material tests
1	Penn DOT 3 DD (30) Control	PennDOT 3	Control Specimen	¾ in. thick flange Material tests only
1	Penn DOT 3 V (22) 800 F	PennDOT 3	800 F	¾ in. thick flange Flame jet and material tests
1	Penn DOT 3 W (23) 1200 F	PennDOT 3	1200 F	¾ in. thick flange Flame jet and material tests

Part	Specimen ID	Origin	Type or Temperature	Description
2	Penn DOT 5 KK (37) Control	PennDOT 5	Control Specimen	½ in. thick web Material tests only
2	Penn DOT 5 GG (33) 800 F	PennDOT 5	800 F	½ in. thick web Flame jet and material tests
2	Penn DOT 5 II (35) 1200 F	PennDOT 5	1200 F	½ in. thick web Flame jet and material tests
2	Penn DOT 5 LL (38) Control	PennDOT 5	Control Specimen	½ in. thick flange Material tests only
2	Penn DOT 5 HH (34) 1200 F	PennDOT 5	1200 F	½ in. thick flange Flame jet and material tests
2	Penn DOT 5 JJ (36) 800 F	PennDOT 5	800 F	½ in. thick flange Flame jet and material tests

Part	Specimen ID	Origin	Type or Temperature	Description
3	Acrolon Q (17) Control W	A709	Control Specimen	½ in. thick plate Material tests only
3	Acrolon A (1) 800 W	A709	800 F	½ in. thick plate Flame jet and material tests
3	Acrolon B (2) 1000 W	A709	1000 F	½ in. thick plate Flame jet and material tests
3	Acrolon C (3) 1200 W	A709	1200 F	½ in. thick plate Flame jet and material tests
3	Acrolon D (4) Uncontrolled W	A709	1200 F uncontrolled	½ in. thick plate Flame jet and material tests
3	Acrolon R (18) Control F	A709	Control Specimen	1 in. thick plate Material tests only
3	Acrolon E (5) 800 F	A709	800 F	1 in. thick plate Flame jet and material tests
3	Acrolon F (6) 1000 F	A709	1000 F	1 in. thick plate Flame jet and material tests
3	Acrolon G (7) 1200 F	A709	1200 F	1 in. thick plate Flame jet and material tests
3	Acrolon H (8) Uncontrolled F	A709	1200 F uncontrolled	1 in. thick plate Flame jet and material tests

Part	Specimen ID	Origin	Type or Temperature	Description
4	Carbothane J (10) Control W	A709	Control Specimen	½ in. thick plate Material tests only
4	Carbothane I (9) 1000 W	A709	1000 F	½ in. thick plate Flame jet and material tests
4	Carbothane K (11) 1200 W	A709	1200 F	½ in. thick plate Flame jet and material tests
4	Carbothane L (12) Uncontrolled W	A709	1200 F uncontrolled	½ in. thick plate Flame jet and material tests
4	Carbothane M (13) 800 F	A709	800 F	1 in. thick plate Material tests only
4	Carbothane O (15) 1200 F	A709	1000 F	1 in. thick plate Flame jet and material tests
4	Carbothane P (16) Uncontrolled F	A709	1200 F uncontrolled	1 in. thick plate Flame jet and material tests

4.3 Specimens and Instrumentation

As shown in Figure 4.3, each plate specimen was approximately 10 x 10 in., and was instrumented with two thermocouples. The thermocouples were attached to the center of the specimens on both sides, i.e., (i) the flame side or bottom, and (ii) the non-flame side or top. Two 1/16” holes were drilled just off center in order to allow the thermocouple wires to pass through the plate from the top to minimize flame disturbance on the plate. For the same reason, the holes and the thermocouples are covered with a smooth layer of fiberglass paste.

The thermocouples were connected to a data acquisition unit which recorded temperatures of the surfaces of the plate at user defined time intervals. A thermal imaging camera was also used to visualize the heat intensities in the flame and on the plate surface. The intensity could also be used to determine the highest temperature in the flame and the difference in temperatures in the specimens. An infrared temperature gun was also used to take spot readings of specimen temperatures and compare it with thermocouple measurements.

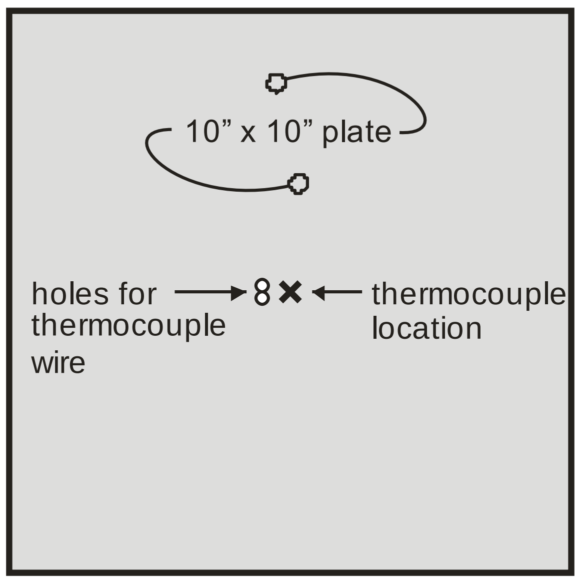


Figure 4.3. Plate Specimen with Thermocouples.

4.4 Post-Fire Evaluation Procedure and Material Testing

All the plate specimens, except those identified as control specimens in Table 4.2 were subjected to controlled fire exposure using the flame jet setup described in Section 4.1. Photographs of the steel plates surfaces (both flame and non-flame side) were taken: (i) before fire exposure, (ii) after fire exposure, (iii) after brushing clean with a wire brush, and (iv) after washing. These photographs constitute physical evidence regarding the appearance of steel bridge elements (plates) with different paint coating systems exposed to fires, and form the basis of post-fire inspection and evaluation guidelines.

After subjecting the plate specimens to controlled fire exposures, material tests were conducted on coupons fabricated according to applicable ASTM standards. As shown in Figure 4.4, from each plate specimen, three Charpy V-notch (CVN) coupons (ASTM E23) were fabricated from the central 3 in., and another three CVN coupons were fabricated from outside the central 3 in. These six CVN coupons were fabricated parallel to the rolling direction with the CVN notch oriented as shown in the Figure. One tension coupon (ASTM E8) is taken from either end of the specimen parallel to the rolling direction. Figure 4.4 shows a drawing of the locations of the material coupons as they were taken from the 10 x 10 in. plate specimens.

Rockwell hardness (ASTM E18) tests were also conducted on all plate specimens. The Rockwell hardness B scale was used for these tests. Three measurements were taken on all specimens as close to the center of the plates as possible. This ensured that the measurements were in the zone of the plate directly affected by flame impingement. Material tests were also conducted on coupons fabricated from the control plate specimens, i.e., plates that were not exposed to fires. These material coupons were also taken as shown in Figure 4.4. The material properties for the control plates were compared with those obtained for the fire exposed plates to evaluate the effects of fire exposures and other parameters on the yield strength, tensile strength, elongation at rupture, fracture toughness, and surface hardness of the steel materials

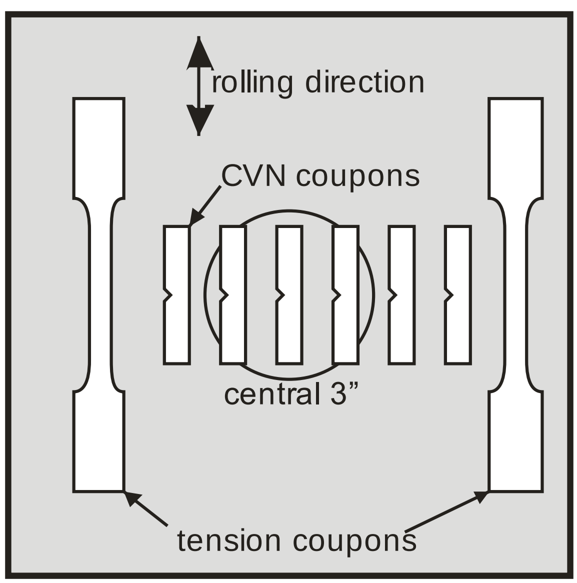


Figure 4.4. Layout of Material Coupons Taken From Plate Specimens

5.0 EXPERIMENTAL RESULTS

5.1 Post-Fire Evaluation of Plate Specimens – Part 1

Figures 5.1-1 to 5.1-4 show photographs of the post-fire evaluation of the plate specimens (Part 1) identified in Table 4.2-1 and listed below. These include photographs taken as described in Section 4.4.

Part	**Specimen ID**	**Origin**	**Type or Temperature**	**Description**
1	Penn DOT 3 S (19) 800 F	PennDOT 3	800 F	½ in. thick web Flame jet and material tests
1	Penn DOT 3 T (20) 1200 F	PennDOT 3	1200 F	½ in. thick web Flame jet and material tests
1	Penn DOT 3 V (22) 800 F	PennDOT 3	800 F	¾ in. thick flange Flame jet and material tests
1	Penn DOT 3 W (23) 1200 F	PennDOT 3	1200 F	¾ in. thick flange Flame jet and material tests

Figures 5.1-5 and 5.1-6 show the measured temperature-time (T-t) curves for these plate specimens with ½ in. and 3/4 in. thickness, respectively. As shown the target temperatures were achieved and maintained for 20 minutes before cooling. The target time of 20 minutes is representative of the typical fire duration that can cause collapse of a bridge; for example, consider the Oakland, California bridge discussed earlier in Section 2.0.

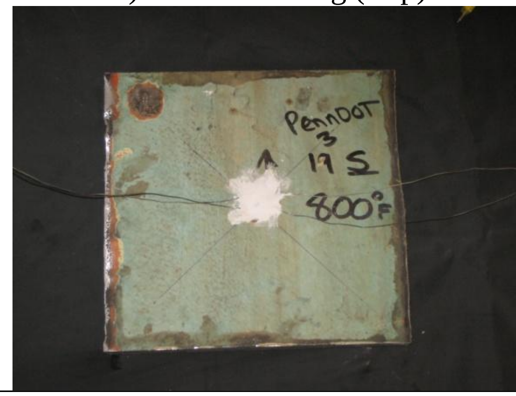
Additionally, Table 5.1-1 includes the standard material test results obtained from testing the coupons fabricated from the plate specimens identified in Table 4.2-1. These material test results included the results from tests conducted on coupons from plates that were already burned by the real fire event, and hence not subjected to additional fire exposure.

As shown in Table 5.1-1, fire exposures have only a minor effect on the steel yield strength, ultimate strength and elongation, and surface hardness. This is irrespective of the steel surface temperature achieved during the fire exposure tests and the steel plate thickness. Additionally, as shown in Table 5.1-1, the fire exposures result in only a slight reduction in the CVN fracture toughness values for the steels. The reduction is slightly higher for the thicker (3/4 in. thick) steel plates.

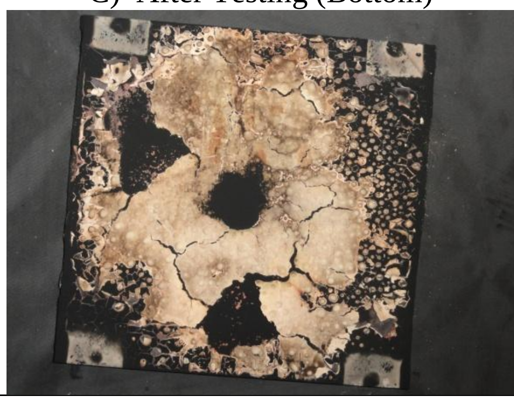
Figures 5.1-7 and 5.1-8 shows box plots that can be used to more comprehensively evaluate the effects of fire exposure on the CVN fracture toughness of steels. These figures focus on ½ in. thick and 3/4 in. thick steel plates that had been subjected to controlled fire exposure using the flame jet setup. The box plots include for each plate specimen: (i) the minimum, maximum, and median values of fracture toughness, and (ii) the first and third quartile fracture toughness values. The first quartile means that 25% of the values will be lower than this value, and third quartile means 75% of the values will be lower than this value. These Figures 5.1-7 and 5.1-8 show that the fire exposures do not have a statistically significant effect on the CVN fracture toughness of steels, which numerically still satisfies the 15 ft-lb limit for Zone 2 (AASHTO 2010 §6.6.2).

A) Before Testing (Bottom)

B) Before Testing (Top)

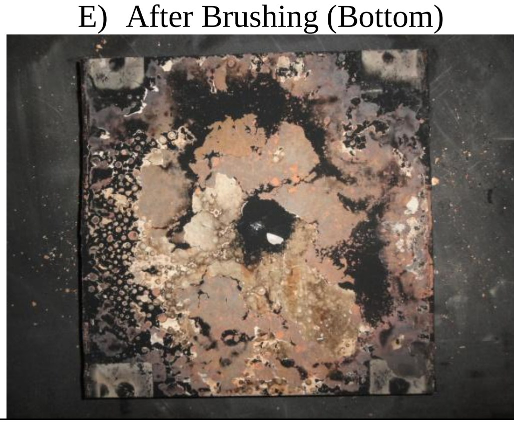


C) After Testing (Bottom)

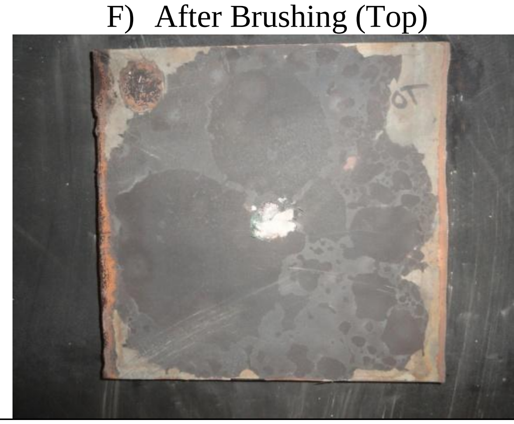


D) After Testing (Top)

E) After Brushing (Bottom)



F) After Brushing (Top)

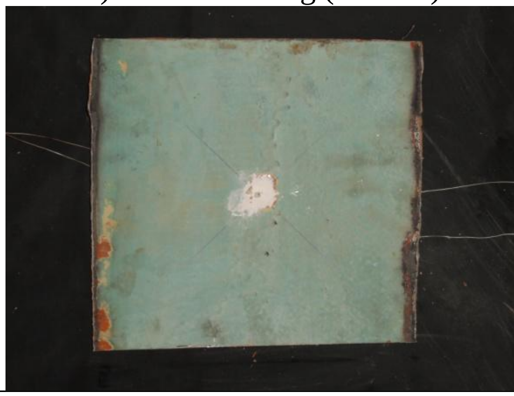


G) After Washing (Bottom)

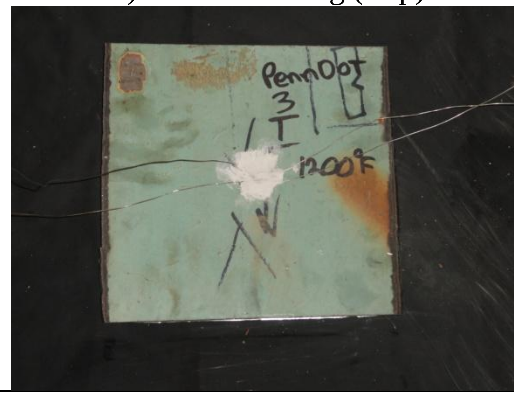
H) After Washing (Top)

Figure 5.1-1. Post-Fire Evaluation of Penn DOT 3 S (19) 800^{o}F

A) Before Testing (Bottom)

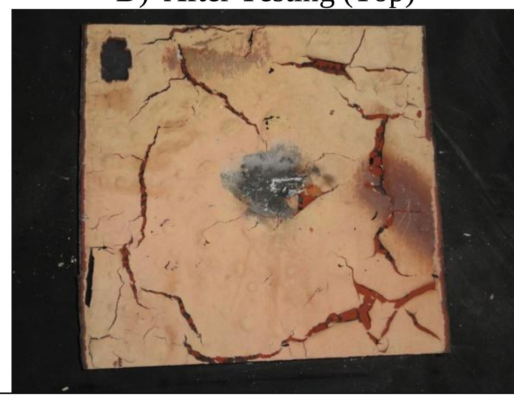


B) Before Testing (Top)



C) After Testing (Bottom)

D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)

G) After Washing (Bottom)

H) After Washing (Top)

Figure 5.1-2. Post-Fire Evaluation of Penn DOT 3 T (20) 1200°F

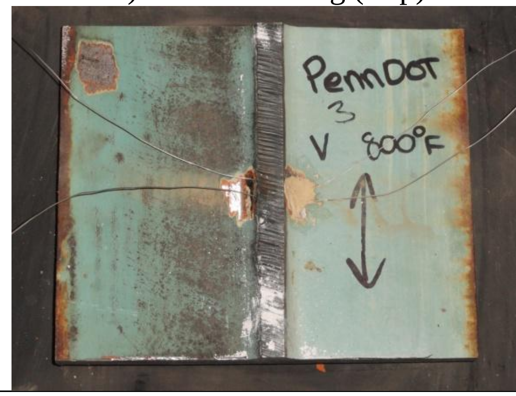
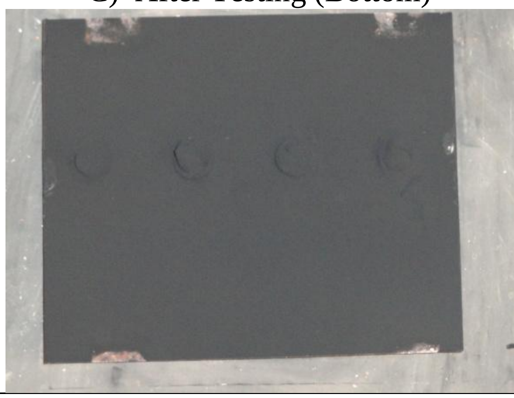
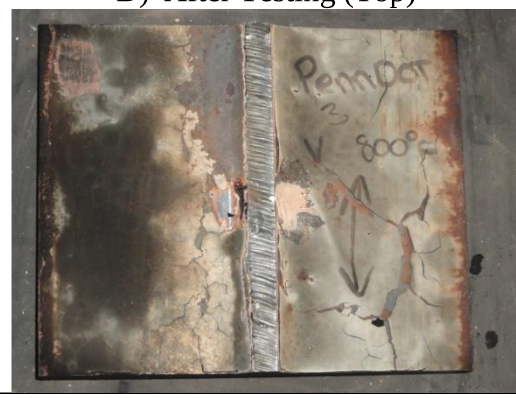
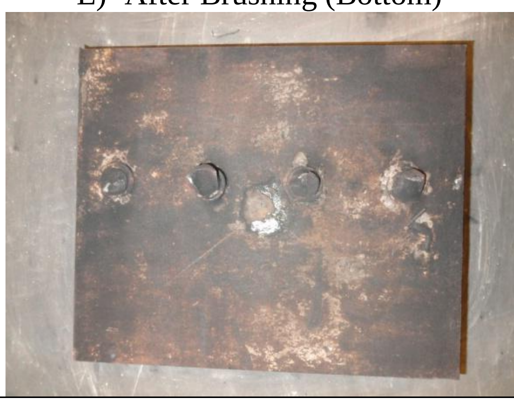
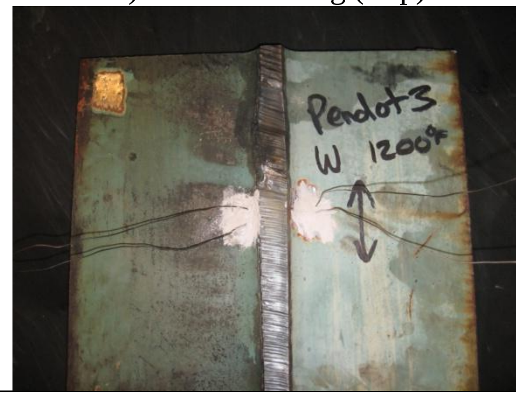
A) Before Testing (Bottom)	B) Before Testing (Top)
	
