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NUREG/CR-6987

Analysis of Structural Materials Exposed to a Severe Fire Environment

Office of Nuclear Material Safety and Safeguards

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Analysis of Structural Materials Exposed to a Severe Fire Environment

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[1] The bulk of the work described in this report was completed by Mr. Dunn, for the NRC, while employed by Southwest Research Institute®

ABSTRACT

On Sunday morning, April 29, 2007, a gasoline tanker truck carrying 32,500 L [8,600 gal] crashed while heading south along Interstate (I) 880 in Oakland, California. The single-vehicle accident occurred in the MacArthur Maze, which is a network of connector ramps that merges highways I-80, I-580, and I-880. The resulting fire led to the collapse of the I-580 overpass, directly above I-880, approximately 17 minutes after the fire started (based on a review of surveillance camera video of the fire). Early news media reports of the accident and subsequent collapse cited sources at the accident scene estimating that temperatures reached as high as 1,650 °C [3,000 °F] (above the melting point of steel); however, initial inspection of the remaining girders along with photographic documentation revealed that the steel girders did not experience any melting. After the damaged sections were dismantled, removed, and placed in a storage yard, steel girder samples were obtained and analyzed. Samples from the tanker truck were also collected. The main objective of the work reported here was to examine the collected samples and estimate the temperatures reached during the fire. The microstructures of the girders were examined for phase transformations and microstructural alterations that would identify exposure to elevated temperatures. Samples were collected from girders that were known to be close to the fire and from locations that were away from the fire. Weld samples collected near the fire were transformed, whereas no transformation was observed on corresponding samples that were away from the fire. Thermal exposures of selected samples were conducted to determine the effect of temperature on the microstructure of the stiffener welds and the grain size of the girders. Based on a comparison of the samples collected from hot regions and the test samples that were thermally exposed, the girders close to the fire reached a minimum temperature of 850 °C [1,562 °F]. Grain-size measurements suggest that the hottest sections reached temperatures of approximately 1,000 °C [1,832 °F]. Paint degradation was also found to be dependent on the conditions of thermal exposure. At a temperature of 750 °C [1,382 °F], the paint was completely destroyed, which agrees with the material evaluation results of the girders closest to the fire. Near the truck, several alloys did not melt including brass, copper, and cast iron, which have melting points of 930, 1,084, and >1,177 °C [1,706, 1,983, and >2,150 °F], respectively. Melting of multiple truck components manufactured from several aluminum alloys {melting points of 590 to 720 °C [1,094 to 1,328 °F]} was noted. Hardness data and microstructures of hardened steel bolts suggest an exposure temperature between 700 and 750 °C [1,292 and 1,382 °F]. The observed oxide spalling on the steel truck frame suggests a temperature exceeding 500 °C [932 °F]. Based on the information obtained from the materials analyses, the temperatures of the samples collected near the tanker truck on the I-880 road bed were between 590 and 930 °C [1,094 and 1,706 °F]. The I-580 girders, located directly above the fire where hot gases accumulated and where direct flame impingement occurred, reached a temperature between 850 and 1,000 °C [1,562 and 1,832 °F].

CONTENTS

FIGURES

FIGURES (continued)

FIGURES (continued)

TABLES

EXECUTIVE SUMMARY

The Interstate (I) 580 overpass collapse occurred on Sunday morning, April 29, 2007. The fire that eventually led to the overpass collapse began at about 3:38 a.m. when a gasoline tanker truck carrying 32,500 L [8,600 gal] of gasoline crashed and caught fire. The tanker truck was heading south along I-880 at the time of the accident and crashed near the I-580 overpass near the eastern end of the San Francisco–Oakland Bay Bridge in Oakland, California.

The accident occurred in the area known as the MacArthur Maze, which is a network of connector ramps that merges highways I-80, I-580, and I-880. Shortly after arriving at the accident, the firefighters reportedly saw that the I-580 ramp was sagging. The fire heated the steel girders in the I-580 construction to temperatures where the steel strength was reduced and insufficient to support the weight of the elevated roadway. At about 3:55 a.m., the I-580 overpass collapsed. Nearly the entire fire and collapse was captured by a surveillance video camera situated at a nearby water treatment facility, which was adjusted to view the fire following the accident.

The main objective of the work reported here was to analyze samples collected from the I-580 steel girders and the tanker truck and determine the temperature of the fire that led to the overpass collapse. Modeling of the MacArthur Maze fire was also conducted, and the results of the modeling work will be described in a separate report. Welds in the girders were examined for possible phase transformations that would identify exposure to elevated temperatures. After the damaged sections were dismantled, removed, and placed in a storage yard, samples collected included material from girders that were known to be near the fire and from locations that were known to be further away. Among the most informative samples were the stiffeners on the plate girders, because these were evenly spaced along all girders and were relatively thin materials that would be expected to be more responsive to temperature changes.

Microstructural changes were observed to have occurred on samples collected near the fire. No transformation of the structural welds or increases in the grain size were observed on corresponding samples collected from locations that were away from the fire, thus defining some temperature gradients that resulted from the exposure. Thermal exposures of selected samples were conducted to determine the effect of temperature on the microstructure of the stiffener welds and the stiffener base metal. The transformation of the welds from an as-deposited dendritic microstructure to a microstructure that consisted of ferrite and pearlite was observed at temperatures of at least 800 °C [1,472 °F]. Based on a comparison of the samples collected from hot regions and the test samples that were thermally exposed, it appears that the girders close to the fire reached a minimum temperature of 850 °C [1,562 °F] for the weld transformation to have occurred. Based on the grain size of the thermally exposed and slow-cooled specimens, the girder sections in the hottest regions of the fire reached a maximum temperature in the range of 980 to 1,020 °C [1,796 to 1,868 °F].

Additional information from photographs of the damaged overpass and the tanker truck and descriptions obtained from the California Department of Transportation (Caltrans) also provided information that could be used to estimate the temperature of materials near the fire. Photographs taken by Caltrans during demolition show evidence of paint degradation that increases in the areas close to the fire. Paint degradation was also found to be dependent on the conditions of thermal exposure. At a temperature of 750 °C [1,382 °F], the paint was completely destroyed.

Materials collected from the tanker truck were also used to estimate the fire temperature. The wide range of samples collected and the condition of the samples suggest that a significant range of temperatures was present near the truck. Spalling of the iron oxides on the truck frame suggests an exposure of at least 500 °C [932 °F]. The tanker truck had many components, such as the tank and the wheels, manufactured from aluminum alloys. Parts of these components melted, indicating exposure temperatures of 590 to 720 °C [1,094 to 1,328 °F]. Analyses of hardened steel fasteners suggest an exposure temperature between 700 and 750 °C [1,292 and 1,382 °F]. Several alloys were found that did not melt during the fire including brass, copper, and cast iron, which have melting points of 930, 1,084, and >1,177 °C [1,706, 1,983, and >2,150 °F], respectively, indicating the exposure temperatures for these components were less than the melting temperature for these alloys.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated original data contained in this report meet quality assurance requirements described in the Geosciences and Engineering Division Quality Assurance Manual. Data used in this report are primarily derived from other publicly available sources. Each data source is cited in this report and should be consulted for determining the level of quality of those cited data. The work presented in this report is documented in Dunn (2007, 2008).

ANALYSES AND CODES: No CNWRA computer analysis results are used in this report.

REFERENCES

Dunn, D. "Scientific Notebook 907." San Antonio, Texas: CNWRA. pp. 1–79. 2008.

_____. "Scientific Notebook 884." San Antonio, Texas: CNWRA. pp. 1–108. 2007.

1 INTRODUCTION

1.1 Background

The Interstate (I) 580 overpass collapse occurred on Sunday morning, April 29, 2007. The fire that eventually led to the overpass collapse started at about 3:38 a.m. when a gasoline tanker truck carrying 32,500 L [8,600 gal] of gasoline crashed and caught fire. The tanker truck was heading south along I-880 at the time of the accident. While nearing the I-580 overpass, the vehicle crashed on the 50-foot-high ramp connecting westbound I-80 to southbound I-880. The driver escaped from the burning vehicle and was treated for burns to his face, head, and neck.

The accident occurred in an area known as the MacArthur Maze, which is a network of connector ramps that merges highways I-80, I-580, and I-880 in Oakland, California. An aerial map of the area is shown in Figures 1-1 and 1-2. Shortly after arriving, the firefighters from the Oakland Fire Department reportedly saw that the I-580 ramp was sagging. Heat from the fire had heated the steel girders to temperatures where the steel strength was reduced and insufficient to support the weight of the elevated roadway. The I-580 overpass collapsed at about 3:55 a.m. The main portion of the fire spread along a section of the I-880 roadway and burned for more than 2 hours. Some of the gasoline went through the scupper drain near Bent[1] 35 on I-880 and burned on the ground around the support column of the bent.

Photographs of the scene after the fire was extinguished are shown in Figures 1-3 to 1-6. The photos, obtained from the California Department of Transportation (Caltrans) website, show the damage that resulted from the fire. Figure 1-3 identifies the roads and the relevant features of I-580. Two span sections of I-580 fell and landed on parts of I-880. The box girder beam at Bent 19, which was welded steel construction supporting the two adjacent spans, was pulled off of the support columns and partially landed on the tanker truck. The I-580 section between Bent 19 and Bent 20 was draped over I-880 and contacted the ground below (Figure 1-4). A portion of the I-580 span between Bent 19 and Bent 20 landed on I-880. Heat from the fire and stress from the weight of the span construction caused a section of the span to bend over the edge of the I-880 roadway.

After the accident, the tanker truck was located on the I-880 roadway near Bent 19. The main cab of the truck was located between Bent 19 and Bent 20 with the frame rails and the partially melted aluminum tank located under the Box Beam Cap of Bent 19. Figure 1-7, taken during the demolition process, shows the final position and location of the tanker truck with respect to the collapsed I-880 overpass. The tanker truck remains were removed from the I-880 roadway and temporarily located near the accident scene. As shown in Figure 1-8, the major remnants consisted of the truck frame, engine, transmission, axles, and portions of the tank that did not melt during the fire. Subsequently, the tanker truck was relocated and placed into storage while the California Highway Patrol (CHP) conducted an accident investigation.

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[1]A bent is a supporting unit of a bridge, overpass, or elevated roadway, normally consisting of vertical piers/column(s) and a horizontal beam positioned transverse to the length of the structure.

Figure 1-1. Aerial Photograph of Interstate Interchange (www.google.com)

1.2 Objectives and Scope

The objective of the work reported here was to evaluate the characteristics of the sampled structural materials exposed to the MacArthur Maze fire of April 29, 2007, and to estimate an approximate range of temperatures to which the sampled structures and tanker truck materials were exposed. Melting, solid-state transformations, and thermally induced degradation may provide information on the temperatures witnessed during the fire. To meet this objective, a site visit to the Caltrans storage yard where the girder sections were placed after demolition was made to collect physical samples of structural steel girders, rivets, welds, and paint flakes; take photographs of bridge structures and components; and gather relevant, site-specific information from Caltrans. After the accident investigation was completed, the CHP allowed the truck to be examined and a limited number of samples were collected for analyses.

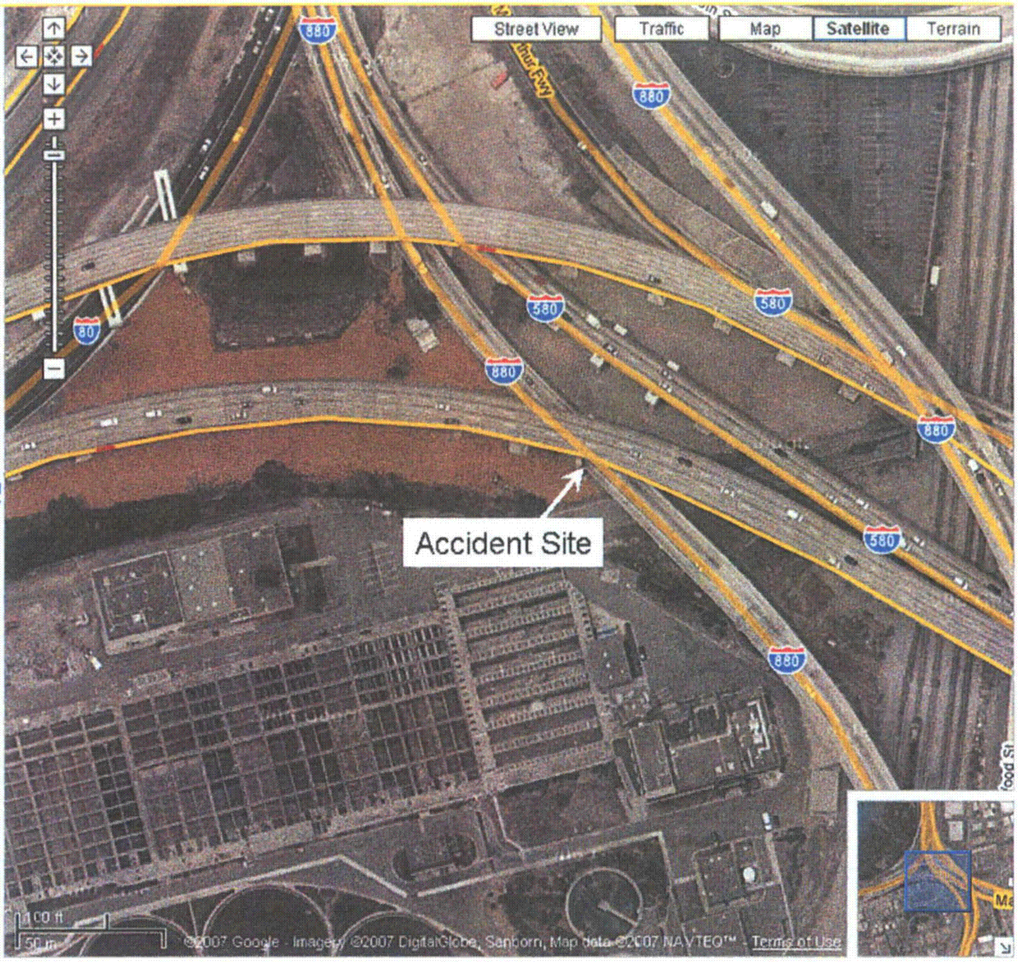


Figure 1-2. Aerial Photograph of Interstate Interchange. The Accident Occurred on Interstate-880 Just Under the Interstate-580 Overpass (www.google.com).

