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Evaluation of Effects of Fire on the I-465 Mainline Bridges—Volume II

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JOINT TRANSPORTATION RESEARCH PROGRAM
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16. Abstract

Currently, when a bridge has been involved in a fire loading, DOT and inspectors are called to determine if the bridge is passable to traffic. Inspectors must close the bridge for an indefinite period of time to take material samples from the bridge and have them tested to find if the strength of the materials meets AASHTO specifications. This procedure can take time and severely impact the economy of surrounding municipalities due to bridge closure. When a bridge is visually distorted, the recommendations of what must be done to repair the bridge may be intuitive; but when no apparent deformations are visible, a way of inspecting the bridge should be uniform and easily performed. The implementation of the findings of this report and the included inspection guide will provide inspectors a general idea of the changes in material properties of the bridge steel, based on the visual appearance of the steel.

A method of testing 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. After each different test, material properties may be determined and compared to virgin or unexposed steel and AASHTO specifications to see 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.

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EXECUTIVE SUMMARY

EVALUATION OF EFFECTS OF FIRE ON THE I-465 MAINLINE BRIDGES—VOLUME II

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. In order to assist with the investigation of damaged bridges, a method of testing has been developed that allows researchers to extract 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 parameters such as paint coatings on the steel, thickness of steel, temperature and duration of fire exposure. After each test, material properties may be determined and compared to virgin or unexposed steel and AASHTO specifications to see if the material properties have changed or if the material is below minimum standards. An inspection manual was developed from this testing to assist with diagnosing bridges after fire events based on visual inspections.

Findings

The results presented in this report show the following:

- Fire exposures have only a minor effect on the steel yield strength, ultimate strength, 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 steel. In some cases the fracture toughness is seen to increase as in part four of this report. This could be because the steel is being heated for 20 minutes and allowed to cool. This is very similar to a process known as tempering, where heating of steel is utilized to make it tougher.
- Fire exposures do not have a statistically significant effect on the CVN fracture toughness of steels (after running a T-test on the CVN data, there seems to be no correlation between the values), which will continue to numerically satisfy the 15 ft-lb limit for Zone 2 if the control specimen satisfies the Zone 2 requirement.

Implementation

If a bridge has sustained a fire load and is visually distorted, the recommendations of what must be done to repair the bridge may be intuitive; but when no apparent deformations are visible, a way of inspecting the bridge should be uniform and easily performed. The implementation of the findings of the report and the included inspection guide will provide inspectors with a general idea of the changes in material properties of the bridge steel, based on the visual appearance of the steel. Having this preplan will allow bridges to be inspected and reopened in a more timely manner.

Testing allowed 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. Each specific test is photographed at certain stages that would be seen in the field after a bridge is involved in a fire. These photographs can then be compared to actual bridge damage and a method of repair, if required, can be decided.

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1. 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:

- 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˚C) in temperature (*1*).
- 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 (*1*).
- 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 (*2*).
- 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 main-line 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. Experimental evaluations indicated no major differences between the material properties with or without fire exposure damage (*3*).

2. BACKGROUND

2.1 Background

Limited research has been conducted on the fire behavior and post-fire evaluation of steel bridges. Kodur et al. (*1*) and Astaneh-Asl et al. (*4*), 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. (*1*) 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. (*5*) 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. (*4*) discuss the effects of elevated temperatures due to fire on the material properties of steel bridges. As shown in Figure 2.1, the steel tension yield strength decreases gradually up to 500˚C (932˚F). It is reduced to about 50% of its nominal yield strength at 600˚C (1112˚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˚C (932˚F), and failure may be inevitable if temperatures keep increasing while the loading is sustained.

Astaneh-Asl et al. (*4*) 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˚C (932˚F), the concrete compressive strength is reduced to 50% of its nominal strength.

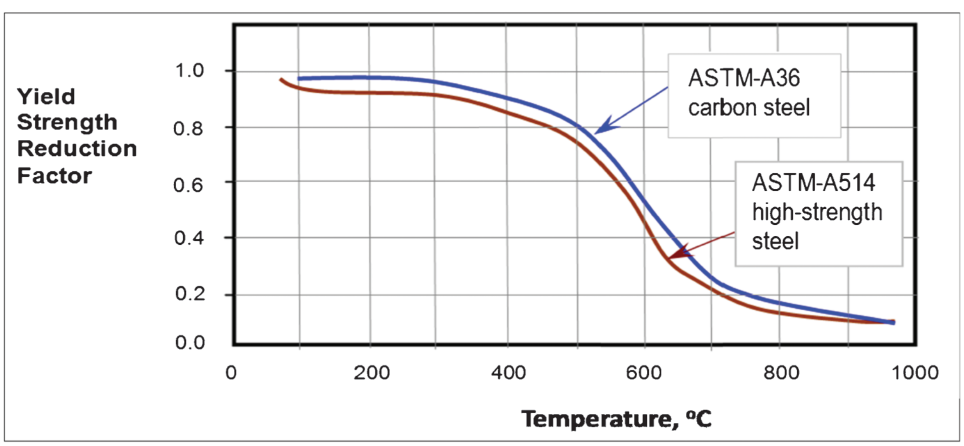


Figure 2.1 Reduction in tensile yield strength with temperature (*4*).

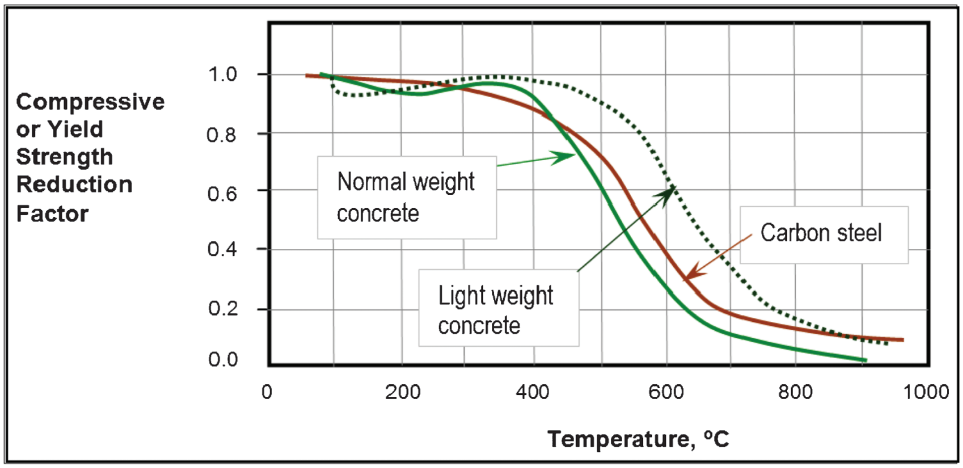


Figure 2.2 Reduction in concrete compressive strength with temperature (*4*).

Figure 2.3 shows the reduction in the tensile strength of high strength low alloy (HSLA) reinforcing steel and pre-stressing steel with elevated temperatures. As shown, the tensile strength of pre-stressing 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)

Astaneh-Asl et al. (*4*) 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:

1. No fire protection.
2. Active protection.
3. 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) (*7*) does not have specific fire resistance requirements, design guidelines, or assessment and repair strategies for bridges exposed to fire.

Kodur et al. (*1*) 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. (*1*) and Astaneh-Asl et al. (*4*) 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

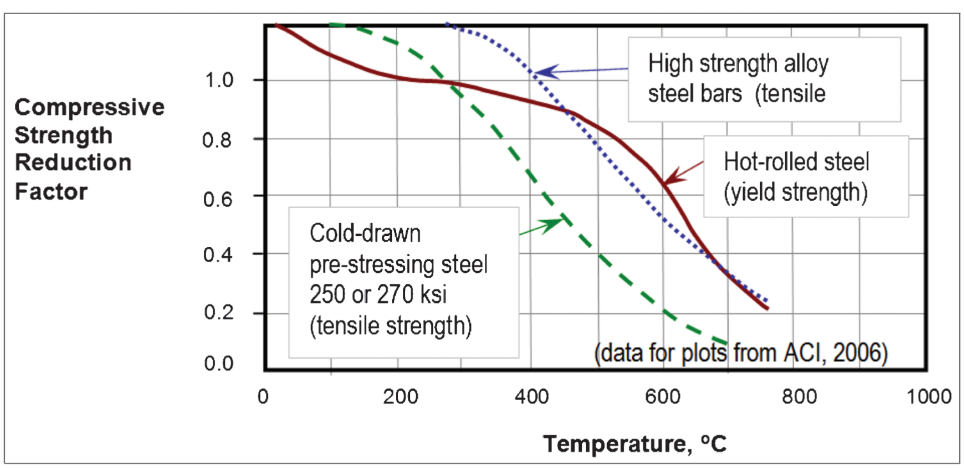


Figure 2.3 Reduction in strength of pre-stressing steel and high strength alloy bars with temperature (*4*).

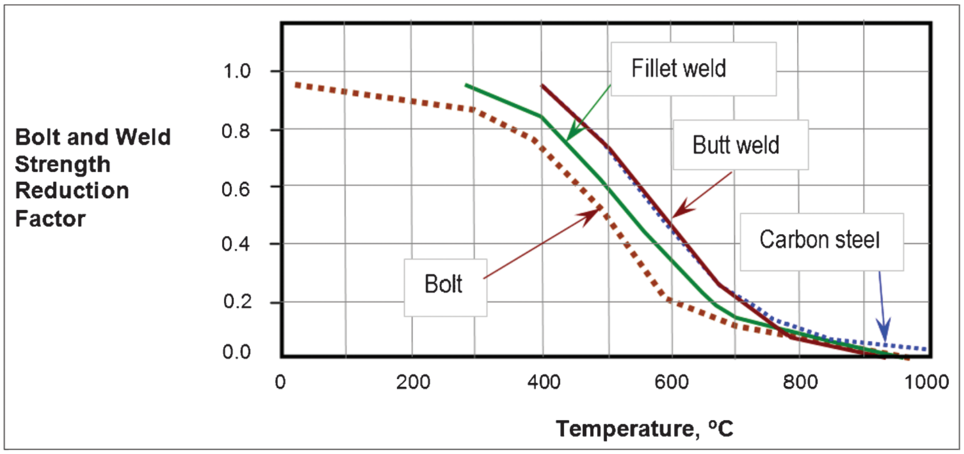


Figure 2.4 Reduction in strength of bolts, welds, reinforcing bars with temperature (*4*).

to significant fire exposures but have not sustained large deformations. There is a significant 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.

The following four steps are recommended for post-fire assessment (*1*):

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

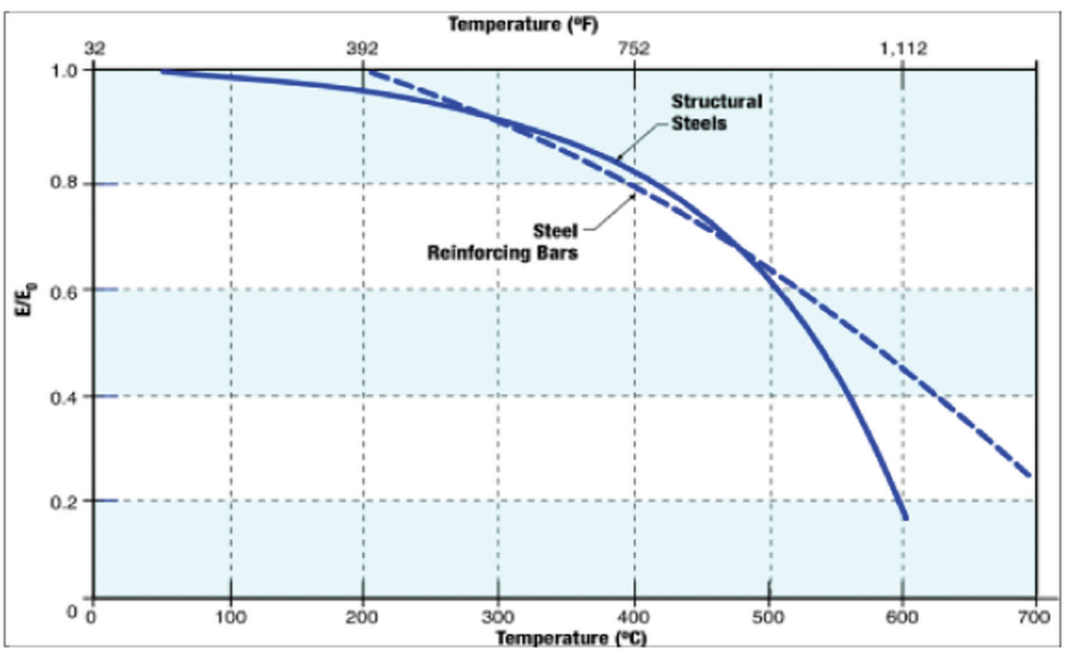


Figure 2.5 Reduction in modulus of steel with respect to temperature (*6*).

may be repaired, while severely damaged ones should be replaced.

2.2 Summary

Currently, when a bridge has been involved in a fire loading, DOT and inspectors are called to determine if the bridge is passable to traffic. Inspectors must close the bridge for an indefinite period of time to take material samples from the bridge and have them tested to find if the strength of the materials meets AASHTO specifications. This procedure can take time and severely impact the economy of surrounding municipalities due to bridge closure. When a bridge is visually distorted, the recommendations of what must be done to repair the bridge may be intuitive; but when no apparent deformations are visible, a way of inspecting the bridge should be uniform and easily performed. There is a need for an inspection guideline and the implementation of the findings of this report and the included inspection guide will provide inspectors a general idea of the changes in material properties of the bridge steel, based on the visual appearance of the steel.

3. PROBLEM STATEMENT, RESEARCH OBJECTIVES AND METHODOLOGY

State highway agencies (for example, Pennsylvania Department of Transportation (PennDOT), Indiana Department of Transportation (INDOT), etc.) have to occasionally perform post-fire inspections and evaluations of steel bridges exposed to significant 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 at the site of the event. The bridge inspectors have very little information available on site, and even less research-based knowledge to draw upon to make decisions regarding the structural integrity and material properties of the fire exposed bridge and its elements.

The objectives of this research are to develop simple but experimental research-based inspection or evaluation tools that can be used to:

1. 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.
2. Aid in the estimation of the mechanical properties of the fire exposed steel bridge elements based on the temperatures and fire durations estimated from the visual inspection.
3. Support decisions regarding the integrity of the bridges 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. This report focuses on the effects of fire exposure on steel bridge elements with paint coating systems endorsed by Bulletin 15 issued by the PennDOT.

Research objectives have been achieved by conducting controlled fire exposure tests on steel bridge elements with PennDOT endorsed paint coating systems as follows.

- Steel bridge elements (plates) with paint coatings have been exposed to fires from a specially designed jet flame setup with a sooting fuel type (e.g., ethylene). Two different paint coating systems (Acrolon and Carbothane) have been considered in the tests. Additionally, some steel plates from actual steel bridges (decommissioned by PennDOT and provided to the researchers) have also been evaluated.
- 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°F (427, 538, and 649 ℃)) 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 brushed with a metal 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 uni-axial tension tests (ASTM E8/AASHTO T68) (*8*), Charpy V-notch (CVN) fracture toughness tests (ASTM E23/AASHTO T266) (*9*), and surface hardness tests (ASTM E18/AASTHO T80) (*10*) 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 were used to develop guidelines for evaluating steel bridge elements exposed to fires.

4. EXPERIMENTAL INVESTIGATIONS

4.1 Test Setup

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 the flame to the outside of the laboratory safely.

The flame jet consists of an 8 mm nozzle connected to an adjustable meter which allows 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℃ (5252°F). This temperature assumes a pre-mixed flame and no heat loss. However, in the tests there is heat loss to the specimen and cooling from the ambient surroundings.

Ethylene fuel is not mixed with air until it exits the nozzle. Flow rate is initially set at 30 mg/s and adjusted with time depending upon the desired temperature. Steel plate specimens were suspended over the flame jet

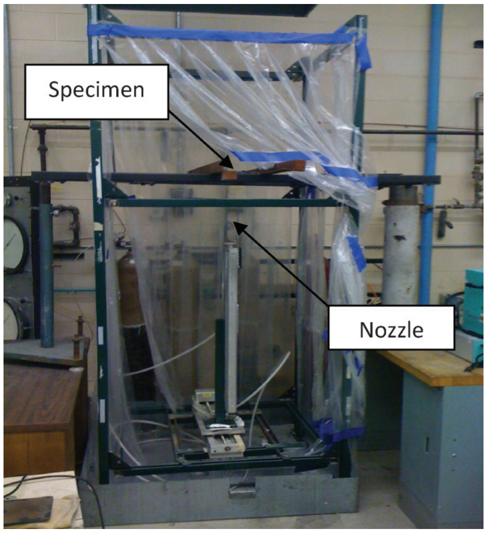


Figure 4.1 Photograph of jet flame test set up.

using four fixed tabs, one at each corner of the specimen. The nozzle is attached to a screw jack which allows it to traverse along three axes. Steel plate specimens were 10 x 10 in. squares cut from plate stock or out of web and flange materials provided by PennDOT as described in the following sub-section.

4.2 Flame Characterization

A soot-producing, turbulent, non-premixed, impinging jet flame was utilized to heat steel plates positioned perpendicular to the flame axis. The flame was established on a 480 mm long tube with an inner diameter (*D*) of 8 mm. The burner exit was positioned 48 cm (60 diameters) from the square steel plate (25.4 by 25.4 by 1.9 cm). Ethylene (C_2H_4) mass flow rate (993 mg/s) was calibrated using a dry test meter and controlled by setting the pressure upstream of a choked orifice plate. The nominal jet exit Reynolds number (*Re*) was 15,200 based on cold gas properties, the exit velocity, and the burner diameter.

Time-dependent infrared radiation intensity of the flame was measured using an infrared camera (FLIR Phoenix) with a 25 mm lens and an InSb detector. The infrared camera measures radiation intensity along lines-of-sight through the flame as described by a solution to the radiative transfer equation. A narrow-band filter (2.77 $\pm$ 0.12 μm) was used to measure the radiation emitted by water vapor and soot. Spatial resolution of the radiation intensity measurements was 1 mm^2 for each pixel at the center of the flame. The camera was calibrated using a blackbody source placed at the same distance from the camera as the flame center. Camera sensitivity was optimized by adjusting the integration time (50–200 μs) for each location of the flame. The nominal sampling frequency was 335 Hz. Experimental uncertainty in the radiation intensity data is estimated to be +/-15% (95% confidence) based on repeated measurements of a non-sooting turbulent, non-premixed flame.

Radiation heat flux measurements of the flame were acquired using a radiometer and radiation heat flux meter. Average radiation heat flux was measured using a Schmidt-Boelter radiometer with a 150° view angle. A sapphire window on the radiometer allows for measurements of the flame radiation while isolating convection heat transfer effects. Radiation heat flux measurements were acquired along the flame length with the radiometer located 0.57 m from the flame axis and in the radial direction near the burner exit. Fraction of chemical energy radiated to the surrounding is an important global flame characteristic for fire safety applications. The radiant fraction was estimated by integrating the radiation heat flux measurements around a cylindrical surface enclosing the flame.

Temperature along the flame centerline and radius at 60 diameters downstream was measured using a type K thermocouple. Measurements were corrected for radiation heat loss effects by performing an energy balance of the thermocouple.

Figure 4.2 shows consecutive time-dependent and time-averaged infrared images of the soot-producing turbulent jet diffusion flame without impingement. Note that the time-dependent infrared images at different flame heights were recorded at different times. The turbulent nature of the flame is evident by observing regions of high and low intensity in the time-dependent infrared images. Time-averaged radiation intensity is low in the fuel-rich region near the burner exit, increases to a maximum near 80 diameters downstream, and decreases thereafter due to mixing between the hot combustion products and cool surrounding air. X/D is plotted on the vertical axis, where X is the distance from the nozzle to a point in the flame and D is the diameter of the jet nozzle. R over D is plotted on the horizontal axis where R is the distance to a point in the flame radially and D is the diameter of the jet nozzle.

Figures 4.3 and 4.4 illustrate consecutive time-dependent and time-averaged infrared images of the flame impinging on a steel plate positioned at 48 diameters downstream of the burner exit. Images shown in Figures 4.3 and 4.4 were recorded 3 and 13 minutes respectively after the flame began heating the plate. A high intensity region is apparent on flame-side (lower surface) of the steel plate with an average maximum intensity (250 W/m^2-sr, where sr is a steradian the unit of a whole angle) that is approximately 100% larger than that of the flame without impingement. A lower intensity region is apparent on the plume-side (upper surface) of the steel plate indicating the plate is only being heated from one side. It is important to note that the high radiation intensity region is approximately uniform across the width of the plate suggesting the plate is at a nearly uniform temperature.