C) After Testing (Bottom)	D) After Testing (Top)
	
E) After Brushing (Bottom)	F) After Brushing (Top)
	
G) After Washing (Bottom)	H) After Washing (Top)
	

Figure 5.1-3. Post-Fire Evaluation of Penn DOT 3 V (22) 800^{o}F

A) Before Testing (Bottom)

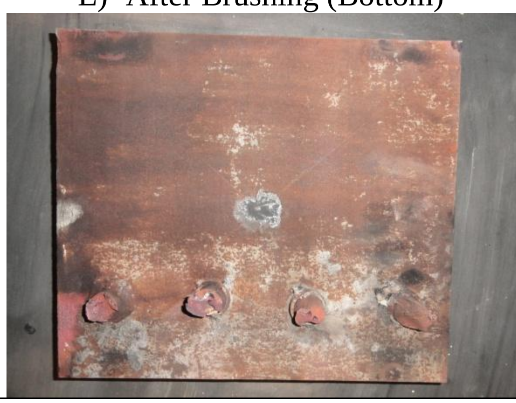
B) Before Testing (Top)



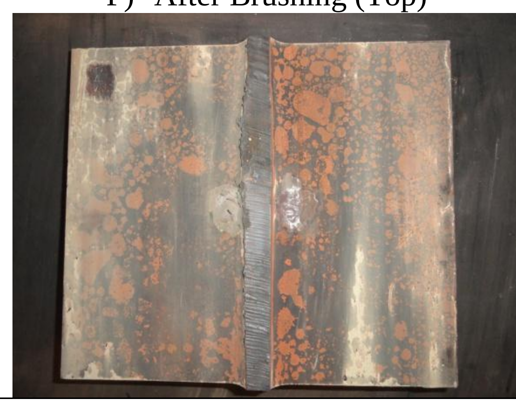
C) After Testing (Bottom)

D) After Testing (Top)

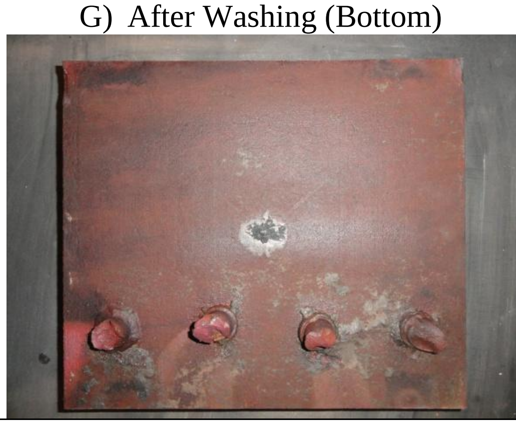
E) After Brushing (Bottom)



F) After Brushing (Top)



G) After Washing (Bottom)



H) After Washing (Top)

Figure 5.1-4. Post-Fire Evaluation of Penn DOT 3 W (23) 1200^{o}F

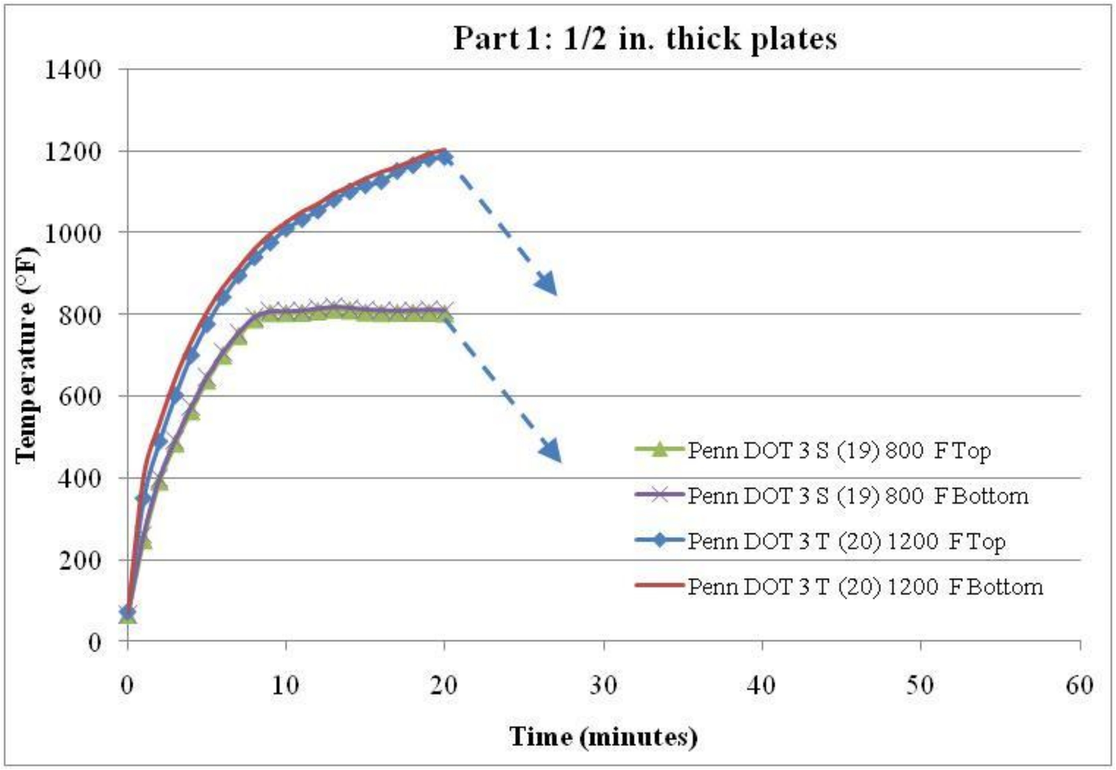


Figure 5.1-5 Measured Temperature-Time Curves for ½ in. Thick Part 1 Plate Specimens

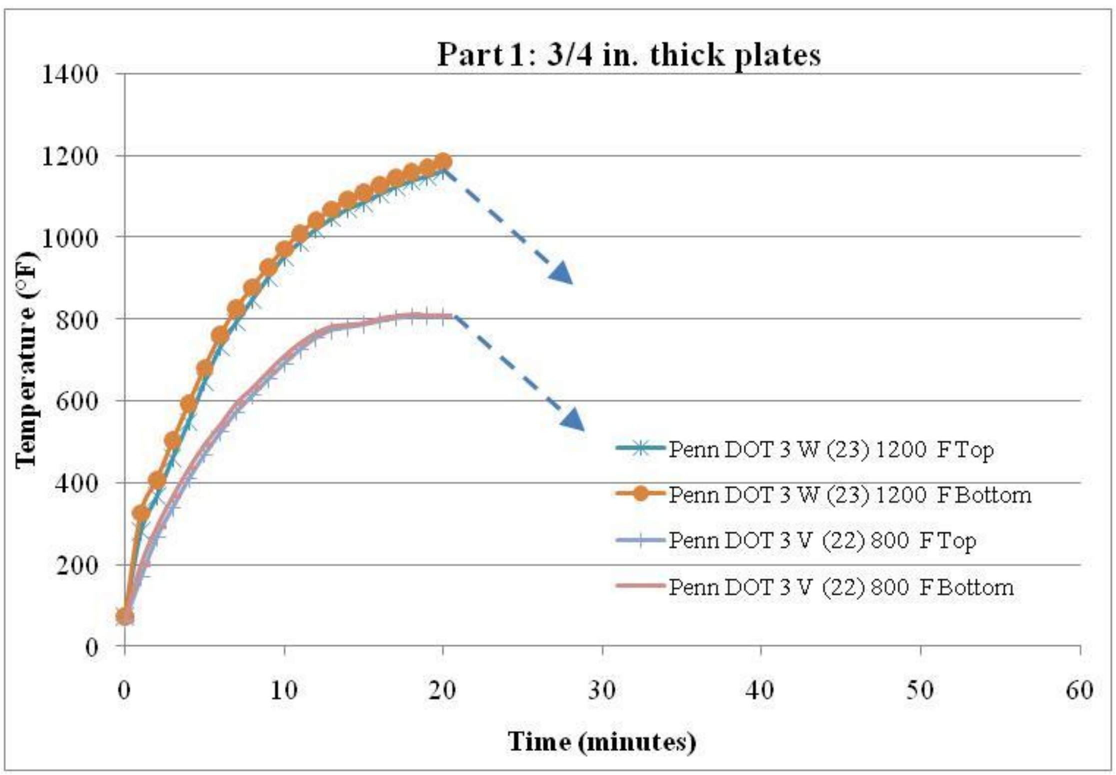


Figure 5.1-6. Measured Temperature-Time Curves for 3/4 in. Thick Part 1 Plate Specimen

Table 5.1-1 Material Test Results for Coupons from Plate Specimens (Part 1)

Specimen ID		σ_y	σ_u	%e	CVN results				AVG	Hardness Test				AVG
Penn DOT 2 AA (27) Control ½ in. thickness	**Coupon 1**	**36.3**	**64**	**42**	**Inner 3**	**42**	**47**	**52**	**47.0**	**Top**	**71**	**70.5**	**70**	**70.5**
	Coupon 2	**40.4**	**64**	**41**	**Outer 3**	**53**	**42**	**54**	**49.7**	**Bottom**	**70**	**71.5**	**71**	**70.8**
Penn DOT 1 Y (25) Burned ½ in. thickness	Coupon 1	40.6	64.5	44	Inner 3	29	44	43	38.7	Top	69	70.5	70.5	70
	Coupon 2	34.8	64.5	41	Outer 3	34	20	30	28.0	Bottom	71	72	73	72
Penn DOT 4 EE (31) Burned ½ in. thickness	Coupon 1	40.3	63	43	Inner 3	32	40	29	33.7	Top	67	71	70	69.3
	Coupon 2	35.9	62	43	Outer 3	21	41	36	32.7	Bottom	64.5	65.5	66	65.3
Penn DOT 2 BB (28) Control ¾ in. thickness	**Coupon 1**	**36.1**	**63**	**50**	**Inner 3**	**42**	**67**	**60**	**56.3**	**Top**	**62**	**58.5**	**64**	**61.5**
	Coupon 2	**37**	**62**	**48**	**Outer 3**	**43**	**52**	**65**	**53.3**	**Bottom**	**55**	**62**	**71**	**62.6**
Penn DOT 1 Z (26) Burned ¾ in. thickness	Coupon 1	36.5	64.5	50	Inner 3	61	45	62	56.0	Top	68	71.5	70	69.8
	Coupon 2	36.9	64	50	Outer 3	32	45	66	47.7	Bottom	70	69.5	69	69.5
Penn DOT 4 FF (32) Burned ¾ in. thickness	Coupon 1	36.4	62.5	50	Inner 3	44	57	40	47.0	Top	60	65	66.5	63.8
	Coupon 2	63	41.1	50	Outer 3	53	54	64	57.0	Bottom	65.5	66.5	68.5	66.8
Penn DOT 3 CC (29) Control ½ in. thickness	**Coupon 1**	**38.4**	**61**	**42**	**Inner 3**	36	37	43	38.7	**Top**	**68**	**68**	**70**	**68.6667**
	Coupon 2	**36.5**	**60.5**	**45**	**Outer 3**	52	15	18	28.3	**Bottom**	**68.5**	**68**	**67.5**	**68**
Penn DOT 3 S (19) 800°F ½ in. thickness	Coupon 1	41.5	62.5	44	Inner 3	29	44	43	38.7	Top	71	71	71	71
	Coupon 2	34.2	61.5	34	Outer 3	34	20	30	28.0	Bottom	70.5	70.5	70.5	70.5
Penn DOT 3 T (20) 1200°F ½ in. thickness	Coupon 1	40.7	62	45	Inner 3	35	40	39	38.0	Top	63	68	69.5	66.8
	Coupon 2	37.1	61.5	42	Outer 3	30	48	31	36.3	Bottom	65	68	70	67.6
Penn DOT 3 DD (30) Control ¾ in. thickness	**Coupon 1**	**38.9**	**63.5**	**47**	**Inner 3**	**71**	**62**	**56**	**63.0**	**Top**	**66.5**	**67**	**67**	**66.8**
	Coupon 2	**36.3**	**63**	**45**	**Outer 3**	**46**	**66**	**60**	**57.3**	**Bottom**	**74**	**73**	**76**	**74.3**
PennDOT 3 V (22) 800°F ¾ in. thickness														
Penn DOT 3 W (23) 1200°F ¾ in. thickness	Coupon 1	36.5	62.5	49	Inner 3	34	14	40	29.3	Top	75.5	73	72	73.5
	Coupon 2	39.3	63	50	Outer 3	41	43	43	42.3	Bottom	76	77	75	76.0

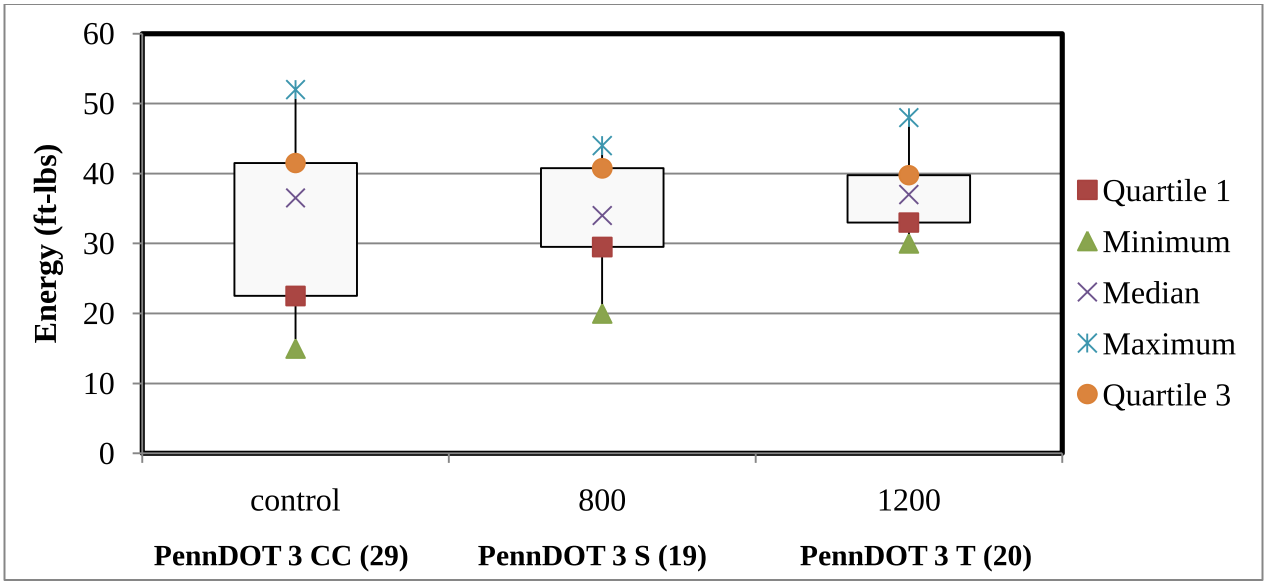


Figure 5.1-7. Statistical Evaluation of CVN Fracture Toughness Values for 1/2 in. thick Plate Specimens (Part 1)

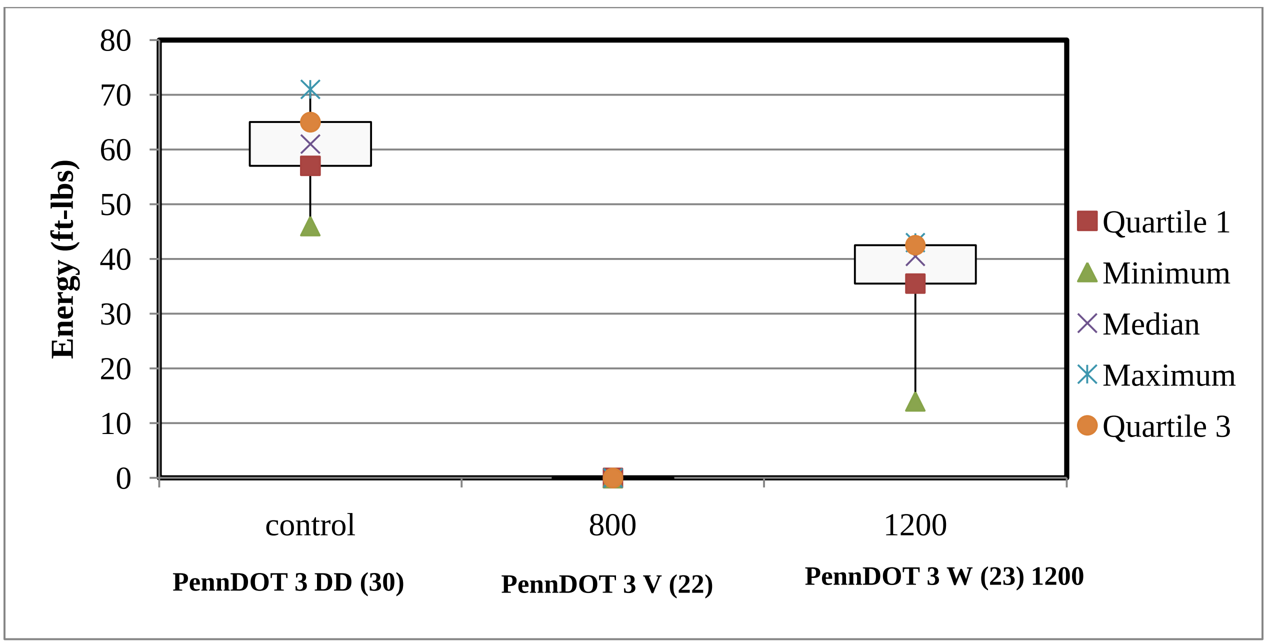


Figure 5.1-8. Statistical Evaluation of CVN Fracture Toughness Values for ¾ in. thick Plate Specimens (Part 1)

5.2 Post-Fire Evaluation of Plate Specimens – Part 2

Figures 5.2-1 to 5.2-4 show photographs of the post-fire evaluation of the plate specimens (Part 2) identified in Table 4.2-1 and listed below. These include photographs taken as described in Section 4.4.

2	Penn DOT 5 GG (33) 800 F	PennDOT 5	800 F	½ in. thick web Flame jet and material tests
2	Penn DOT 5 II (35) 1200 F	PennDOT 5	1200 F	½ in. thick web Flame jet and material tests
2	Penn DOT 5 HH (34) 1200 F	PennDOT 5	1200 F	½ in. thick flange Flame jet and material tests
2	Penn DOT 5 JJ (36) 800 F	PennDOT 5	800 F	½ in. thick flange Flame jet and material tests

Figures 5.2-5 and 5.2-6 show the measured temperature-time (T-t) curves for these plate specimens with ½ in. thick webs and flanges, respectively. As shown the target temperatures were achieved and maintained for 20 minutes before cooling.