Metallurgical analyses of several material samples from the steel structure of I-580 were conducted to determine the temperature of the structure during the fire. The spalling of concrete can be used to indicate temperature. Although Caltrans staff observed spalling of the concrete bridge deck on I-880, definitive measurements of the area of spalling were not available. Another notable observation is the alteration of paint used to protect the steel structure. Samples collected from the tanker truck included a variety of materials including steel, stainless steel, aluminum alloys, copper alloys, and nonmetallic materials. This report focuses on the analysis of possible phase transformations in the I-580 steel structure and the tanker truck materials. The relationship between temperature and microstructural changes and the melting points of the collected samples was used to bound the range of temperatures witnessed during the fire.

Modeling of the MacArthur Maze fire was also conducted. The National Institute of Standards and Technology Fire Dynamics Simulator code was used to calculate gas temperatures and the temperatures of the I-580 overpass. The geometry of the overpass, volume of fuel, and weather conditions were considered in the modeling effort. Results of the modeling work will be described in a subsequent report.

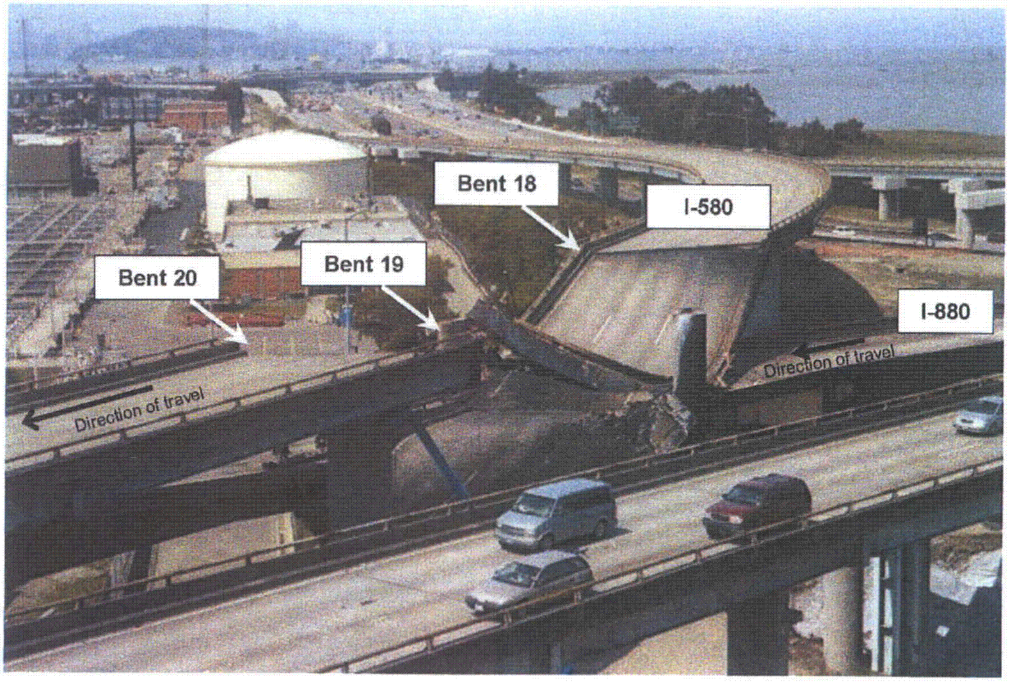


Figure 1-3. Post Fire Aerial View of Collapsed Section of Interstate-580 Looking West
California Department of Transportation (2007a)

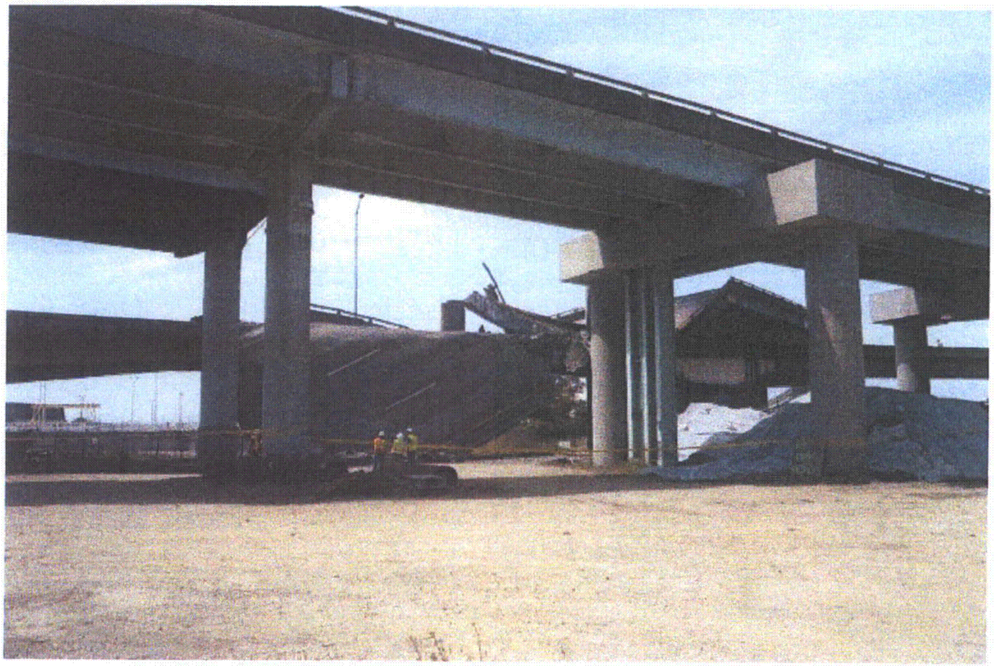


Figure 1-4. Post Fire Ground View of Collapsed Section of Interstate-580
California Department of Transportation (2007a)

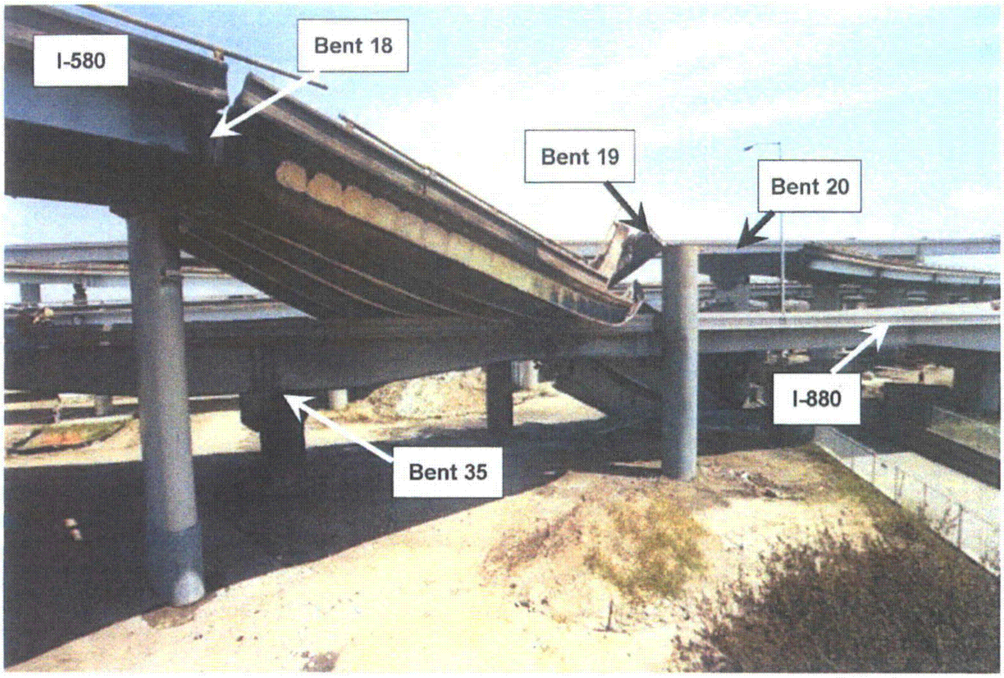


Figure 1-5. Post Fire View of Collapsed Section of Interstate-580 From Bent 18. Picture From California Department of Transportation (2007a).

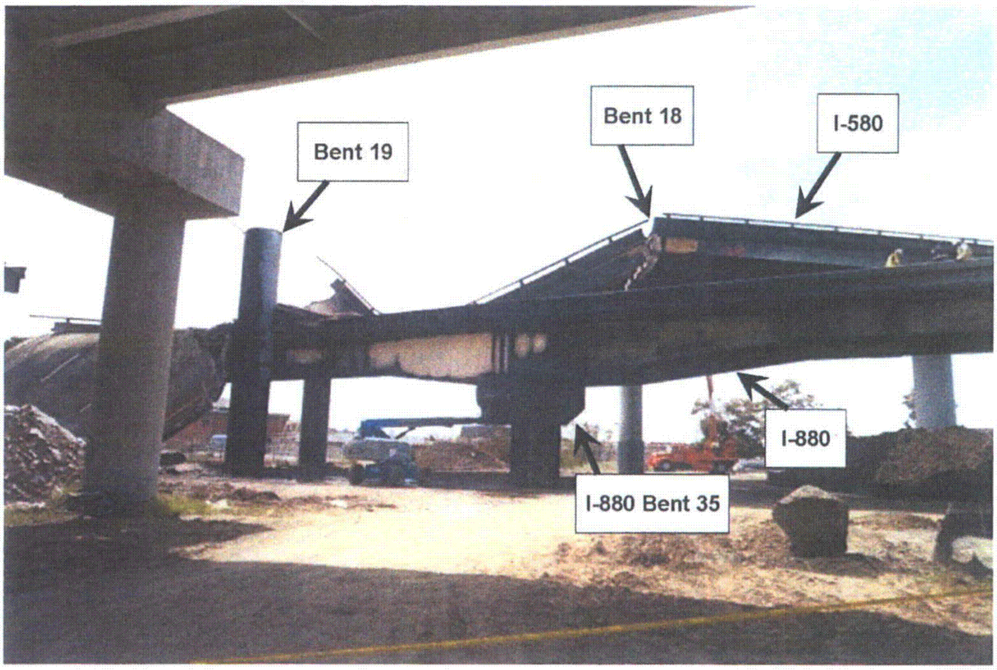


Figure 1-6. Post Fire View of Collapsed Section of Interstate-580. Picture From California Department of Transportation (2007a).

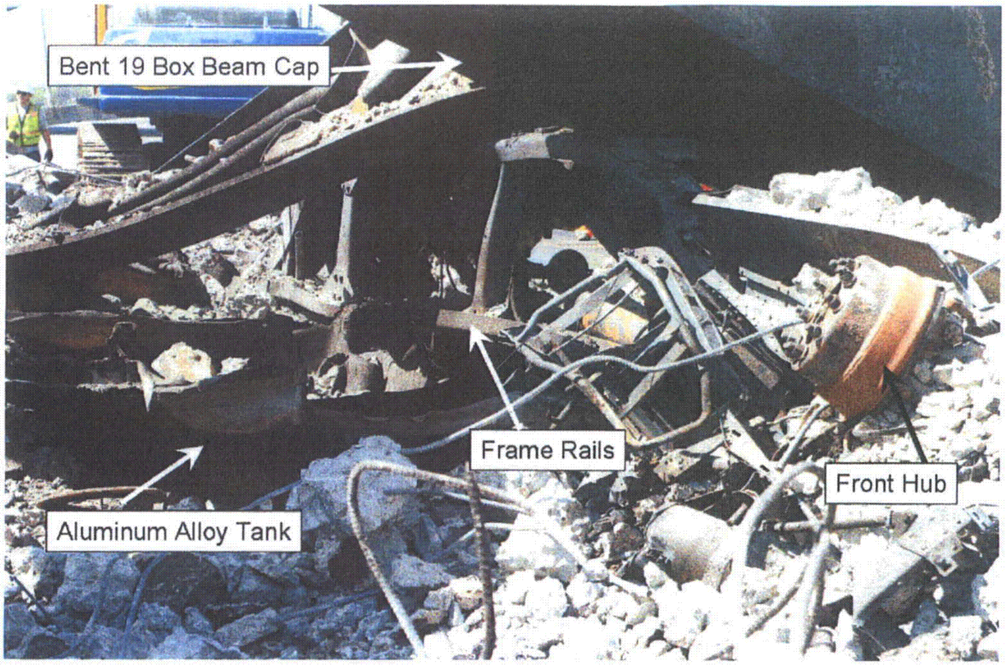


Figure 1-7. View of the Tanker Truck Under the Bent 19 Box Beam Cap (Image Supplied by California Highway Patrol)