Figure 4.5 reports the time-averaged infrared radiation intensity along diametric paths of the turbulent

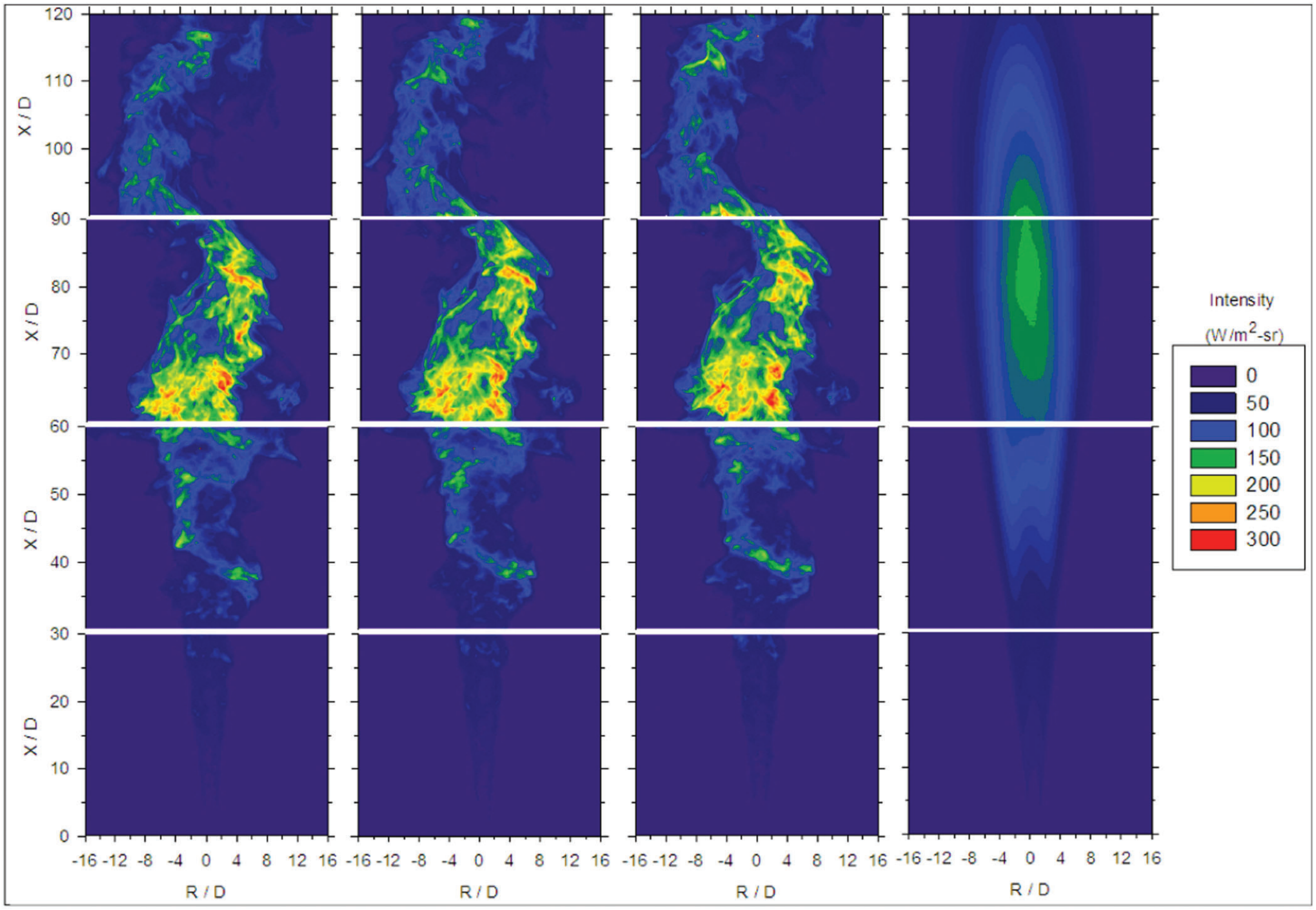


Figure 4.2 Time-dependent and time-averaged infrared images of a turbulent ethylene diffusion flame.

ethylene diffusion flame with and without impingement. Peak intensity of the impinging flame occurs approximately 5 diameters upstream of the surface of the plate. Intensity remains approximately constant along the edge of the plate indicating the thickness of the plate is at a nearly uniform temperature consistent with conclusion ascertained from thermocouple measurements on the top and bottom surface of the plate.

Figures 4.6 and 4.7 report the radiation heat flux distribution of the flame without impingement in the axial and radial directions, respectively. These measurements were integrated to estimate that the total radiation heat loss from the flame is 14.8 kW. Total chemical energy of the flame based on the ethylene heat of combustion and the mass flow rate is 46.8 kW. This results in a radiant fraction of 0.32 for the present flame.

Figures 4.8 and 4.9 show the flame temperature along the centerline and radius at a distance of 60 diameters downstream, respectively. Flame temperatures are reported with and without a correction for

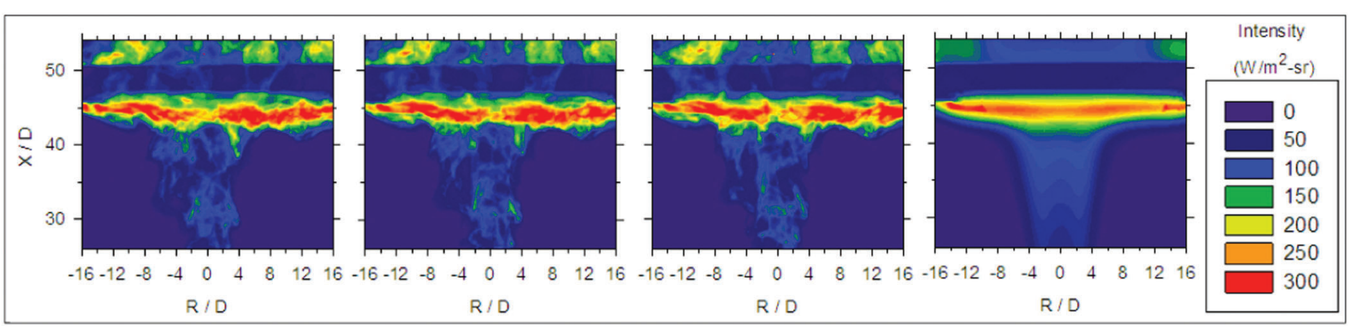


Figure 4.3 Time-dependent and time-averaged infrared images of a turbulent ethylene diffusion flame impinging on a steel plate positioned at 48 diameters downstream of the burner exit. Images were acquired 3 minutes after the flame began heating the plate.

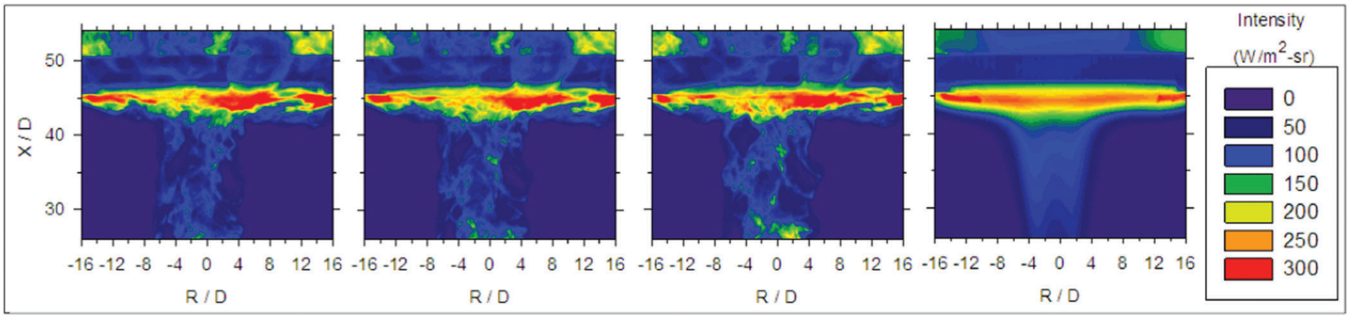


Figure 4.4 Time-dependent and time-averaged infrared images of a turbulent ethylene diffusion flame impinging on a steel plate positioned at 48 diameters downstream of the burner exit. Images were acquired 13 minutes after the flame began heating the plate.

radiation heat loss effects from the thermocouple. Figure 4.8 illustrates that the peak temperature occurs near 90 diameters downstream which is within 10 diameters of the peak radiation intensity location. Flame gas temperature at the location where the plate was positioned (60 diameters) is 1570°F and approximately 370°F larger than the maximum achievable plate temperature of 1200°F. This difference is attributed to the fact that the plate is losing heat from the top surface due to radiation.

Figure 4.9 shows the flame gas temperature radial distribution at 60 diameters downstream and indicates it is nearly constant between the flame axis and 5 diameters (4 cm) in the radial direction. Thereafter the gas temperature decreases exponentially to the ambient temperature as the hot gases are mixed with the surrounding air.

4.3 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 (*11*) plate stock as follows:

1. PennDOT engineers provided a pallet of beam sections from a steel bridge that had been exposed to a real fire event. Sections that had been directly exposed to the fire and those that were away from the fire (unexposed) were included. Beam sections had ¾ in. thick flanges and ½ in. thick webs with an indeterminate paint coating on them.
2. PennDOT engineers 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. 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 from Hirschfeld Industries the second largest bridge fabricator in the Unites States. 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 was also prepared. This paint coating system is also described below.

PennDOT has a list of approved coatings in Bulletin 15 for *existing* and *new* structural steels. All steels are required to be coated with three-coat zinc-rich paint

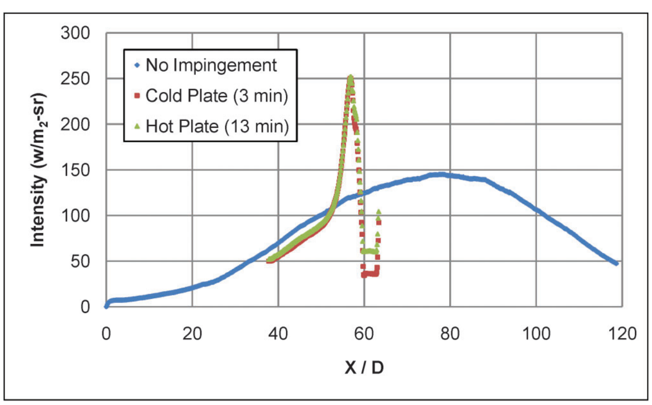


Figure 4.5 Time-averaged infrared radiation intensity along diametric paths of a turbulent ethylene diffusion flame with and without impingement.

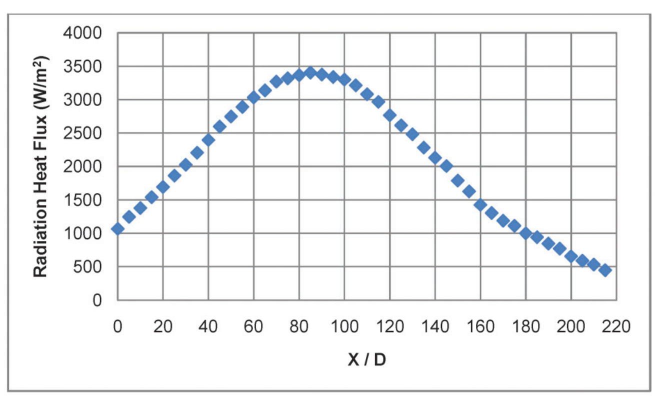


Figure 4.6 Axial radiation heat flux distribution of an ethylene diffusion flame without impingement.

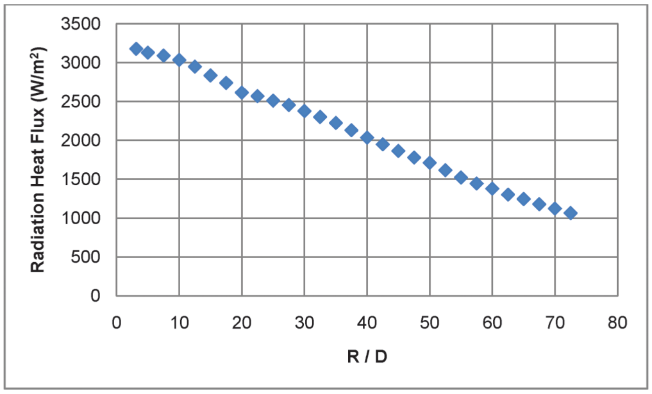


Figure 4.7 Radial radiation heat flux distribution (X/D = 0) of an ethylene diffusion flame without impingement.

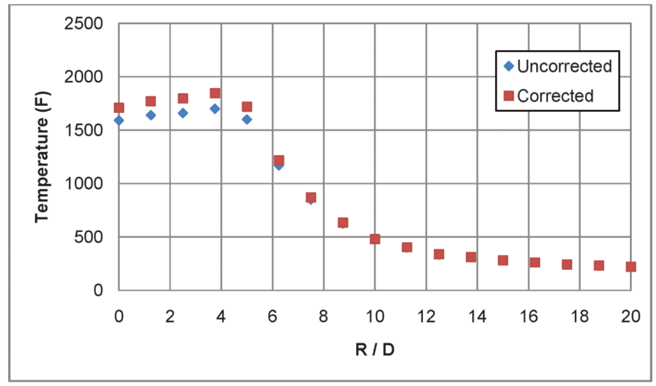


Figure 4.9 Radial temperature distribution (X/D = 60) of an ethylene diffusion flame without impingement uncorrected and corrected for radiation heat loss from the thermocouple.

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 4.1 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.

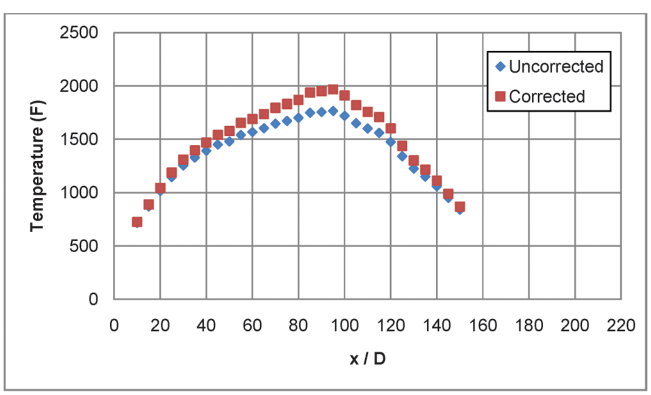


Figure 4.8 Temperature distribution along the flame centerline of an ethylene diffusion flame without impingement uncorrected and corrected for radiation heat loss from the thermocouple.

- As shown in Table 4.1, 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 4.1, 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°F and 1200°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 4.1, 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°F and 1200°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 4.1, a total of five specimens each were tested for the two plate thicknesses (½ in. and 1 in.). These included:

1. Control specimen (that was not heated).
2. Three specimens that were exposed to controlled fires using the flame jet setup to achieve surface temperatures of 800°F, 1000°F, 1200°F.
3. One specimen that was exposed to an uncontrolled fire using the flame jet setup, which resulted in 1200°F surface temperature.

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

TABLE 4.1
Test Matrix

Part	Specimen ID	Origin	Type or Temperature	Description
1	PennDOT 2 AA (27) Control	PennDOT 2	Control Specimen	½ in. thick web; material tests only
1	PennDOT 1 Y (25) Burned	PennDOT 1	Burned Specimen	½ in. thick burned web; material tests only
1	PennDOT 4 EE (31) Burned	PennDOT 4	Burned Specimen	½ in. thick burned web; material tests only
1	PennDOT 2 BB (28) Control	PennDOT 2	Control Specimen	¾ in. thick flange; material tests only
1	PennDOT 1 Z (26) Burned	PennDOT 1	Burned Specimen	¾ in. thick burned flange; material tests only
1	PennDOT 4 FF (32) Burned	PennDOT 4	Burned Specimen	¾ in. thick burned flange; material tests only
1	PennDOT 3 CC (29) Control	PennDOT 3	Control Specimen	½ in. thick web; material tests only
1	PennDOT 3 S (19) 800 F	PennDOT 3	800 F	½ in. thick web; flame jet and material tests
1	PennDOT 3 T (20) 1200 F	PennDOT 3	1200 F	½ in. thick web; flame jet and material tests
1	PennDOT 3 DD (30) Control	PennDOT 3	Control Specimen	¾ in. thick flange; material tests only
1	PennDOT 3 V (22) 800 F	PennDOT 3	800 F	¾ in. thick flange; flame jet and material tests
1	PennDOT 3 W (23) 1200 F	PennDOT 3	1200 F	¾ in. thick flange; flame jet and material tests
2	PennDOT 5 GG (33) 800 F	PennDOT 5	800 F	½ in. thick web; flame jet and material tests
2	PennDOT 5 II (35) 1200 F	PennDOT 5	1200 F	½ in. thick web fame jet and material tests
2	PennDOT 5 LL (38) Control	PennDOT 5	Control Specimen	½ in. thick flange; material tests only
2	PennDOT 5 HH (34) 1200 F	PennDOT 5	1200 F	½ in. thick flange; flame jet and material tests
2	PennDOT 5 JJ (36) 800 F	PennDOT 5	800 F	½ in. thick flange; flame jet and material tests
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
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

(steel blue in color). As shown in Table 4.1, a total of four ½ in. thick plate specimens were tested. These included:

1. Control specimen (that was not heated).
2. Two specimens that were exposed to controlled fires using the flame jet setup to achieve surface temperatures of 1000˚F and 1200˚F.
3. One specimen that was exposed to an uncontrolled fire resulting in 1200˚F surface temperature.

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˚F and 1200˚F, and one specimen that was exposed to an uncontrolled fire resulting in 1200˚F surface temperature.

Typical heating curves are shown in Chapter 5. Generally, heated specimens were brought to their target temperatures and this was maintained for 20 minutes. "Uncontrolled" specimens were maintained at their target temperature for 40 minutes.

Thus, the parameters included in the experimental investigations are:

1. Effects of real fire events on material properties.
2. Plate thickness.
3. Coating type.
4. Surface temperature achieved.
5. Duration of fire.

4.4 Specimens and Instrumentation

As shown in Figure 4.10, each plate specimen is approximately 10 x 10 in., and is instrumented with two thermocouples. Thermocouples are attached to the center of the specimens on both sides, i.e. the flame side or bottom and 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.

Thermocouples are connected to a data acquisition unit which records temperatures of the surfaces of the plate at user defined time intervals. A thermal imaging camera is also used to visualize the heat intensities in

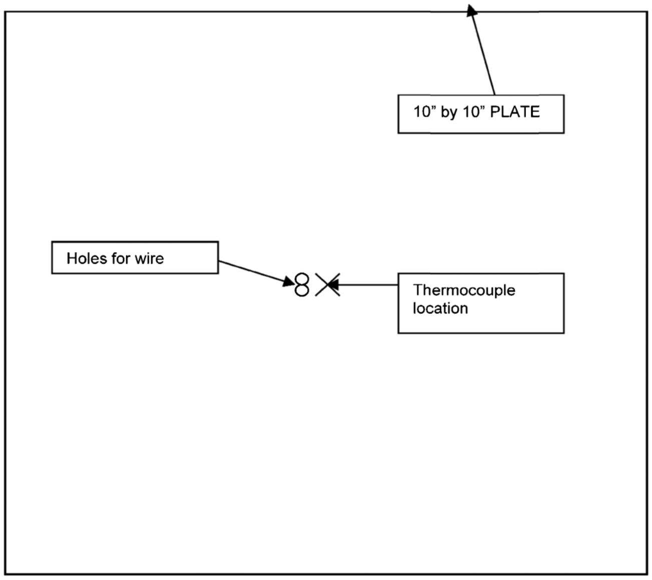


Figure 4.10 Plate specimen with thermocouples.

the flame and on the plate surface. Intensity can be used to determine the highest temperature in the flame and the difference in temperatures in the specimens. An infrared temperature gun is also used to take spot readings of specimen temperatures and compare it with thermocouple measurements.

4.5 Post-Fire Evaluation Procedure and Material Testing

All plate specimens, except those identified as control specimens in Table 4.1 were subjected to controlled fire exposure using the flame jet setup described in Section 4.1. Photographs of the steel plate surfaces (both flame and non-flame side) were taken:

1. Before fire exposure.
2. After fire exposure.
3. After brushing clean with a wire brush.
4. 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 4.11, three Charpy V-notch (CVN) coupons (ASTM E23) (*9*) were fabricated from the central 3 in. of each plate specimen. 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) (*8*) is taken from either end of the specimen parallel to

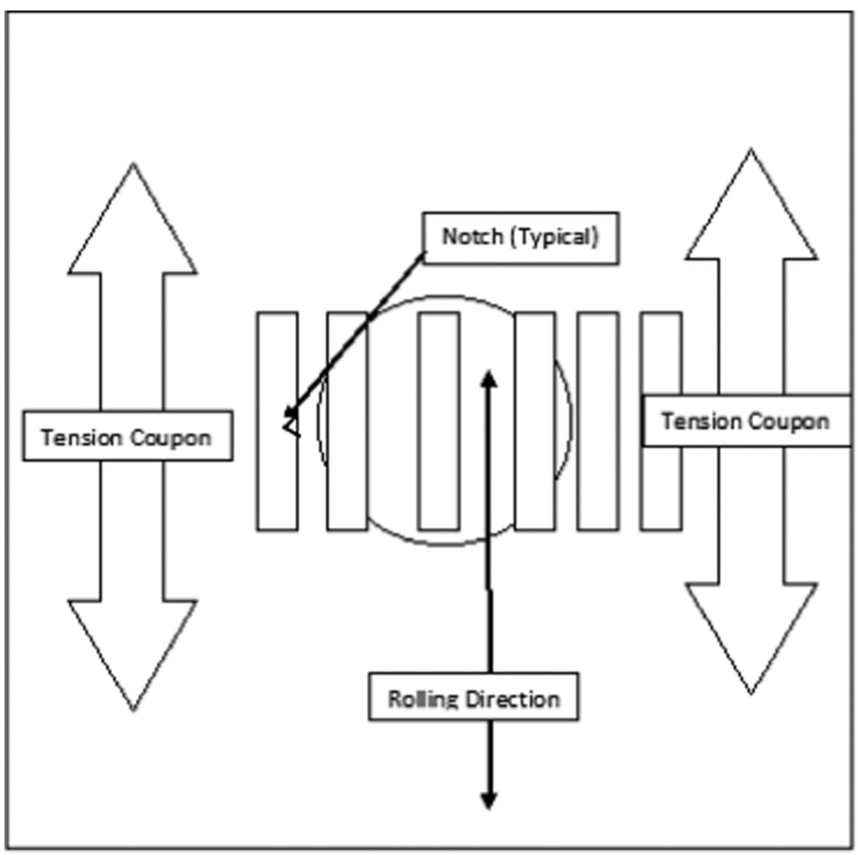


Figure 4.11 Layout of material coupons taken from plate specimens.

the rolling direction. Figure 4.11 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) (*10*) tests were conducted on all plate samples. 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 4.11. 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.

For part 3 web plates, CVN samples are used to determine if the microstructure of the steel changed from control throughout the testing process. Each CVN is to be polished on the surface of the sample that was directly impinged by testing flames. After polishing the samples are photographed at 300 times magnification and studied. These material properties will help investigators determine a course of action for a bridge that has sustained fire loading.

5. EXPERIMENTAL RESULTS

5.1 Post-Fire Evaluation of Plate Specimens – Part 1

Figures 5.1 to 5.4 show photographs of the post-fire evaluation of the plate specimens (Part 1) identified in Table 4.1 and again in Table 5.1. These include photographs taken as described in Section 4.5.