Additionally, Table 5.2-1 includes the standard material test results obtained by testing the coupons fabricated from the ½ in. thick plate specimens identified in Table 4.2-1. As shown in Table 5.2-1, fire exposures have only a minor effect on the steel yield strength, ultimate strength and elongation, and surface hardness. This is irrespective of the steel surface temperature achieved during the fire exposure tests. Additionally, as shown in Table 5.2-1, the fire exposures result in only a slight reduction in the CVN fracture toughness values for the steels.

Figures 5.2-7 and 5.2-8 shows box plots that can be used to more comprehensively evaluate the effects of fire exposure on the CVN fracture toughness of steels. These figures focus on ½ in. thick webs and the 1/2 in. thick flange steel plates that had been subjected to controlled fire exposure using the flame jet setup. The box plots include for each plate specimen: (i) the minimum, maximum, and median values of fracture toughness, and (ii) the first and third quartile fracture toughness values. The first quartile means that 25% of the values will be lower than this value, and third quartile means 75% of the values will be lower than this value. These Figures show that the fire exposures do not have a statistically significant effect on the CVN fracture toughness of steels, which numerically still satisfies the 15 ft-lb limit for Zone 2 (AASHTO 2010 §6.6.2).

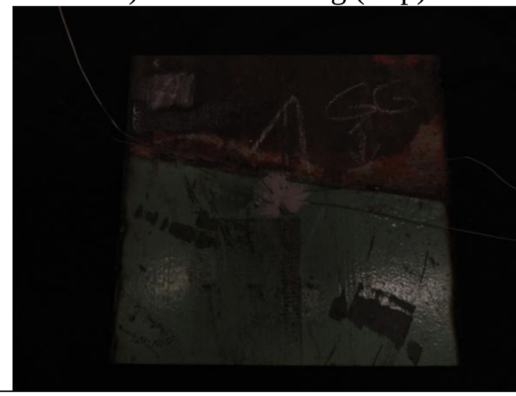
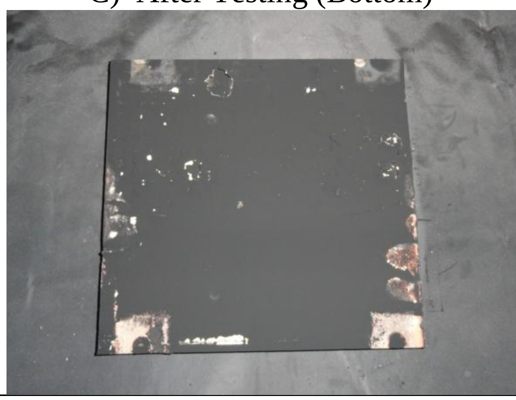
A) Before Testing (Bottom)	B) Before Testing (Top)
	
C) After Testing (Bottom)	D) After Testing (Top)
	
E) After Brushing (Bottom)	F) After Brushing (Top)
	
G) After Washing (Bottom)	H) After Washing (Top)
	

Figure 5.2-1. Post-Fire Evaluation of Penn DOT 5 GG (33) 800^{o}F

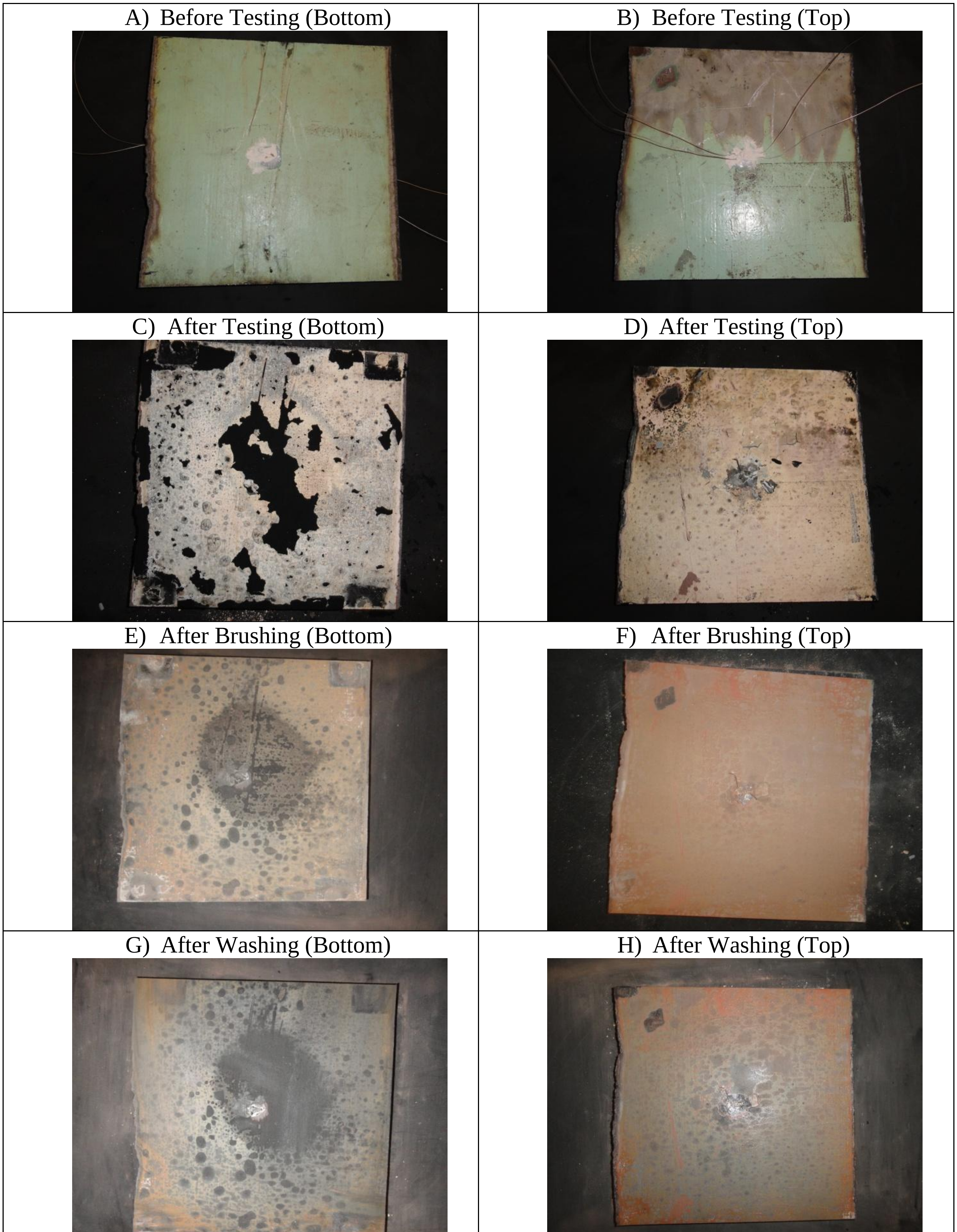
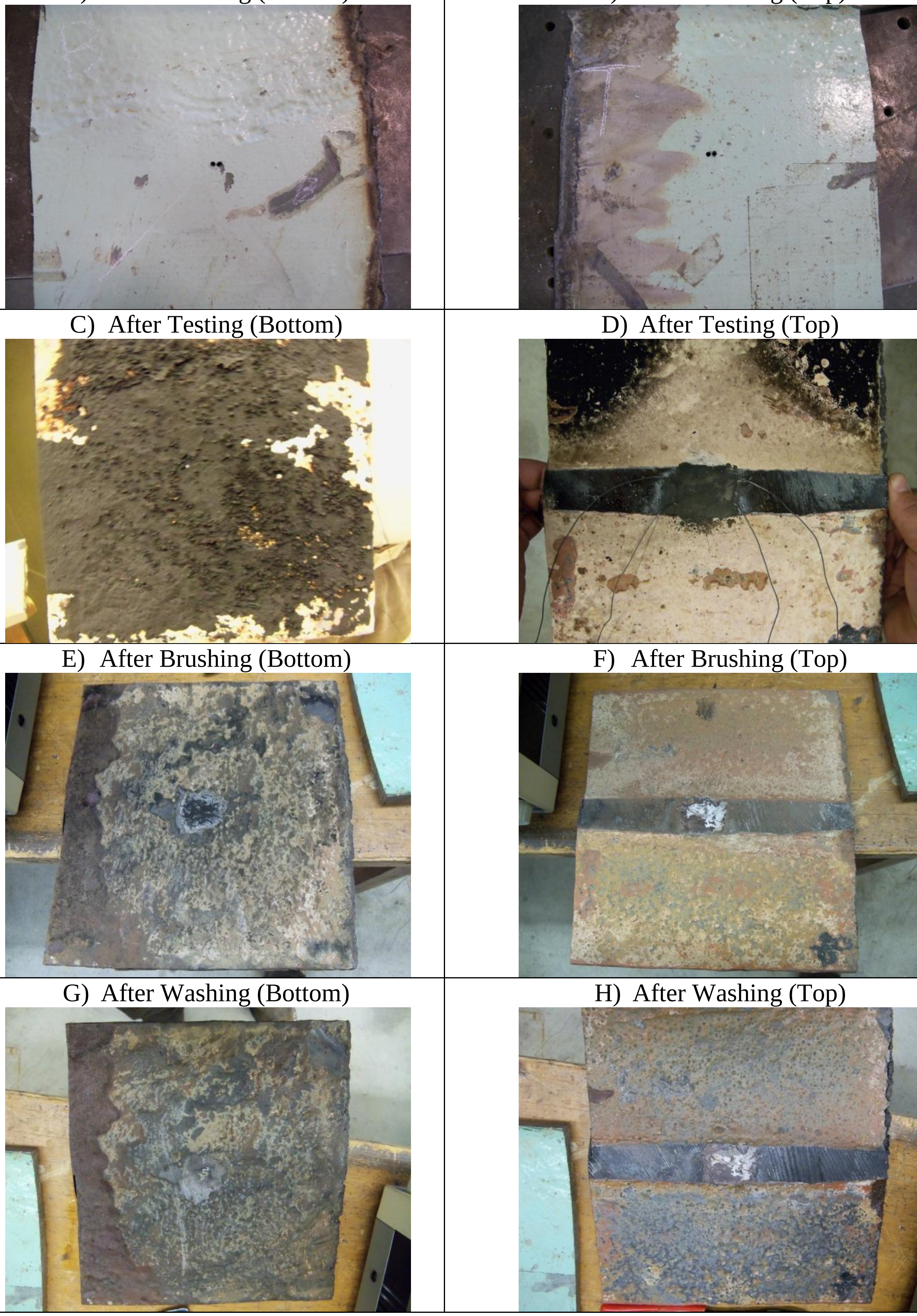


Figure 5.2-2. Post-Fire Evaluation of Penn DOT 5 II (35) 1200^{o}F



A) Before Testing (Bottom)

B) Before Testing (Top)

C) After Testing (Bottom)

D) After Testing (Top)

E) After Brushing (Bottom)

F) After Brushing (Top)

G) After Washing (Bottom)

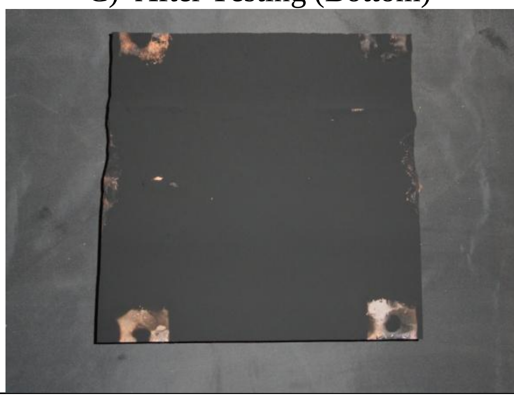
H) After Washing (Top)

Figure 5.2-3. Post-Fire Evaluation of Penn DOT 5 HH (34) 1200^{o}F

A) Before Testing (Bottom)

B) Before Testing (Top)

C) After Testing (Bottom)



D) After Testing (Top)

E) After Brushing (Bottom)

F) After Brushing (Top)

G) After Washing (Bottom)

H) After Washing (Top)

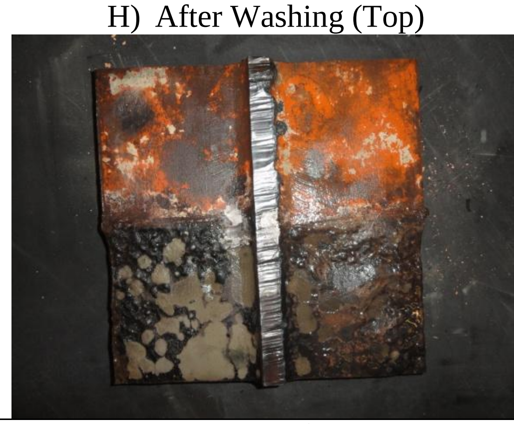


Figure 5.2-4. Post-Fire Evaluation of Penn DOT 5 JJ (36) 800^{o}F

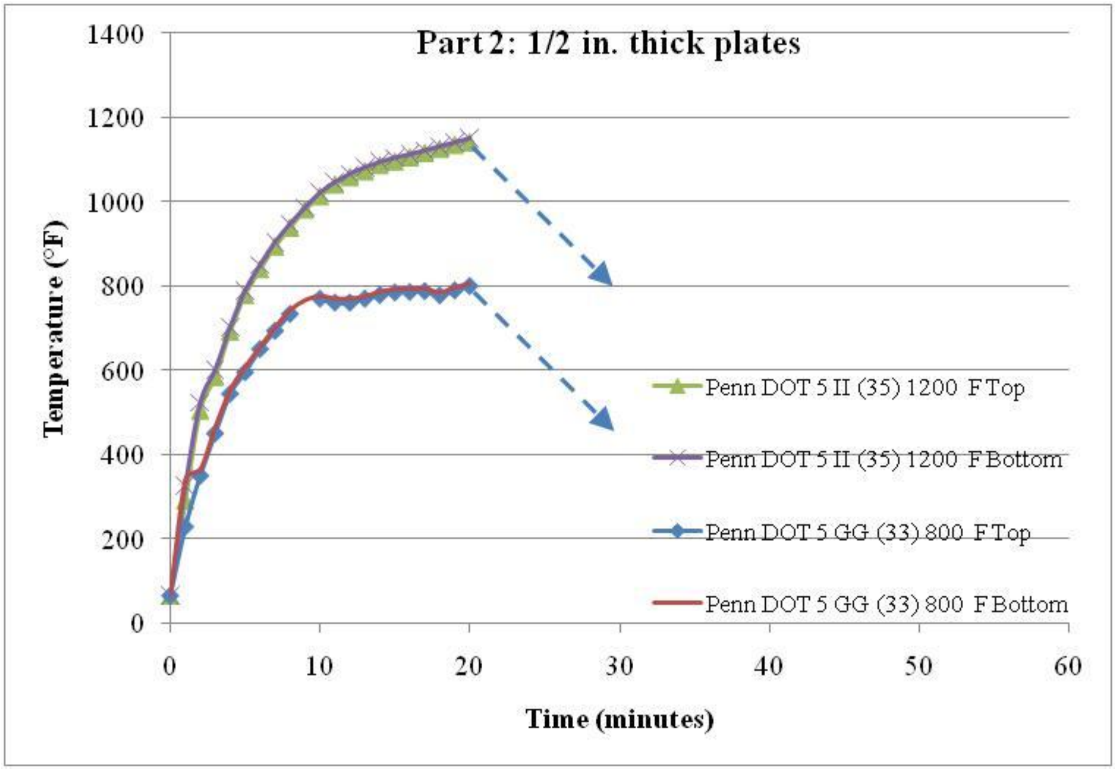


Figure 5.2-5 Measured Temperature-Time Curves for ½ in. Thick Part 2 Plate Specimens (Web)

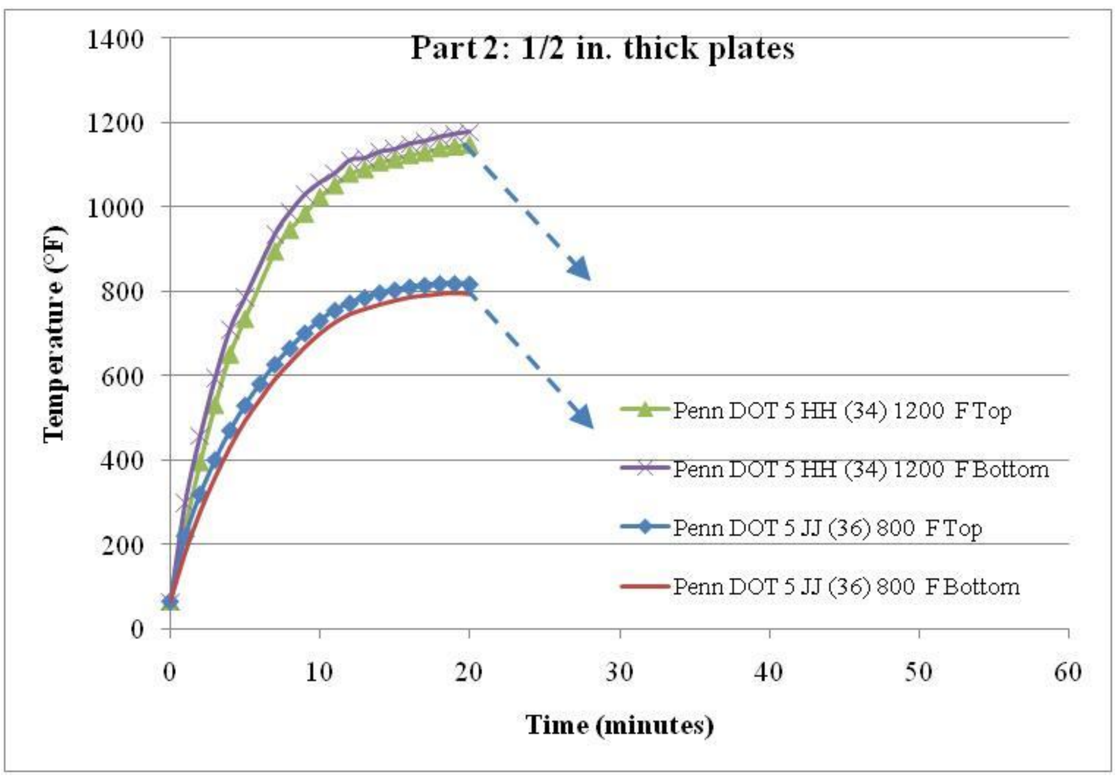


Figure 5.2-6. Measured Temperature-Time Curves for ½ in. Thick Part 2 Plate Specimens (Flanges)