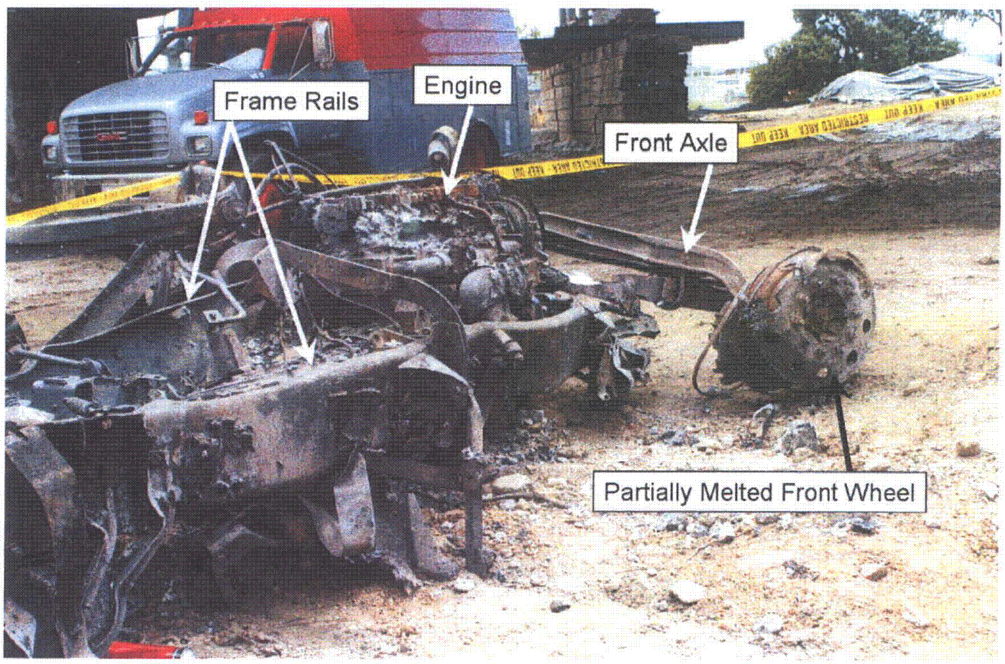


Figure 1-8. Tanker Truck After Being Removed From the Interstate-880 Roadway (Image Supplied by California Highway Patrol)

2 INTERSTATE-580 OVERPASS SAMPLES

After the fire was allowed to burn out, overpass repair was initiated. Initial work was associated with the demolition of the two collapsed spans of the overpass and removal of the structural materials. Photographs taken by Caltrans, and posted on its website, were used to document the progress during the post accident repair. These photographs are also useful in identifying the approximate locations of the samples collected. Photos of the structure during demolition are shown in Figures 2-1 to 2-6. The overpass was completely disconnected from Bent 20 and the Interstate (I) 580 roadway where it fell over I-880. The Box Beam Cap at Bent 19 had separated from one of the support columns (Figure 2-1). At Bent 18, the roadway was still connected to the remaining roadway. Figure 2-5 shows the roadway during demolition after two of the plate girders (the outer ones) were removed from Bent 18 to Bent 19. Remains of the tanker truck were located under the Box Beam Cap at Bent 19 (Figure 2-6).

After the demolition was complete, the structural steel girders were cut into approximately 8-m [26-ft] sections and sent to a metal recycler. A portion of the box and plate girders was later recovered from the recycler and placed in a Caltrans storage yard. Each girder section in the storage yard was numbered after recovery from the recycler. These numbers were not associated with the original location prior to collapse, but were used to identify samples obtained. Photographs of the girders in the Caltrans storage yard are shown in Figures 2-7 to 2-12.

The plate girder beams were not specifically marked during the demolition of the collapsed span; however, for some of the plate girder sections, the location could be identified relative to the original structure using the photographic documentation from Caltrans. Samples from the plate girders were obtained from the structure near Bent 18 and Bent 20. Samples obtained near the connection to Bent 20 showed some signs of fire damage to the latex paint (Figure 2-13). The underlayer of red-colored lead-containing paint was mostly intact but had evidence of blistering from the thermal exposure. For plate girders near Bent 18, the latex paint was mostly intact, retaining its original gray color (Figure 2-14). Between Bent 18 and Bent 19, the plate girders from I-580 were in contact with the I-880 roadway (Figure 2-2). Significant beam distortion is apparent as a consequence of heating, the resultant weakening of the steel structure, and the load imparted of the concrete structure. No paint was noted on these beam sections. Based on this observation, it was determined that the plate girder section marked as Number 5 (Figure 2-7) was originally located between Bent 18 and Bent 19 where the I-580 overpass was in contact with I-880 (Figure 2-2). Originally, the plate girder was approximately 48 in [122 cm] deep. As shown in Figure 2-15, the end of Plate Girder 5 that was believed to be closest to Bent 19 experienced web buckling as a result of the loss of strength at elevated temperature, and the subsequent impact with the I-880 road bed. Plate Girder 1 also had a similar appearance (Figure 2-16).

Figure 2-1. Photo During Demolition. Large Hydraulic Hammers Were Used to Break up the Concrete Bridge Deck. The West End of Box Beam Cap 19 Was Still Connected to the Support Column, Whereas the East End Collapsed and Was in Contact With Interstate-880. Picture From California Department of Transportation (2007b).

Figure 2-2. Photo During Demolition. View of Plate Girders and Box Beam Cap at Bent 19. Picture From California Department of Transportation (2007c).

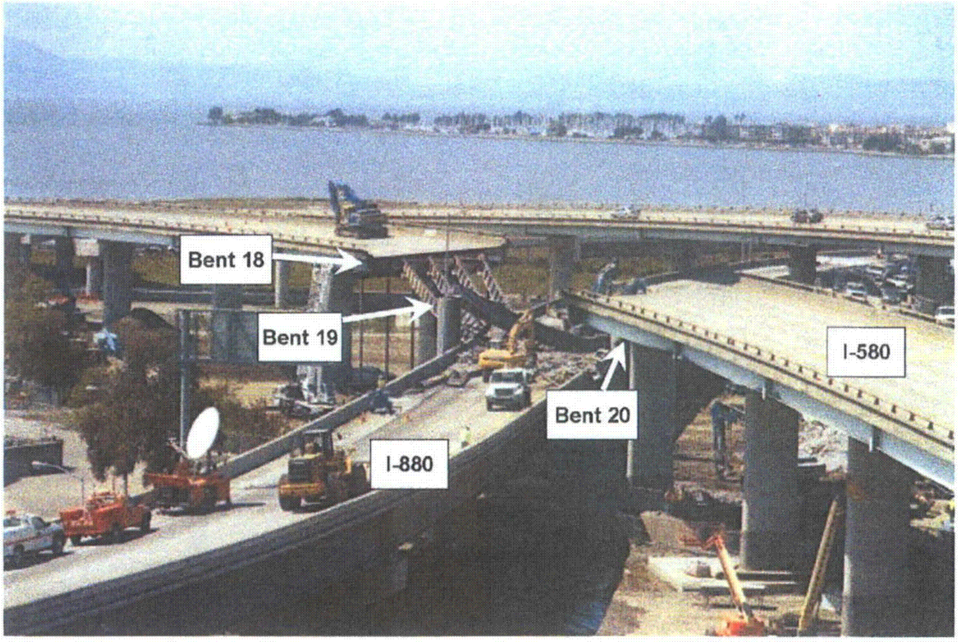


Figure 2-3. Aerial View of Damage During Demolition Looking Northwest. Picture From California Department of Transportation (2007c).

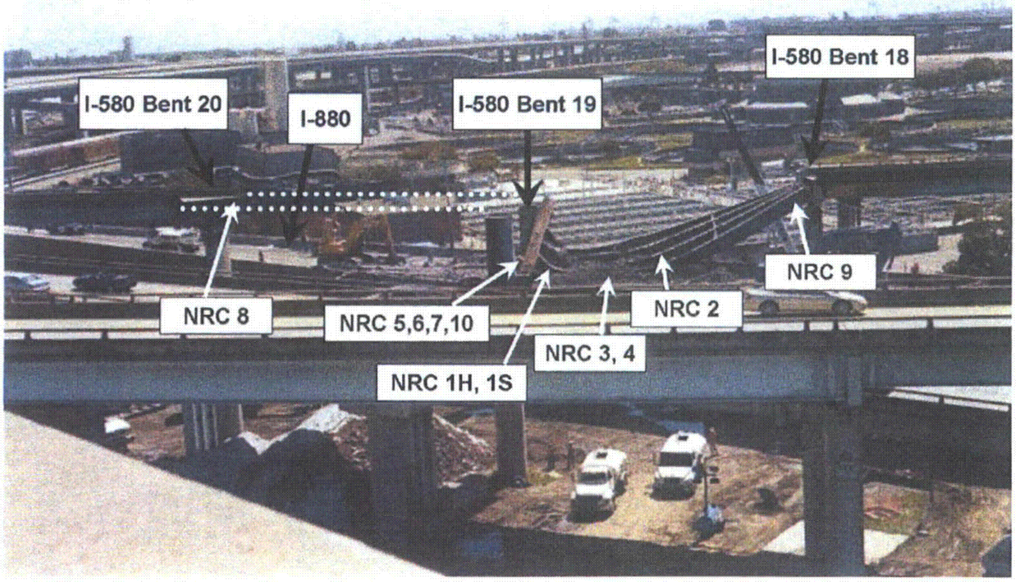


Figure 2-4. View of Damage During Demolition Looking Southwest. Added Labels Show the Locations of Bents 18, 19, and 20 and Approximate Locations of Collected Specimens. Dotted Lines Represent Preaccident Overpass Structure That Was Demolished and Removed Prior to This Photograph. Original Picture From California Department of Transportation (2007c).

Figure 2-5. Torch Cutting of Plate Girders at Bent 18. Picture From California Department of Transportation (2007c).

Figure 2-6. Remains of the Tanker Truck Under the Box Beam Cap at Bent 19. Picture From California Department of Transportation (2007c).

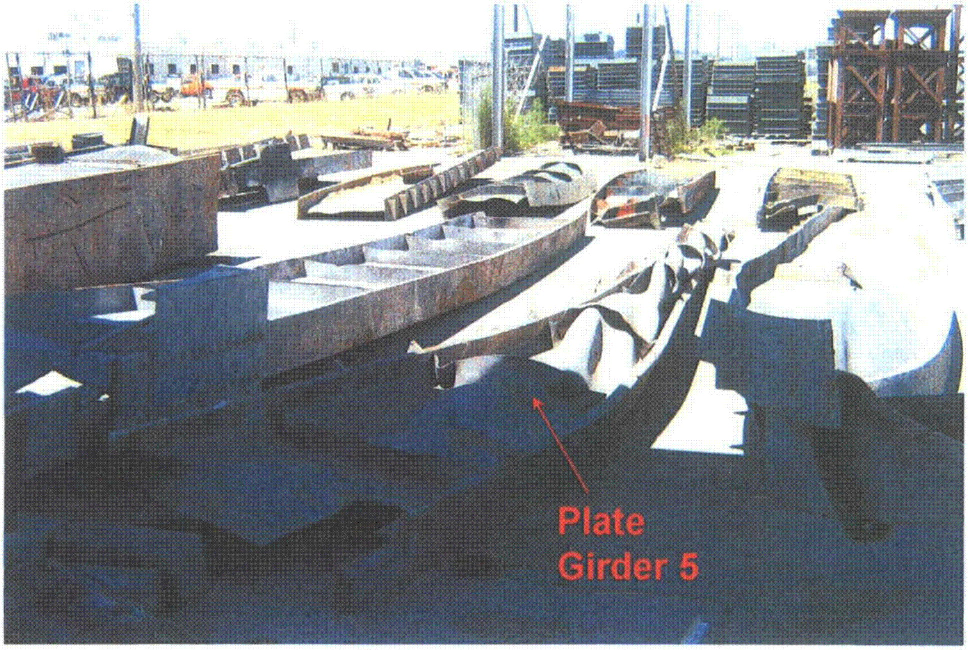


Figure 2-7. Photograph of Girders and Box Beam Cap Sections at California Department of Transportation Storage Yard Near the Accident Site Showing a Portion of the Box Beam Cap From Bent 19 and Various Plate Girder Sections. The Obvious Distortion on Plate Girder 5 Is Visible Near the Center of the Image.

Figure 2-8. Photograph of Girders at the California Department of Transportation Storage Yard Showing Various Plate Girder Sections

Figure 2-9. Photograph at the California Department of Transportation Storage Yard Showing the Significant Damage on Plate Girder 3, Which Was Attached to the Box Beam Cap at Bent 19. Rivet Holes in Plate Girder 3 Are Visible at the Bottom of the Image.

Figure 2-10. Photograph at the California Department of Transportation Storage Yard Showing the Two Box Beam Cap Sections and Other Plate Girder Sections

Figure 2-11. Photograph at the California Department of Transportation Storage Yard Showing Box Beam Cap Section 7 (Left) and Box Beam Cap Section 8 (Right)

Figure 2-12. Photograph at the California Department of Transportation Storage Yard Showing Box Beam Cap Section 8

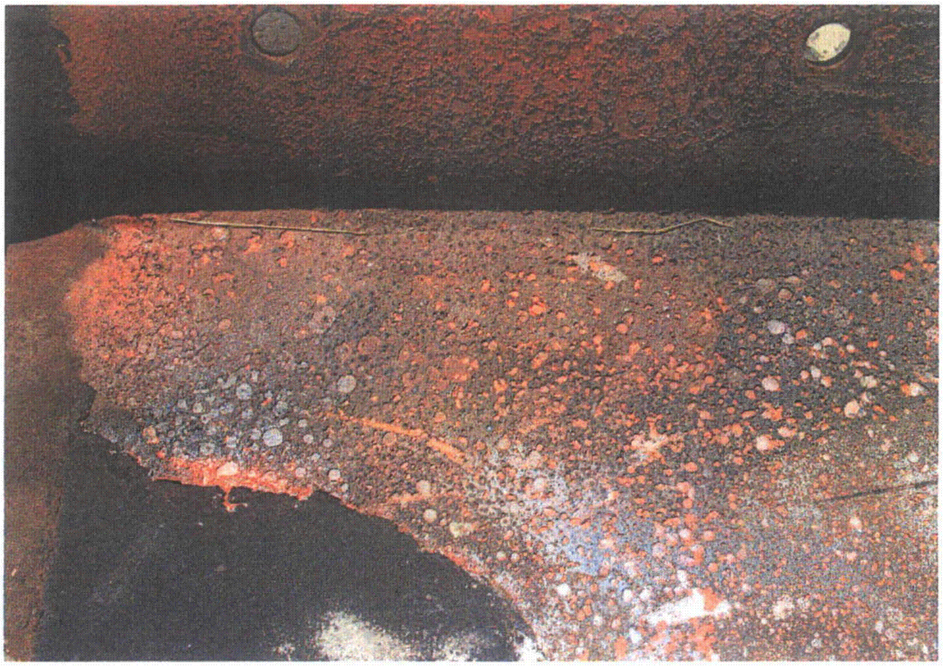


Figure 2-13. Photograph of Plate Girder 9 at the California Department of Transportation Storage Yard. Latex Paint Was Heavily Damaged, Exposing the Red-Colored Lead-Containing Paint.