Figures 5.5 and 5.6 show the measured temperature-time (T-t) curves for these plate specimens with ½ in. and ¾ in. thickness, respectively. As shown the target temperatures were achieved and maintained for 20 minutes before cooling. 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 Chapter 1.

Additionally, Table 5.2 includes the standard material test results obtained from testing the coupons fabricated from the plate specimens identified in Table 5.1. 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 5.2, 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 5.2, 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 (¾ in. thick) steel plates. Test results for PennDOT 3 V (22) 800°F ¾ in. thickness were not returned from material testing facility.

Figures 5.7 and 5.8 show 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 ¾ in. thick steel plates that had been subjected to controlled fire exposure using the flame jet setup. Box plots included for each plate specimen:

1. Minimum, maximum, and median values of fracture toughness.
2. First and third quartile fracture toughness values. First quartile means that 25% of the values are lower than this value, and third quartile means 75% of the values are 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 (*7*). The data returned from the material testing shows that all specimens were well within the tolerances set forth by ASTM. Two separate tensile coupons were 5% shy of the expected values but with the second value of each specimen the average is over the minimum expected values.

5.2 Post-Fire Evaluation of Plate Specimens – Part 2

Figures 5.9 to 5.12 show photographs of the post-fire evaluation of the plate specimens (Part 2) identified in Table 4.1 and again in Table 5.3. These include photographs taken as described in Section 4.5.

Figures 5.13 and 5.14 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 5.4 includes the standard material test results obtained by testing the coupons fabricated from the ½ in. thick plate specimens identified in Table 5.1. As shown in Table 5.4, 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 5.4, the fire exposures result in only a slight reduction in the CVN fracture toughness values for the steels.

Figures 5.15 and 5.16 show 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 ½ in. thick flange steel plates that had been subjected to controlled fire exposure using the flame jet setup. Box plots included for each plate specimen:

1. Minimum, maximum, and median values of fracture toughness.
2. First and third quartile fracture toughness values. First quartile means that 25% of the values are lower than this

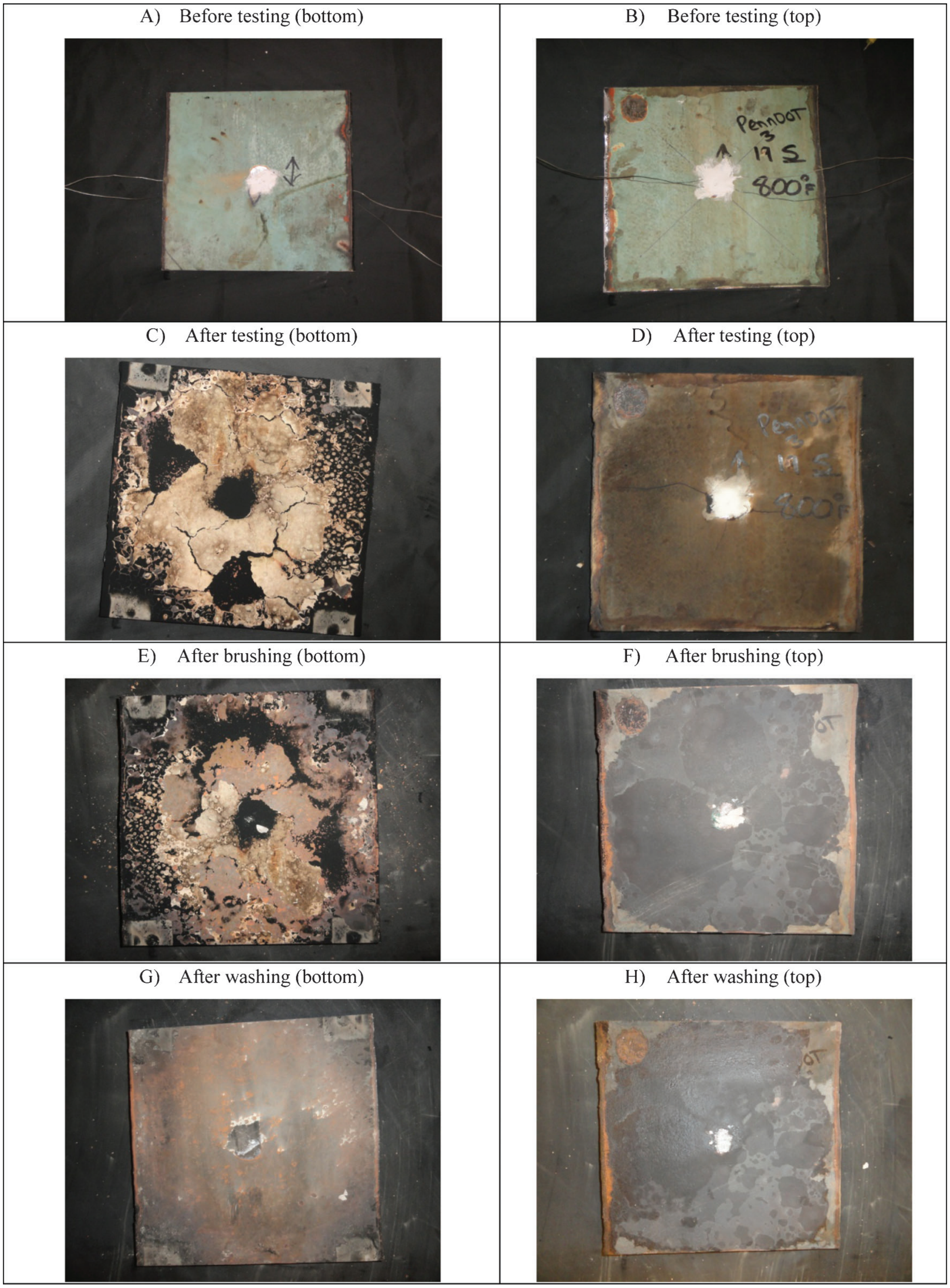


Figure 5.1 Post-fire evaluation of PennDOT 3 S (19) 800°F.

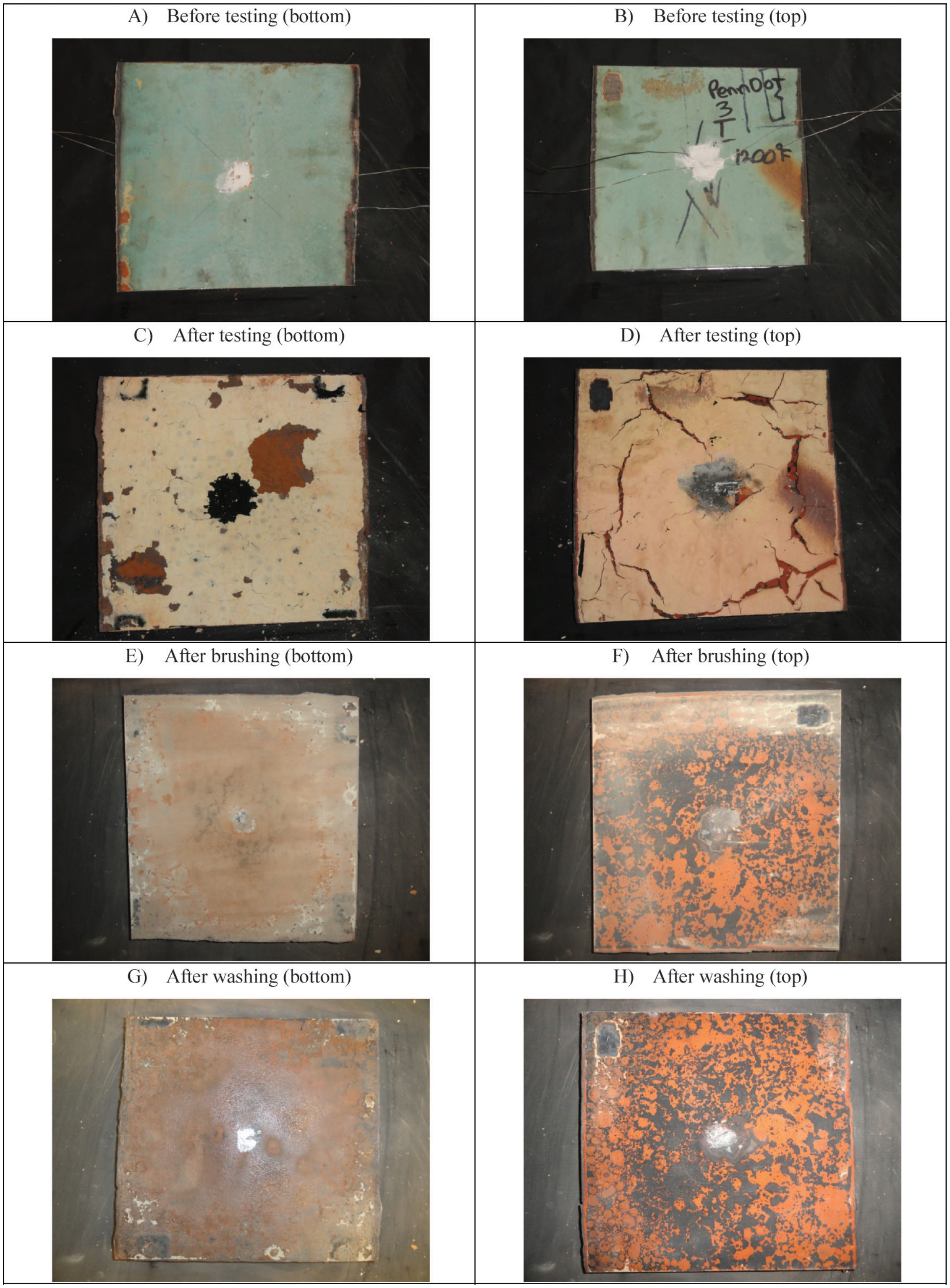


Figure 5.2 Post-fire evaluation of PennDOT 3 T (20) 1200°F.

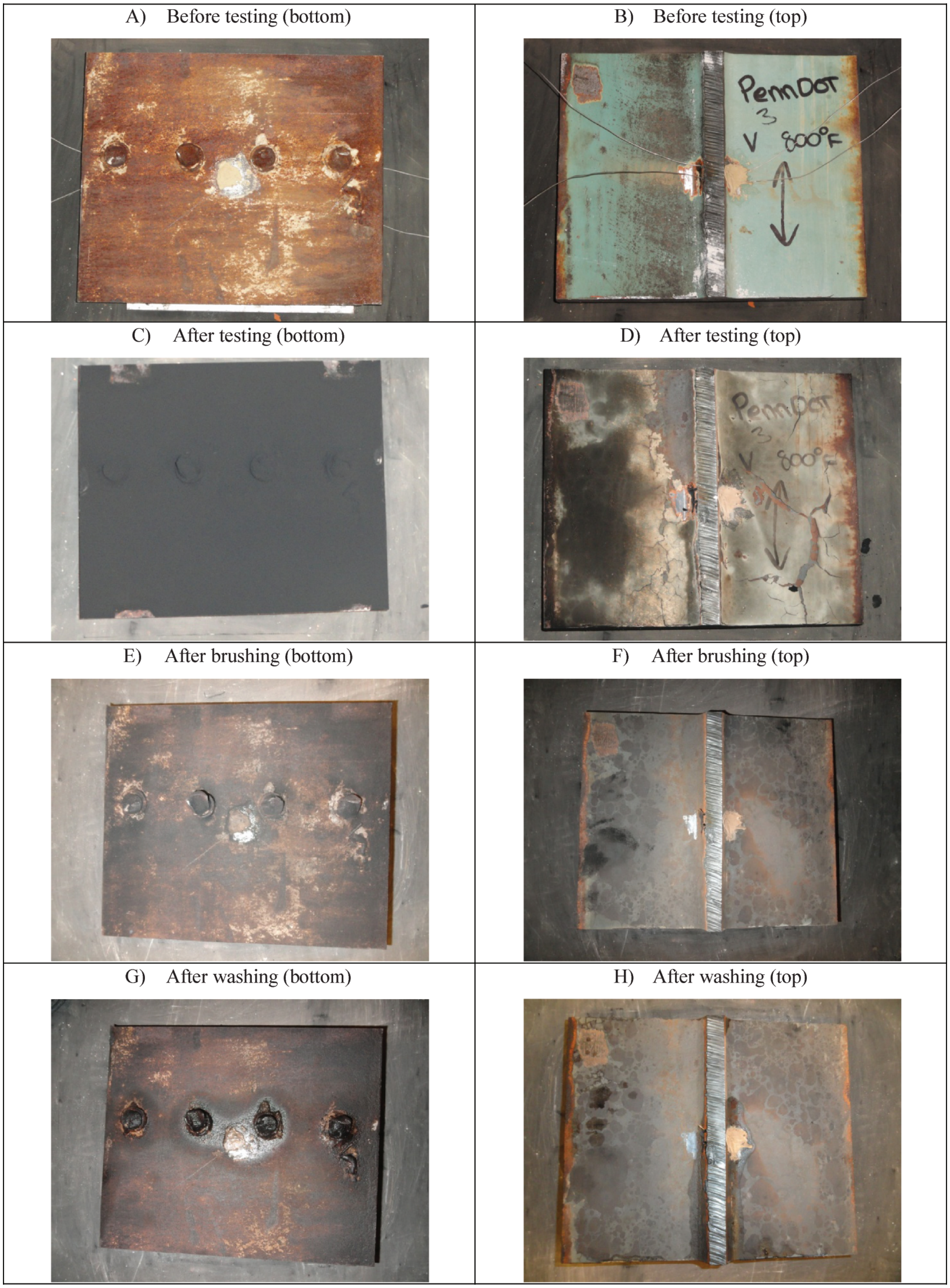


Figure 5.3 Post-fire evaluation of PennDOT 3 V (22) 800^{o}F.

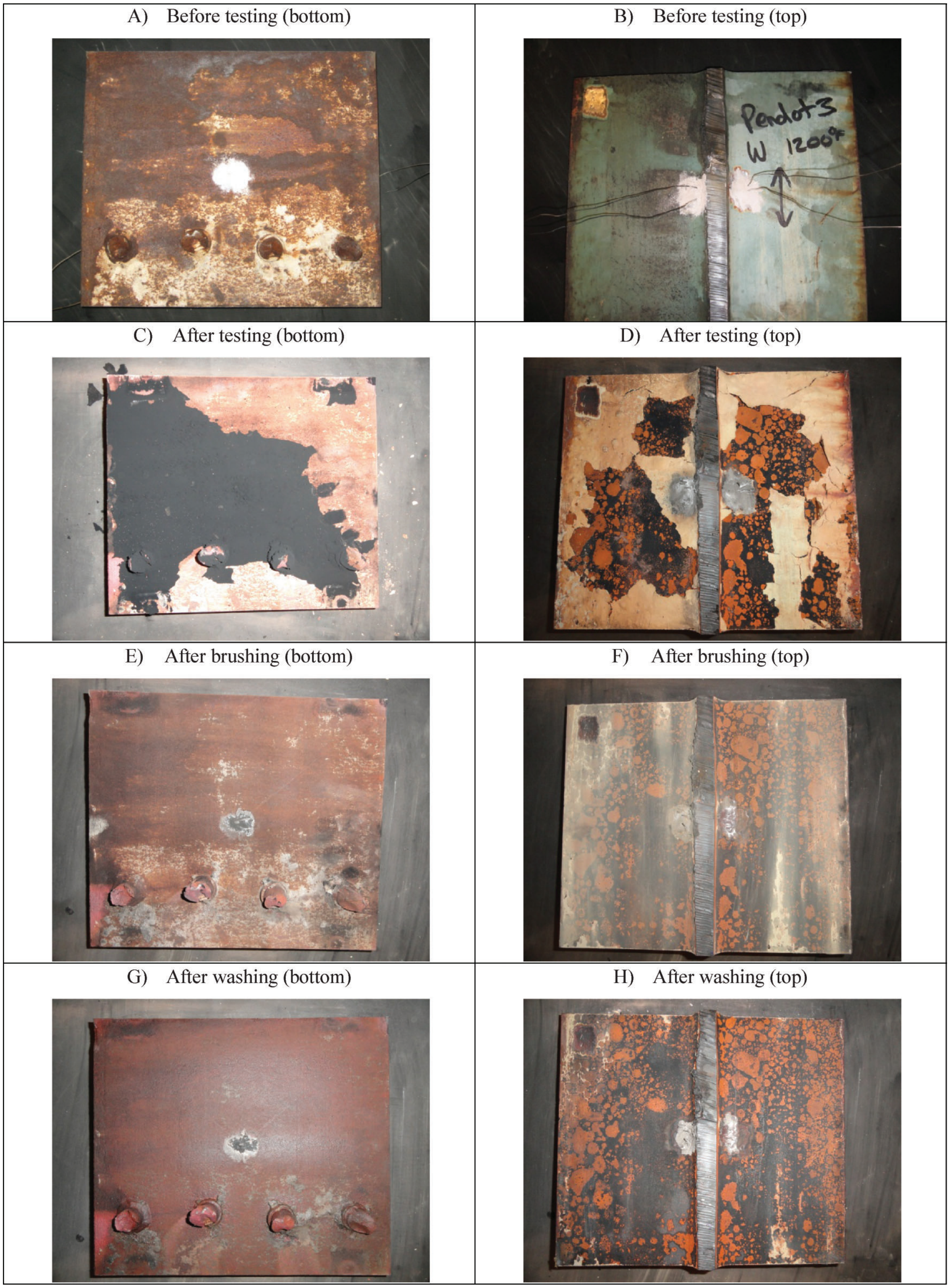


Figure 5.4 Post-fire evaluation of PennDOT 3 W (23) 1200°F.

TABLE 5.1
Test Matrix (Part 1)

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

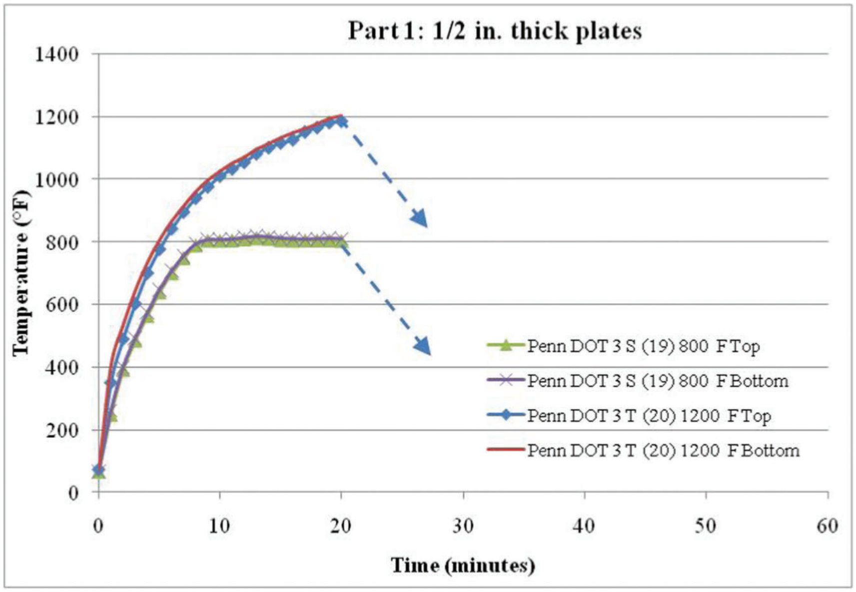


Figure 5.5 Measured temperature-time curves for ½ in. thick Part 1 plate specimens.

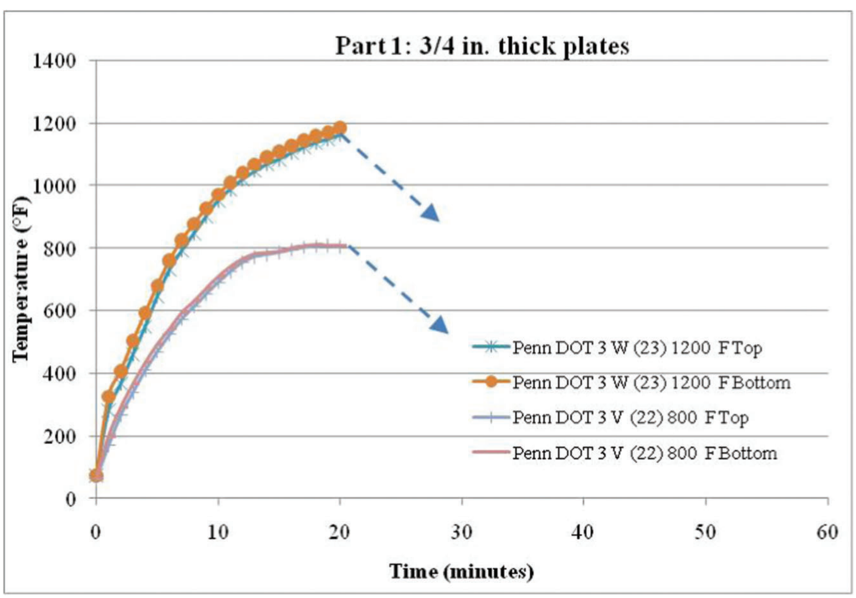


Figure 5.6 Measured temperature-time curves for ¾ in. thick Part 1 plate specimens.