Table 5.2-1 Material Test Results for Coupons from Part 2 Plate Specimens

Specimen ID		σy	σu	%e	CVN results				AVG	Harndness Test				AVG
Penn DOT 5 KK (37) Control ½ in. plate thickness (web)	**Coupon 1**	**48.3**	**71.5**	**44**	**Inner 3**	**65**	**54**	**46**	**55.0**	**Top**	**75**	**74.5**	**75**	**74.8333**
	Coupon 2	**45**	**71.5**	**40**	**Outer 3**	**65**	**34**	**37**	**45.3**	**Bottom**	**73.5**	**75**	**72.5**	**73.6667**
Penn DOT 5 GG (33) 800°F ½ in. plate thickness (web)	Coupon 1	48.2	71.5	37	Inner 3	64	60	50	58.0	Top	75	73.5	75	74.5
	Coupon 2	42.3	72.5	39	Outer 3	67	30	32	43.0	Bottom	76	76	71	74.3333
Penn DOT 5 II (35) 1200°F ½ in. plate thickness (web)	Coupon 1	47.8	71	41	Inner 3	50	60	64	58.0	Top	72.5	73	73	72.8333
	Coupon 2	43.3	71.5	42	Outer 3	30	69	65	54.7	Bottom	69.5	73	75.5	72.6667
Penn DOT 5 LL (38) Control ½ in. plate thickness (flange)	**Coupon 1**	**45.4**	**70.5**	**29**	**Inner 3**	**41**	**35**	**29**	**35.0**	**Top**	**70**	**68.5**	**70**	**69.5**
	Coupon 2	**44.2**	**69**	**42**	**Outer 3**	**47**	**28**	**38**	**37.7**	**Bottom**	**67**	**67.5**	**68.5**	**67.6667**
Penn DOT 5 JJ (36) 800°F ½ in. plate thickness (flange)	Coupon 1	43	70	39	Inner 3	38	25	34	32.3	Top	65	69	70.5	68.2
	Coupon 2	41.8	68.5	41	Outer 3	38	27	48	37.7	Bottom	60	66	62	62.6
Penn DOT 5 HH (34) 1200°F ½ in. plate thickness (flange)	Coupon 1	42.8	67.5	46	Inner 3	10	21	30	20.3	Top	73	74	72.5	73.2
	Coupon 2	39.6	66.5	46	Outer 3	48	25	34	35.7	Bottom	70.5	72	69.5	70.6

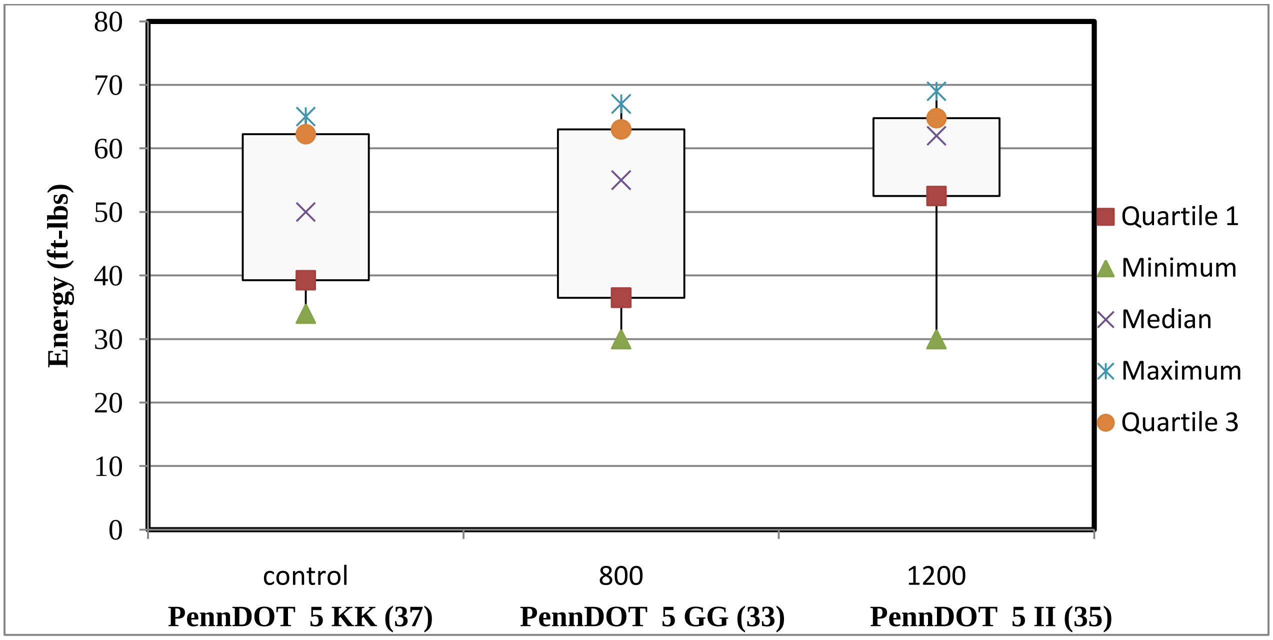


Figure 5.2-7. Statistical Analysis of CVN Fracture Toughness for Part 2 Plate Specimens (1/2 in. thick webs)

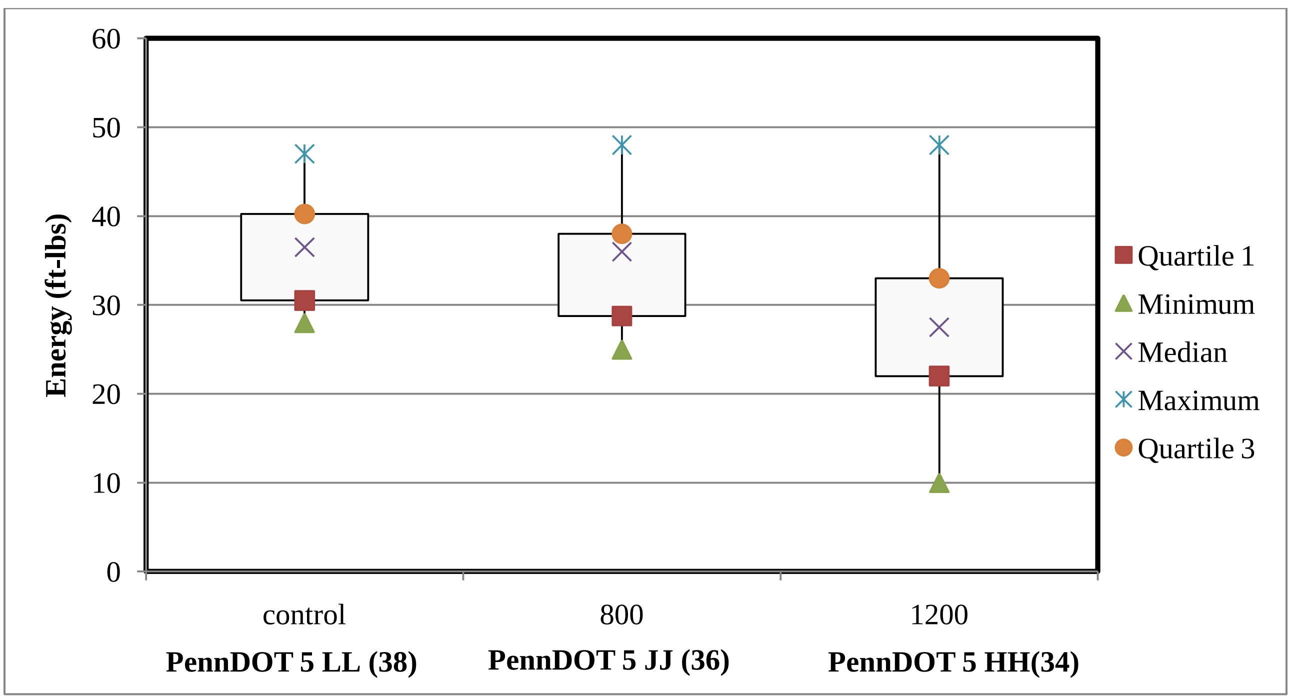


Figure 5.2-8. Statistical Analysis of CVN Fracture Toughness for Part 2 Plate Specimens (1/2 in. thick flanges)

5.3 Post-Fire Evaluation of Plate Specimens – Part 3[1]

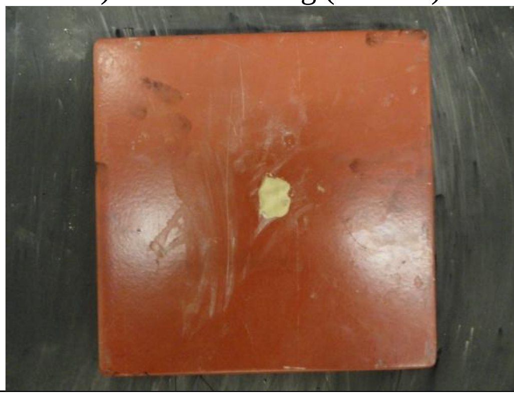
Figures 5.3-1 to 5.3-8 show photographs of the post-fire evaluation of the plate specimens (Part 3) identified in Table 4.2-1 and listed below. These include photographs taken as described in Section 4.4.

Part	**Specimen ID**	**Origin**	**Type or Temperature**	**Description**
3	Acrolon A (1) 800 W	A709	800 F	½ in. thick plate Flame jet and material tests
3	Acrolon B (2) 1000 W	A709	1000 F	½ in. thick plate Flame jet and material tests
3	Acrolon C (3) 1200 W	A709	1200 F	½ in. thick plate Flame jet and material tests
3	Acrolon D (4) Uncontrolled W	A709	1200 F uncontrolled	½ in. thick plate Flame jet and material tests
3	Acrolon E (5) 800 F	A709	800 F	1 in. thick plate Flame jet and material tests
3	Acrolon F (6) 1000 F	A709	1000 F	1 in. thick plate Flame jet and material tests
3	Acrolon G (7) 1200 F	A709	1200 F	1 in. thick plate Flame jet and material tests
3	Acrolon H (8) Uncontrolled F	A709	1200 F uncontrolled	1 in. thick plate Flame jet and material tests

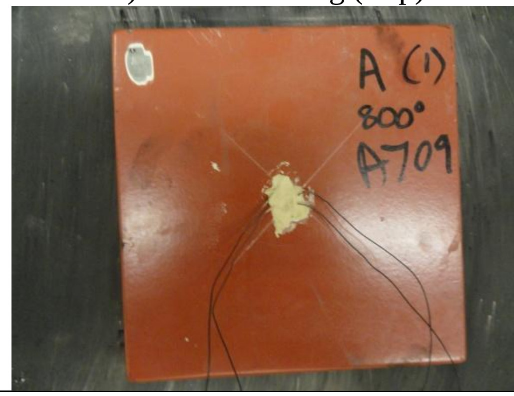
Figures 5.3-9 and 5.3-10 show the measured temperature-time (T-t) curves for the ½ in. thick and 1 in. thick plate specimens, respectively. As shown the target temperatures of 800, 1000, and 1200 ^{o}F were achieved and maintained for 20 minutes before cooling. The uncontrolled fire test reached a maximum temperature of 1200 ^{o}F also, and was allowed to continue (burn out) for 40 minutes before cooling.

[1] CVN tests for these specimens were delayed and not available at the time of report submission. An addenda and amended report will be issued with these data when they are available

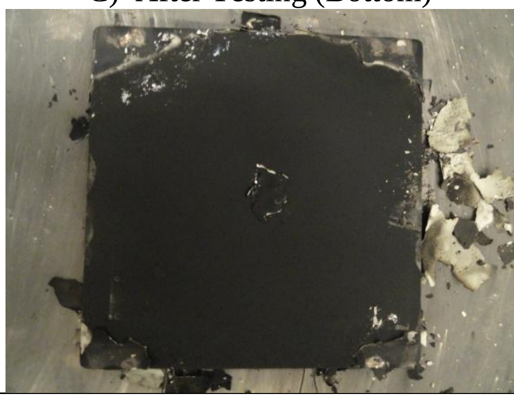
A) Before Testing (Bottom)



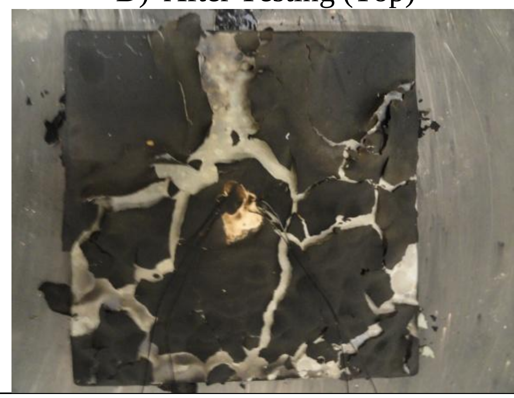
B) Before Testing (Top)



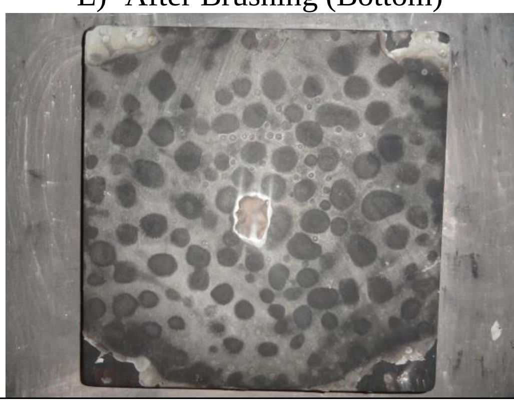
C) After Testing (Bottom)



D) After Testing (Top)



E) After Brushing (Bottom)



F) After Brushing (Top)

G) After Washing (Bottom)

H) After Washing (Top)

Figure 5.3-1. Post-Fire Evaluation of Acrolon A (1) 800°F

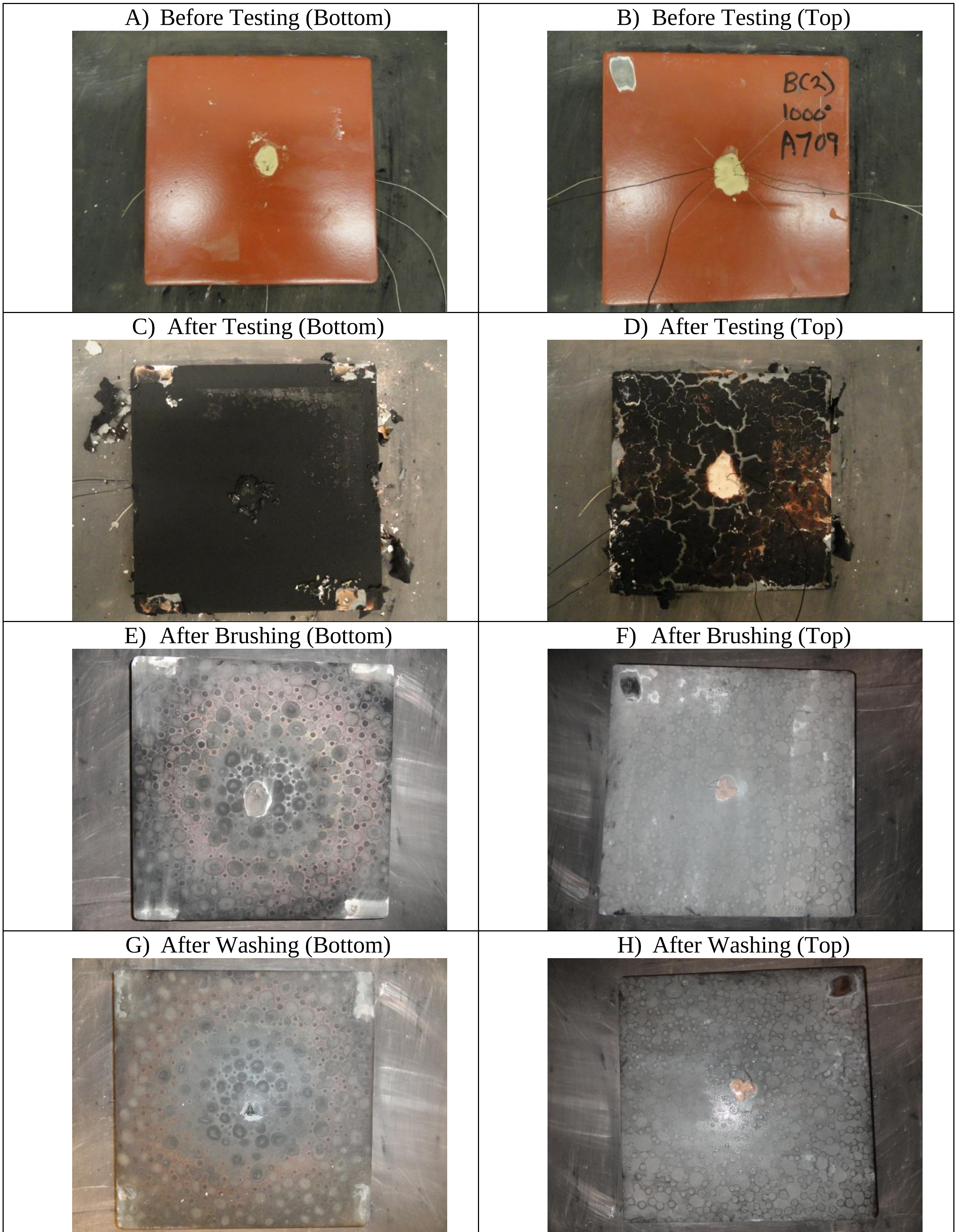


Figure 5.3-2. Post-Fire Evaluation of Acrolon B (2) 1000^{o}F

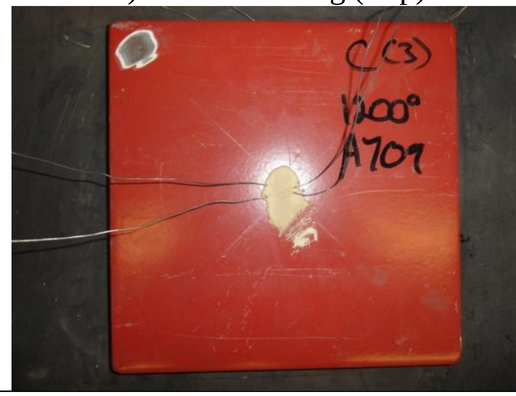
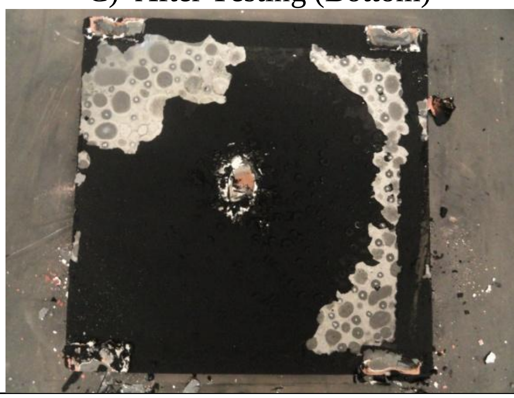
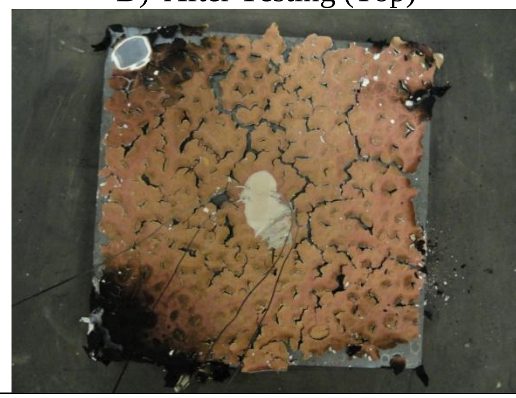
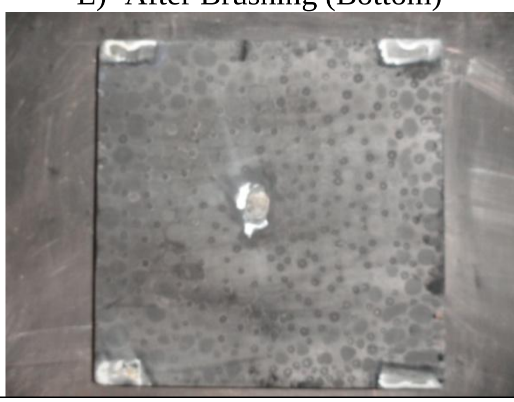
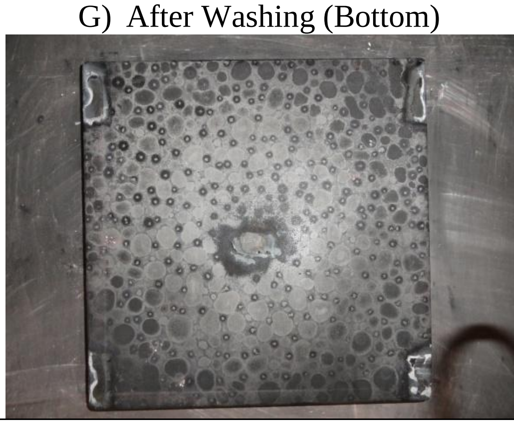
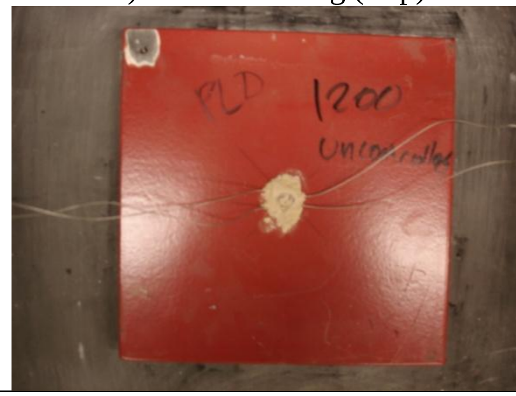
A) Before Testing (Bottom)	B) Before Testing (Top)
	