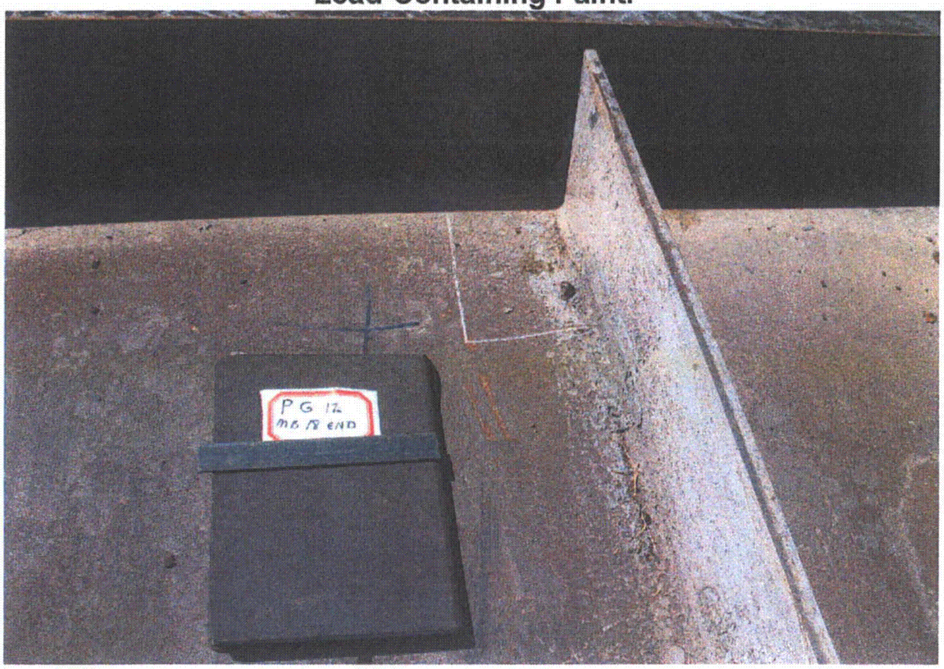


Figure 2-14. Photograph at California Department of Transportation Storage Yard of Plate Girder 12 Near the Bent 18 End. The Latex Paint Was Mostly Intact at This Location.

Figure 2-15. Photograph of Plate Girder 5 Believed To Be Between Bent 18 and Bent 19. Buckling of the Plate Girder Appears To Have Occurred at Elevated Temperature.

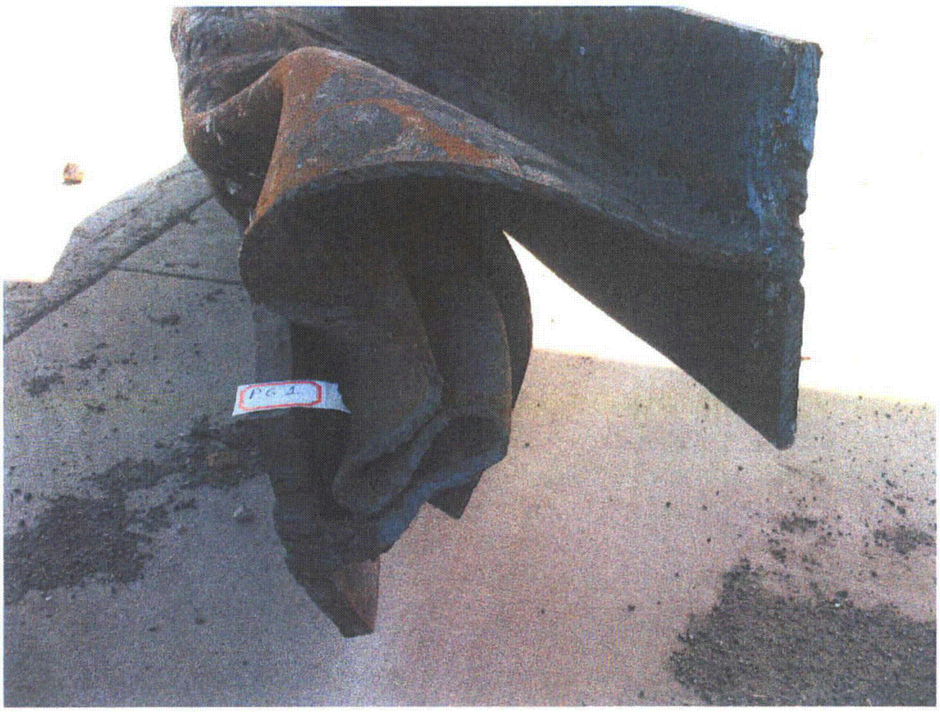


Figure 2-16. Photograph of Plate Girder 1. Buckling of the Plate Girder Appears To Have Occurred at Elevated Temperature.

Table 2-1 describes the physical samples the U.S. Nuclear Regulatory Commission (NRC) and Southwest Research Institute® (SwRI) staff collected during the site visit on June 13, 2007. The approximate locations of the samples collected are shown in Figure 2-4.

Table 2-1. Description of Samples Collected

Sample Number	Description
NRC 1H	Plate Girder 3 at Bent 19 end with rivet holes. Specimen did not contain weld metal (Figures 2-9 and 2-17).
NRC 1S	Plate Girder 3 with stiffener near Bent 19. Specimen contained weld metal (Figures 2-9 and 2-17).
NRC 2	Plate Girder 4 with butt weld. Specimen contained weld metal (Figure 2-18).
NRC 3	Plate Girder 5 likely located between Bent 18 and Bent 19 with stiffener heavy distortion. Specimen contained weld metal (Figures 2-7 and 2-15).
NRC 4	Plate Girder 5 likely located between Bent 18 and Bent 19 with stiffener medium distortion. Specimen contained weld metal (Figures 2-7 and 2-15).
NRC 5	Box Beam Cap 7 lower plate with side and weld. Specimen contained weld metal (Figures 2-11 and 2-21).
NRC 6	Plate girder found attached to Box Beam Cap 8 with reduction in area (Figures 2-12 and 2-22).
NRC 7	Rivet head located in Box Beam Cap 8 (Figures 2-12 and 2-23).
NRC 8	Plate Girder 10 near Bent 20 web and plate with weld. Specimen contained weld metal (Figure 2-24).
NRC 9	Plate Girder 12 with stiffener near Bent 18. Specimen contained weld metal (Figure 2-25).
NRC 10	Flakes peeled off of plate girder angles on Box Beam Cap 8 (Figure 2-23).

Although the actual melting temperatures of alloys including carbon steel are composition dependent, low carbon steels have melting temperatures near 1,515 °C [2,760 °F]. For comparison, pure iron has a slightly higher melting temperature of 1,538 °C [2,800 °F]. None of the steel girder sections in the Caltrans storage yard, however, displayed indications of melting.

Review of the extensive photographic documentation compiled by Caltrans during the I-580 demolition also revealed no indications that any of the steel girders were exposed to temperatures where melting would be expected. With no indication of melting, it was apparent that the determination of temperature would have to be performed using other information. Possibilities considered included observed melting of alloys used on the tanker truck, spalling of concrete, damage to paint, and solid-state phase transformations in the structural steel members. Damage to the paint of the steel girders served as a useful indication of temperature, especially with the extensive photographic documentation available from Caltrans.

Figures 2-17 to 2-25 show the samples as they were obtained from the Box Beam Cap sections and plate girders, with descriptions of each of the samples provided in Table 2-1. Many of the samples collected contained welds. Samples collected included material from areas where the temperature was expected to be at the highest and also from girders that were at significant distances from the fire and were cooler.

Figure 2-17. Photograph of Plate Girder 3 and Samples NRC 1H (With Holes) and NRC 1S (With Stiffener). Samples Were Located Near Bent 19.

Figure 2-18. Photograph of Plate Girder 4 and Sample NRC 2

Figure 2-19. Photograph of Plate Girder 5 and Sample NRC 3

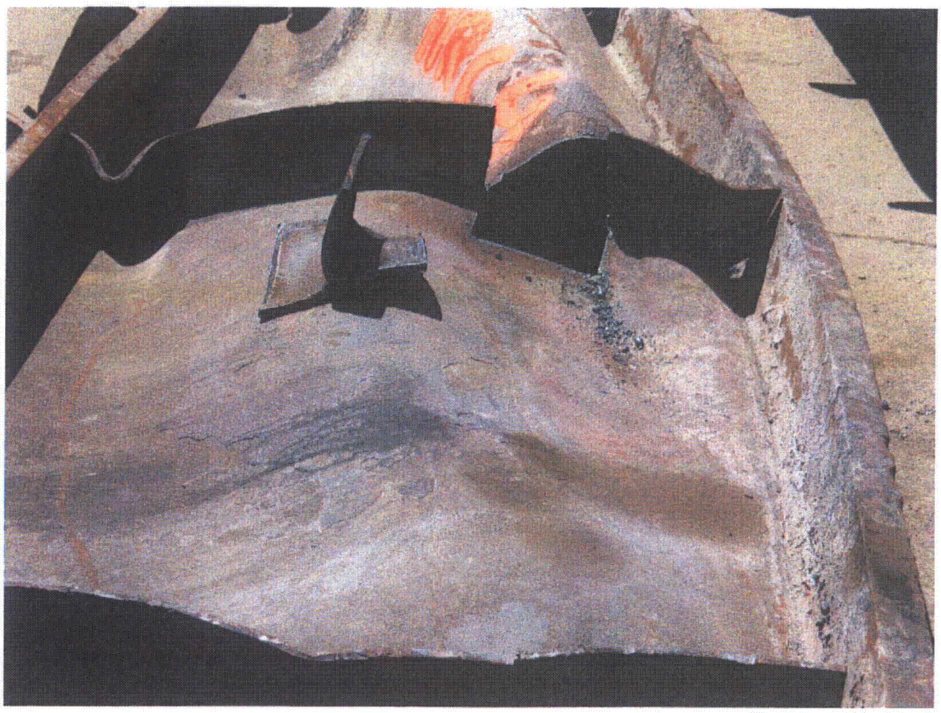


Figure 2-20. Photograph of Plate Girder 5 and Sample NRC 4

Figure 2-21. Photograph of Box Beam Cap Section 7 and Sample NRC 5

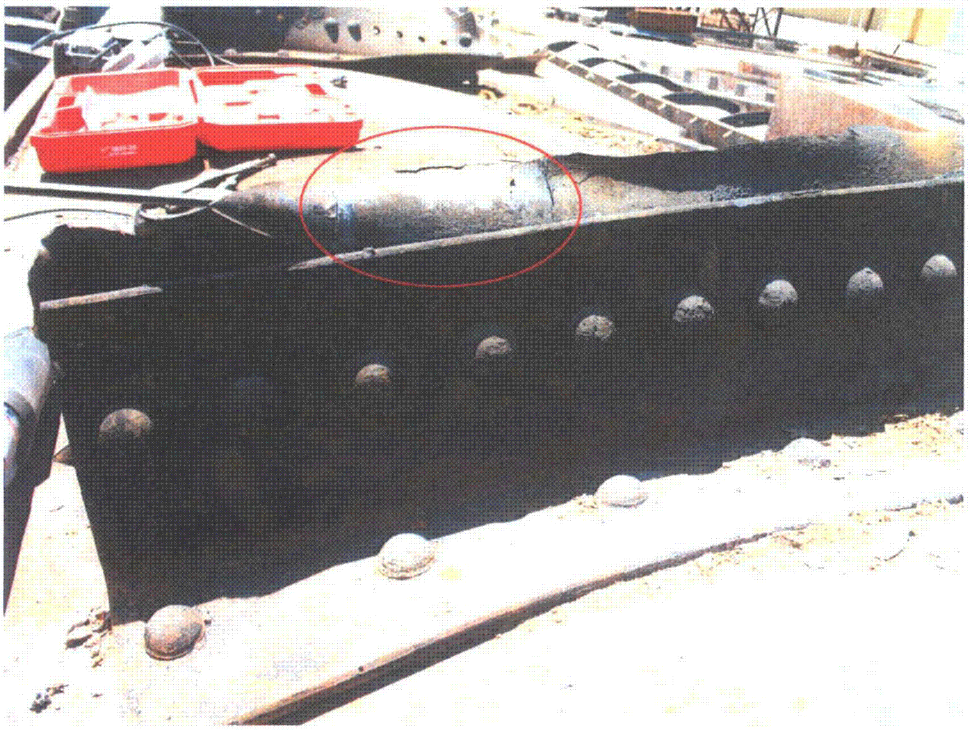


Figure 2-22. Photograph of Box Beam Cap Section 8 and Sample NRC 6. Sample Collected Prior to Removal Is Circled.