TABLE 5.2
Material Test Results for Coupons from Plate Specimens (Part 1)

Specimen ID		σ_y	σ_u	%e	CVN results				AVG	Hardness Test				AVG
PennDOT 2 AA (27)	Coupon 1	36.3	64	42	Inner 3	42	47	52	47.0	Top	71	70.5	70	70.5
Control ½ in. thickness	Coupon 2	40.4	64	41	Outer 3	53	42	54	49.7	Bottom	70	71.5	71	70.8
PennDOT 1 Y (25) Burned	Coupon 1	40.6	64.5	44	Inner 3	29	44	43	38.7	Top	69	70.5	70.5	70.0
½ in. thickness	Coupon 2	34.8	64.5	41	Outer 3	34	20	30	28.0	Bottom	71	72	73	72.0
PennDOT 4 EE (31) Burned	Coupon 1	40.3	63	43	Inner 3	32	40	29	33.7	Top	67	71	70	69.3
½ in. thickness	Coupon 2	35.9	62	43	Outer 3	21	41	36	32.7	Bottom	64.5	65.5	66	65.3
PennDOT 2 BB (28)	Coupon 1	36.1	63	50	Inner 3	42	67	60	56.3	Top	62	58.5	64	61.5
Control ¾ in. thickness	Coupon 2	37	62	48	Outer 3	43	52	65	53.3	Bottom	55	62	71	62.6
PennDOT 1 Z (26) Burned	Coupon 1	36.5	64.5	50	Inner 3	61	45	62	56.0	Top	68	71.5	70	69.8
¾ in. thickness	Coupon 2	36.9	64	50	Outer 3	32	45	66	47.7	Bottom	70	69.5	69	69.5
PennDOT 4 FF (32) Burned	Coupon 1	36.4	62.5	50	Inner 3	44	57	40	47.0	Top	60	65	66.5	63.8
¾ in. thickness	Coupon 2	41.1	63	50	Outer 3	53	54	64	57.0	Bottom	65.5	66.5	68.5	66.8
PennDOT 3 CC (29)	Coupon 1	38.4	61	42	Inner 3	36	37	43	38.7	Top	68	68	70	68.7
Control ½ in. thickness	Coupon 2	36.5	60.5	45	Outer 3	52	15	18	28.3	Bottom	68.5	68	67.5	68.0
PennDOT 3 S (19) 800°F ½	Coupon 1	41.5	62.5	44	Inner 3	29	44	43	38.7	Top	71	71	71	71.0
in. thickness	Coupon 2	34.2	61.5	34	Outer 3	34	20	30	28.0	Bottom	70.5	70.5	70.5	70.5
PennDOT 3 T (20) 1200°F	Coupon 1	40.7	62	45	Inner 3	35	40	39	38.0	Top	63	68	69.5	66.8
½ in. thickness	Coupon 2	37.1	61.5	42	Outer 3	30	48	31	36.3	Bottom	65	68	70	67.6
PennDOT 3 DD (30)	Coupon 1	38.9	63.5	47	Inner 3	71	62	56	63.0	Top	66.5	67	67	66.8
Control ¾ in. thickness	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	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PennDOT 3 W (23) 1200°F	Coupon 1	36.5	62.5	49	Inner 3	34	14	40	29.3	Top	75.5	73	72	73.5
¾ in. thickness	Coupon 2	39.3	63	50	Outer 3	41	43	43	42.3	Bottom	76	77	75	76.0

NOTE: Yield stress is expected to be 36 KSI. Tensile Stress is expected to be 58 – 80 ksi. Elongation is expected to be 21% minimum in 2′′. Zone II non fracture critical requirement is 15 ft-lb @ 40°F.

value, and third quartile means 75% of the values are 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 (*7*). The data returned from the material testing shows that all specimens were well within the tolerances set forth by ASTM. One CVN specimen fell below the 15 ft-lb mark, but the average of the three CVN's in the area was over the minimum standard.

5.3 Post-Fire Evaluation of Plate Specimens – Part 3

Figures 5.17 to 5.24 show photographs of the post-fire evaluation of the plate specimens (Part 3) identified in Table 4.1 and again in Table 5.5. These include photographs taken as described in Section 4.5.

Figures 5.25 and 5.26 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°F, 1000°F, and 1200°F were achieved and maintained for 20 minutes before cooling.

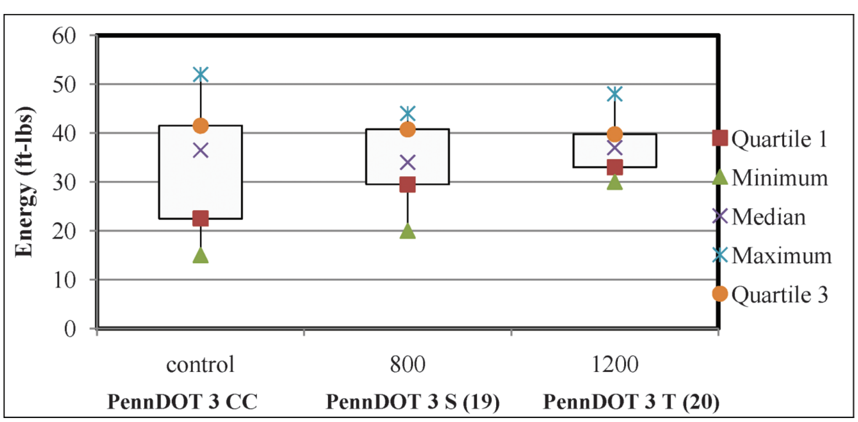


Figure 5.7 Statistical evaluation of CVN fracture toughness values for ½ in. thick plate specimens (Part 1).

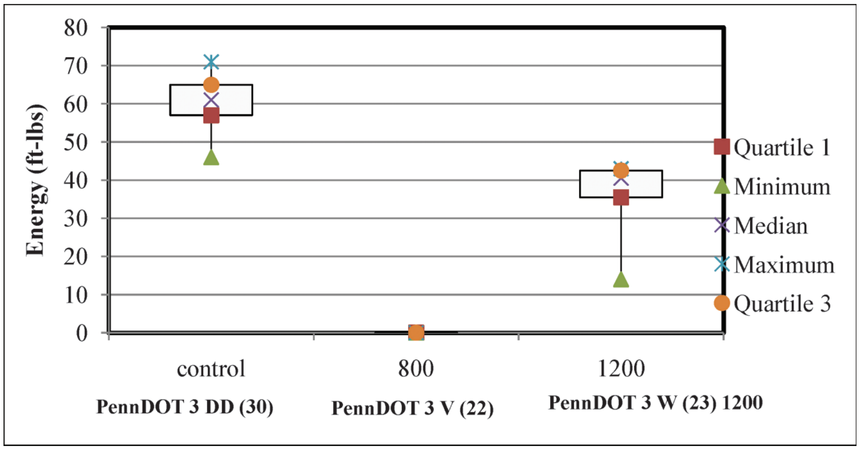


Figure 5.8 Statistical evaluation of CVN fracture toughness values for ¾ in. thick plate specimens (Part 1).

The uncontrolled fire test reached a maximum temperature of 1200˚F also, and was allowed to continue (burn out) for 40 minutes before cooling.

Additionally, Table 5.6 includes the standard material test results obtained by testing the coupons fabricated from the ½ in. thick plate specimens identified in Table 5.1. As shown in Table 5.6, 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 5.6, the fire exposures result in a reduction in the CVN fracture toughness values for the steels.

Figures 5.27 and 5.28 show 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 ½ in. thick flange steel plates that had been subjected to controlled fire exposure using the flame jet setup. Box plots included for each plate specimen:

1. Minimum, maximum, and median values of fracture toughness.
2. First and third quartile fracture toughness values. First quartile means that 25% of the values are lower than this value, and third quartile means 75% of the values are 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 (*7*). The data returned from the material testing shows that all specimens were well within the tolerances set forth by ASTM.

5.4 Post-Fire Evaluation of Plate Specimens – Part 4

Figures 5.29 to 5.34 show photographs of the post-fire evaluation of the plate specimens (Part 4) identified in Table 4.1 and again in Table 5.7. These include photographs taken as described in Section 4.5.

Figures 5.35 and 5.36 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˚F, 1000˚F, and 1200˚F were achieved and maintained for 20 minutes before cooling. The uncontrolled fire test reached a maximum temperature of 1200°F also, and was allowed to continue (burn out) for 40 minutes before cooling.

Additionally, Table 5.8 includes the standard material test results obtained by testing the coupons fabricated from the ½ in. thick plate specimens identified in Table 5.1. As shown in Table 5.8, 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 5.8, the fire exposures result in a reduction in the CVN fracture toughness values for the steels. Note that Carbothane J (10) Control W was only large enough for three CVN specimens.

Figures 5.37 and 5.38 show 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 ½ in. thick flange steel plates that had been subjected to controlled fire exposure using the flame jet setup. Box plots include for each plate specimen:

1. Minimum, maximum, and median values of fracture toughness.
2. First and third quartile fracture toughness values. First quartile means that 25% of the values are lower than this value, and third quartile means 75% of the values are 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 (*7*). The data

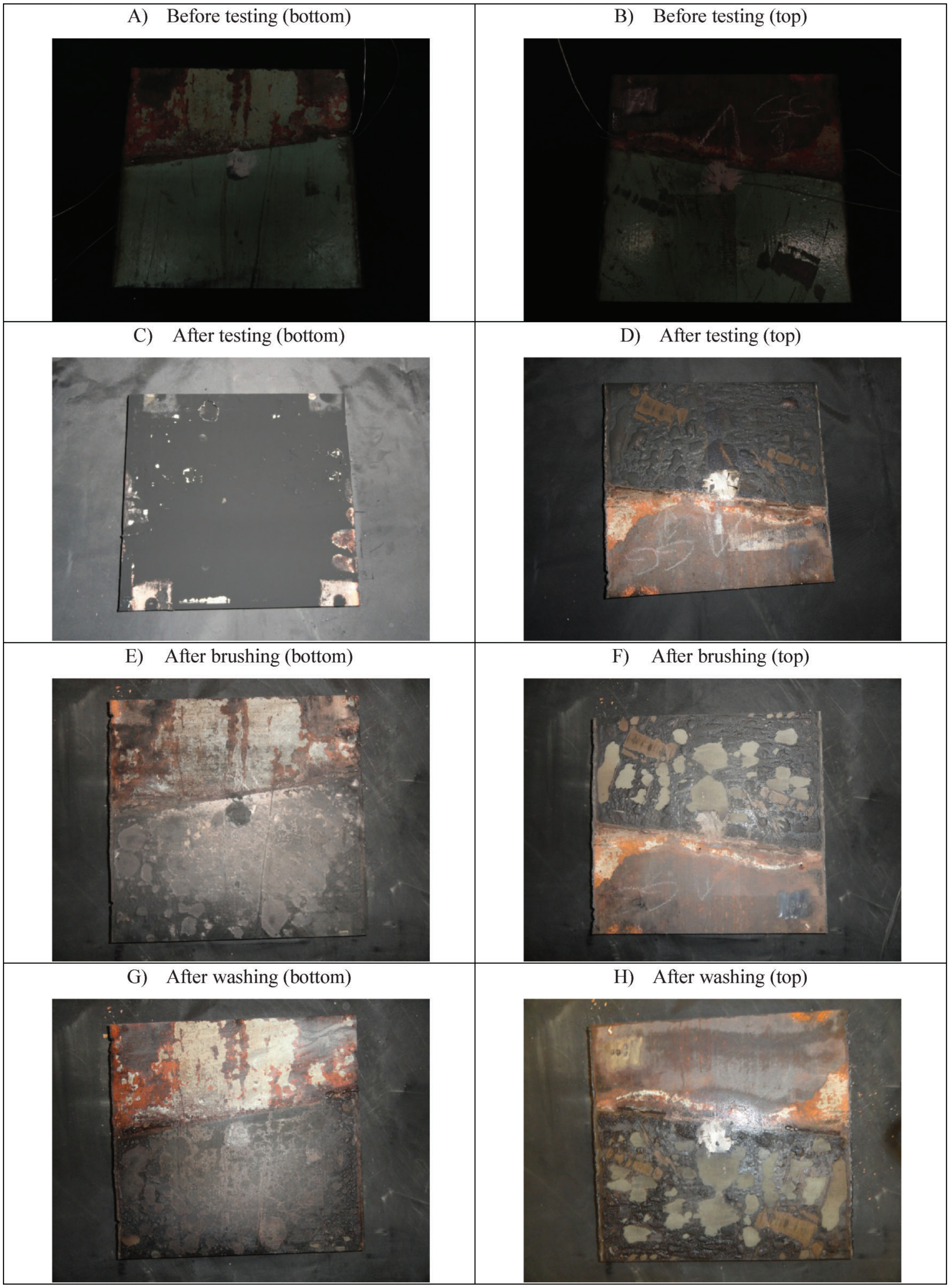


Figure 5.9 Post-fire evaluation of PennDOT 5 GG (33) 800°F.

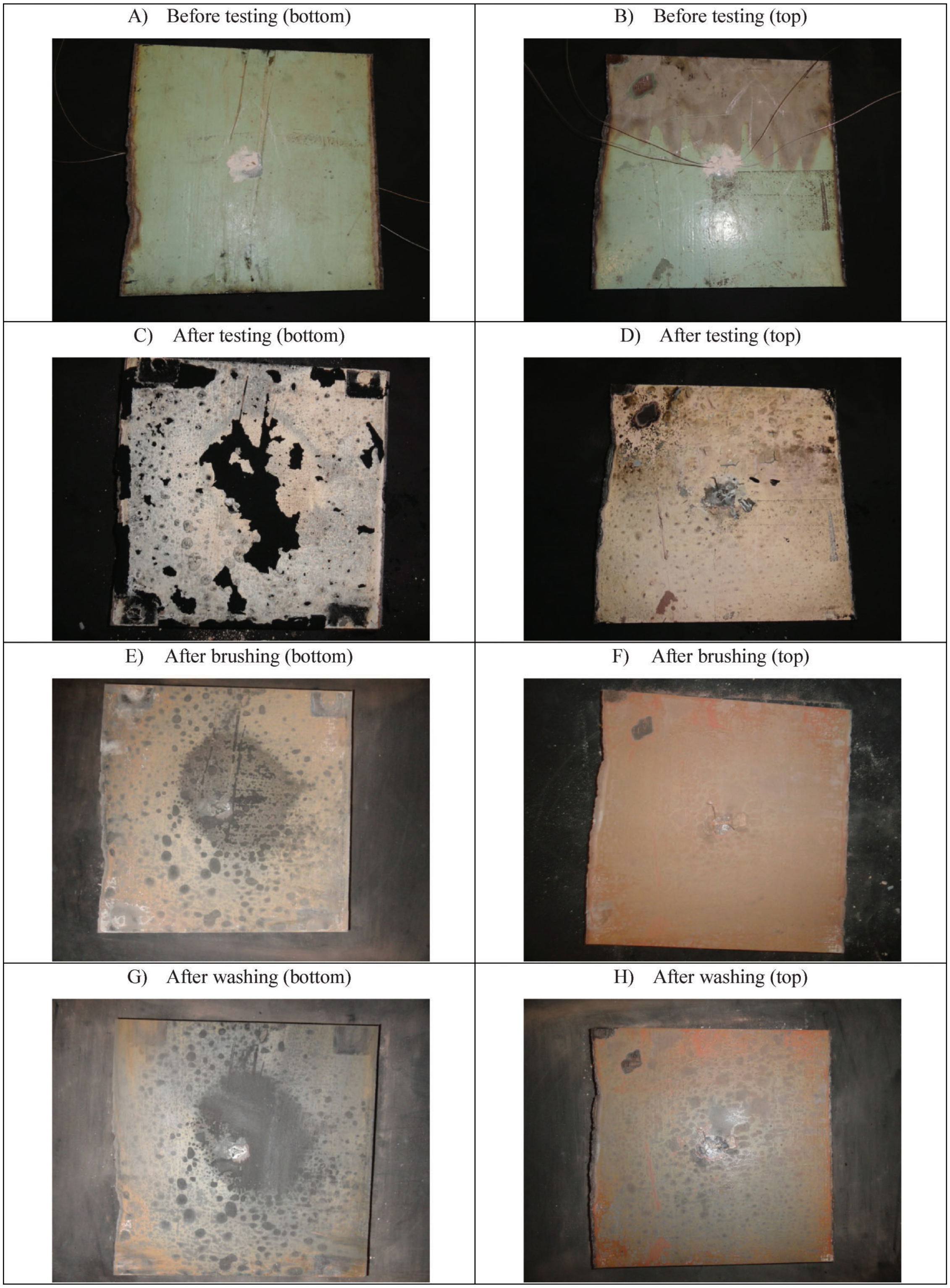


Figure 5.10 Post-fire evaluation of PennDOT 5 II (35) 1200°F.

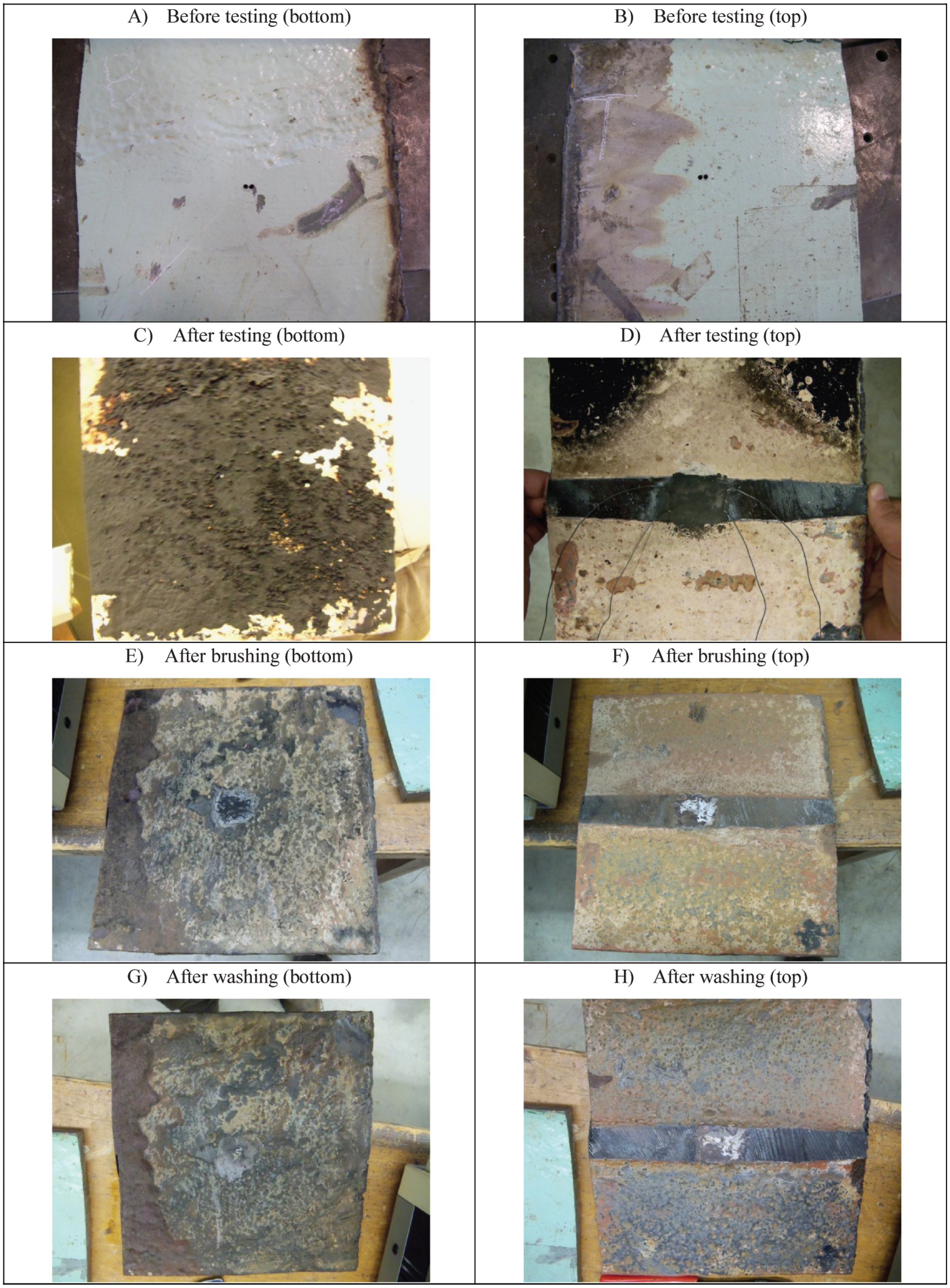


Figure 5.11 Post-fire evaluation of PennDOT 5 HH (34) 1200°F.

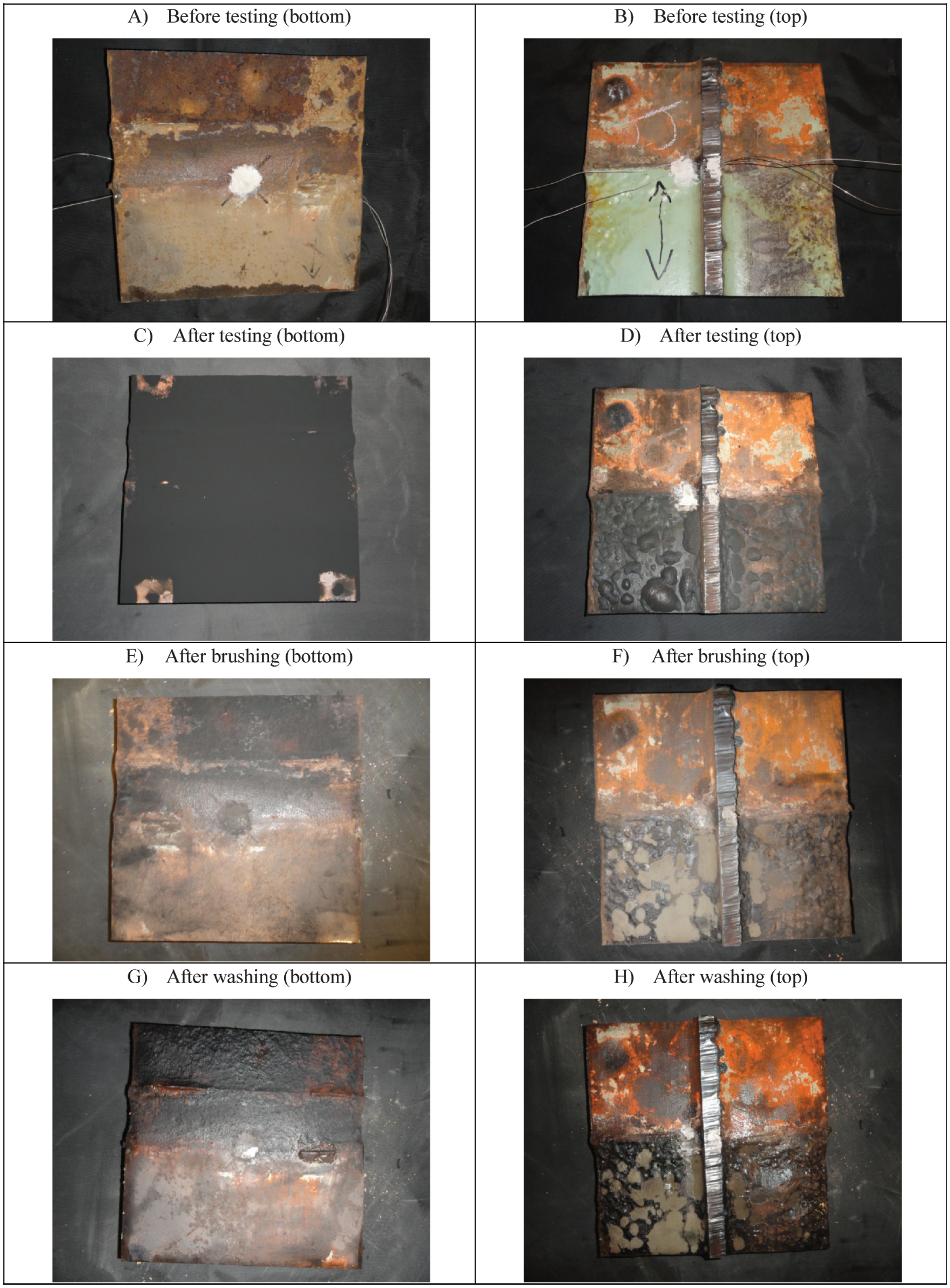


Figure 5.12 Post-fire evaluation of PennDOT 5 JJ (36) 800°F.