C) After Testing (Bottom)	D) After Testing (Top)
	
E) After Brushing (Bottom)	F) After Brushing (Top)
	
G) After Washing (Bottom)	H) After Washing (Top)
	

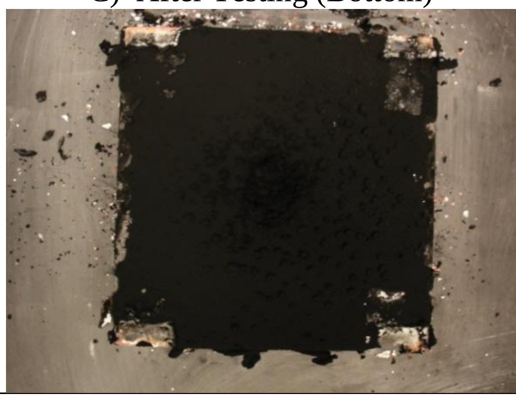
Figure 5.3-3. Post-Fire Evaluation of Acrolon C (3) 1200^{o}F

A) Before Testing (Bottom)

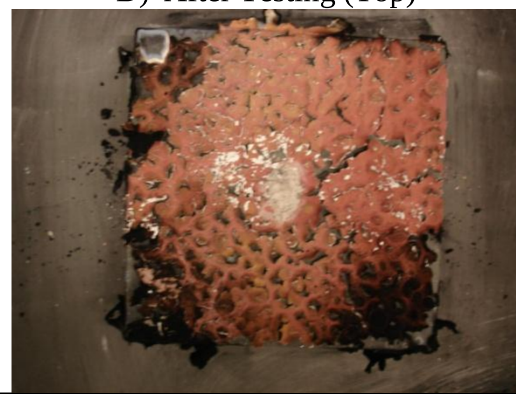
B) Before Testing (Top)



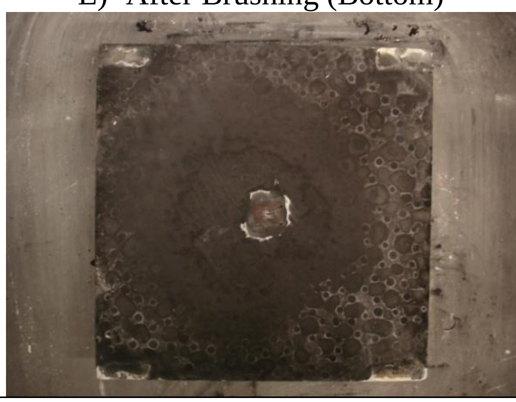
C) After Testing (Bottom)



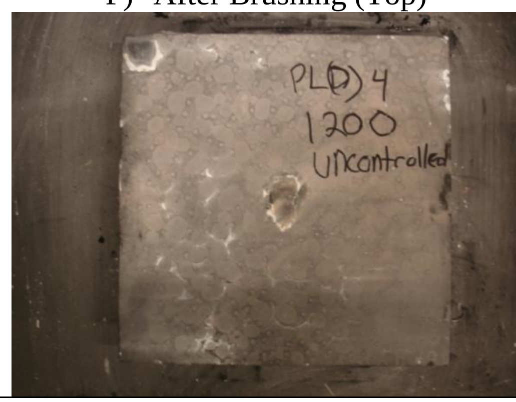
D) After Testing (Top)



E) After Brushing (Bottom)



F) After Brushing (Top)



G) After Washing (Bottom)

H) After Washing (Top)

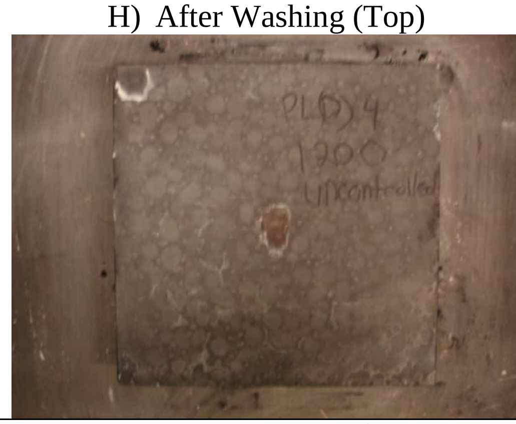
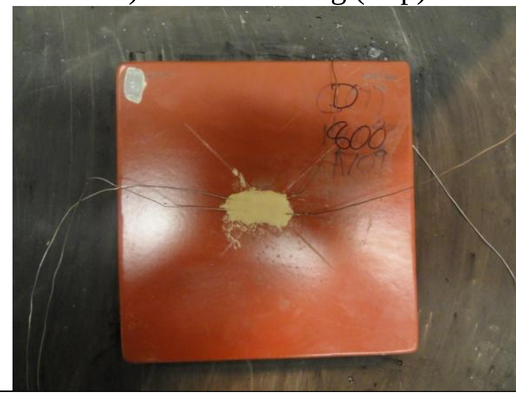


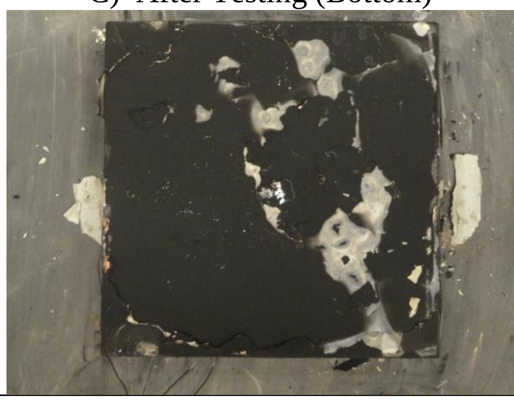
Figure 5.3-4. Post-Fire Evaluation of Acrolon D (4) Uncontrolled 1200^{o}F

A) Before Testing (Bottom)

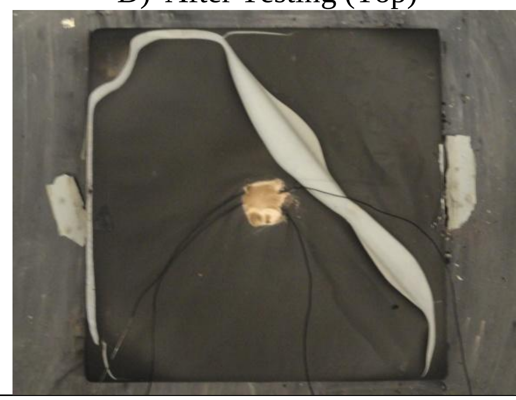
B) Before Testing (Top)



C) After Testing (Bottom)

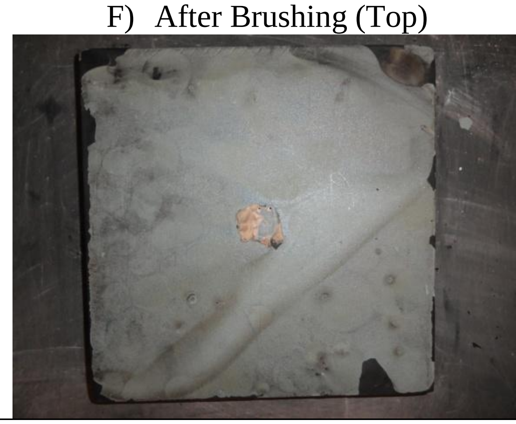


D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)

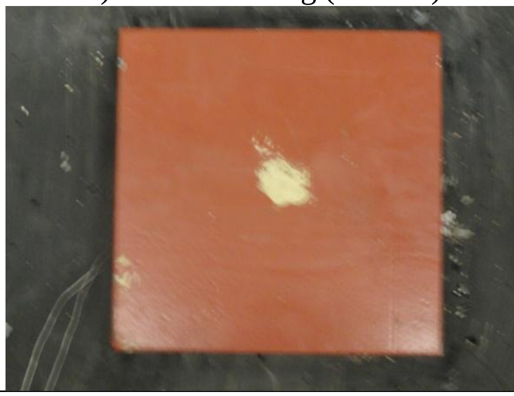


G) After Washing (Bottom)

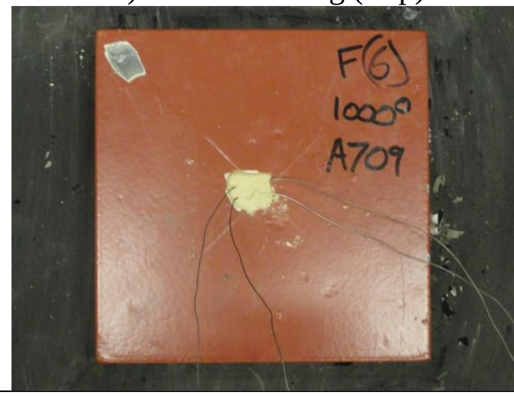
H) After Washing (Top)

Figure 5.3-5. Post-Fire Evaluation of Acrolon E (5) 800^{o}F

A) Before Testing (Bottom)

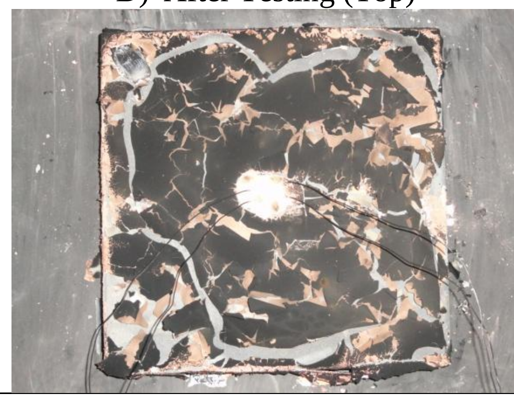


B) Before Testing (Top)



C) After Testing (Bottom)

D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)

G) After Washing (Bottom)

H) After Washing (Top)

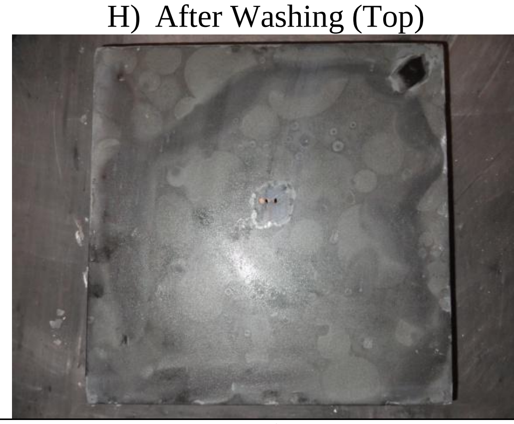
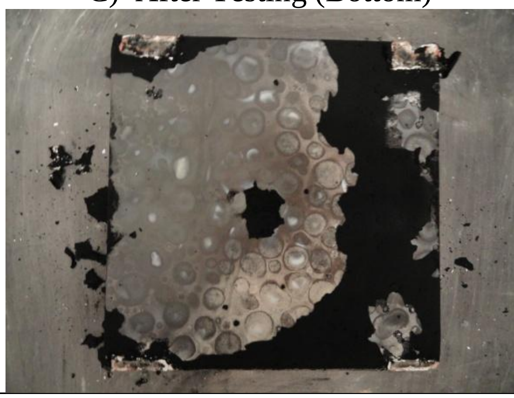


Figure 5.3-6. Post-Fire Evaluation of Acrolon F (6) 1000^{o}F

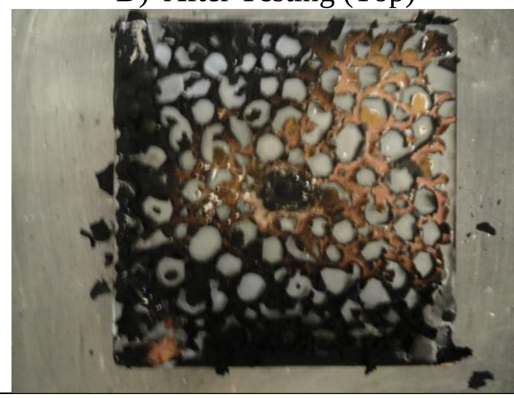
A) Before Testing (Bottom)

B) Before Testing (Top)

C) After Testing (Bottom)



D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)

G) After Washing (Bottom)

H) After Washing (Top)

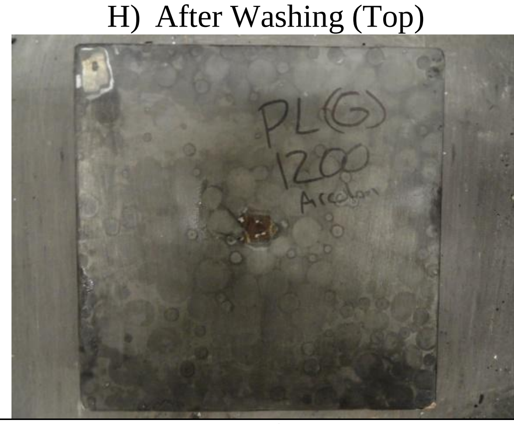
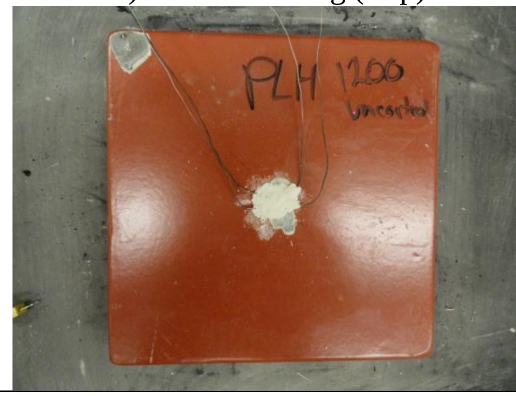


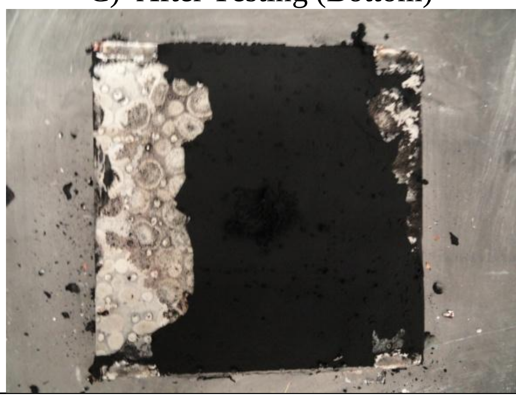
Figure 5.3-7. Post-Fire Evaluation of Acrolon G (7) 1200^{o}F

A) Before Testing (Bottom)

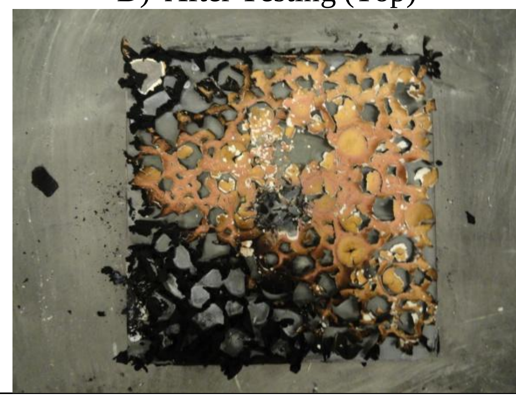
B) Before Testing (Top)



C) After Testing (Bottom)

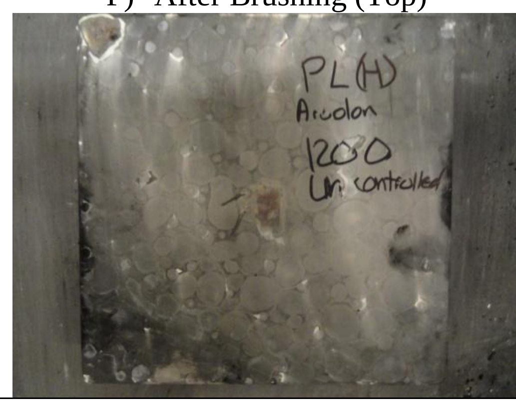


D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)



G) After Washing (Bottom)

H) After Washing (Top)

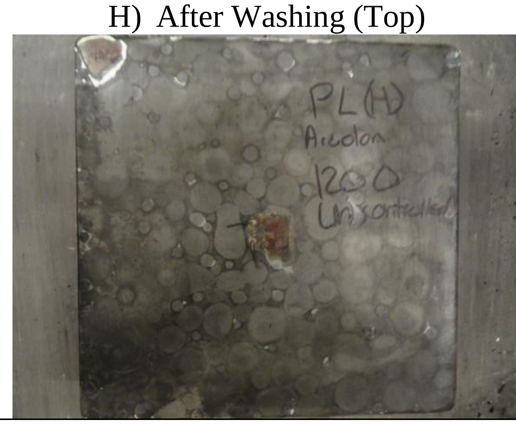


Figure 5.3-8. Post-Fire Evaluation of Acrolon H (8) Uncontrolled 1200^{o}F

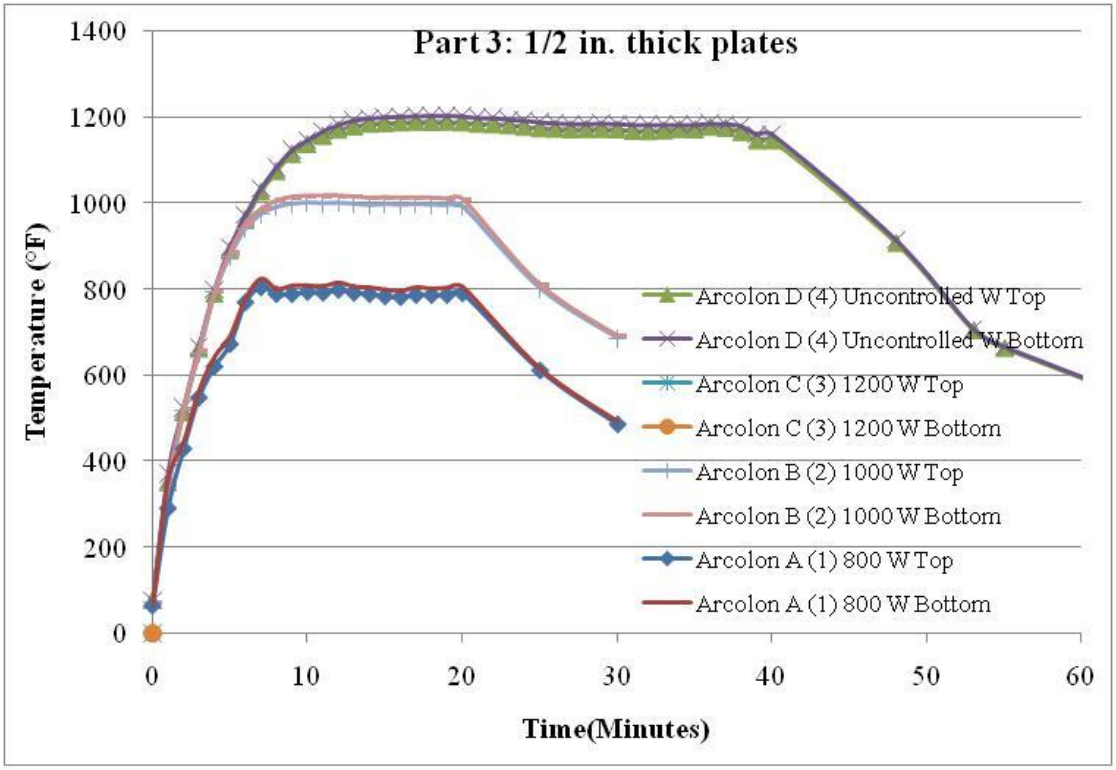


Figure 5.3-9. Measured Temperature-Time Curves for ½ in. Plate Specimens with Acrolon coating (Part 3).