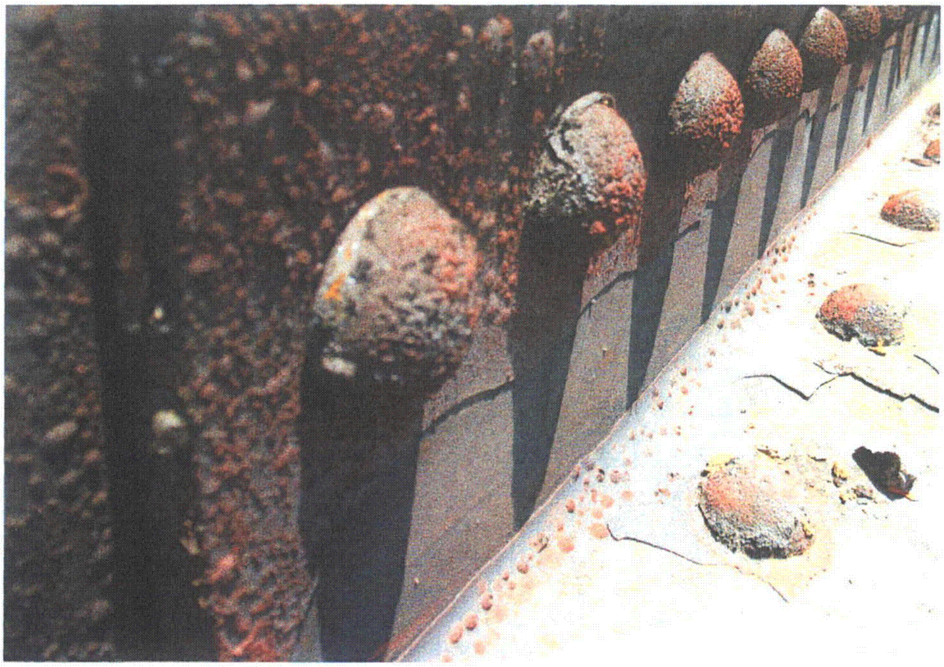


Figure 2-23. Photograph of Box Beam Cap Section 8 and Rivets Identical to Sample NRC 7 and Easily Dislodged Flakes Identical to Sample NRC 10

Figure 2-24. Photograph of Plate Girder 10 and Sample NRC 8

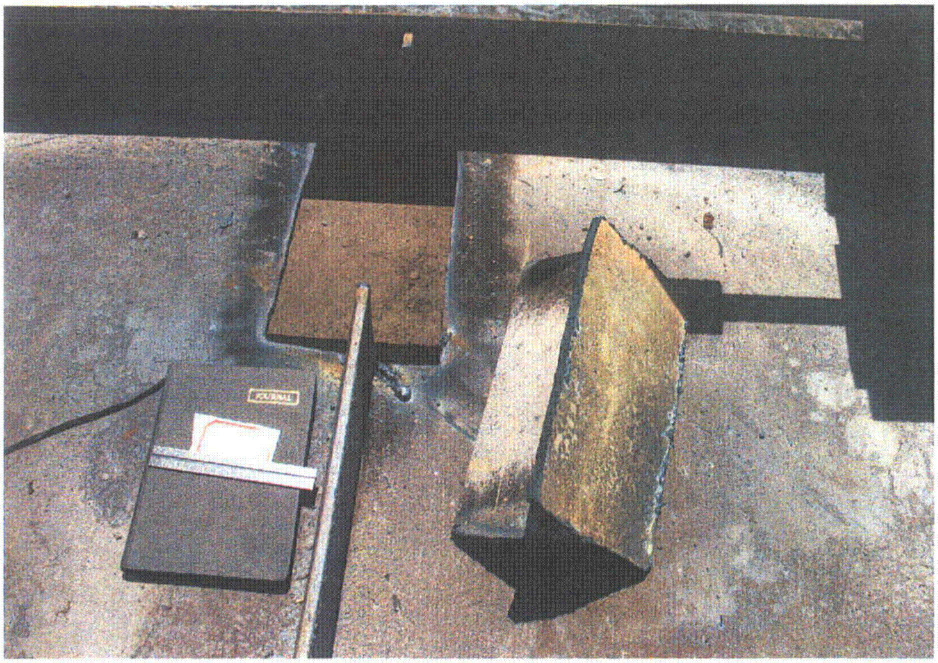


Figure 2-25. Photograph of Plate Girder 12 and Sample NRC 9

Compositional analyses indicate that the weld metal and base metal both contain approximately 0.2 percent carbon (Table 2-2). The iron-carbon phase diagram is shown in Figure 2-26. For the hypoeutectoid composition containing 0.2 percent carbon, the transformation to austenite is initiated at approximately 725 °C [1,337 °F] (Ac_1) and is expected to be fully austenitic above 840 °C [1,554 °F] (Ac_3). Because of the size and materials of construction, most of the welds in the girders were not postweld heat treated. In the original as-built state, the welds were as-deposited weld metal. Note that the as-welded condition is typical for structural steels and postweld heat treatment of low carbon steel is not necessary for such applications. The microstructure was expected to be a dendritic microstructure consisting of ferrite and carbide precipitates. Based on the time–temperature transformation diagrams for low carbon manganese steels, very fast cooling rates would be required to have a significant fraction of retained austenite (United States Steel Company, 1951). The temperatures of the steel girders would have been subjected to rapid heating during the fire owing to the large size of the ignited fuel pool. Cooling of the girders after the fire was likely slow because of the large mass of the girders, the insulating effect of the concrete after the collapse, and fire control with limited active firefighting to prevent runoff contamination. Heating of the welds to sufficiently high temperatures should have resulted in a phase transformation to an equilibrium microstructure consisting of pearlite and ferrite. Based on composition of the steel girders and the iron-carbon phase diagram, transformation of as-deposited weld metal may require heating to temperatures above the austenitic transformation temperature followed by slow cooling.

Table 2-2. Compositional Analysis of Weld and Base Metals (Weight Percent)		
Element	**Weld on Sample NRC 5**	**Plate From Sample NRC 9**
Carbon	0.21	0.19
Manganese	1.02	0.35
Phosphorus	0.010	0.004
Sulfur	0.014	0.017
Copper	0.12	0.12
Silicon	0.19	0.10
Aluminum	0.01	<0.01
Chromium	0.01	<0.01
Nickel	0.07	0.03
Iron	Remainder	Remainder

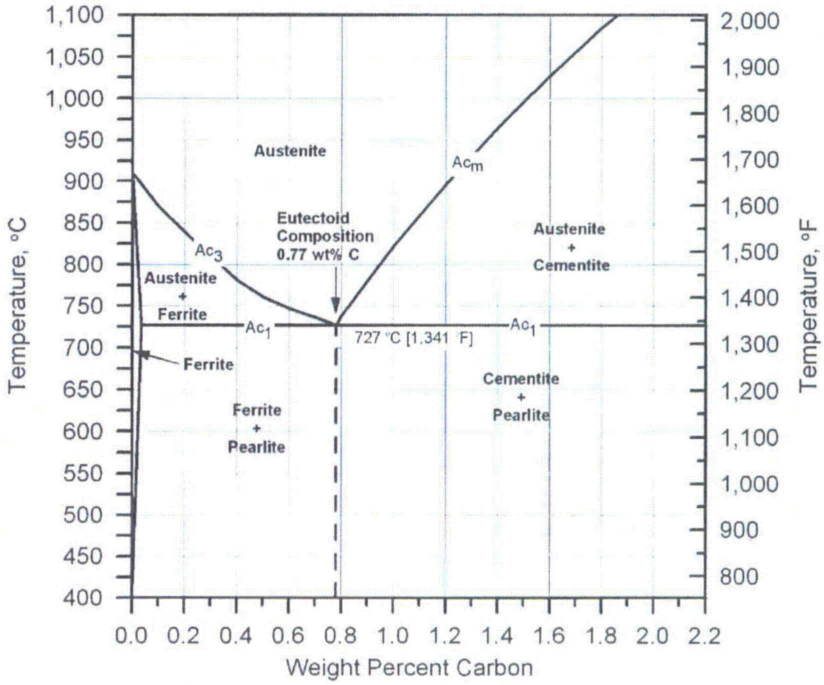


Figure 2-26. Iron Carbon Phase Diagram (American Society for Metals, 1978a)

3 ANALYSES OF THE INTERSTATE-580 OVERPASS SAMPLES

Samples collected were analyzed using traditional metallurgical methods. Metallurgical sections were prepared using a liquid-cooled saw to perform coarse cutting. Specimens for analysis were obtained from material that was at least 50 mm [2 in] from torch cut edges to avoid including any material that was altered by the high-temperature cutting operation. The altered material from the cutting operation was confined to a much smaller distance from the torch cut edge. During the collection of Sample NRC 9 from Plate Girder 12, damage to the latex paint was limited to a distance that was approximately 13 mm [0.5 in] from the torch cut edge. The limited distance of the paint damage provides some objective evidence that metallurgical alteration of the material would be limited to a narrow region near the torch cut edge. The metallurgical sections were placed in epoxy mounts. The sections were ground using progressively finer grinding papers followed by polishing using commercially available media. The polished sections were then etched using nital (a mixture of ethanol and nitric acid). Etched samples were immersed in alcohol to prevent corrosion by either atmospheric exposure or by residual amounts of etchant retained within pores in the sample.

3.1 Bridge Girder Paint Degradation

Specimens from Sample NRC 9 were cut and exposed to temperatures ranging from 100 to 800 °C [212 to 1,472 °F] to evaluate the effect of exposure temperature on the paint. The composition of the paint will affect elevated temperature performance. Initially, the specimens were covered with a gray-green-colored paint that was over a red-colored lead-containing paint. The conditions of exposure and the appearance of the specimens after exposure are shown in Table 3-1. Figure 3-1 shows the appearance of the specimens with a control specimen for comparison. After exposure to a temperature of 100 °C [212 °F], the paint appeared to be discolored and darkened. This observation appears to be consistent with information from McIntyre and Ashbaugh (1996) where the degradation of vinyl and alkyd paints used in coatings are typically observed to blister or char at a temperature of 93 °C [200 °F]. After exposure to 400 °C [752 °F], the specimens were orange. This color was most likely due to the oxidation and removal of the epoxy paint and exposure of the older lead-containing paint. At 600 °C [1,112 °F], the lead-containing paint is oxidized to a yellow-white color and at 700 °C [1,292 °F] the paint is mostly removed from the metal surface.

Table 3-1. Postexposure Description of Samples Used to Evaluate Temperature Effects on Paint

Sample	Thermal Exposure	Appearance
NRC 9-20	none	Gray-green color as collected
NRC 9-21	100 °C [212 °F]	Yellow-green slightly darkened
NRC 9-22	200 °C [392 °F]	Yellow-green slightly darkened
NRC 9-23	300 °C [572 °F]	Light brown-tan
NRC 9-24	400 °C [752 °F]	Orange
NRC 9-25	500 °C [932 °F]	Orange with yellow areas
NRC 9-26	600 °C [1,112 °F]	Yellow-white
NRC 9-35	700 °C [1,292 °F]	Mostly removed with small amounts of yellow remaining paint
NRC 9-36	800 °C [1,472 °F]	No paint, dark oxide layer on specimen

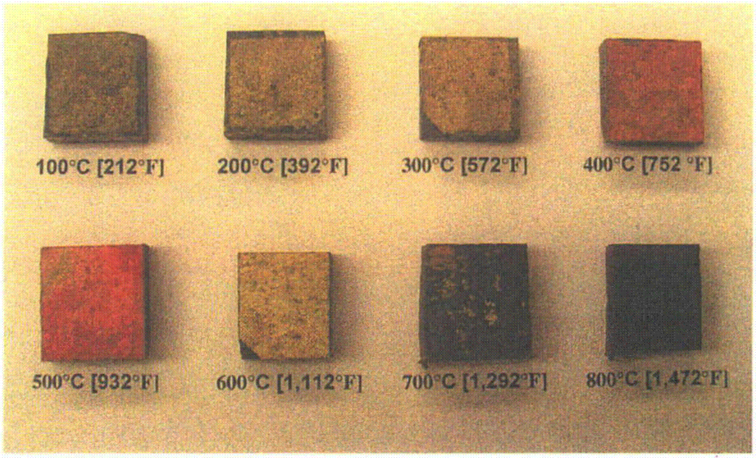


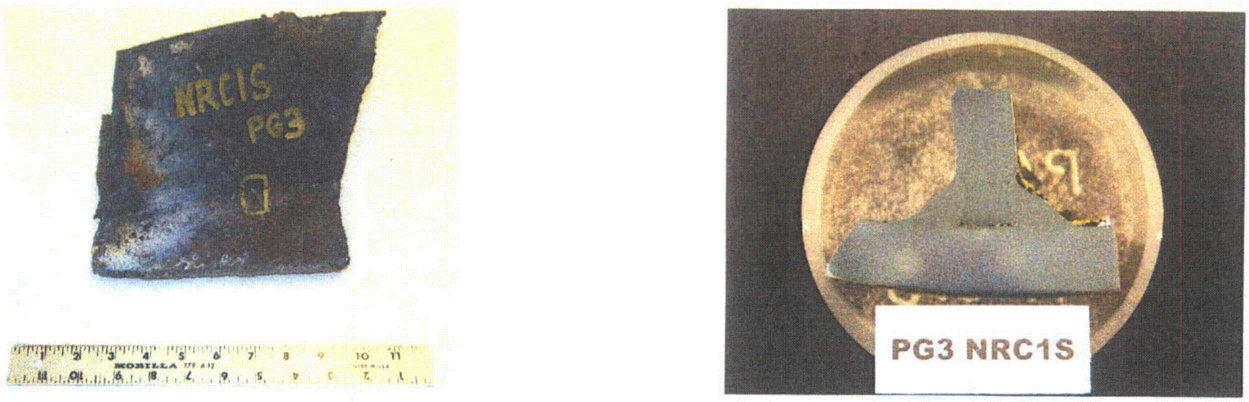
Figure 3-1. Picture of the Paint Evaluation Specimens After Thermal Exposure

3.2 Metallurgical Analysis of As-Received Interstate-580 Overpass Samples

A summary of the analysis results is included in Table 3-2 and includes girder sections that were believed to be near the fire (i.e., near Bent 19) and samples that were known to be in much cooler locations such as near Bent 18. Figure 3-2 shows the sample material NRC 1S from Plate Girder 3 as collected and the metallurgical specimen after mounting and polishing. The microstructure of the base alloy in the plate girder reveals a microstructure of ferrite and pearlite that was expected for this material (Figure 3-3). The weld on this sample appears to be mostly in the as-welded condition that, depending on cooling rate, should include mainly ferrite and some carbide. Some small areas of pearlite are visible, which suggests that the weld was exposed to elevated temperatures after welding. Because these are single pass welds, it is unlikely that the altered microstructure occurred during fabrication, and more likely that it occurred during the fire exposure.