TABLE 5.3
Test Matrix (Part 2)

Specimen ID	Origin	Type or Temperature	Description
PennDOT 5 GG (33) 800 F	PennDOT 5	800 F	½ in. thick web; flame jet and material tests
PennDOT 5 II (35) 1200 F	PennDOT 5	1200 F	½ in. thick web; flame jet and material tests
PennDOT 5 HH (34) 1200 F	PennDOT 5	1200 F	½ in. thick flange; flame jet and material tests
PennDOT 5 JJ (36) 800 F	PennDOT 5	800 F	½ in. thick flange; flame jet and material tests

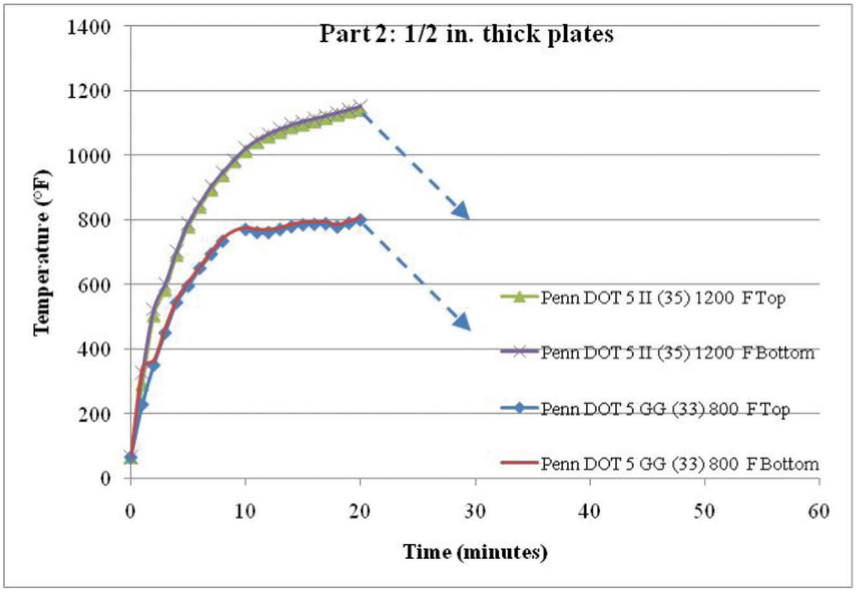


Figure 5.13 Measured temperature-time curves for ½ in. thick Part 2 plate specimens (web).

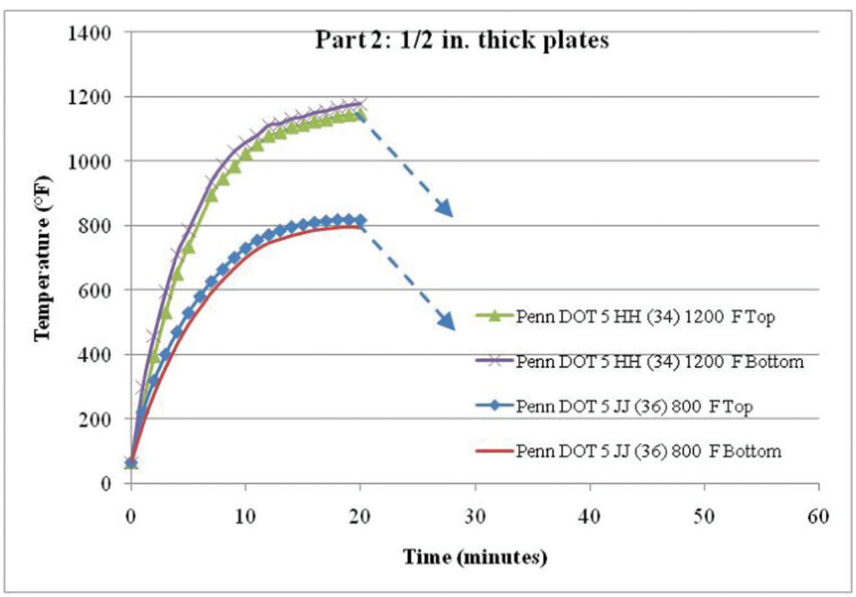


Figure 5.14 Measured temperature-time curves for ½ in. thick Part 2 plate specimens (flanges).

TABLE 5.4
Material Test Results for Coupons from Part 2 Plate Specimens

Specimen ID		σy	σu	%e	CVN results				AVG	Hardness Test				AVG
PennDOT 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	74.8
	Coupon 2	45	71.5	40	Outer 3	65	34	37	45.3	Bottom	73.5	75	72.5	73.7
PennDOT 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	74.3
PennDOT 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	72.8
	Coupon 2	43.3	71.5	42	Outer 3	30	69	65	54.7	Bottom	69.5	73	75.5	72.7
PennDOT 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	67.7
PennDOT 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
PennDOT 5 HH (34) 1200˚F½ 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

Note* Yield stress is expected to be 36 KSI. Tensile Stress is expected to be 58 – 80 ksi. Elongation is expected to be 21% minimum in 2′′. Zone II non fracture critical requirement is 15 ft-lb @ 40˚F.

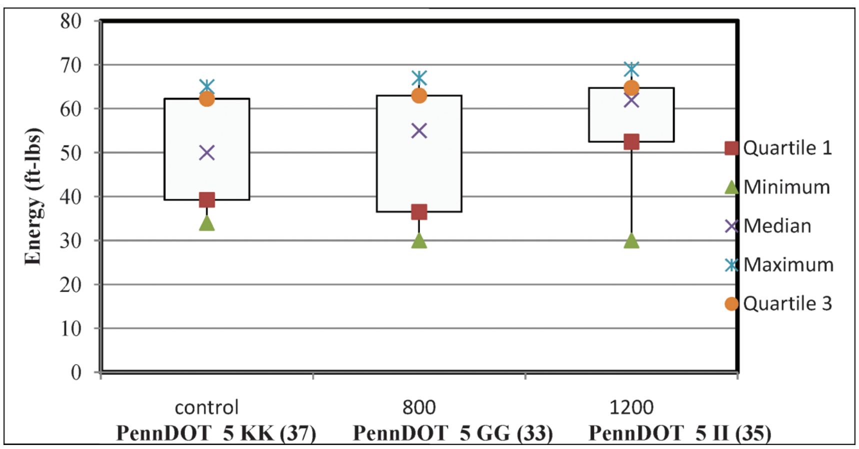


Figure 5.15 Statistical analysis of CVN fracture toughness for Part 2 plate specimens (½ in. thick webs).

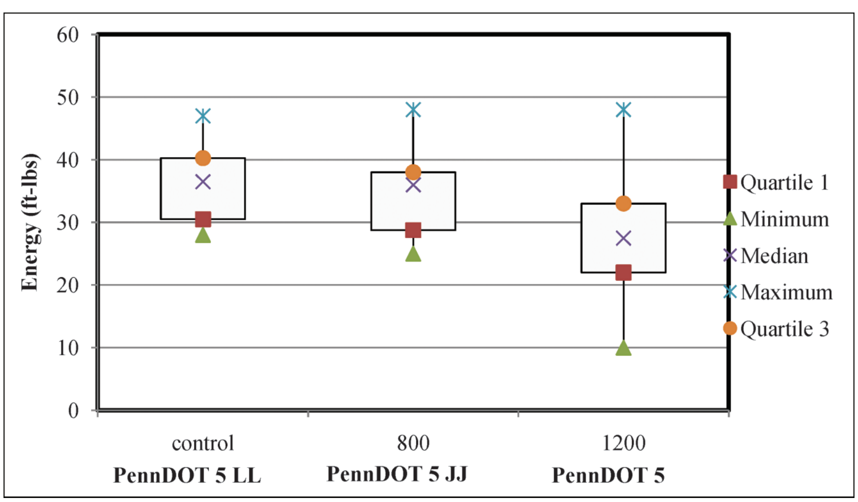


Figure 5.16 Statistical analysis of CVN fracture toughness for Part 2 plate specimens (½ in. thick flanges).

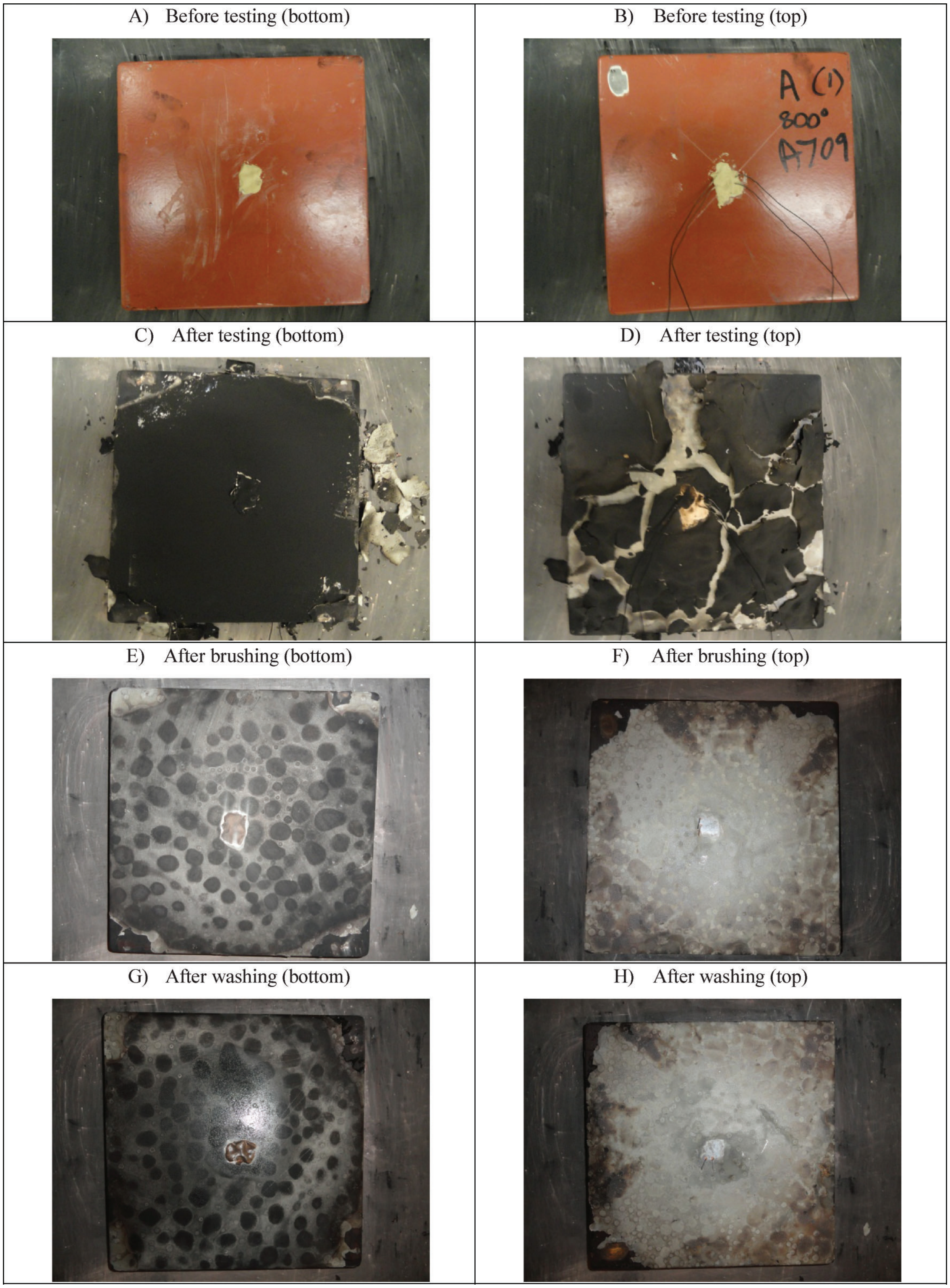


Figure 5.17 Post-fire evaluation of Acrolon A (1) 800°F.

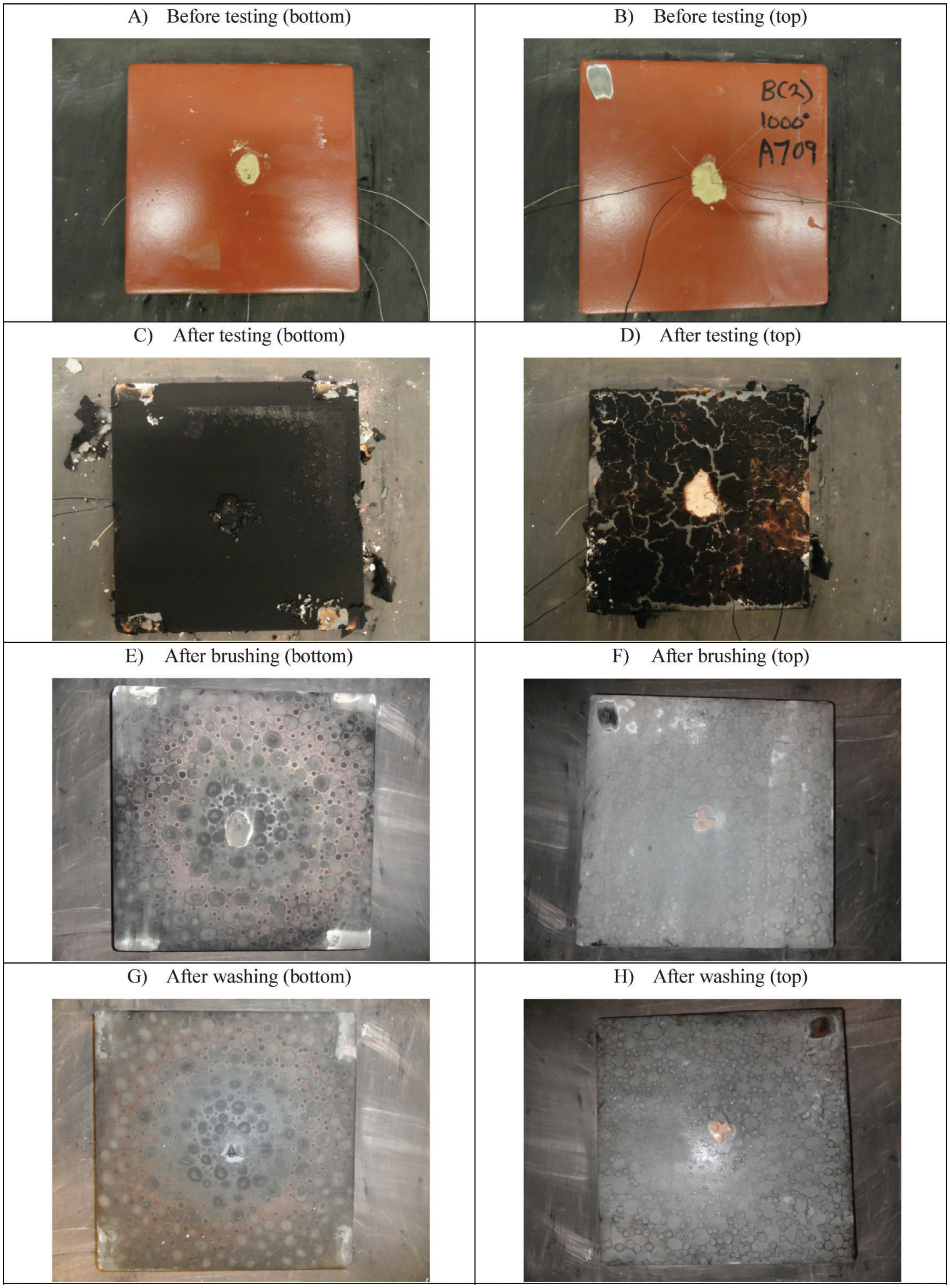


Figure 5.18 Post-fire evaluation of Acrolon B (2) 1000°F.

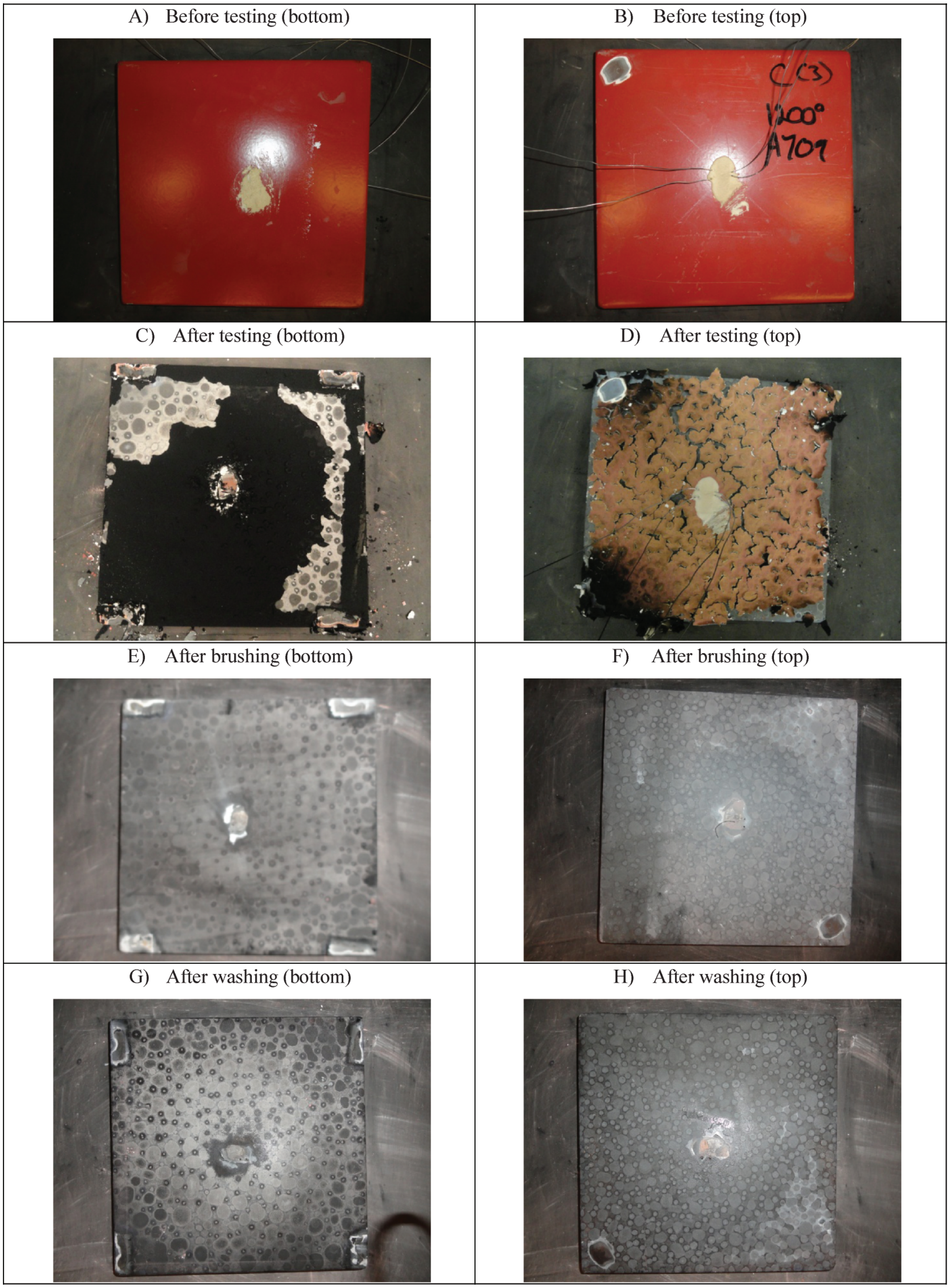


Figure 5.19 Post-fire evaluation of Acrolon C (3) 1200°F.