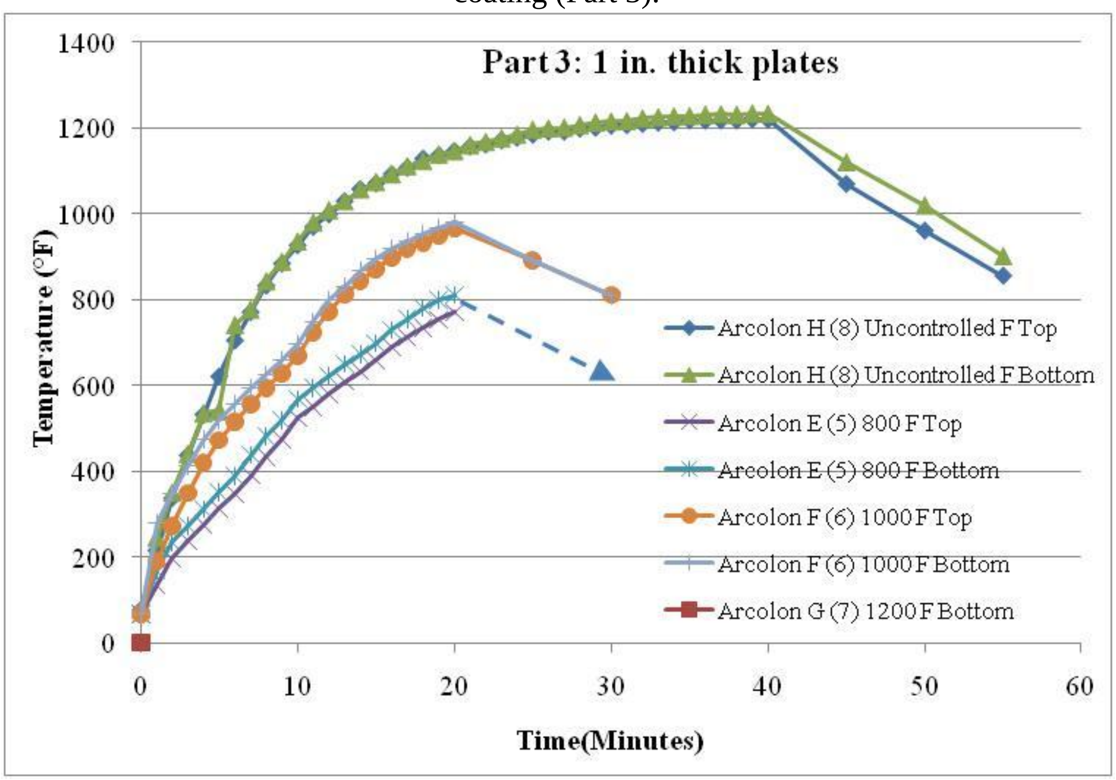


Figure 5.3-9. Measured Temperature-Time Curves for 1 in. Plate Specimens with Acrolon coating (Part 3).

Table 5.3-1 Material Test Results for Coupons from Part 3 Plate Specimens

Specimen ID		σ_y	σ_u	%e	CVN results				AVG	Hardness Test				AVG
Arcolon Q (17) Control W	**Coupon 1**	**57**	**82**	**35**	**Inner 3**					**Top**	**84**	**84**	**84**	**84.0**
	Coupon 2	**58.5**	**83.5**	**39**	**Outer 3**					**Bottom**	**83**	**83**	**82**	**82.7**
Arcolon A (1) 800 W	Coupon 1	58.5	82.5	36	Inner 3					Top	84	84	85	84.3
	Coupon 2	59.5	83	36	Outer 3					Bottom	84	85	84	84.3
Arcolon B (2) 1000 W	Coupon 1	59.5	82	38	Inner 3					Top	84	84	85	84.3
	Coupon 2	58	81.5	38	Outer 3					Bottom	86	86	85	85.7
Arcolon C (3) 1200 W	Coupon 1	57.5	81	37	Inner 3					Top	85	85	84	84.7
	Coupon 2	58	80.5	37	Outer 3					Bottom	84	84	83	83.7
Arcolon D (4) Uncontrolled W	Coupon 1	58.5	81	36	Inner 3					Top	83	83	84	83.3
	Coupon 2	58.5	81	34	Outer 3					Bottom	84	83	83	83.3
Arcolon R (18) Control F	**Coupon 1**	**56**	**80**	**44**	**Inner 3**					**Top**	**86**	**85**	**85**	**85.3**
	Coupon 2	**57**	**80**	**51**	**Outer 3**					**Bottom**	**84**	**84**	**83**	**83.7**
Arcolon E (5) 800 F	Coupon 1	56.5	80.5	50	Inner 3					Top	86	85	85	85.3
	Coupon 2	56.5	80.5	49	Outer 3					Bottom	84	84	83	83.7
Arcolon F (6) 1000 F	Coupon 1	57	80.5	50	Inner 3					Top	84	85	84	84.3
	Coupon 2	57	80.5	50	Outer 3					Bottom	86	86	85	85.7
Arcolon G (7) 1200 F	Coupon 1	58	80.5	44	Inner 3					Top	82	83	83	82.7
	Coupon 2	58	80.5	44	Outer 3					Bottom	83	83	83	83.0
Arcolon H (8) Uncontrolled F	Coupon 1	59.5	80	50	Inner 3					Top	85	85	86	85.3
	Coupon 2	59.5	80.5	48	Outer 3					Bottom	84	84	84	84.0

5.4 Post-Fire Evaluation of Plate Specimens – Part 4[2]

Figures 5.4-1 to 5.4-6 show photographs of the post-fire evaluation of the plate specimens (Part 4) identified in Table 4.2-1 and listed below. These include photographs taken as described in Section 4.4.

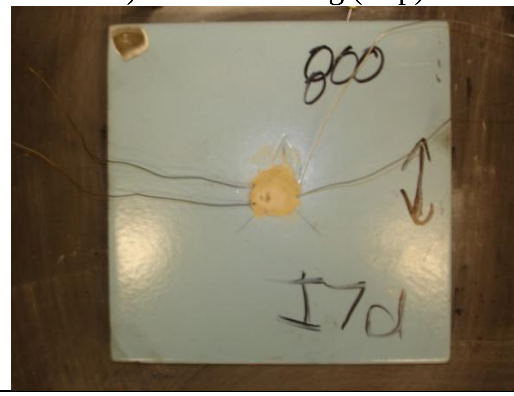
Part	**Specimen ID**	**Origin**	**Type or Temperature**	**Description**
4	Carbothane I (9) 1000 W	A709	1000 F	½ in. thick plate Flame jet and material tests
4	Carbothane K (11) 1200 W	A709	1200 F	½ in. thick plate Flame jet and material tests
4	Carbothane L (12) Uncontrolled W	A709	1200 F uncontrolled	½ in. thick plate Flame jet and material tests
4	Carbothane M (13) 800 F	A709	800 F	1 in. thick plate Material tests only
4	Carbothane O (15) 1200 F	A709	1000 F	1 in. thick plate Flame jet and material tests
4	Carbothane P (16) Uncontrolled F	A709	1200 F uncontrolled	1 in. thick plate Flame jet and material tests

Figures 5.4-7 and 5.4-8 show the measured temperature-time (T-t) curves for the ½ in. thick and 1 in. thick plate specimens, respectively. As shown the target temperatures of 800, 1000, and 1200^{o}F were achieved and maintained for 20 minutes before cooling. The uncontrolled fire test reached a maximum temperature of 1200^{o}F also, and was allowed to continue (burn out) for 40 minutes before cooling.

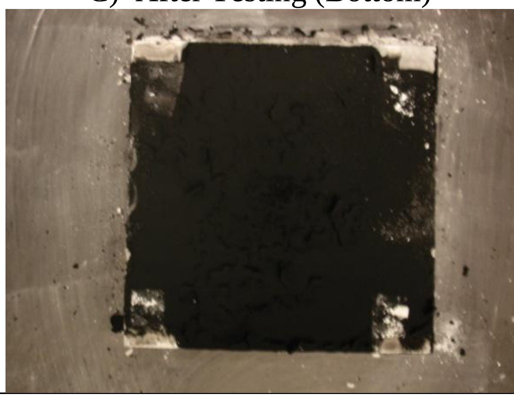
[2] CVN tests for these specimens were delayed and not available at the time of report submission. An addenda and amended report will be issued with these data when they are available

A) Before Testing (Bottom)

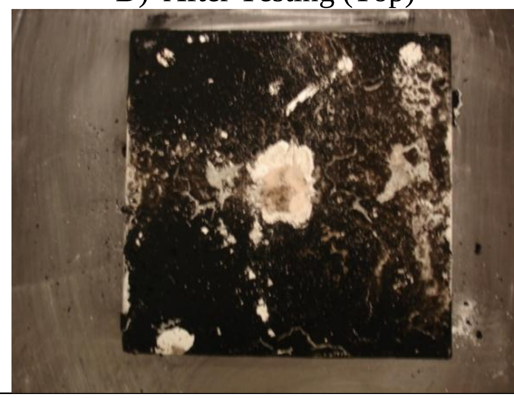
B) Before Testing (Top)



C) After Testing (Bottom)

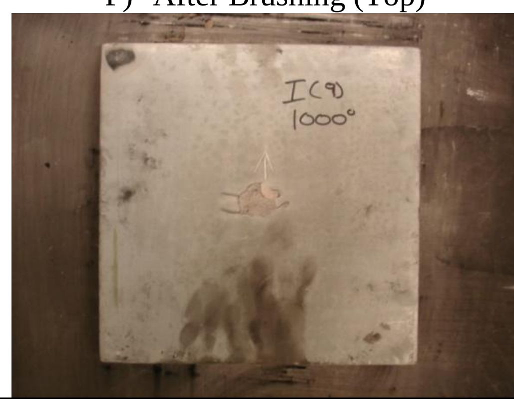


D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)



G) After Washing (Bottom)

H) After Washing (Top)

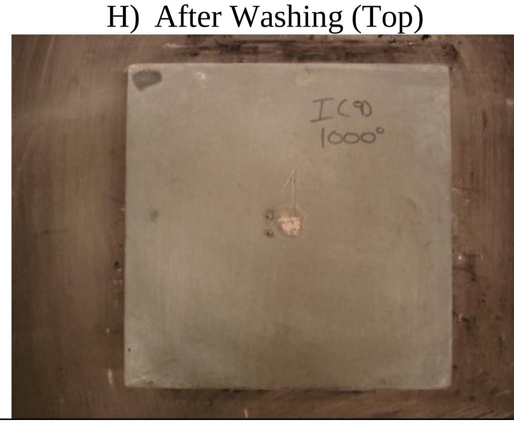
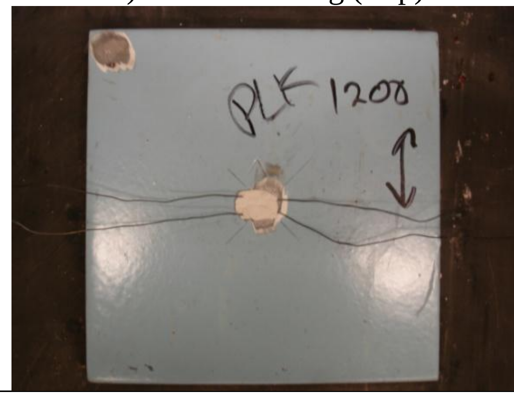


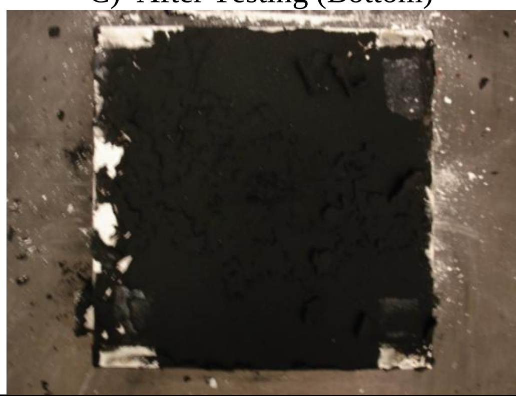
Figure 5.4-1. Post-Fire Evaluation of Carbothane I (9) 1000^{o}F

A) Before Testing (Bottom)

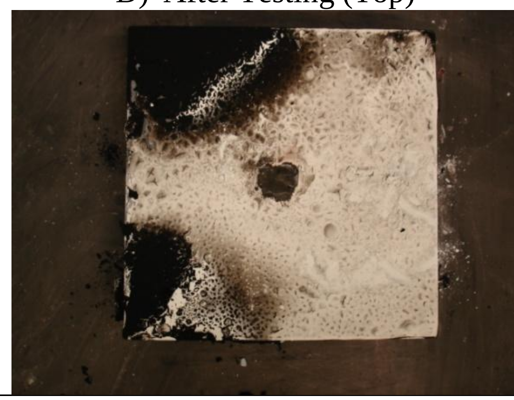
B) Before Testing (Top)



C) After Testing (Bottom)

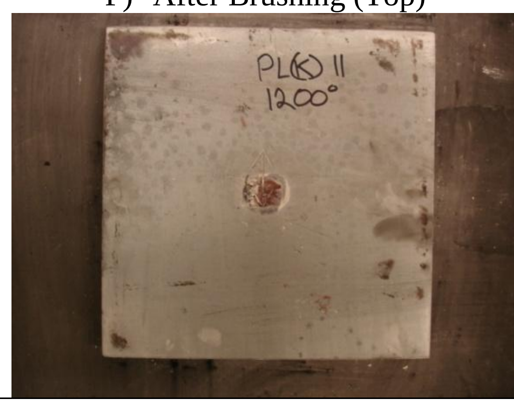


D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)



G) After Washing (Bottom)

H) After Washing (Top)

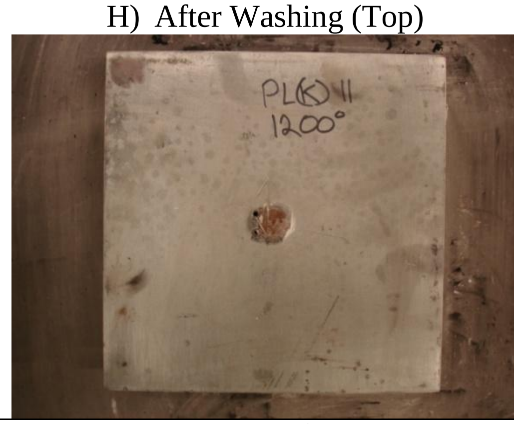
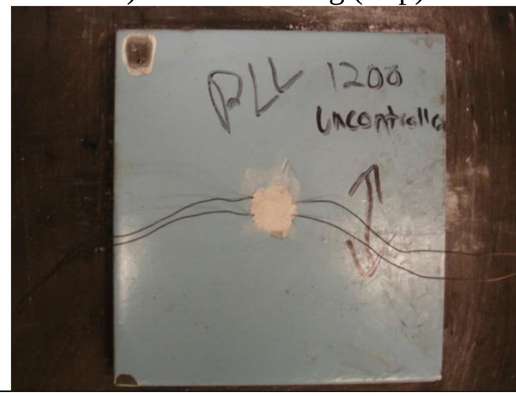


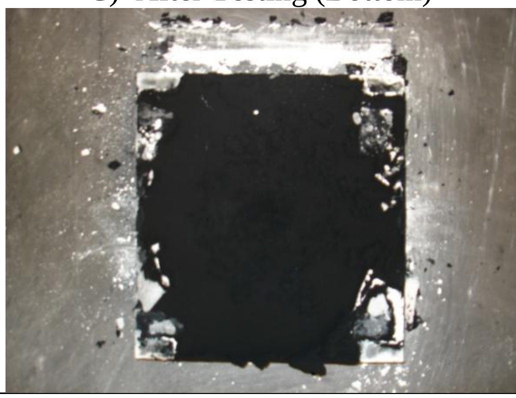
Figure 5.4-2. Post-Fire Evaluation of Carbothane K (11) 1200^{o}F

A) Before Testing (Bottom)

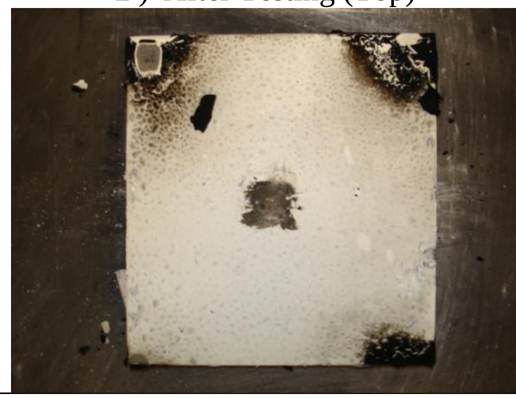
B) Before Testing (Top)



C) After Testing (Bottom)

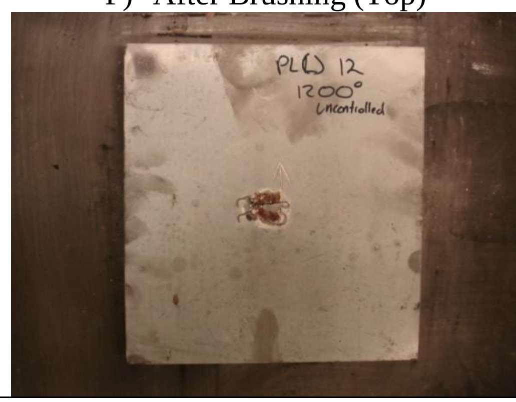


D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)