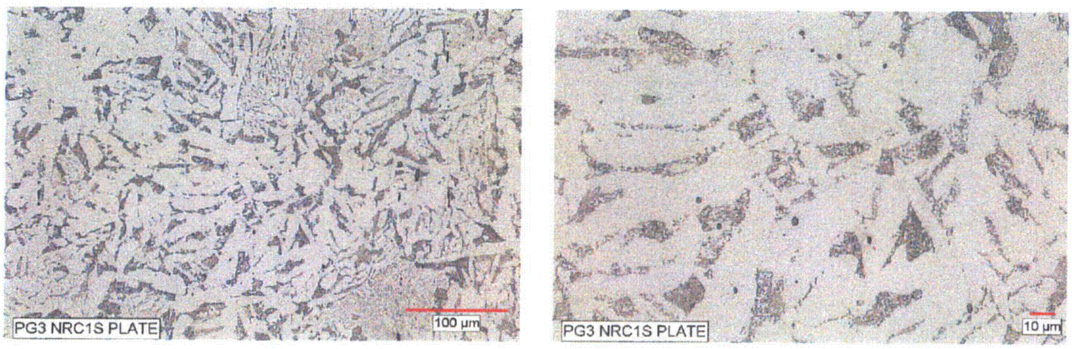
Figure 3-4 shows Sample NRC 2, which is a plate girder with a butt weld. A macrophotograph of the specimen after mounting and polishing is shown in Figure 3-4(B). Figure 3-5 shows the microstructure of the weld in Sample NRC 2. The microstructure of the plate weld consists of both pearlite and ferrite. In addition, the weld does not contain any of the dendritic structure that was likely to be present immediately after fabrication. While the results suggest that the weld was exposed to an elevated temperature, it is not clear whether this occurred during the fire. Unfortunately, none of the other beams had a butt weld that was not believed to be compromised during the demolition processes. The Sample NRC 2 came from Plate Girder 4, which had significant deformation on the bottom of the girder. The original location of Plate Girder 4 is not known, but it may have been between Bent 18 and Bent 19. The deformation may have been caused by contact with the concrete barrier on the edge of I-880 (Figure 2-2). An alternate explanation for the microstructure of the weld would be that the plate was hot worked after welding, which is sometimes required during fabrication and construction. Such practice would not have significantly altered the mechanical properties of the steel girder. This may have been performed to straighten the plate before or during girder construction. Without a comparison sample that was known to have been far enough from the fire where thermal alteration of the weld was unlikely, no definitive statement can be made about the temperature that this sample may have reached.

Table 3-2. Results of Microstructure Examination From Collected Samples		
NRC Sample Number	**Description**	**Results**
NRC 1H	Plate Girder 3 at Bent 19 end with rivet holes. Specimen did not contain weld metal.	Plate was pearlite and ferrite.
NRC 1S	Plate Girder 3 with stiffener near Bent 19. Specimen contained weld metal.	Weld was as-deposited weld metal consisting of a dendritic microstructure with columnar and equiaxed grains. Some pearlite was also present. Weld and plate were pearlite and ferrite.
NRC 2	Plate Girder 4 with butt weld. Specimen contained weld metal.	Weld was pearlite and ferrite. Plate microstructure was pearlite and ferrite.
NRC 3	Plate Girder 5 likely located between Bents 18 and 19 with stiffener heavy distortion. Specimen contained weld metal.	Weld was pearlite and ferrite. Plate and stiffener were pearlite and ferrite.
NRC 4	Plate Girder 5 likely located between Bents 18 and 19 with stiffener medium distortion. Specimen contained weld metal.	Weld was pearlite and ferrite. Plate and stiffener were pearlite and ferrite.
NRC 5	Box Beam Cap Section 7 lower plate with side and weld. Specimen contained weld metal.	Weld was mostly as-deposited weld metal with a dendritic microstructure and columnar and equiaxed grains some indications of pearlite and ferrite in the weld. Plate was pearlite and ferrite.
NRC 6	Plate girder found attached to Box Beam Cap Section 8 with reduction in area.	Pearlite and ferrite; no indication of either melting or cold work.
NRC 7	Rivet head located in Box Beam Cap Section 8.	Not analyzed. Corresponding sample that was not thermally exposed was not available.
NRC 8	Plate Girder 10 near Bent 20. Web and plate with weld. Specimen contained weld metal.	Weld was as-deposited weld metal with dendritic microstructure with columnar and equiaxed grains. Web and plate were pearlite and ferrite.
NRC 9	Plate Girder 12 web with stiffener near Bent 18. Specimen contained weld metal.	Weld is as-deposited weld metal with dendritic microstructure with columnar and equiaxed grains. Web and stiffener are pearlite and ferrite.
NRC 10	Flakes peeled off of plate girder angles on Box Beam Cap Section 8.	Fe and Pb.

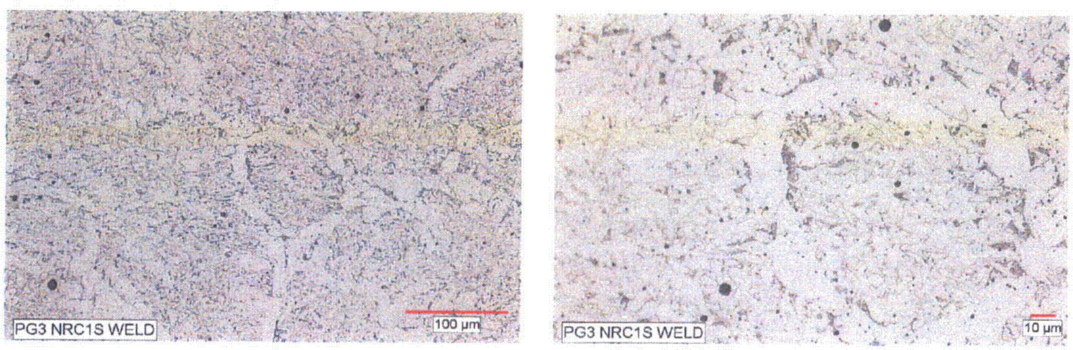


(A) (B)

Figure 3-2. (A) Photograph of Collected Sample NRC 1S; (B) Metallurgical Specimen From NRC 1S After Mounting, Polishing, and Etching

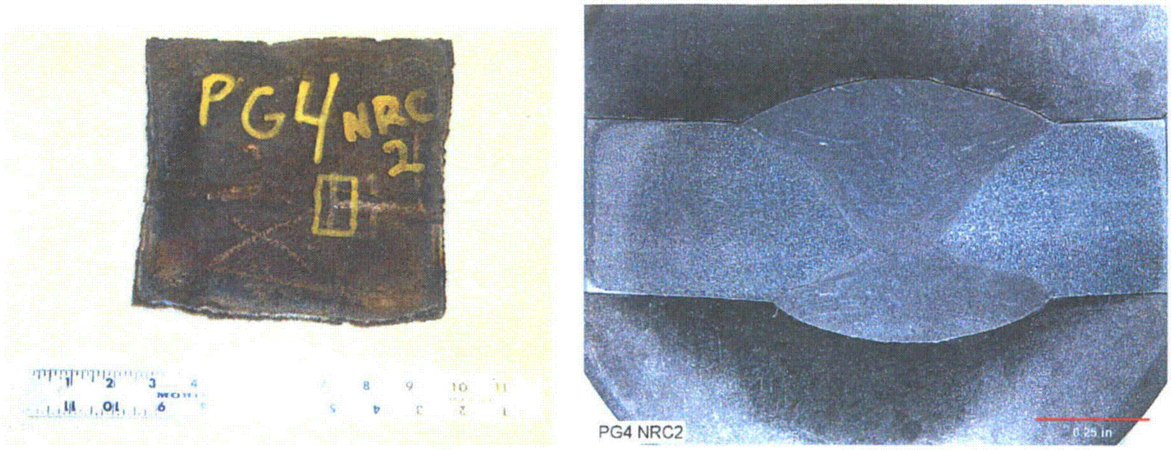


(A) (B)



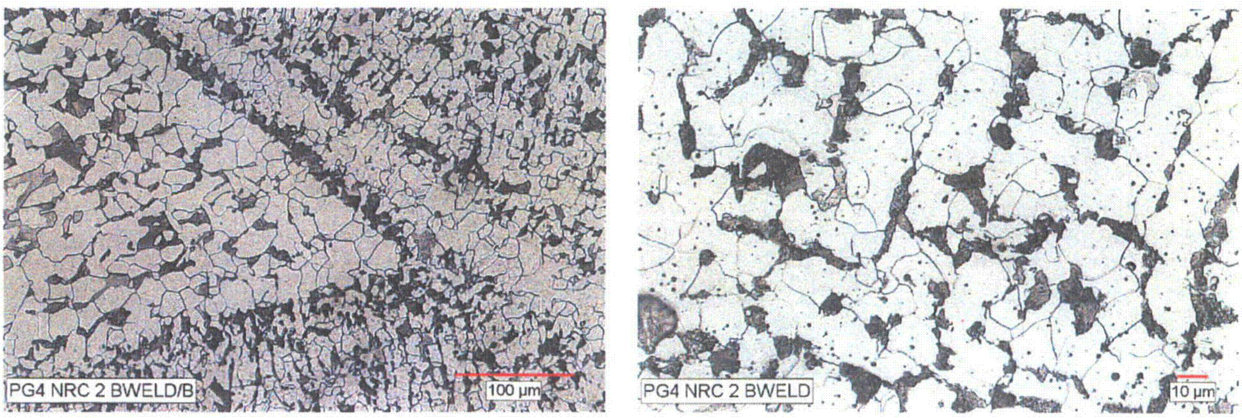
(C) (D)

Figure 3-3. (A,B) Microstructure of Plate Girder on Sample NRC 1S Showing Ferrite (Light-Colored Phase) and Pearlite (Dark-Colored Phase) and (C,D) Microstructure of Stiffener Fillet Weld Showing As-Welded Appearance With Evidence of Ferrite and Pearlite



(A) (B)

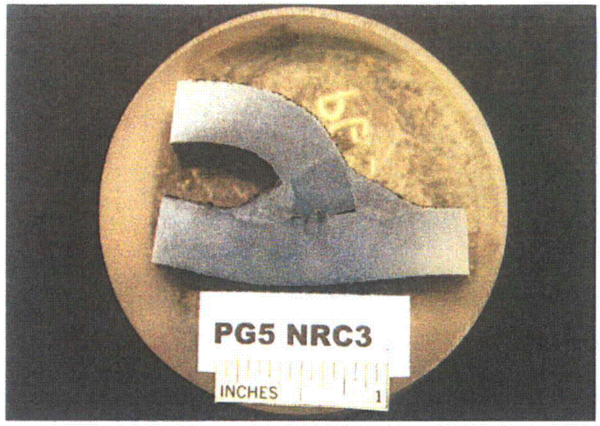
Figure 3-4. (A) Photograph of Collected Sample NRC 2; (B) Metallurgical Specimen From NRC 2 After Mounting, Polishing, and Etching



(A) (B)

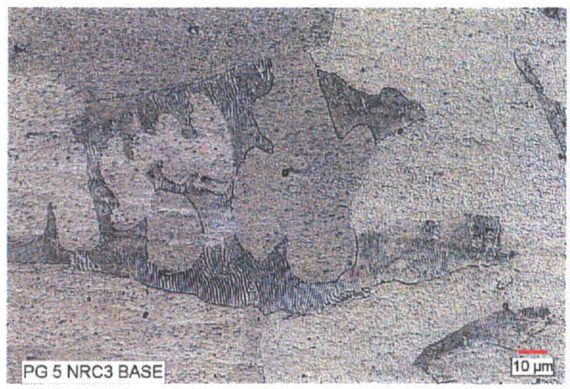
Figure 3-5. (A) Microstructure of Plate Girder and Weld on Sample NRC 2 Showing Ferrite and Pearlite; (B) Microstructure of Plate Girder Butt Weld Ferrite and Pearlite

Figure 3-6 shows Sample NRC 3 and the specimen after mounting, polishing, and etching. The distortion of the plate and the stiffener are obvious, given that the plate and stiffener were originally perpendicular to one another. Figure 3-7 shows the microstructures of the plate girder, the stiffener, and the weld. As expected, the plate and the stiffener consist of ferrite and pearlite. The welds are also ferrite and pearlite and contain no indication of a dendritic structure that would have been present immediately after welding. A higher magnification image of the weld, shown in Figure 3-7(D), clearly indicates pearlite in a ferrite matrix.