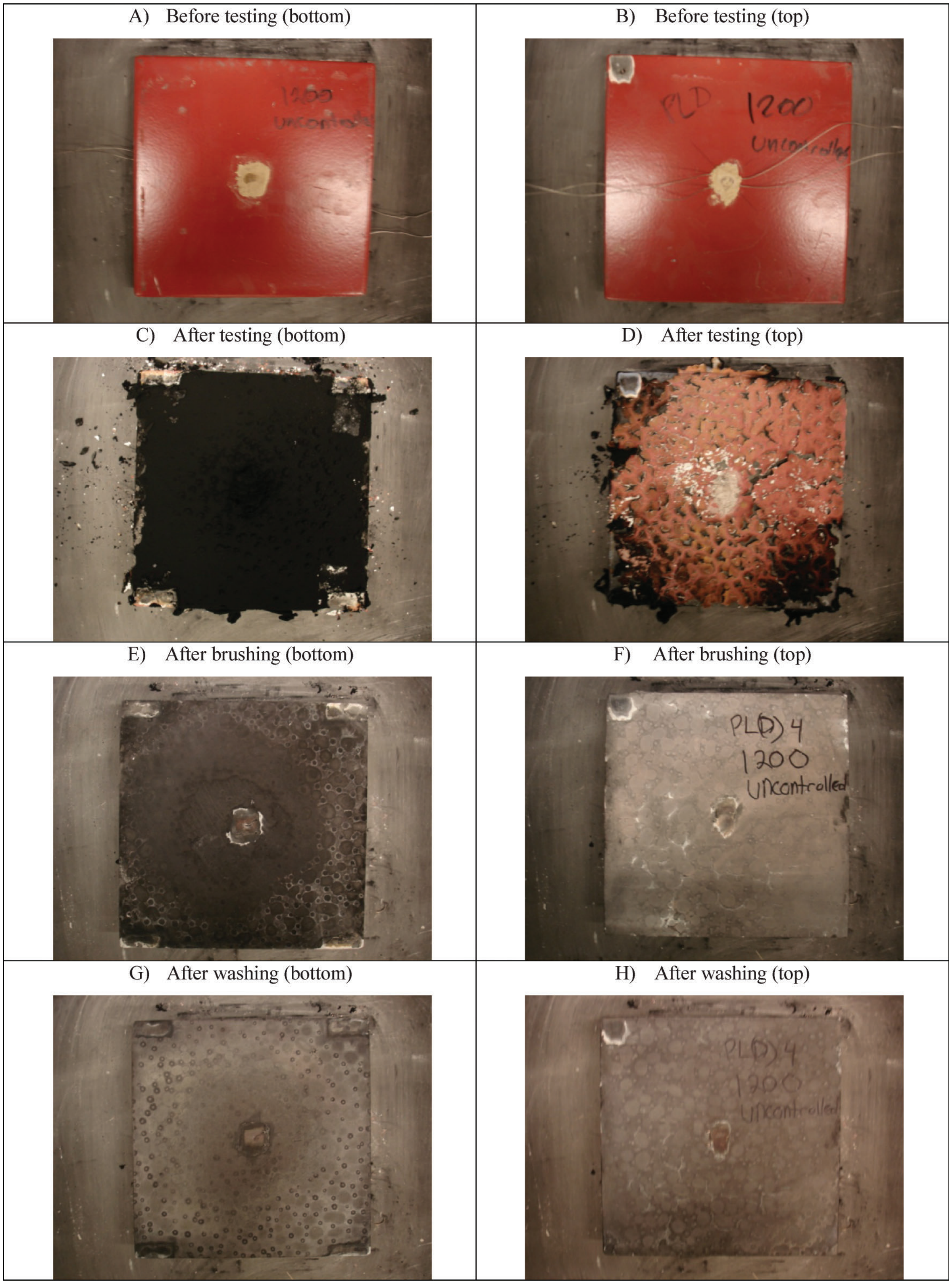


Figure 5.20 Post-fire evaluation of Acrolon D (4) uncontrolled 1200°F.

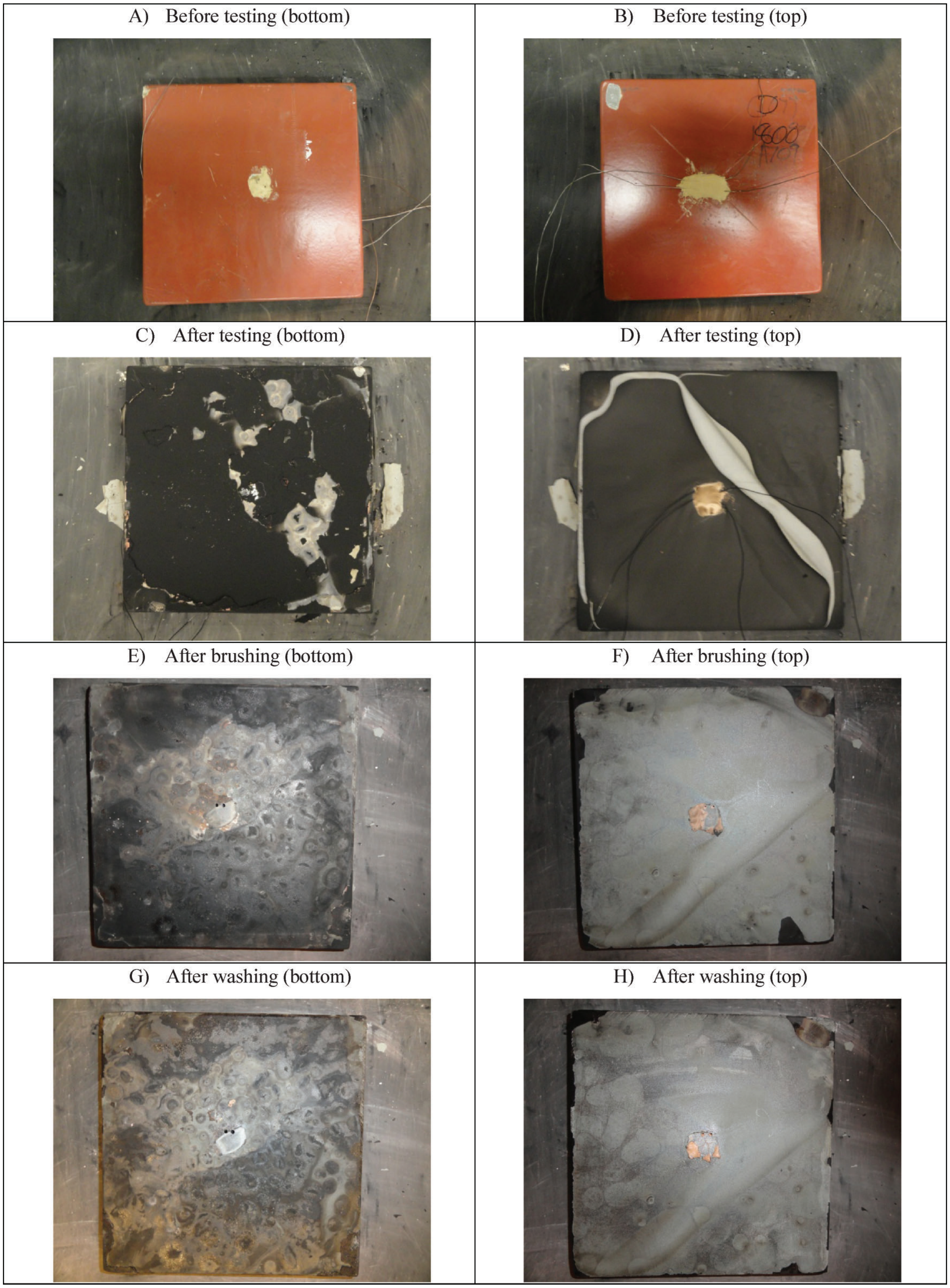


Figure 5.21 Post-fire evaluation of Acrolon E (5) 800°F.

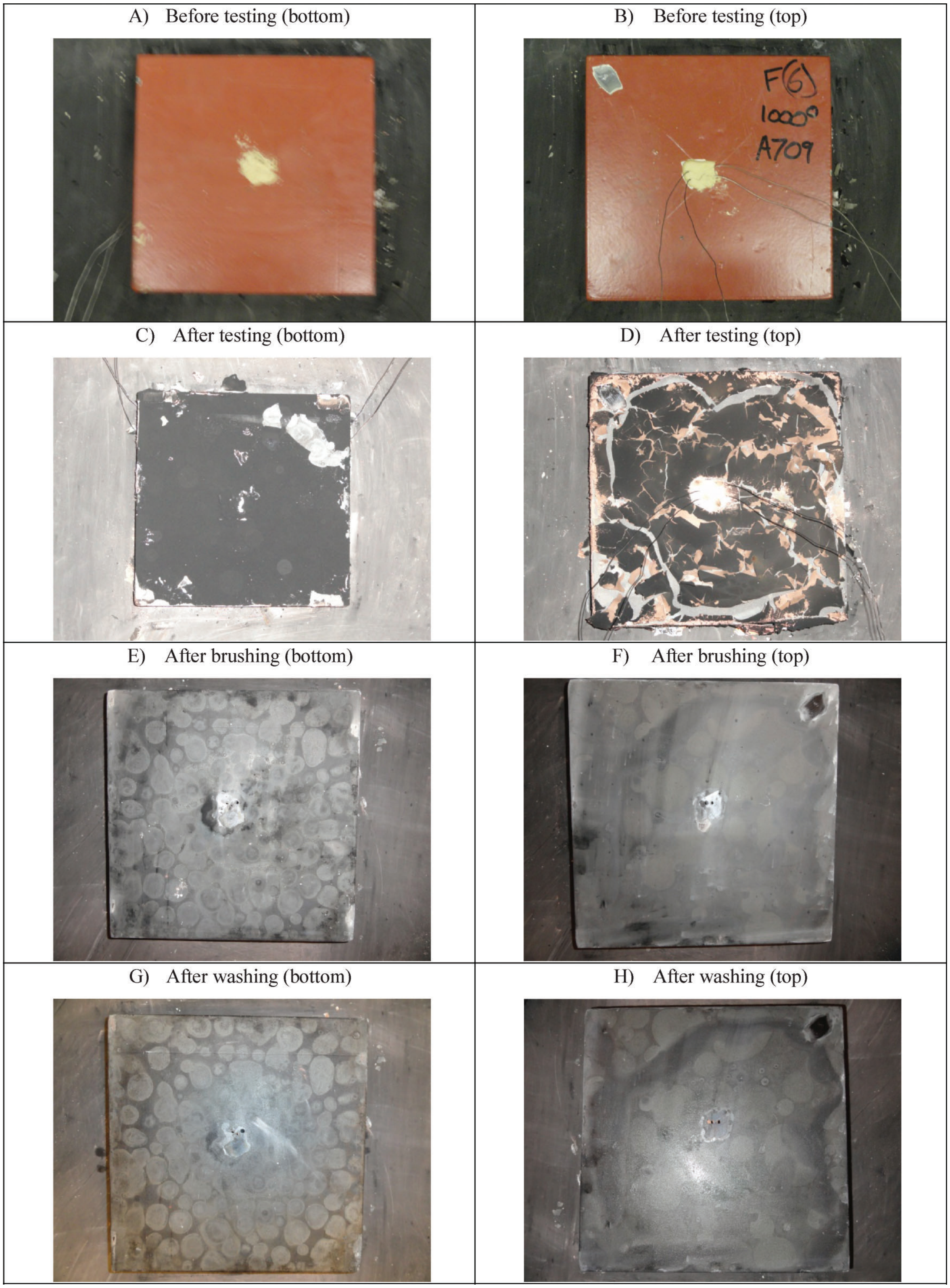


Figure 5.22 Post-fire evaluation of Acrolon F (6) 1000°F.

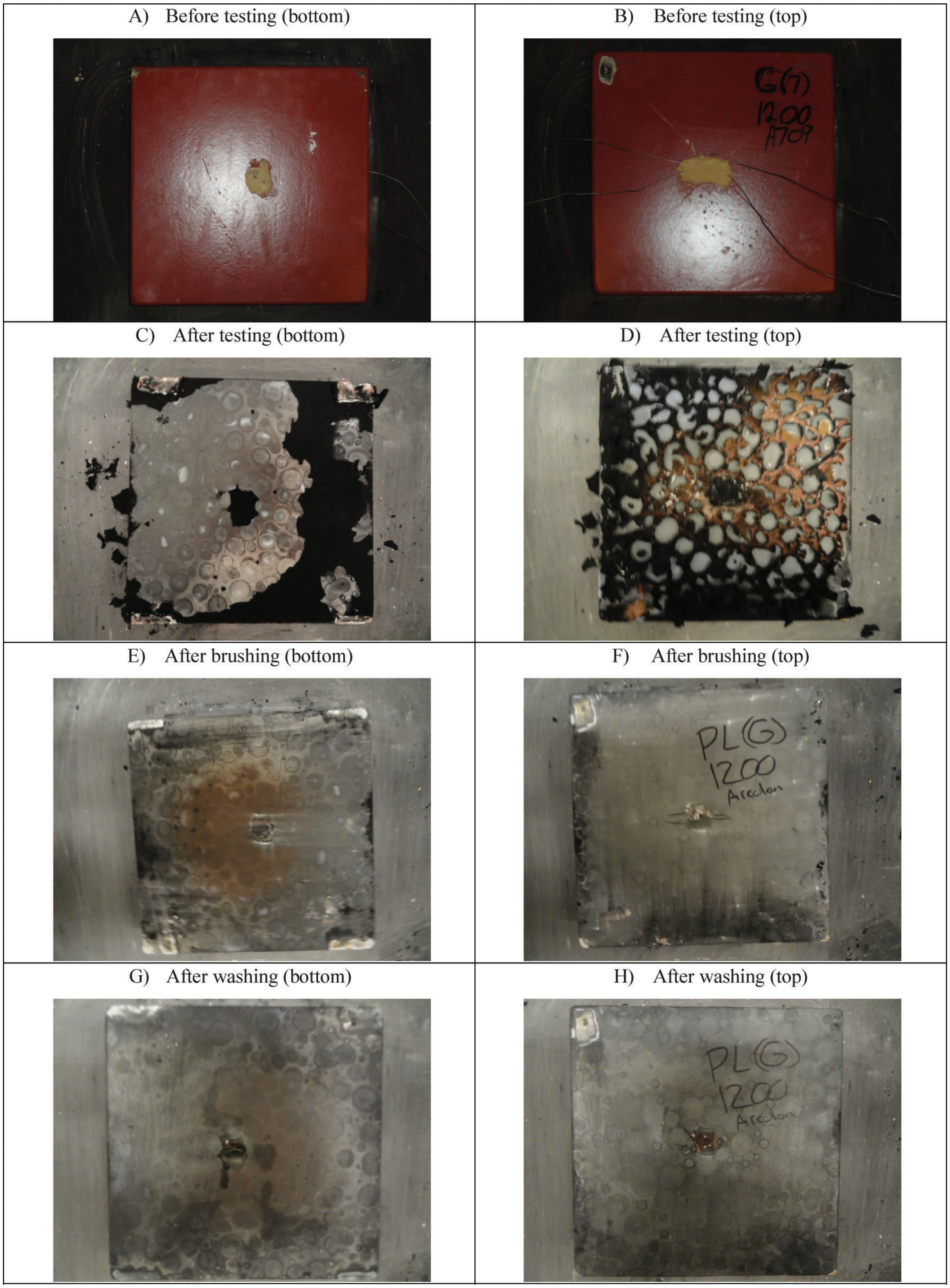


Figure 5.23 Post-fire evaluation of Acrolon G (7) 1200°F.

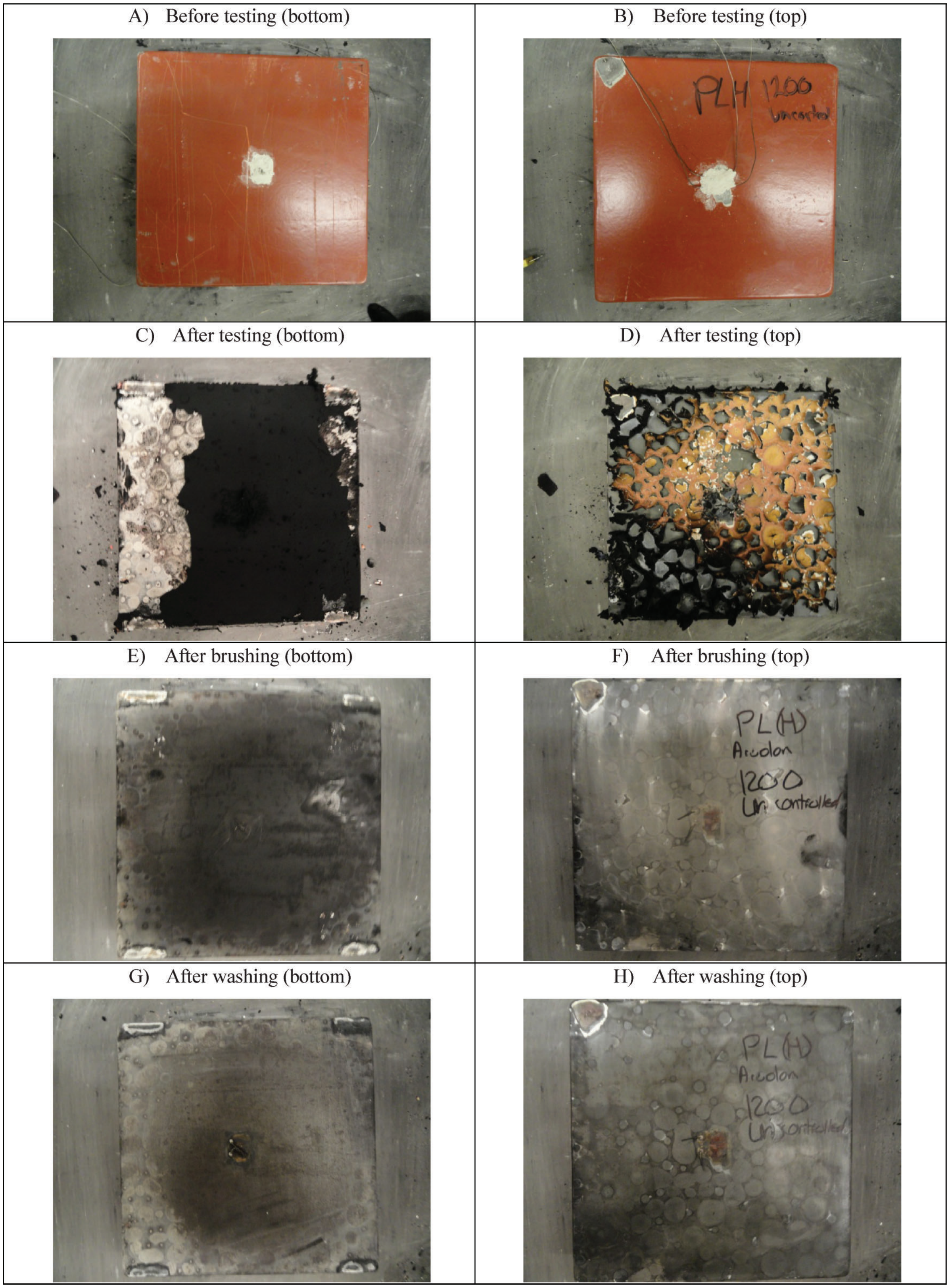


Figure 5.24 Post-fire evaluation of Acrolon H (8) uncontrolled 1200°F.

TABLE 5.5
Test Matrix (Part 3)

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

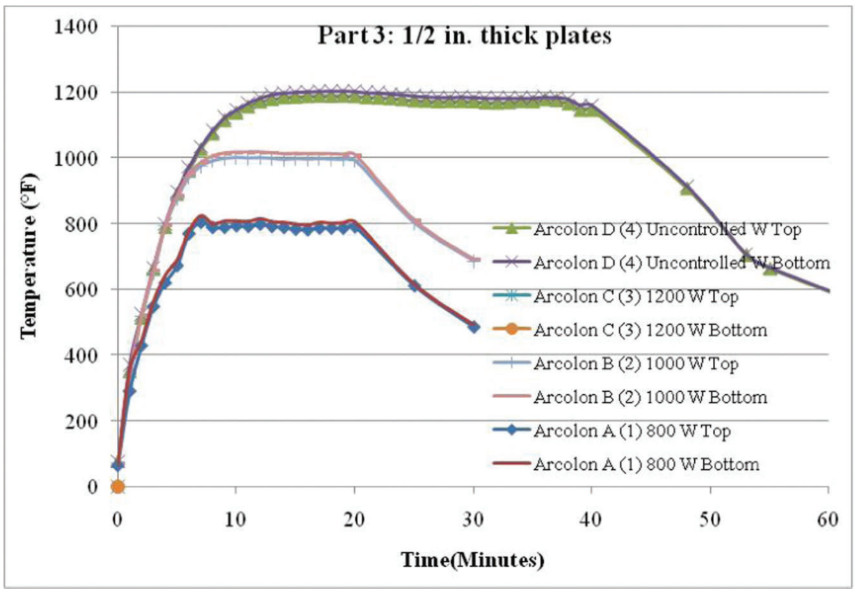


Figure 5.25 Measured temperature-time curves for ½ in. plate specimens with Acrolon coating (Part 3).

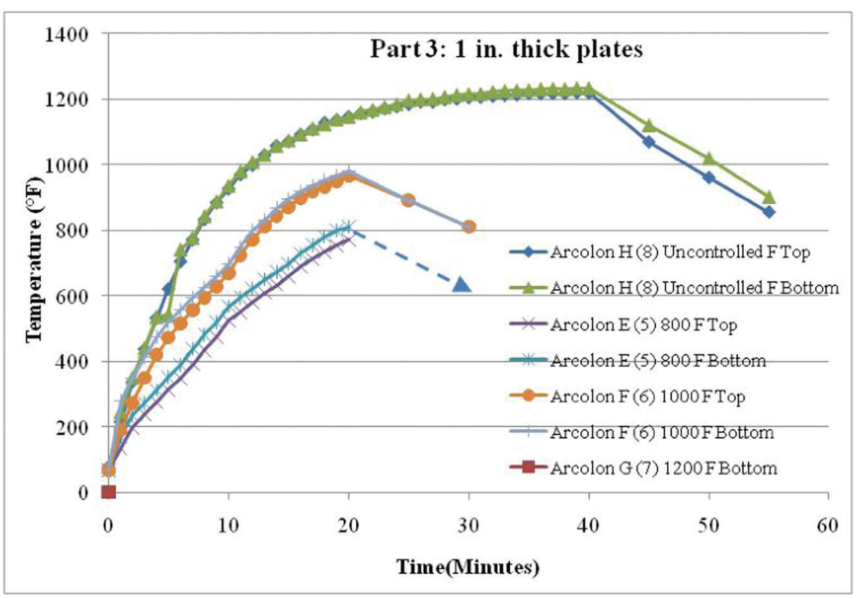


Figure 5.26 Measured temperature-time curves for 1 in. plate specimens with Acrolon coating (Part 3).