G) After Washing (Bottom)

H) After Washing (Top)

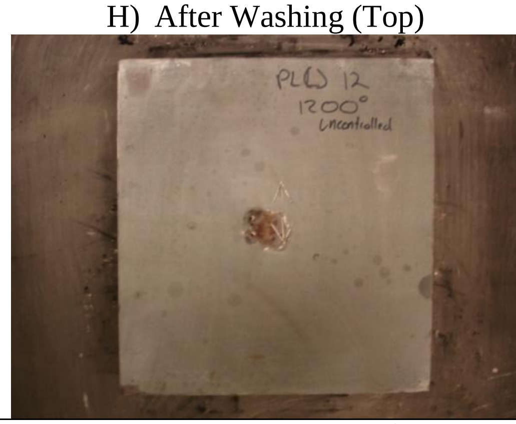
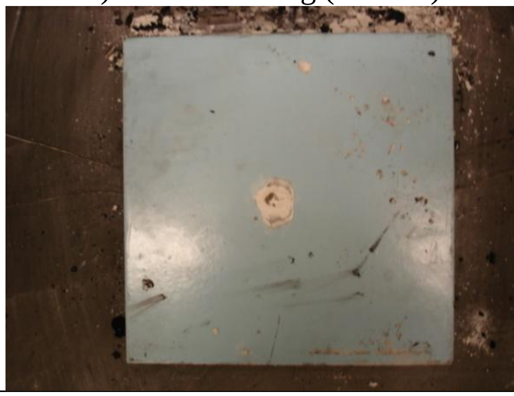
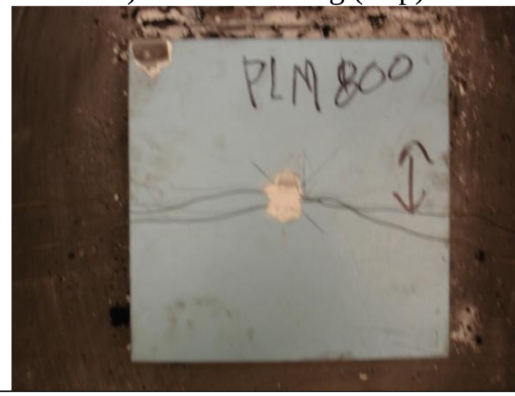


Figure 5.4-3. Post-Fire Evaluation of Carbothane L (12) Uncontrolled 1200°F

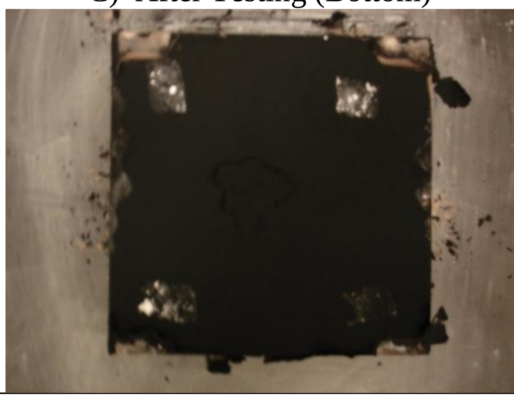
A) Before Testing (Bottom)



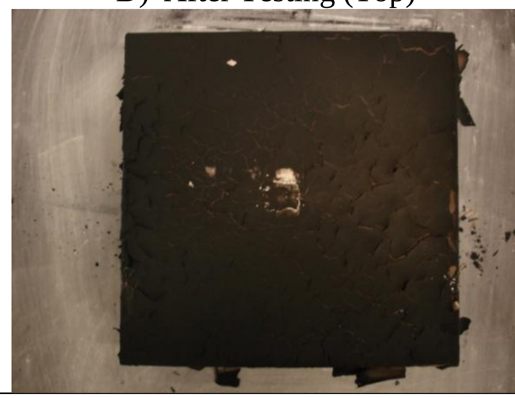
B) Before Testing (Top)



C) After Testing (Bottom)

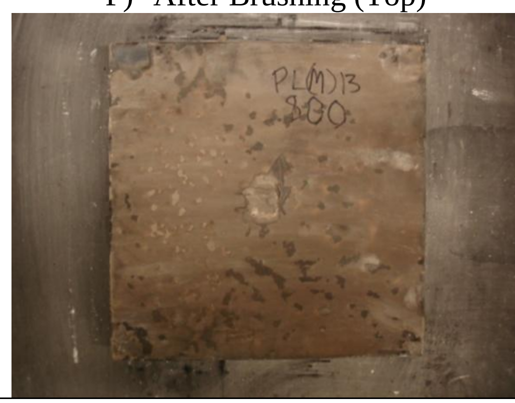


D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)



G) After Washing (Bottom)

H) After Washing (Top)

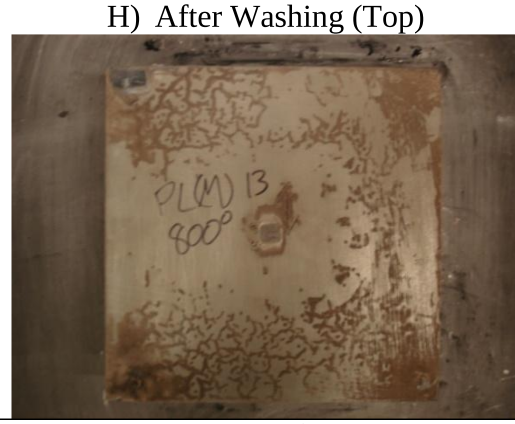
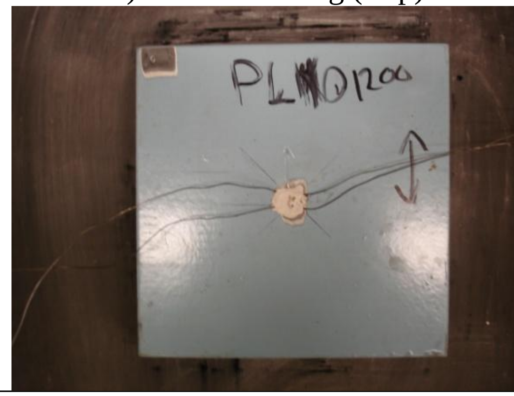


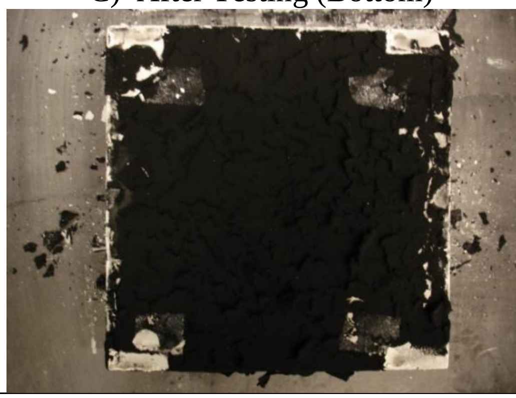
Figure 5.4-4. Post-Fire Evaluation of Carbothane M (13) 800^{o}F

A) Before Testing (Bottom)

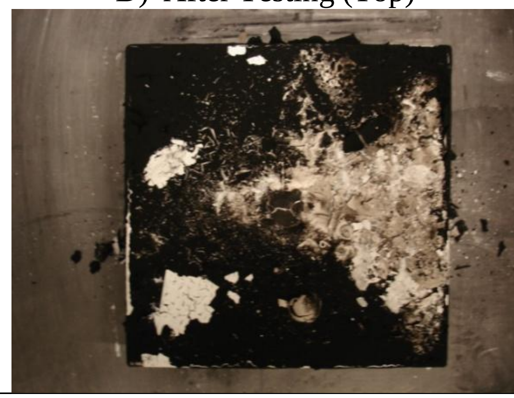
B) Before Testing (Top)



C) After Testing (Bottom)

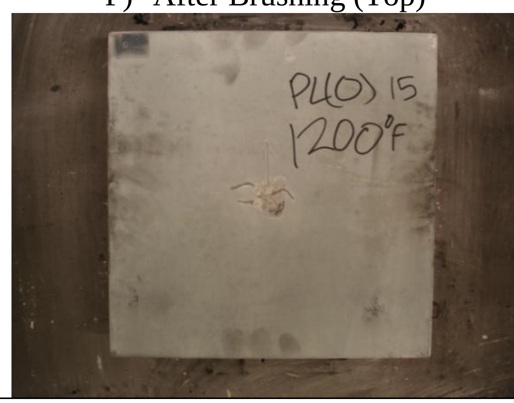


D) After Testing (Top)



E) After Brushing (Bottom)

F) After Brushing (Top)



G) After Washing (Bottom)

H) After Washing (Top)

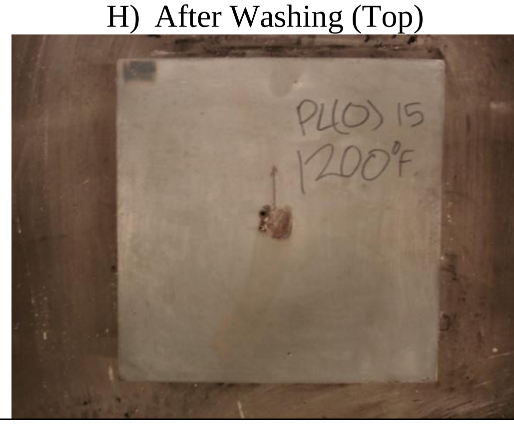
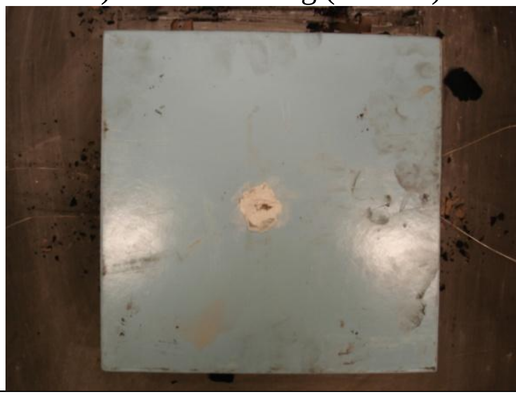
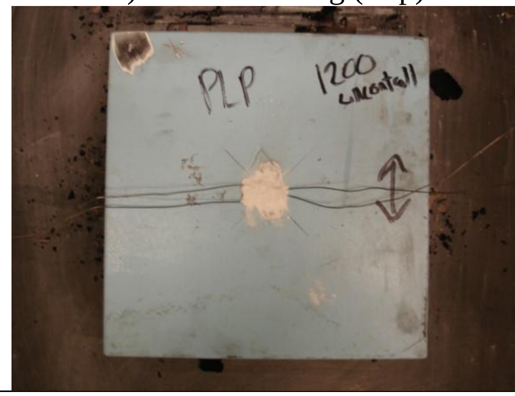


Figure 5.4-5. Post-Fire Evaluation of Carbothane O (15) 1200°F

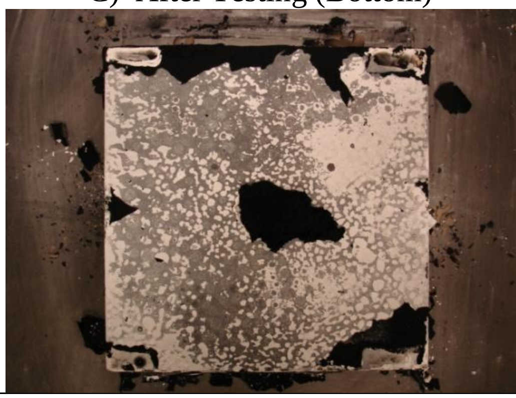
A) Before Testing (Bottom)



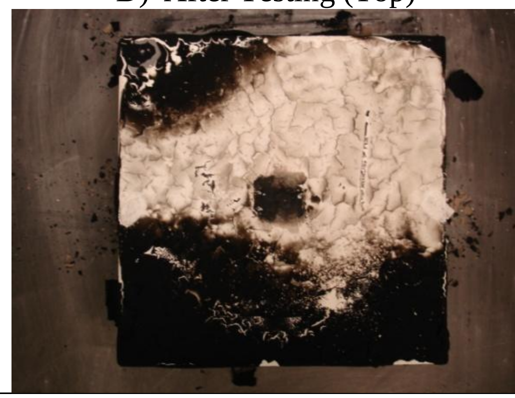
B) Before Testing (Top)



C) After Testing (Bottom)

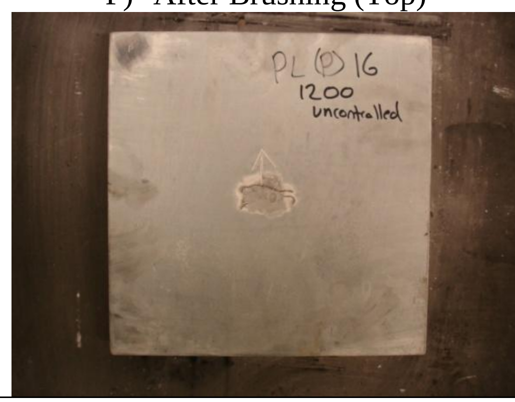


D) After Testing (Top)

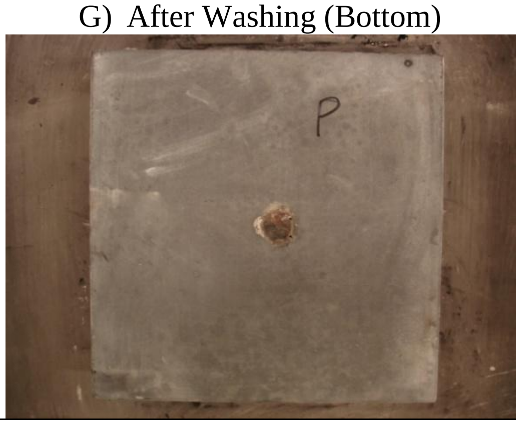


E) After Brushing (Bottom)

F) After Brushing (Top)



G) After Washing (Bottom)



H) After Washing (Top)

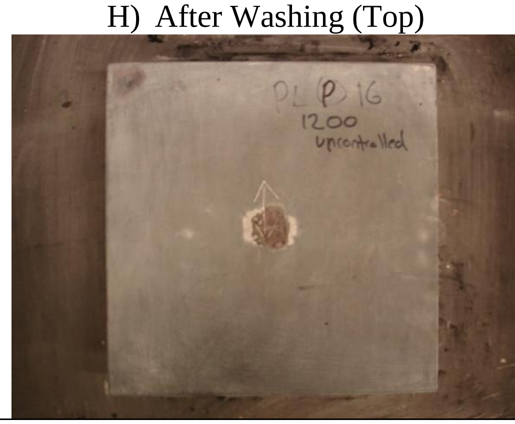


Figure 5.4-6. Post-Fire Evaluation of Carbothane P (16) Uncontrolled 1200°F

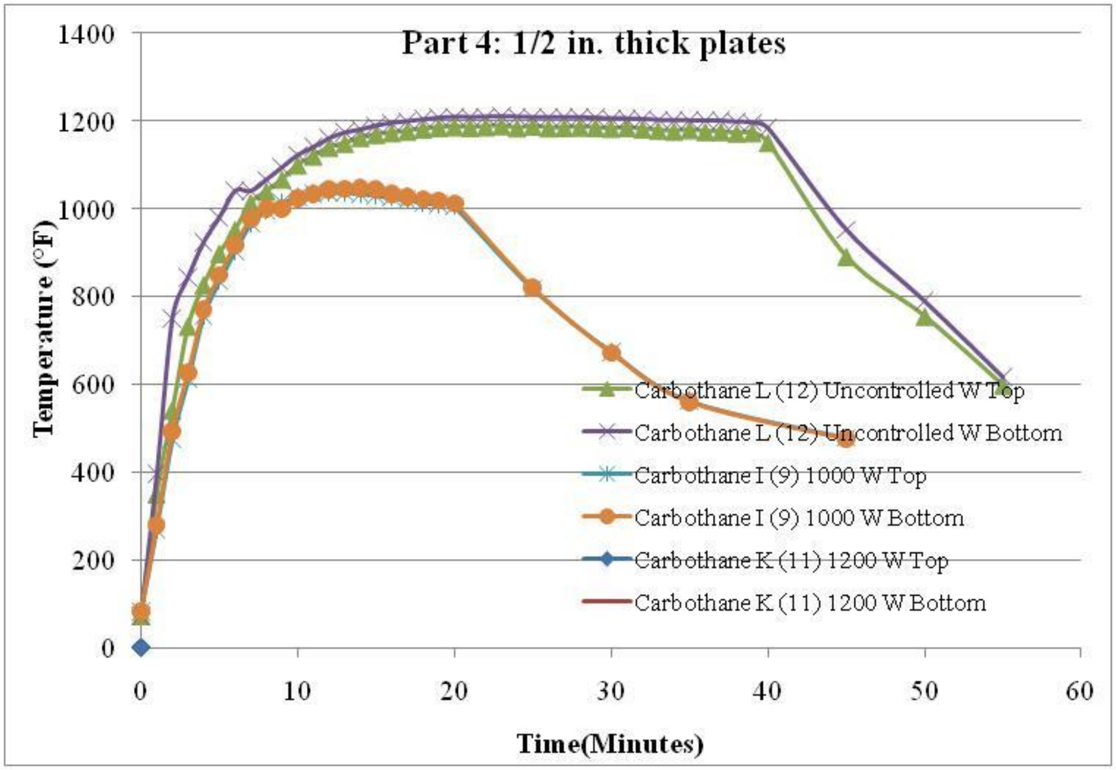


Figure 5.4-7. Measured Temperature-Time Curves for ½ in. Thick Carbothane Plates (Part 4).

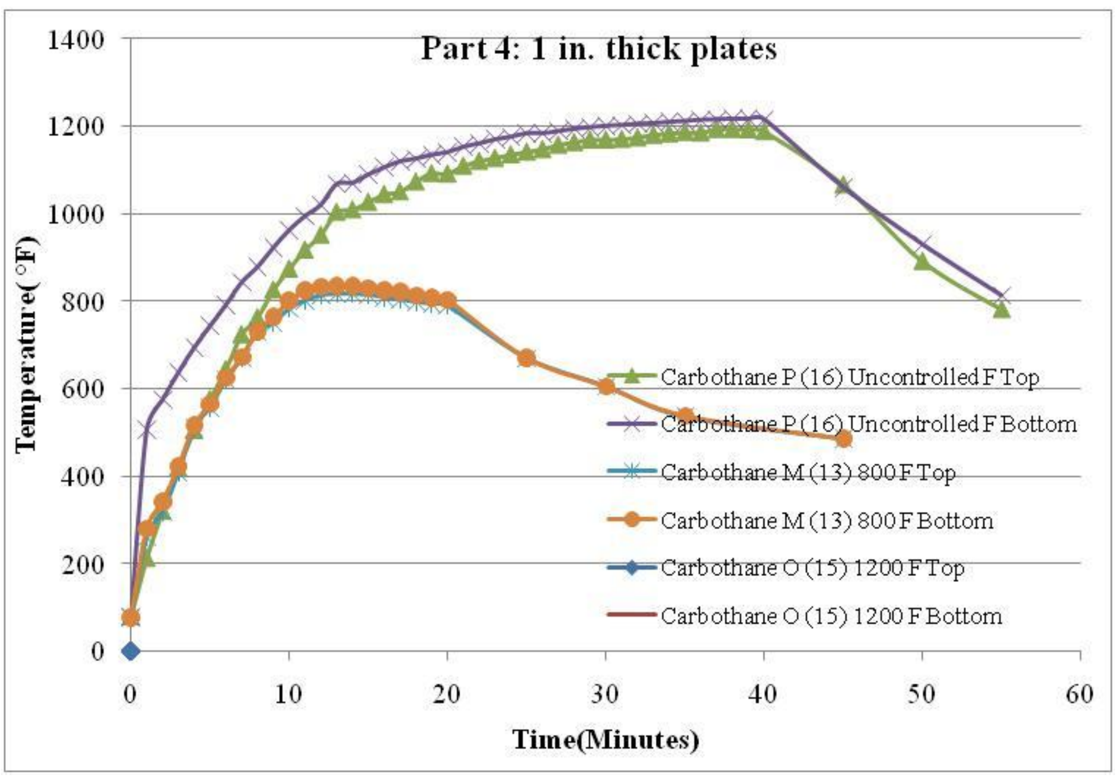


Figure 5.4-8. Measured Temperature-Time Curves for 1 in. Thick Carbothane Plates (Part 4).