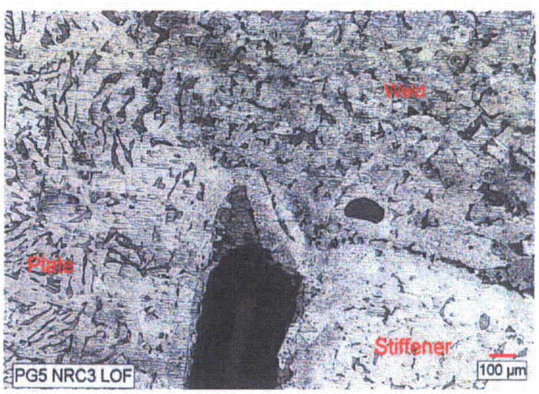


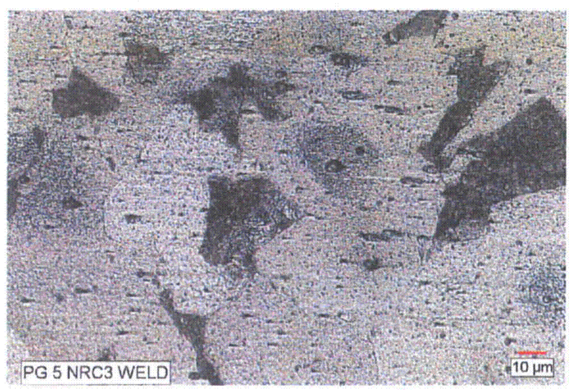
(A) (B)

Figure 3-6. (A) Photograph of Collected Sample NRC 3; (B) Metallurgical Specimen From NRC 3 After Mounting, Polishing, and Etching



(A) (B)





(C) (D)

Figure 3-7. (A,B) Microstructure of Plate Girder on Sample NRC 3 Showing Ferrite and Pearlite; (C) Microstructure of Stiffener Fillet Weld Plate Girder and Stiffener; (D) Microstructure of Fillet Weld Showing Ferrite and Pearlite

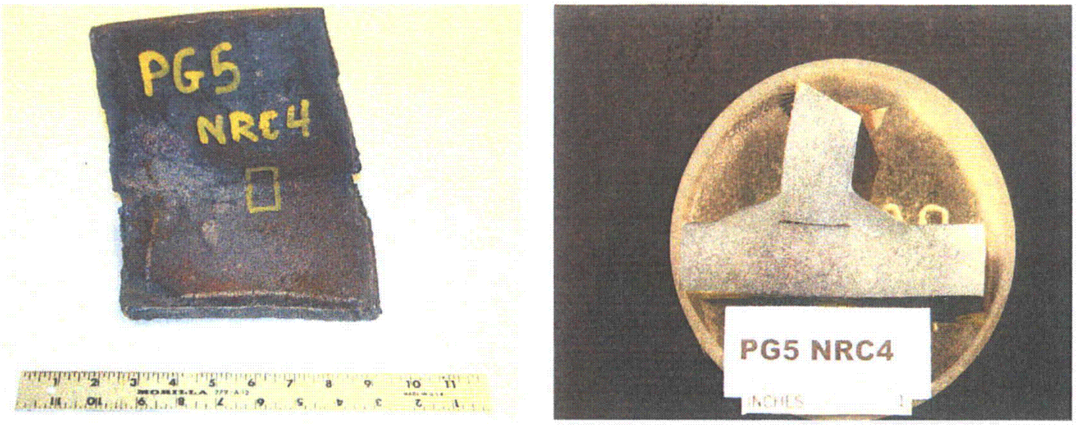
Sample NRC 4 is shown in the as-collected condition and after preparation in Figure 3-8. Samples NRC 3 and NRC 4 were collected from different locations on the same girder. Sample NRC 3 was likely located closer to Bent 19 compared to Sample NRC 4. Figure 3-9 shows the microstructure of the weld, plate, and stiffener. In all areas, the microstructure is ferrite and pearlite. Similar to Sample NRC 3, the weld on Sample NRC 4 showed no signs of any dendritic structure that was likely to be present after welding. Comparison of the higher magnification images shown in Figures 3-9(B) (plate) and 3-9(D) (weld) clearly indicates that the welds were fully transformed and are practically indistinguishable from the plate. Sample NRC 5 is shown before and after preparation in Figure 3-10. This section from the box girder contained a large volume of weld metal, and the weld was produced in at least two passes. A small area where there was no fusion between the plates is apparent in Figure 3-10(B). The microstructure of the plate and the weld is shown in Figure 3-11. The microstructure of the plate and weld both consist of pearlite and ferrite. The weld on this sample appears to be mostly in the as-welded condition with a dendritic appearance containing mainly ferrite and some carbide. It is not clear whether pearlite is present in small quantities. Certainly, the weld is largely unaltered, suggesting that the weld did not reach temperatures where transformation could occur. Note that this sample was not an ideal witness for temperature owing to its very large mass and the complex shape of the structural member from which the sample was taken. Sample NRC 6 is shown in Figure 3-12. This sample does not contain weld metal. As shown in Figure 2-22, the sample was found still attached to Box Beam Cap Section 8. The sample was a section of a plate girder that appeared to be pulled to failure under conditions where the material was very ductile, as shown in Figure 3-12(B). The microstructure near the ductile failure end of the specimen is shown in Figure 3-13. The microstructure did not show obvious indications of cold work. Because no cold work is apparent in the microstructure, the material was likely heated to at least 550 °C [1,022 °F], which is typically the minimum annealing temperature for low carbon steels.

Figure 3-14 shows Sample NRC 8 in the as-collected condition and after metallurgical specimen preparation. The sample had a large volume of weld metal, and it was apparent that the weld was produced in at least two passes on each side. Figure 3-15 shows the microstructure of the weld and the plate. The microstructure of the base alloy in the plate girder revealed a microstructure of ferrite and pearlite [Figure 3-15(B)]. The weld on this sample appears to be mostly in the as-welded condition with a dendritic appearance. The appearance of the weld suggests that the sample was not exposed to temperatures where the weld would be transformed to an equilibrium microstructure.

Figure 3-16 shows Sample NRC 9 in the as-collected condition and after metallurgical specimen preparation. This sample was obtained from a plate girder that was known to be near Bent 18. Because the gray-colored paint was still present on the sample, it is apparent that this portion of the girder was not subjected to elevated temperatures that would result in microstructural alteration. The microstructure of the sample is shown in Figure 3-17. The microstructure of the weld consisted of a dendritic structure with ferrite and possibly carbide. No evidence of a postweld transformation was observed in the as-collected sample.

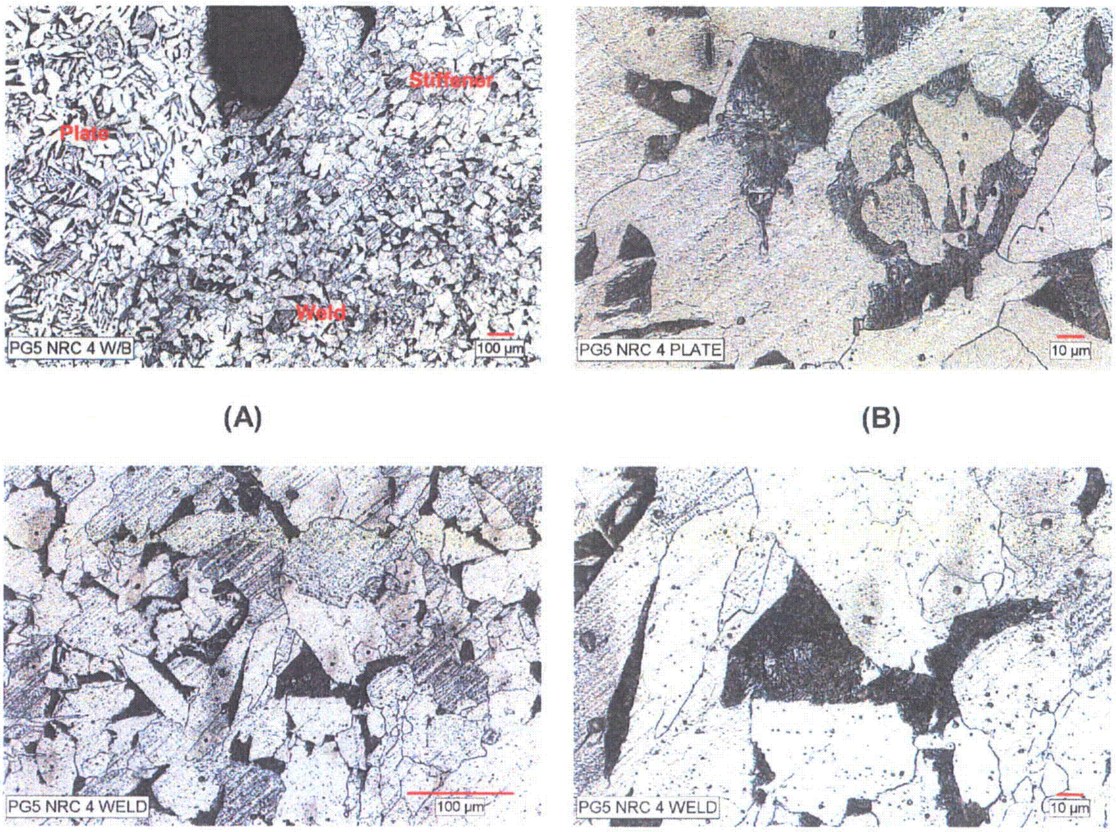
3.3 Metallurgical Analysis of Thermally Exposed Structural Welds

When the samples were collected, it was recognized that the microstructure of the weld may be a useful indication of temperature. Sample NRC 9 was significantly larger than the other



(A) (B)

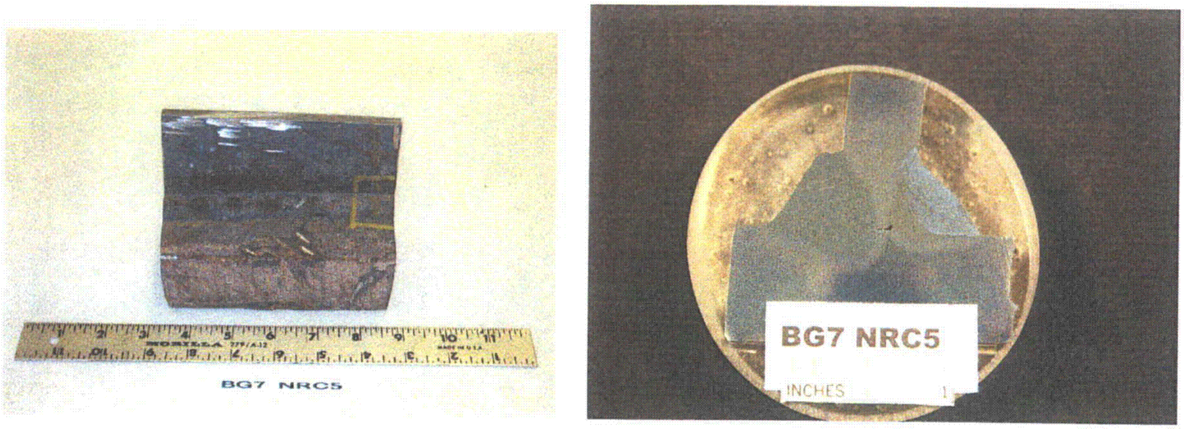
Figure 3-8. (A) Photograph of Collected Sample NRC 4; (B) Metallurgical Specimen From NRC 4 After Mounting, Polishing, and Etching



(A) (B)

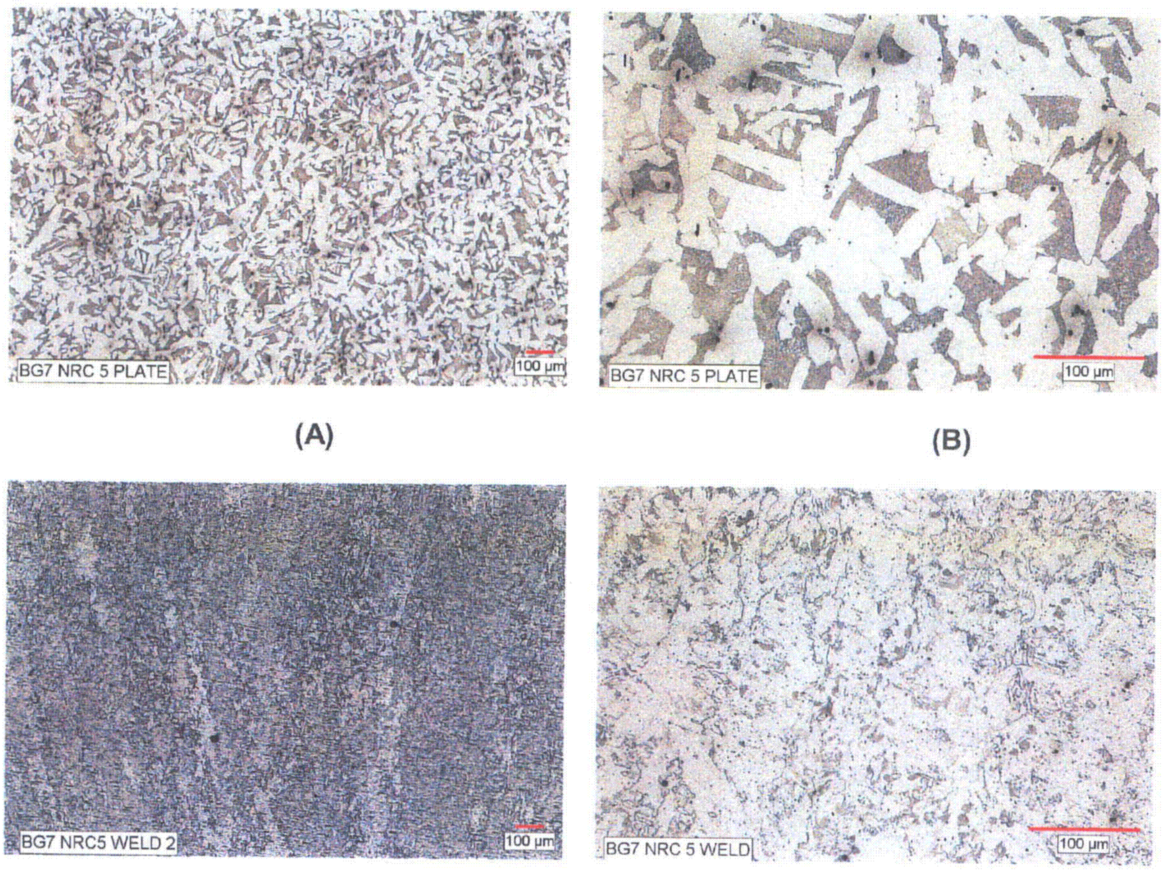
(C) (D)

Figure 3-9. (A) Microstructure of Stiffener Fillet Weld Plate Girder and Stiffener on Sample NRC 4; (B) Higher Magnification of Microstructure of Plate Girder; (C,D) Microstructure of Fillet Weld Showing Ferrite and Pearlite



(A) (B)