TABLE 5.6
Material Test Results for Coupons from Part 3 Plate Specimens

Specimen ID		σy	σu	%e	CVN results				AVG	Hardness Test				AVG
Arcolon Q (17) Control W	Coupon 1	57	82	35	Inner 3	102	107	32	80.3	Top	84	84	84	84.0
	Coupon 2	58.5	83.5	39	Outer 3	77	31	32	46.7	Bottom	83	83	82	82.7
Arcolon A (1)800 W	Coupon 1	58.5	82.5	36	Inner 3	X	31	32	31.5	Top	84	84	85	84.3
	Coupon 2	59.5	83	36	Outer 3	31	31	34	32.0	Bottom	84	85	84	84.3
Arcolon B (2)1000 W	Coupon 1	59.5	82	38	Inner 3	94	107	86	95.7	Top	84	84	85	84.3
	Coupon 2	58	81.5	38	Outer 3	91	95	97.0	94.3	Bottom	86	86	85	85.7
Arcolon C (3) 1200 W	Coupon 1	57.5	81	37	Inner 3	87	104	102	97.7	Top	85	85	84	84.7
	Coupon 2	58	80.5	37	Outer 3	94	101	113	102.7	Bottom	84	84	83	83.7
Arcolon D (4) Uncontrolled W	Coupon 1	58.5	81	36	Inner 3	25	24	27	25.3	Top	83	83	84	83.3
	Coupon 2	58.5	81	34	Outer 3	28	24	26	26.0	Bottom	84	83	83	83.3
Arcolon R (18)Control F	Coupon 1	56	80	44	Inner 3	77	81	28	62.0	Top	86	85	85	85.3
	Coupon 2	57	80	51	Outer 3	92	34	34	53.3	Bottom	84	84	83	83.7
Arcolon E (5) 800 F	Coupon 1	56.5	80.5	50	Inner 3	78	82	93	84.3	Top	86	85	85	85.3
	Coupon 2	56.5	80.5	49	Outer 3	87	96	60	81.0	Bottom	84	84	83	83.7
Arcolon F (6) 1000 F	Coupon 1	57	80.5	50	Inner 3	78	83	92	84.3	Top	84	85	84	84.3
	Coupon 2	57	80.5	50	Outer 3	88	79	75	80.7	Bottom	86	86	85	85.7
Arcolon G (7) 1200 F	Coupon 1	58	80.5	44	Inner 3	73	78	77	76.0	Top	82	83	83	82.7
	Coupon 2	58	80.5	44	Outer 3	85	80	80	81.7	Bottom	83	83	83	83.0
Arcolon H (8) Uncontrolled F	Coupon 1	59.5	80	50	Inner 3	87	58	94	79.7	Top	85	85	86	85.3
	Coupon 2	59.5	80.5	48	Outer 3	61	62	85	69.3	Bottom	84	84	84	84.0

Note* Yield stress is expected to be 50 KSI. Tensile Stress is expected to be 58 ksi. Elongation is expected to be 19% minimum in 2′′. Zone II non fracture critical requirement is 15 ft-lb @ 40°F.

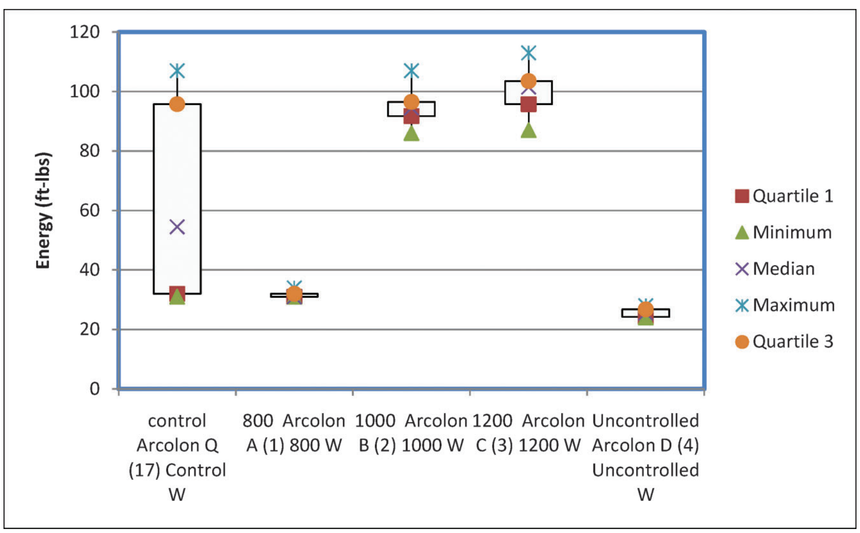


Figure 5.27 Statistical analysis of CVN fracture toughness for Part 3 plate specimens (½ in. thick webs).

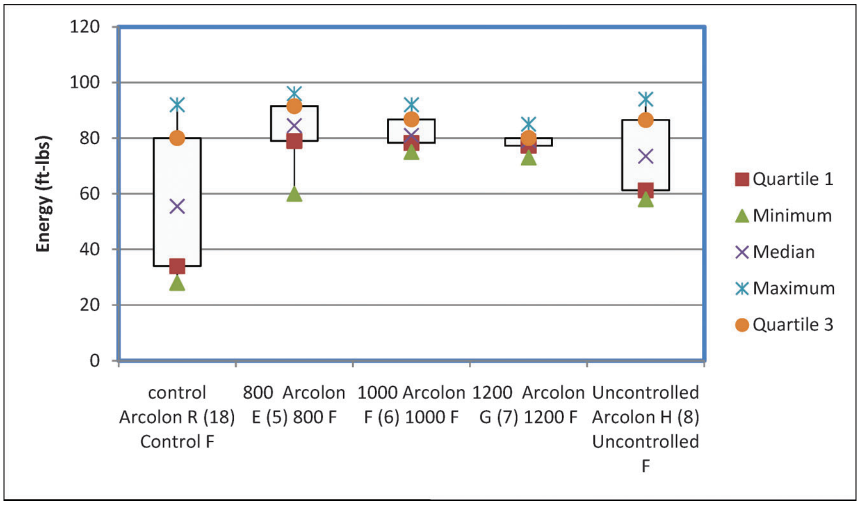


Figure 5.28 Statistical analysis of CVN fracture toughness for Part 3 plate specimens (1 in. thick flanges).

returned from the material testing shows that all specimens were well within the tolerances set forth by ASTM. The control specimen in this particular section is exceptionally low compared to the plates tested under fire conditions. This could be because the fact that the steel could go through some tempering during the heating and cooling process.

5.5 Microstructure Investigation

For part 3 web plates, CVN samples were used to determine if the microstructure of the steel changed from control throughout the testing process. Each CVN was polished on the surface of the sample that was directly impinged by testing flames. After polishing, the samples were photographed at 300 times magnification and studied. The photographs are shown in Figure 5.39. Images consist largely of two separate colors. The darker color represents Pearlite, and the lighter yellowish color is Ferrite. As the plates progress in temperature, Ferrite and Pearlite become more evenly scattered and the structure of each particle is more visible although the grain sizes appear to be about the same.

5.6 Findings and Conclusions from Post-Fire Evaluations

The post-fire evaluation photographs shown in Sections 5.1 through 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, whereas 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. In some cases the fracture toughness is seen to increase as in part 4. This could be because of the fact that the steel is being heated for 20 minutes and allowed to cool. This is very similar to

Figure 5.29 Post-fire evaluation of Carbothane I (9) 1000°F.

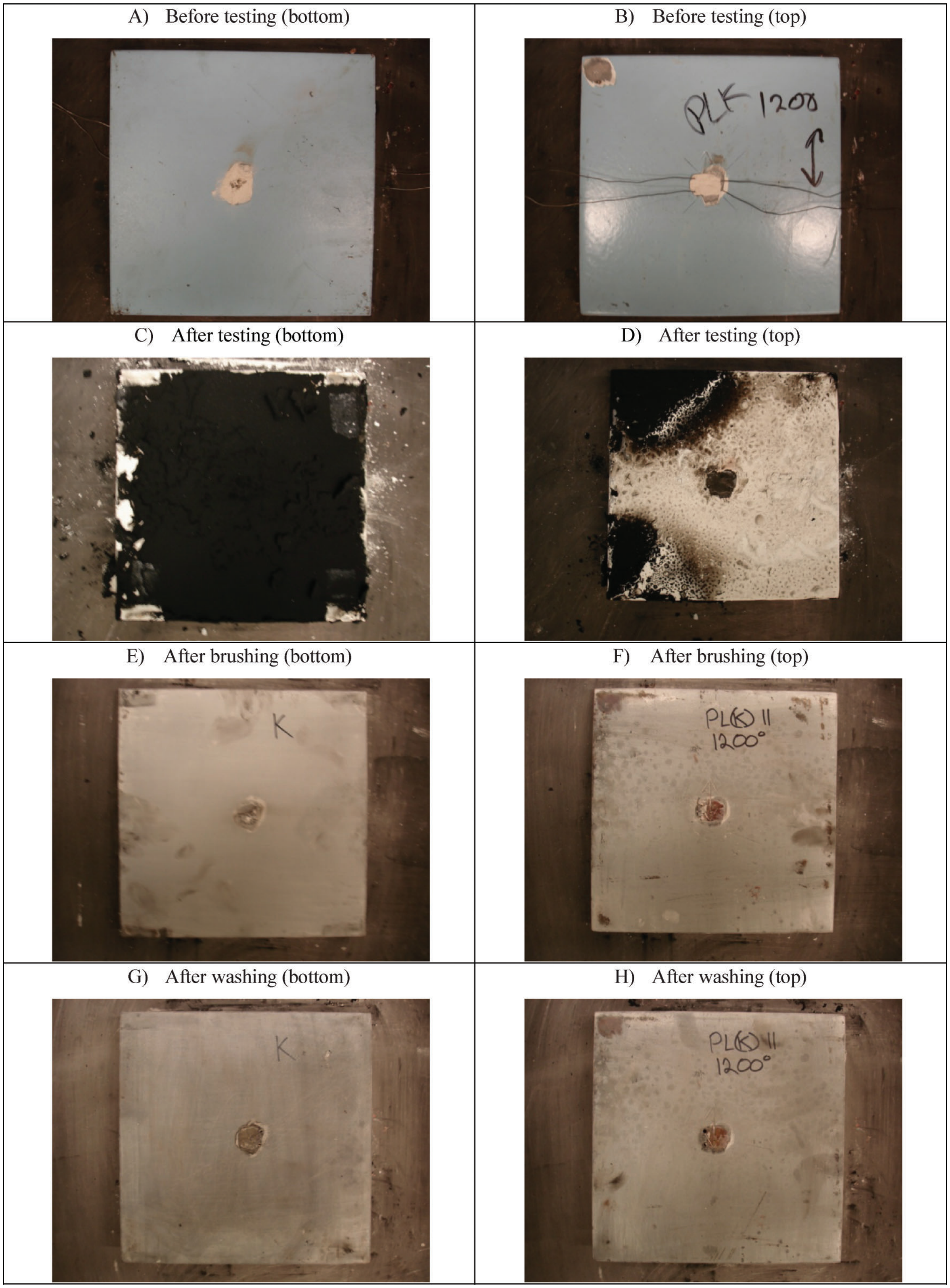


Figure 5.30 Post-fire evaluation of Carbothane K (11) 1200°F.

Figure 5.31 Post-fire evaluation of Carbothane L (12) uncontrolled 1200°F.

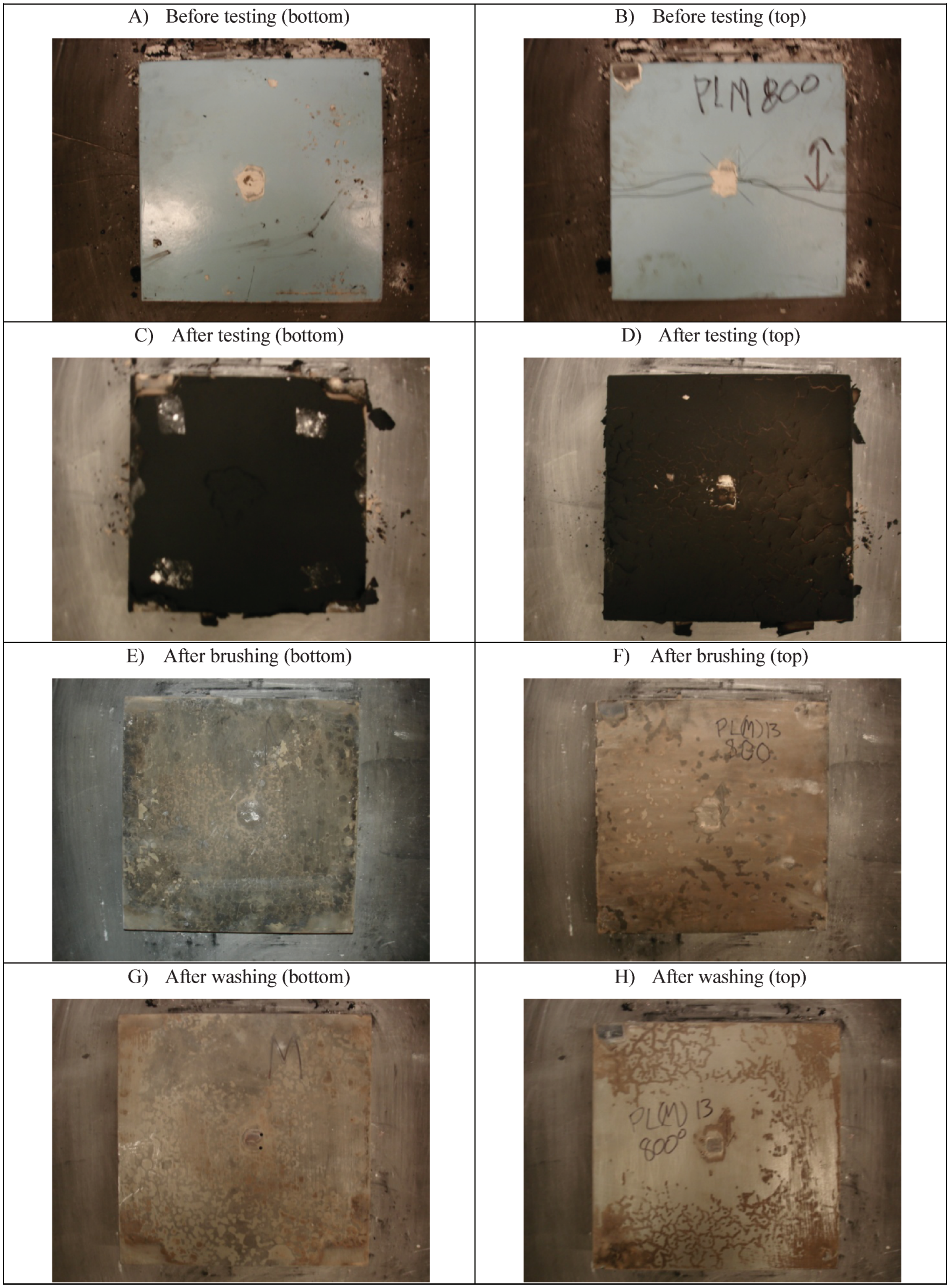


Figure 5.32 Post-fire evaluation of Carbothane M (13) 800˚F.

Figure 5.33 Post-fire evaluation of Carbothane O (15) 1200°F.

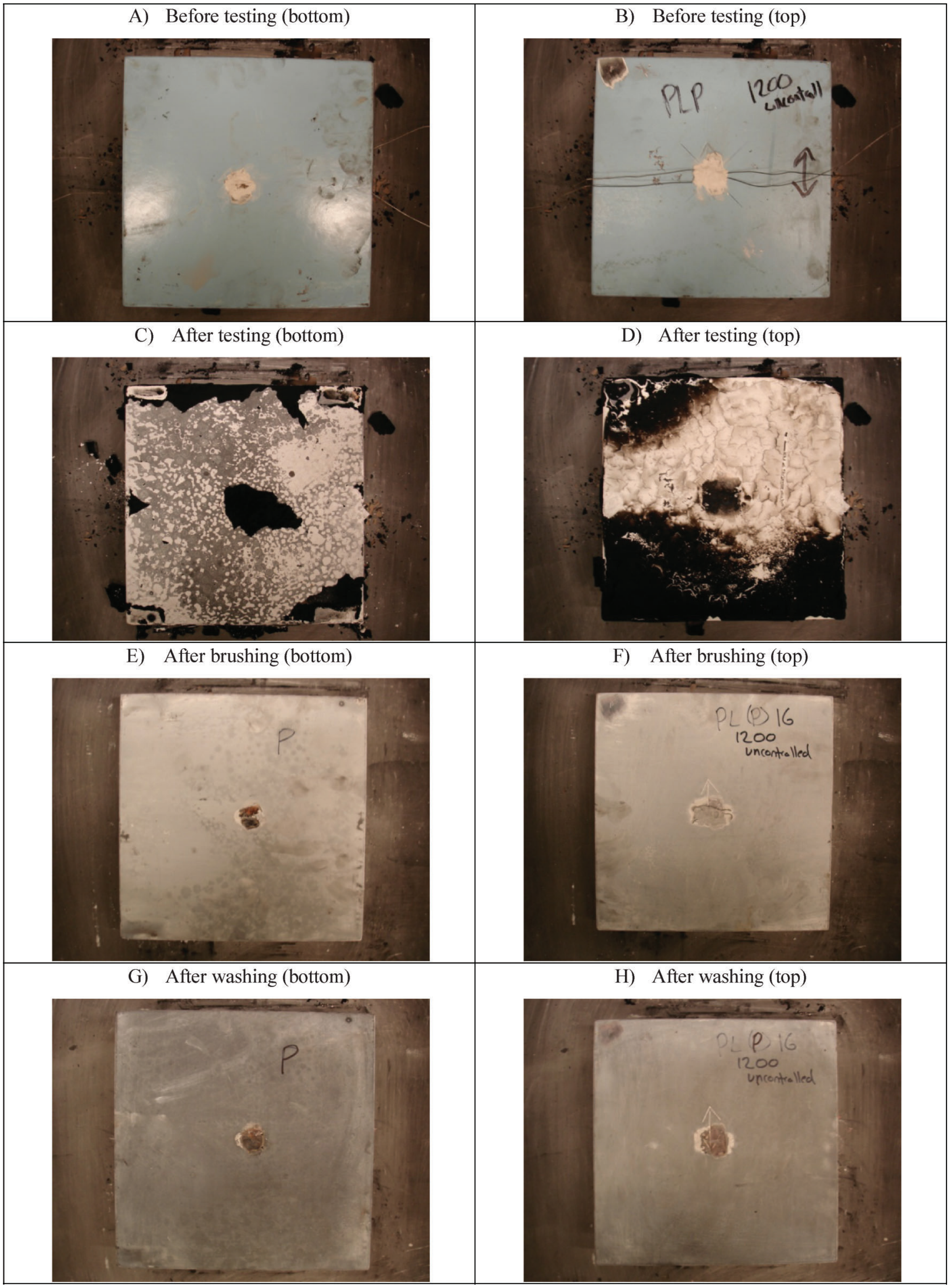


Figure 5.34 Post-fire evaluation of Carbothane P (16) uncontrolled 1200°F.

TABLE 5.7
Test Matrix (Part 4)

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

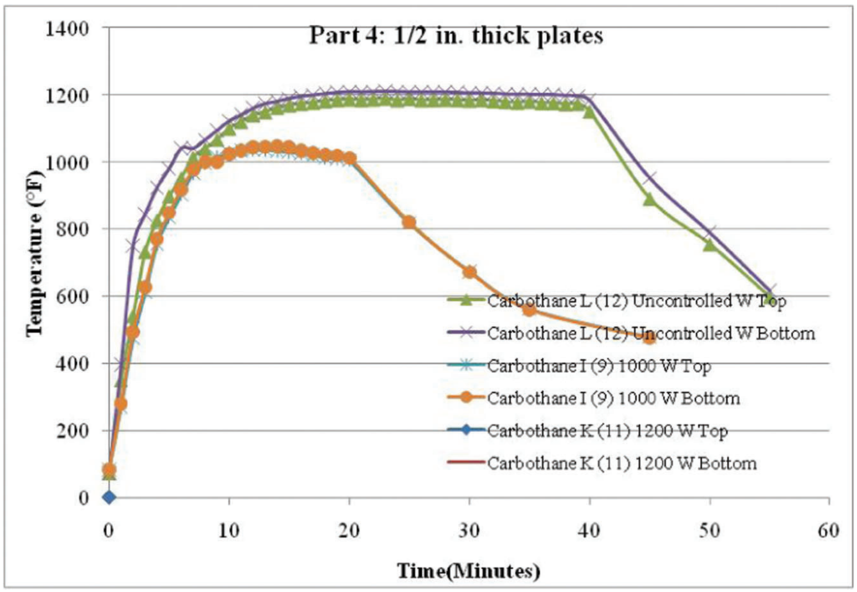


Figure 5.35 Measured temperature-time curves for ½ in. thick Carbothane plates (Part 4).

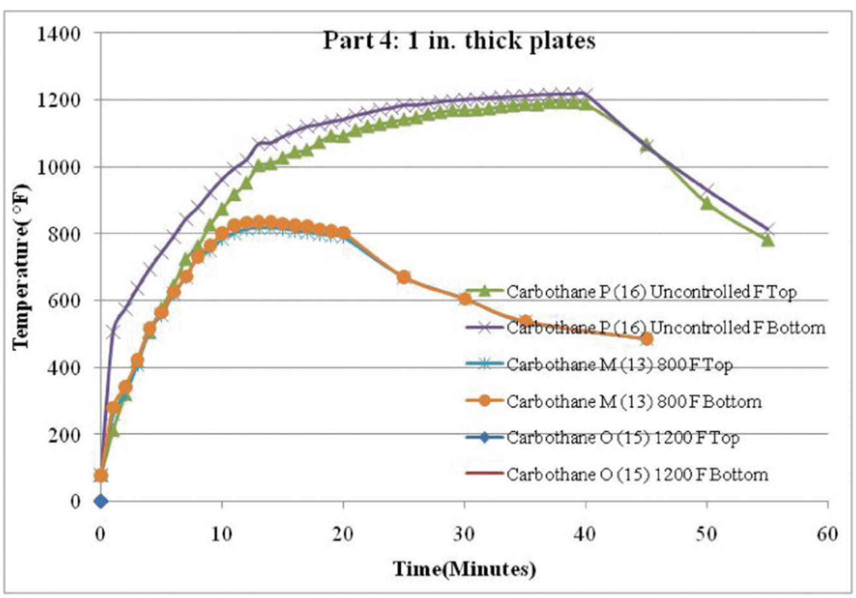


Figure 5.36 Measured temperature-time curves for 1 in. thick Carbothane plates (Part 4).