Table 5.4-1 Material Test Results for Coupons from Part 4 Plate Specimens

Specimen ID		σ_y	σ_u	%e	CVN results				AVG	Harndness Test				AVG
Carbothane J (10) Control W	**Coupon 1**	**-**	**-**	**-**	**Inner 3**					**Top**	**87**	**86**	**87**	**86.7**
	Coupon 2	**-**	**-**	**-**	**Outer 3**					**Bottom**	**87**	**88**	**87**	**87.3**
Carbothane I (9) 1000 W	Coupon 1	58.5	79	40	Inner 3					Top	85	85	86	85.3
	Coupon 2	58.5	79.5	39	Outer 3					Bottom	86	86	85	85.7
Carbothane K (11) 1200 W	Coupon 1	59.5	77.5	42	Inner 3					Top	83	82	83	82.7
	Coupon 2	59.5	79	41	Outer 3					Bottom	93	83	83	86.3
Carbothane L (12)	Coupon 1	60	77.5	43	Inner 3					Top	83	84	83	83.3
Uncontrolled W	Coupon 2	59	78	41	Outer 3					Bottom	83	84	84	83.7
Carbothane M (13) 800 F	Coupon 1	57.5	82.5	47	Inner 3					Top	87	88	87	87.3
	Coupon 2	57.5	82	50	Outer 3					Bottom	85	85	86	85.3
Carbothane O (15) 1200 F	Coupon 1	59	81.5	49	Inner 3					Top	85	84	85	84.7
	Coupon 2	59	51.5	46	Outer 3					Bottom	84	85	85	84.7
Carbothane P (16)	Coupon 1	59	81.5	47	Inner 3					Top	84	85	84	84.3
Uncontrolled F	Coupon 2	60.5	82	47	Outer 3					Bottom	83	84	84	83.7

5.5 Findings and Conclusions from Post-Fire Evaluations

The post-fire evaluation photographs shown in Section 5.1-5.4 indicate that:

- Controlled fire exposures producing steel surface temperatures of 800 °F caused bubbles in the paint surfaces of the decommissioned bridge plates (Parts 1 and 2) and Acrolon coated (Part 3) plates. In some cases these bubbles had popped but the general shape (outline) remained. After brushing the plates, the spots where bubbles were located could still be seen on the surfaces of the plates. Controlled fire exposures producing surface temperatures of 800 °F caused cracking in the paint surfaces of the Carbothane coated plates. A clean gray surface was revealed after brushing and washing the fire exposed plates. It should also be noted that the old paint coatings (on decommissioned bridges) burned off completely, where as the primer coat of the three coat systems remained intact.

- For Acrolon coated plates (Part 3) subjected to controlled fire exposures producing steel surface temperatures of 1000 °F, all the bubbles that had formed in the paint surface had popped and cracked to form a desiccated pattern over the steel surface. Even after washing, the spots where the bubbles existed in the paint system could still be seen on the steel surfaces. The Carbothane coated plates (Part 4) remained cracked and continue to reveal the clean gray surface after brushing and washing. It should also be noted that the old paint coatings (on decommissioned bridges) burned off completely, whereas the primer coat of the three coat systems remained intact.

- For the old coatings and the Acrolon coated plates exposed to controlled or uncontrolled fires causing surface temperatures of 1200 °F, all the bubbles in the paint surface had popped and cracked leaving a faint pattern over the steel surface. After brushing and washing the plates, the spots were the bubbles existed could still be seen very lightly over the steel surface. It should also be noted that the old paint coatings (on decommissioned bridges) burned off completely, whereas the first (primer) coat of the Acrolon system remained intact. The Carbothane paint system starts to flake off after sustaining uncontrolled burns.

The post-fire material test results and comparisons with material properties from control specimens indicate that:

- Fire exposures have only a minor effect on the steel yield strength, ultimate strength, and elongation at rupture, and surface hardness. This is irrespective of the steel surface temperature and duration and steel plate thickness.

- Fire exposures have only a slight reduction in the CVN fracture toughness values for the steels. This reduction is slightly larger for thicker steels, but more material test results are needed to verify / confirm this finding.

- Fire exposure does not have a statistically significant effect on the CVN fracture toughness of steels, which will continue to numerically satisfy the 15 ft-lb limit for Zone 2 if the control specimen satisfies it.

6.0 SUMMARY AND CONCLUSIONS

The experimental investigations were conducted on steel plates (with three-coat paint systems) using a unique flame jet test-setup with a sooting flame and ethylene fuel. The steel plates were exposed to different fire exposure times of 20 – 40 minutes, and the maximum surface temperatures achieved on the plates were around 1200 ^{o}F. As expected, the steel surface temperatures were lower than the flame maximum temperature due to expected thermal losses to the ambiance etc.

Standard ASTM material tests were conducted on coupons taken from the fire exposed steel plates, and used to evaluate the effects of fire exposure on the material properties. The material test results shows that up to steel surface temperatures of 1200 ^{o}F, the fire exposed material will satisfy any of the required AASHTO material specifications as long the virgin (or unexposed) material was also satisfying the same specification before fire exposure.

Repair strategies in these cases would require that the fire exposed bridge be brushed clean, pressure washed, and re-painted.

However, when the bridge is visibly distorted (several inches or feet) by the fire it usually implies that the steel surface temperatures exceeded 1200 ^{o}F during the fire causing significant (more than 60%) loss in stiffness (elastic modulus) and strength. Repair strategies for these bridges may require heat straightening (if the distortion is only a few inches) or complete replacement of the distorted sections or girders (if the distortion is several feet).

The inspection guide shown in the following section is based on the experimental investigations presented in this report. It is limited to maximum steel surface temperatures of 1200 ^{o}F with minor distortions and permanent deformations after the fire. It is expected that there will be excessive distortions or deformations when the steel surface temperatures significantly exceed 1200 ^{o}F, and the corresponding section will just have to be replaced.

7.0 INSPECTION GUIDE FOR STEEL BRIDGES EXPOSED TO FIRES

The results of the research project were used to develop an inspection guide for steel bridges exposed to fire. It is relatively easy to inspect bridges that have clearly visible distortions and require elements (for example, beams or diaphragms etc.) to be replaced. However, it is much more difficult to perform post-fire evaluation of bridges that have not sustained large deformations. This inspection guide focuses on the latter situation and includes provisions for identifying the degree of fire damage to the paint coating systems, and evaluating the structural integrity and material properties of bridges exposed to fires but with minimal fire induced deformations.

The focus of this inspection guide is on the effects of fire exposure on steel bridge elements with paint coating systems endorsed by Bulletin 15 issued by the Pennsylvania DOT for *existing* and *new* structural steels. All steels are required to be coated with three-coat zinc-rich paint systems. Existing steels can be coated with systems from both Carboline and Sherwin Williams. However, new steels can be coated only with systems from Carboline.

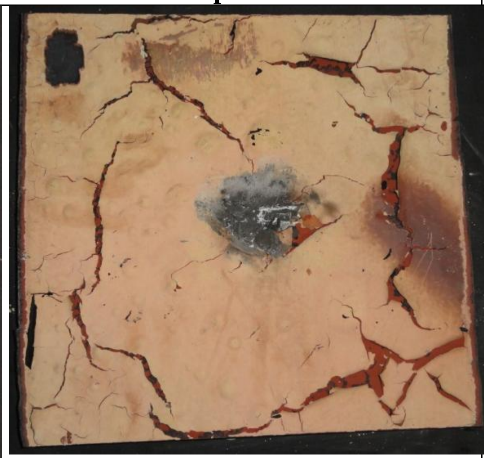
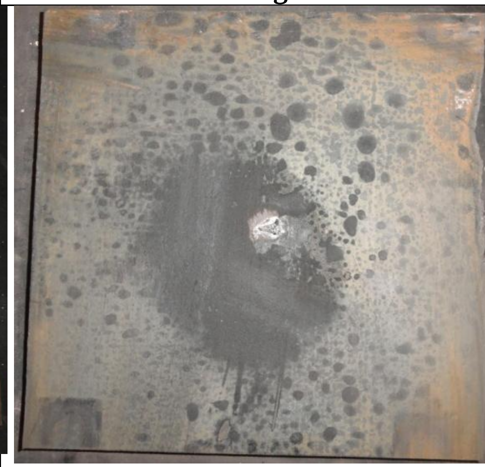
- For existing steels, Sherwin Williams' *Acrolon* coating consists of a primer coat of ZincClad III HS, Macropoxy 646 intermediate coat, and Acrolon 218 HS top coat. This system is rusty red in color.
- For new steels, the inorganic zinc coating system (*Carbothane*) from Carboline must be used. The first coat is Carbozinc 11 HS, followed by an intermediate Carboguard 893 coat, and a finish coat of Carbothane 133. This system is steel blue in color

Additionally, this inspection guide also includes older steel bridges (circa 1960-70) that have been constructed with indeterminate paint coating systems that have been in place for several decades.

As shown in the following pages, the inspection guide includes photographs and descriptions of the visible surfaces of the steel before fire exposure, after fire exposure, after hand wire brushing clean, and after pressure or hand washing clean. It also includes the potential effects of fire exposures on the steel material properties and recommendations for acquiring material samples when required.

Older steel bridges with indeterminate paint coating systems (Same vintage as steel beams provided by Penn-DOT) (Circa: 1960 – 70)			
Before fire exposure	**After fire exposure - 800 °F**	**After brushing surface**	**After washing surface**
			
Description:	*Non-flame side*		
Paint is in reasonable condition. Some scratches, chips, some rust and other typical defects are apparent. (Note: The shiny white patch at plate center was where the paint was scratched off to attach thermocouples)	The plate surface directly exposed to flames will be covered with black soot. Bubbles will be seen in the paint coating on the non-flame side as shown above. Some of these paint bubbles may be cracked, but the material will still be in place.	After hand wire brushing clean, most of the paint will be removed from both the flame and non-flame sides though there may still be some patches of paint. The outline of the bubbles that had formed in the paint may be visible along with discoloration of the plate	After pressure or hand washing clean, all the soot and most of the paint will be removed from both the flame and non-flame sides. Some patches of paint may still be visible.
Material Properties:			
For steel grades with nominal yield stress less than or equal to 50 ksi, fire exposure producing surface conditions as shown above will result in a small (5%) reduction in the material yield strength, ultimate strength, surface hardness, and the CVN fracture toughness. For heat treated steels (e.g., A514, HPS), acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 to evaluate the effects of fire on steel.			

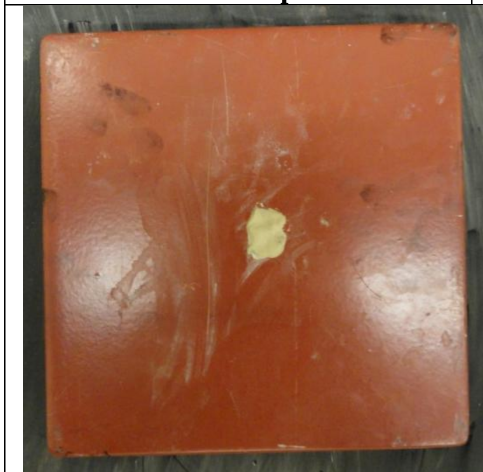
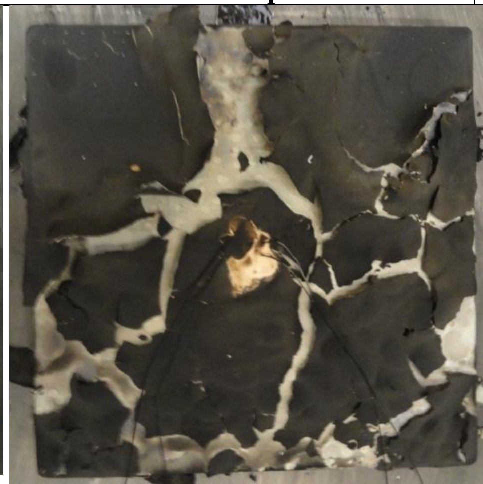
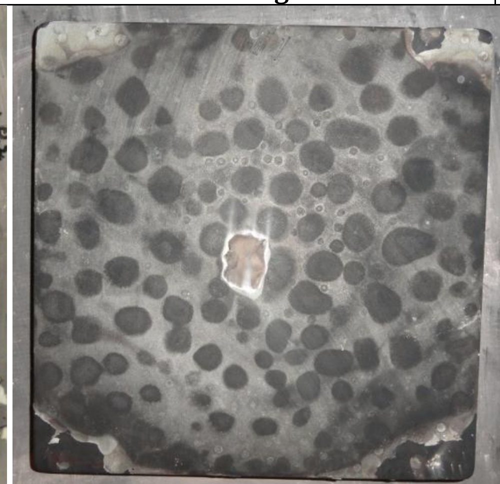
Older steel bridges with indeterminate coating
(Same vintage as steel beams provided by Penn-DOT after being exposed to real fire event) (Circa: 1960 – 70)

Before fire exposure	After fire exposure - 1200 ^{o}F	After brushing surface	After washing surface
			
Description:	*Non-Flame Side*		
Paint is in reasonable condition. Some scratches, chips, some rust and other typical defects are apparent. (Note: The shiny white patch at plate center was where the paint was scratched off to attach thermocouples)	The plate surface directly exposed to flames will be covered with black soot. The paint coating on the non-flame side will be cracked, but the material will still be in place as shown above.	After hand wire brushing clean, most of the paint will be removed from both the flame and non-flame sides though there may still be some patches of paint. The outline of the bubbles that had formed in the paint may be visible along with discoloration of the plate. Larger discolored rings may be seen where flames came in direct contact with steel surfaces.	After pressure or hand washing, all the soot and most of the paint will be removed from both the flame and non-flame sides. Some patches of paint may still be visible.
Material Properties:			

For steel grades with nominal yield stress less than or equal to 50 ksi, fire exposure producing surface conditions as shown above will result in a small (5%) reduction in the material yield strength, ultimate strength, surface hardness. The influence on the CVN fracture toughness can be more significant (+20 to -40%). Conduct CVN fracture toughness tests on material samples taken from the unexposed steel to evaluate reserve margin with respect to minimum CVN toughness requirements.

For heat treated steels (e.g., A514, HPS), acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 to evaluate the effects of fire on steel.

Existing steel bridges with the Sherwin Williams' Acrolon coating system consisting of a primer coat of ZincClad III HS, Macropoxy 646 intermediate coat, and the Acrolon 218 HS top coat. As shown below, this system is rusty red in color.
(A709 beams or plates used in current bridge construction or similar) (Circa:)

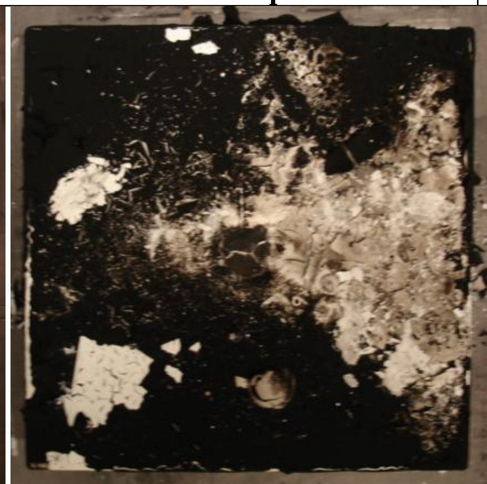
Before fire exposure	**After fire exposure**	**After brushing surface**	**After washing surface**
			
Description:	*Non-Flame Side*		
Paint is in good condition. No significant scratches, chips, rust or other typical defects are apparent. (Note: The shiny white patch at plate center was where the paint was scratched off to attach thermocouples)	The plate surface directly exposed to flames will have little soot because the top-coat of the paint will have fallen off (along with the soot) when the temperature exceeded 700 ^{o}F. The paint coating on the non-flame side will have bubbled and cracked, but the paint material will still be in place as shown above.	After hand wire brushing clean, most of the top coat will be eliminated from both sides. The base coat will still be intact. The outline of the bubbles that formed in the paint may be visible with discoloration of the plate.	After washing clean, all the soot and most of the top coat of the paint system will be removed from both the flame and non-flame sides. The base coat of the paint system will likely remain still intact over the plate surfaces.

Material Properties:

For steel grades with nominal yield stress less than or equal to 50 ksi, fire exposure producing surface conditions as shown above will result in a small (5%) reduction on the material yield strength, ultimate strength, surface hardness.

The influence on the CVN fracture toughness can be ____________. Conduct CVN fracture toughness tests on material samples taken from the unexposed steel to evaluate reserve margin with respect to minimum CVN toughness requirements.
For heat treated steels (e.g., A514, HPS), acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 to evaluate the effects of fire on steel.

Newly painted steel with the inorganic zinc coating system (*Carbothane*) from Carboline. The first coat is Carbozinc 11 HS, followed by an intermediate Carboguard 893 coat, and a finish coat of Carbothane 133. This system is steel blue in color.
(A709 beams or plates used in current bridge construction) (Circa:)

Before fire exposure	After fire exposure	After brushing surface	After washing surface
			
Description:	*Non-Flame Side*		
Paint is in good condition. No significant scratches, chips, rust or other typical defects are apparent. (Note: The shiny white patch at plate center was where the paint was scratched off to attach thermocouples)	The plate surface directly exposed to flames will have little soot because the top coat of the paint will have fallen off (along with the soot) when the temperature exceeded 700 ^{o}F. The paint coating on the non-flame side will have cracked and turned white in color as shown above.	After hand wire brushing clean, most of the top coat will be eliminated from both sides. The base coat will still be intact. There will be no other significant markings (bubbles etc.) visible on the steel surfaces	After washing clean, all the soot and most of the top coat of the paint system will be removed from both the flame and non-flame sides. The base coat of the paint system will remain still intact over the plate surfaces, except for the situation of extremely long duration uncontrolled fires. For such cases, the base coat will also fall off as shown above.

Material Properties:

For steel grades with nominal yield stress less than or equal to 50 ksi, fire exposure producing surface conditions as shown above will result in a small (5%) influence on the material yield strength, ultimate strength, surface hardness.

The influence on the CVN fracture toughness can be ____________. Conduct CVN fracture toughness tests on material samples taken from the unexposed steel to evaluate reserve margin with respect to minimum CVN toughness requirements.

For heat treated steels (e.g., A514, HPS), acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 to evaluate the effects of fire on steel.

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