TABLE 5.8
Material Test Results for Coupons from Part 4 Plate Specimens

Specimen ID		σy	σu	%e	CVN results				AVG	Hardness Test				AVG
Carbothane J (10) Control W	-	-	-	-	Inner 3	32	25	17	24.7	Top	87	86	87	86.7
	-	-	-	-	-	-	-	-	-	Bottom	87	88	87	87.3
Carbothane I (9) 1000 W	Coupon 1	58.5	79	40	Inner 3	282	295	282	286.3	Top	85	85	86	85.3
	Coupon 2	58.5	79.5	39	Outer 3	292	294	290	292.0	Bottom	86	86	85	85.7
Carbothane K (11) 1200 W	Coupon 1	59.5	77.5	42	Inner 3	85	289	298	224.0	Top	83	82	83	82.7
	Coupon 2	59.5	79	41	Outer 3	119	299	292	236.7	Bottom	93	83	83	86.3
Carbothane L (12) Uncontrolled W	Coupon 1	60	77.5	43	Inner 3	162	61	281	168.0	Top	83	84	83	83.3
	Coupon 2	59	78	41	Outer 3	283	229	279	263.7	Bottom	83	84	84	83.7
Carbothane M (13) 800 F	Coupon 1	57.5	82.5	47	Inner 3	110	108	110	109.3	Top	87	88	87	87.3
	Coupon 2	57.5	82	50	Outer 3	96	88	90	91.3	Bottom	85	85	86	85.3
Carbothane O (15) 1200 F	Coupon 1	59	81.5	49	Inner 3	102	76	110	96.0	Top	85	84	85	84.7
	Coupon 2	59	81.5	46	Outer 3	110	89	82	93.7	Bottom	84	85	85	84.7
Carbothane P (16) Uncontrolled F	Coupon 1	59	81.5	47	Inner 3	76	97	107	93.3	Top	84	85	84	84.3
	Coupon 2	60.5	82	47	Outer 3	110	100	99	103.0	Bottom	83	84	84	83.7

NOTE: Yield stress is expected to be 50 KSI. Tensile Stress is expected to be 58 ksi. Elongation is expected to be 19% minimum in 2″. Zone II non fracture critical requirement is 15 ft-lb @ 40°F.

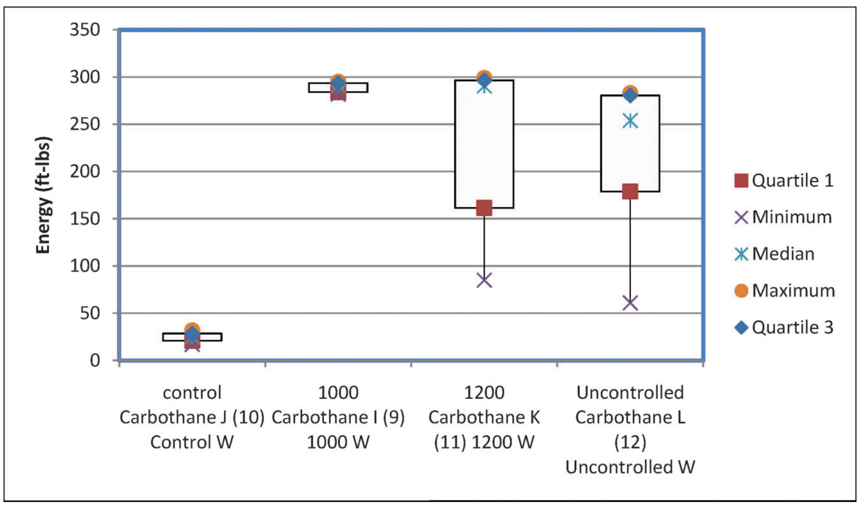


Figure 5.37 Statistical analysis of CVN fracture toughness for Part 4 plate specimens (½ in. thick webs).

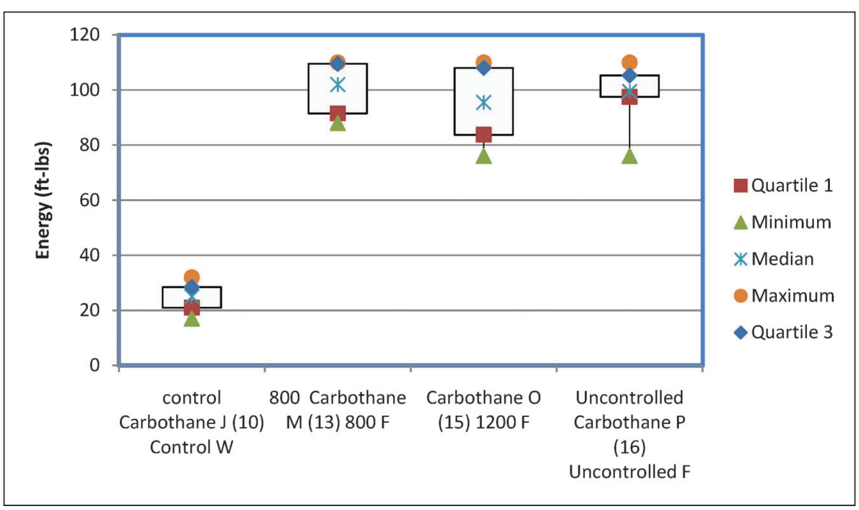


Figure 5.38 Statistical analysis of CVN fracture toughness for Part 4 plate specimens (1 in. thick flanges).

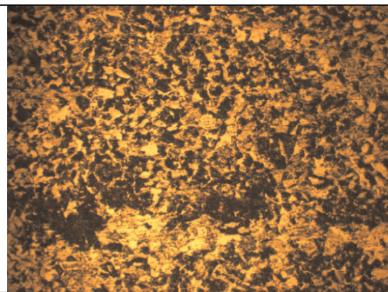
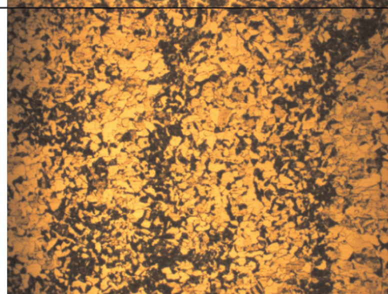
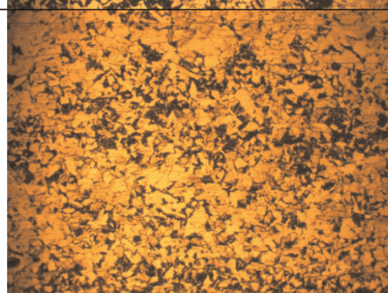
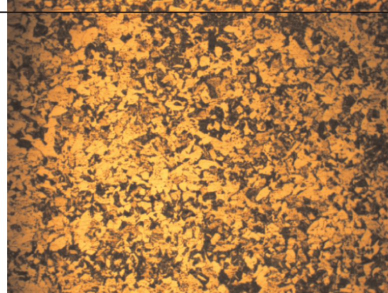
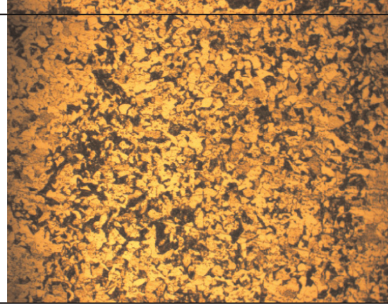
	Acrolon Q (17) Control W
	Acrolon A (1) 800 W
	Acrolon B (2) 1000 W
	Acrolon C (3) 1200 W
	Acrolon D (4) Uncontrolled W

Figure 5.39 300x magnification of Part 3 samples.

a process known as tempering, where heating of steel is utilized to make it tougher.

- Fire exposures do not have a statistically significant (after running a T-test on the CVN data, there seems to be no correlation between the values) 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.

6. SUMMARY AND CONCLUSIONS

The testing and results have proven to be useful in the formation of a guide to inspect bridges after exposed to fire events. For the purposes of this experiment the maximum surface temperature achieved on a plate was around 1200°F. This was done by using a sooting flame with the fuel being ethylene. Material tests that were obtained from each sample show trends in the changes of material properties. Results show that up to 1200°F, the material should satisfy any AASHTO specifications assuming the steel was adequate before undergoing fire loading. Repair strategies in these cases would require that the bridge be pressure washed and painted. When a bridge is seen to be visibly distorted, which occurs shortly after the temperature of the steel reaches 1200°F, repair strategies may require heat straightening or even replacement of the girders. A general inspection guide as shown in the next chapter takes the results of all the test samples and generalizes the outcomes of the material testing and matches that with images of what the steel would look like at a specific temperature.

7. 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.

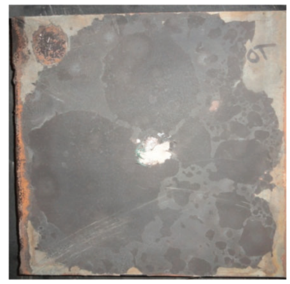
This inspection guide also includes older steel bridges (circa 1960 – 1970) that have been constructed with indeterminate paint coating systems that have been in place for several decades.

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.

7.1 Post-Fire Inspection Guide for Steel Bridges

(Tables 7.1, 7.2, 7.3 and 7.4)

TABLE 7.1
Older Steel Bridges with Indeterminate Paint Coating Systems*

Before Fire Exposure	After Fire Exposure – Up to 800°F *Non-Flame Side*	After Brushing Surface	After Washing Surface
			
Description			
Paint is in reasonable condition. Some scratches, chips, some rust and other defects are apparent. (NOTE: The shiny white patch at plate center is where the paint was scratched off to attach thermocouples.)	The plate surface directly exposed to flames has been covered with black soot. Bubbles have been 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 brushing clean, most of the paint has been removed from both the flame and non-flame sides. 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 have been removed from both the flame and non-flame sides. Some patches of paint may still be visible.

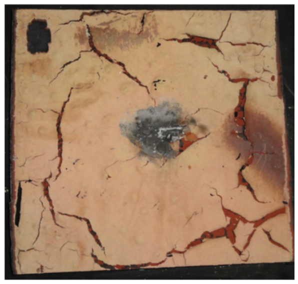
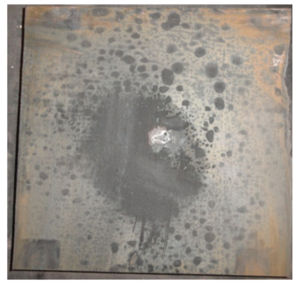
Material Properties

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, acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 (*9*) to evaluate the effects of fire on steel.

*Same vintage as steel beams provided by PennDOT (circa 1960 – 1970).

TABLE 7.2
Older Steel Bridges with Indeterminate Coating*

Before Fire Exposure	After Fire Exposure – Up to 1200°F *Non-Flame Side*	After Brushing Surface	After Washing Surface
			
Description			
Paint is in reasonable condition. Some scratches, chips, rust and other 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 has been covered with black soot. The paint coating on the non-flame side has been cracked, but the material will still be in place as shown above.	After brushing, most of the paint has been removed from both the flame and non-flame sides. 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 clean, all the soot and most of the paint have been removed from both the flame and non-flame sides. Some patches of paint may still be visible.

Material Properties

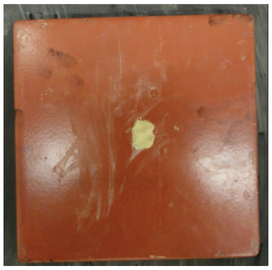
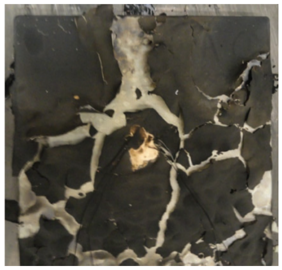
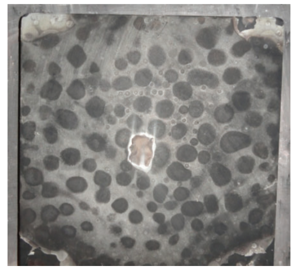
For steel grades with nominal yield stress less than or equal to 50 ksi, fire exposure producing surface conditions as shown above will result in a small (5%) reduction in the material yield strength, ultimate strength, surface hardness.

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, acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 (*9*) to evaluate the effects of fire on steel.

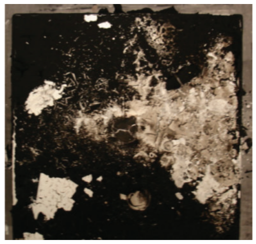
*Same vintage as steel beams provided by PennDOT after being exposed to real fire event (circa 1960 – 1970).

TABLE 7.3
Existing Steel Bridges with the Sherwin Williams' Acrolon Coating System*

Before Fire Exposure	After Fire Exposure – Up to 1200°F *Non-Flame Side*	After Brushing Surface	After Washing Surface
			
Description			
NOTE: Coating system consists of a primer coat of ZincClad III HS, Macropoxy 646 intermediate coat, and the Acrolon 218 HS top coat. As shown above, this system is rusty red in color.			
Paint is in good condition. No significant scratches, chips, rust or other 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°F. The non-flame side will have paint bubbled and cracked, but the paint material will still be in place as shown above.	After brushing clean, most of the top coat has been 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 have been removed from both the flame and non-flame sides. The base coat of the paint system will 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 more significant (+20 to -60%). 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, acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 (*9*) to evaluate the effects of fire on steel.			

*A709 beams or plates used in current bridge construction.

TABLE 7.4
Newly Painted Steel with the Inorganic Zinc Coating System (Carbothane) From Carboline*

Before Fire Exposure	After Fire Exposure – Up to 1200°F *Non-Flame Side*	After Brushing Surface	After Washing Surface
			

Description

NOTE: The coating system consists of a first coat of Carbozinc 11 HS, followed by an intermediate Carboguard 893 coat, and a finish coat of Carbothane 133. As shown above, this system is steel blue in color.

Paint is in good condition. No significant scratches, chips, rust or other 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°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 has been eliminated from both sides. The base coat will still be intact. There have been no other significant markings (bubbles, etc.) visible on the steel surfaces	After washing, all the soot and most of the paint system top coat have been removed from both flame and non-flame sides. The base coat of the paint system will remain 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 more significant (+100 to -0%). 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, acquire material samples from the fire-exposed and unexposed portions of the beams. Conduct CVN fracture toughness tests according to ASTM E23 (*9*) to evaluate the effects of fire on steel.

*A709 beams or plates used in current bridge construction.

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APPENDIX

Effects Of Fire Damage On The Structural Properties Of Steel Bridge Elements Standard Test Method And Commentary*

Test Method	Commentary
1 – Scope 1.1. This test method describes a procedure for performing live fire testing on steel bridge components. This live fire testing is used to build upon an inspection manual. This manual can be used to evaluate a bridge that has undergone a fire event in order to determine its stability.	**C1 – Scope** C1.1. This test method was developed for Pennsylvania DOT in collaboration with Indiana DOT to develop inspection manuals for bridges that have undergone fire events. On occasion, bridges are subjected to fire events, such as a tanker exploding underneath or on top of the bridge. These fire events, although uncommon, may affect a bridge in such a way that there is no visible distortion. If no deflections are found a manual can assist in determining the stability of a bridge. If small deflections are found a method such as heat straightening may be used to correct the bridge. Hence, in order to provide a DOT with an inspection guide, a flame test was developed to subject steel bridge components to fire loading.
2 – Summary of Test Method 2.1. This test is intended to rate the stability of bridge components after being subjected to a fire event. The test uses a soot flame in order to subject bridge components to live fire events. For owners of steel bridges involved in fire events this test method may assist in determining a course of action for repairs.	**C2 – Summary of Test Method** C2.1. The test evaluations are made on a comparative scale. Specifically, fire damaged specimens are evaluated and compared with in service bridges that have experienced a fire event. This approach allows an owner to compare steel bridge components tested in a lab setting to steel bridges in the field. It is important to note that this test is not applicable to bridges that have sustained deformations or temperatures in excess of 1200°F.
3 – Significance and Use 3.1. This test is applicable to any steel bridge sustaining fire loading where deformations are not present and temperatures have not reached 1200°F. The test method was developed to be applicable to any steel bridge that is not visually deformed in order for an inspector to make a determination of what needs to be done to return the steel bridge to service after a fire event.	**C3 – Significance and Use** C3.1. During the course of the research performed, specimens from decommissioned bridge girders including web and flange plates as well as newly painted A709 web and flange plates were tested for qualitative comparison. The size of the specimen was selected such that it fit a jet flame set up. The size selected was 10''x10'' with thickness varying based on flange or web thicknesses
4 – Apparatus 4.1. Jet Flame Tower – A steel superstructure built with bolted adjustable metal rails surrounds three traverse stands. Two adjustable bars that have feet bolted to them allow the specimens to sit in the stand. The adjustable bars on the stand allow for major adjustments in the x,y, and z directions for the specimen. There are three traverse stands surrounded by the metal frame. These traverse stands allow for fine adjustment and distance adjustments from the center of the steel plate samples. See Figure A.1.	**C4 – Apparatus**

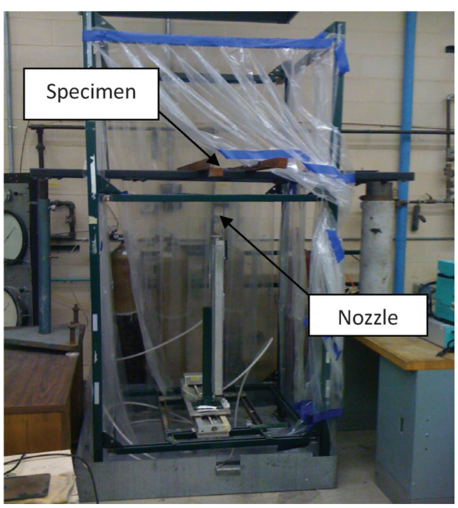

Figure A.1 Test apparatus.

(Continued)

Test Method	Commentary
4.2 Jet Nozzle – An 8mm diameter x 48cm stainless steel nozzle is attached to a flex tube. The flex tube is attached to flow rate gauges. This carries a measured amount of fuel to the nozzle.	
4.3. Metering Station – The metering station is a sequence of valves with gauges that allows gas to be turned on from the cylinders and metered to a set mass flow rate. The mass flow rate is calculated to achieve a designated flame temperature.	C4.3. For purposes of testing with Ethylene gas a mass flow rate of 30mg/s was chosen as the optimum rate for heat of the flame, this can be lowered to control the heat input to the sample.
5 – Materials 5.1. Samples to be tested in the flame jet setup should be small enough for the flame to engulf the bottom surface. For research purposes a dimension of 10in. x 10in. was used. Specimens from decommissioned bridge girders or bridge grade ASTM steel should only be used for the purposes of this experiment. Paint coatings that are approved by state DOT's should only be used when testing steel bridge components.	**C5 – Materials** C5.1. A709 plates were chosen for new steel plates. Decomissioned bridge girders can also be used for good representatives of bridge steel. Pennsylvania DOT has a list of approved paint coatings. Coating used in our testing include Sherwinn Williams "Acrolon" and Carbolines "Carbothane." Both are three coat paint systems.
6 – Test Preparation 6.1. This specimen shall be placed above the jet flame nozzle at a distance proportional to the flames characterization. The fuel used in testing should have a distance temperature curve that can help with placement of the sample depending on the target temperatures. Specimens shall also be instrumented with thermocouples, radiometers, and infared cameras depending upon the experimental results wanted.	
7 – Test Procedure 7.1. Determine what temperatures the test specimen shall reach, duration of fire exposure, and which sample (flange/web section, paint coating) shall be used for a particular test. The sample should be permanently identified by the use of stamps, etc. so that samples may be tracked throughout the experiment.	**C7 – Test Procedure** C7.1. Fire durations of 20 minutes and 40 minutes were used for testing. 20 minutes represents the time it would take for a normal fire to be extinguished from ignition. In some cases fires can last longer, where the 40 minute test is useful.
7.2. Photograph specimen prior to testing. Position the sample over the jet flame nozzle at a distance that correlates with the desired specimen temperature.	C7.2. This photograph would represent an as built photograph in the field. A distance of 48 cm was used for Ethylene testing. Flame characterization can tell where the highest temperatures are in the flame.
7.3. Adjust sample so it is centered over the nozzle. 7.4. Turn on the fuel source. 7.5. Open the metering valves. 7.6. Light the nozzle with a torch. 7.7. Start data acquisition at desired time intervals and adjust calibrated mass flow rates for desired temperature. 7.8. Throughout the duration of the test monitor the temperature and adjust the metering valve accordingly.	
7.9. After testing allow specimen to cool. Then photograph specimen before removing soot.	C7.9. This photograph represents what a bridge will look like after sustaining a fire event
7.10. Remove soot from specimen by brushing or wiping. Photograph after soot has been removed.	C7.10. This photograph would represent what an inspector would see after brushing or wiping a girder with a gloved hand
7.11. Wash the specimen clean by pressure washing. Photograph when dry.	C7.11. This photograph represents what the bridge looks like after washing the bridge
7.12. Prepare specimens for material testing.	C7.12. Number of specimens and type of material tests vary based on size of sample. For the 10"x10" plate, two tensile coupons and six CVN specimens are taken. Once CVN's are tested they may be used for Rockwell Hardness B tests. Note the rolling direction throughout testing
8 – Report 8.1 – The text report shall include the following : 8.1.1 The origin of the steel, test temperature, paint coating, and plate thickness. 8.1.2 Photographs of samples throughout testing process. 8.1.3 Temperature time curves. 8.1.4 Material testing results.	

(Continued)

Test Method	Commentary
9 – Interpretation of Results 9.1. The results will allow bridge owners to qualitatively inspect bridges that have sustained fire events, and have undergone little or no deformations. The results from this test procedure will give bridge owners an idea of material capacities based upon qualitative comparison between the bridge in question and the results from this testing. A general idea of the material qualities should be generated between control samples and flame tested samples from this testing.	