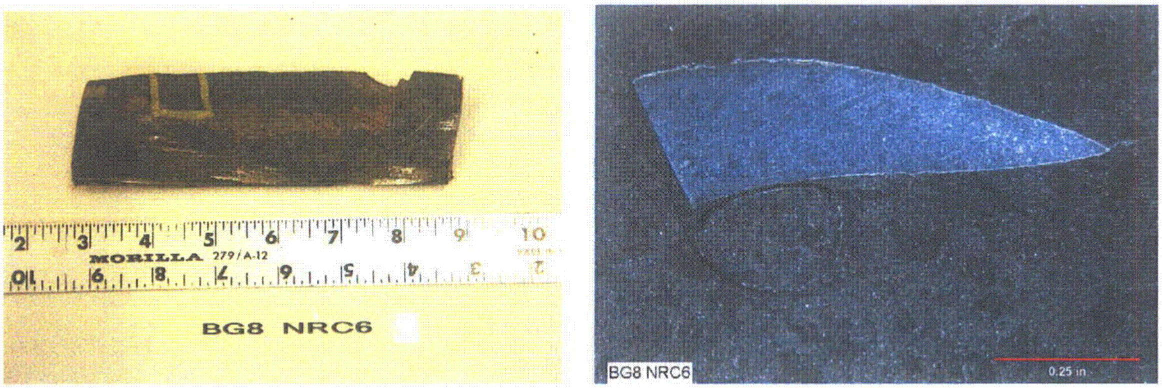
Figure 3-10. (A) Photograph of Collected Sample NRC 5; (B) Metallurgical Specimen From NRC 5 After Mounting, Polishing, and Etching



(A) (B)

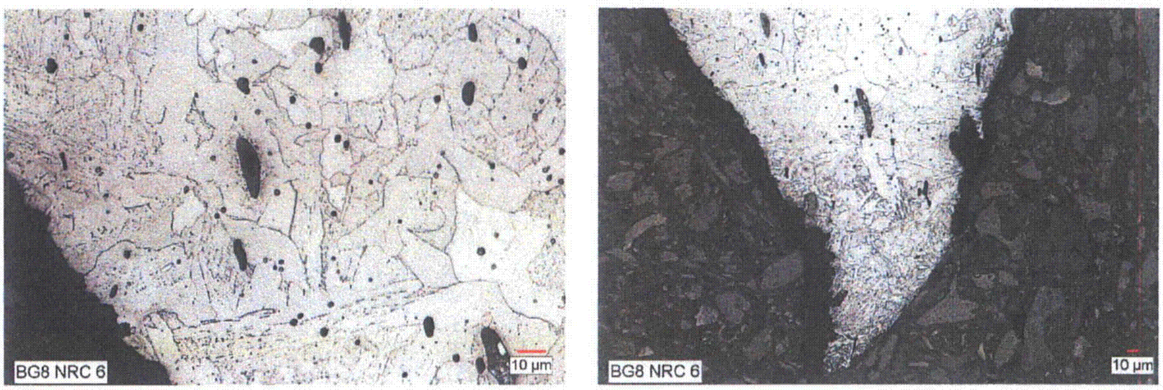
(C) (D)

Figure 3-11. (A,B) Microstructure of Box Beam Cap Plate From Sample NRC 5; (C,D) Microstructure of Fillet Weld Showing As-Welded Appearance Indications of Ferrite and Pearlite



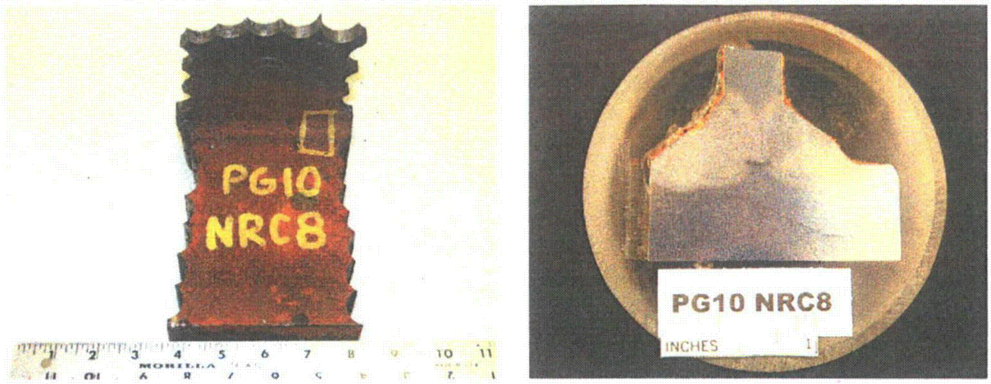
(A) (B)

Figure 3-12. (A) Photograph of Collected Sample NRC 6; (B) Metallurgical Specimen From NRC 6 After Mounting, Polishing, and Etching. The Sample Was Part of a Plate Girder Found Attached to Box Beam Cap Section 8 as Shown in Figure 2-22.



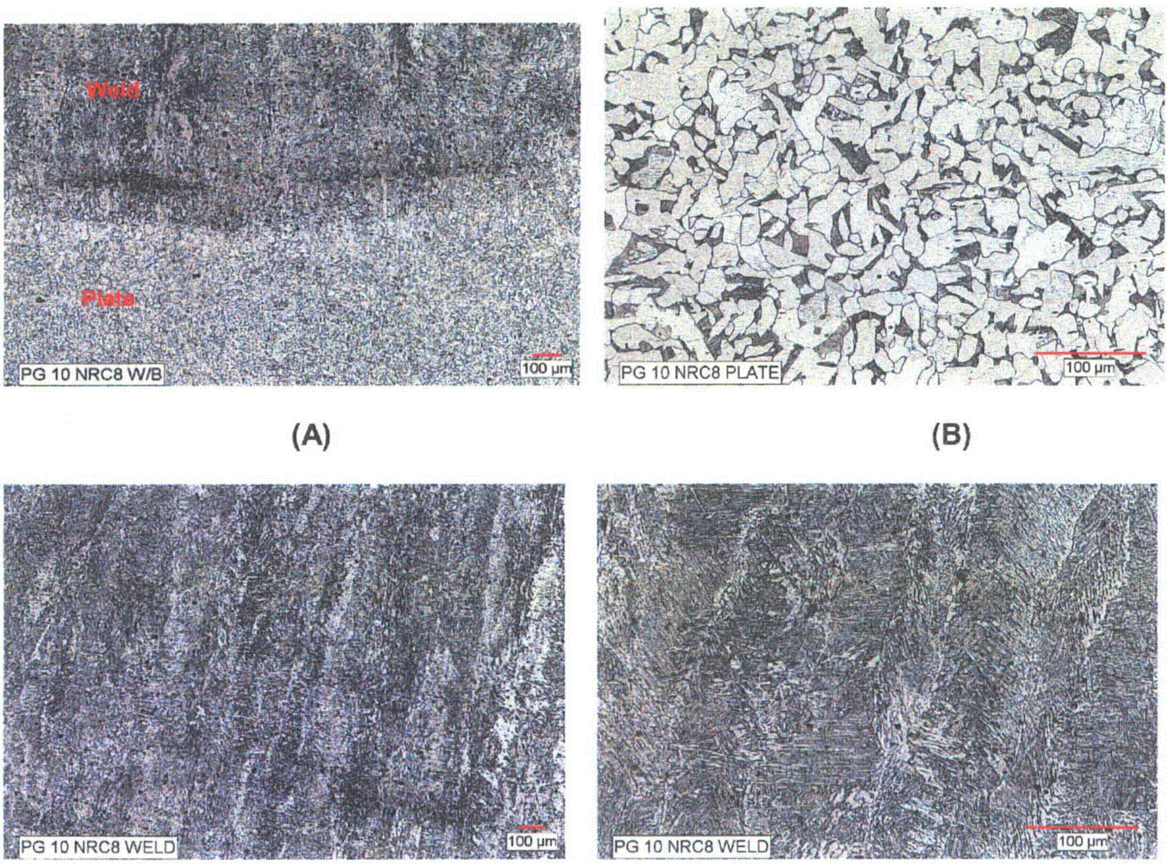
(A) (B)

Figure 3-13. Microstructure of Sample NRC 6, a Plate Girder Section Found Attached to the Box Beam Cap. (A) Microstructure Has Many Inclusions; (B) Near the Tip of the Specimen, No Indication of Cold Work Was Observed.



(A) (B)

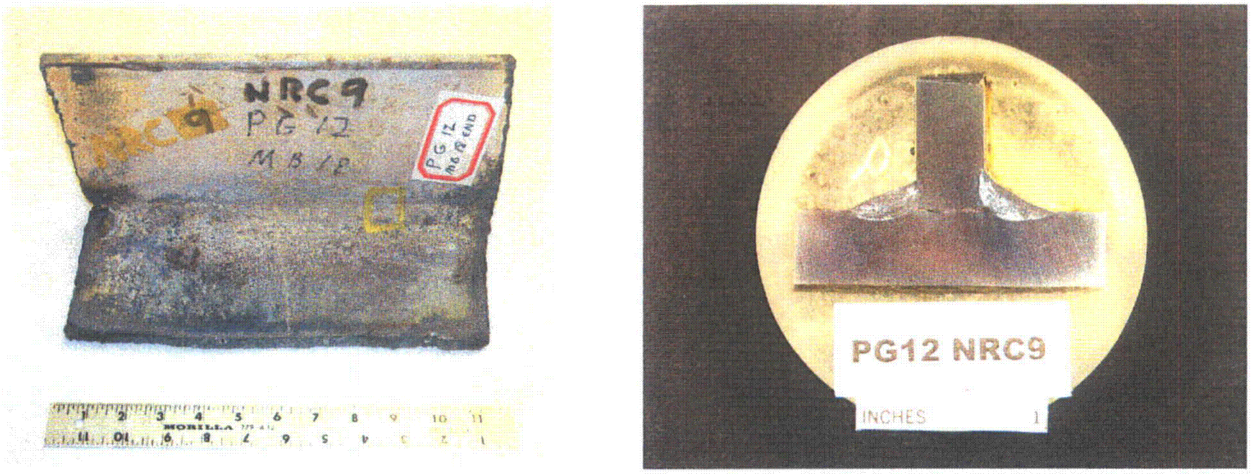
Figure 3-14. (A) Photograph of Collected Sample NRC 8; (B) Metallurgical Specimen From NRC 8 After Mounting, Polishing, and Etching



(A) (B)

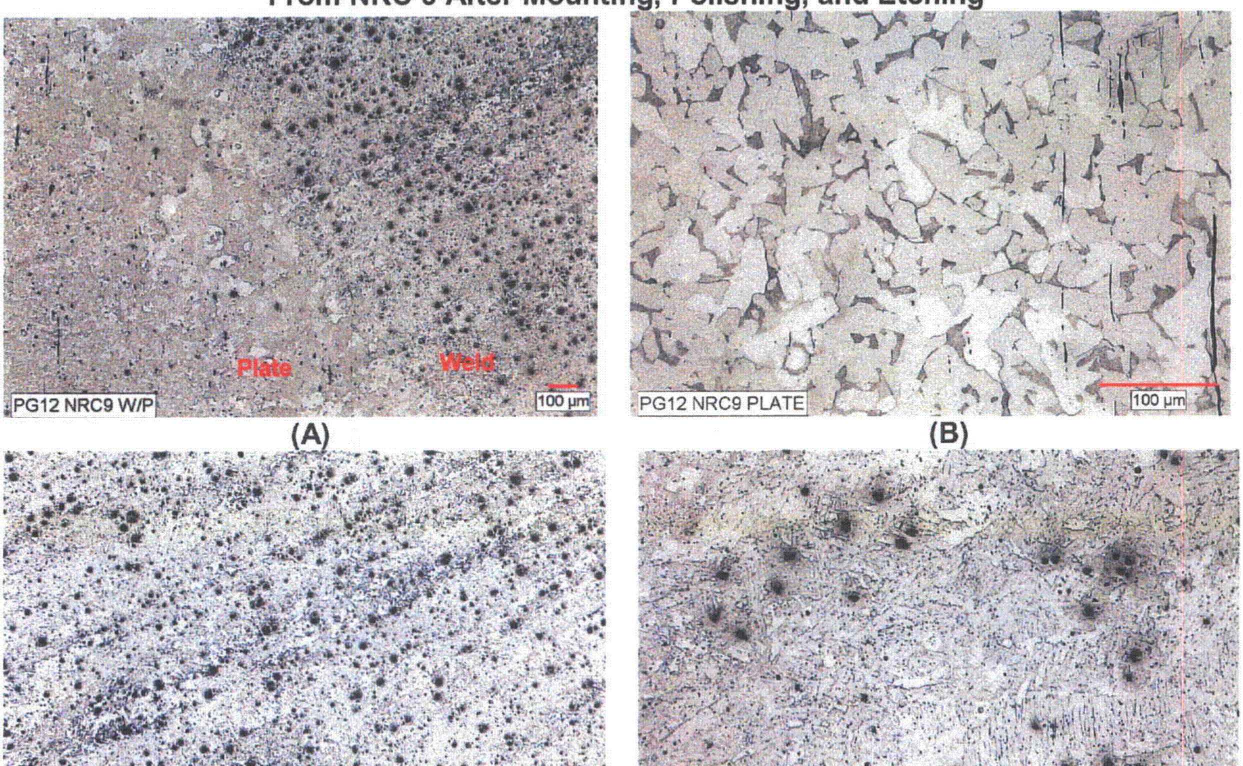
(C) (D)

Figure 3-15. (A) Microstructure of the Weld and Plate for Sample NRC 8; (B) Microstructure of Plate Showing Ferrite and Pearlite Regions; (C,D) Microstructure of Fillet Weld Showing As-Welded Appearance and No Evidence of Ferrite and Pearlite



(A) (B)

Figure 3-16. (A) Photograph of Collected Sample NRC 9; (B) Metallurgical Specimen From NRC 9 After Mounting, Polishing, and Etching



(A) (B) (C) (D)

Figure 3-17. (A) Microstructure of Plate and Weld on Sample NRC 9; (B) Microstructure of Plate Showing Laminations; (C,D) Microstructure of Fillet Weld Showing As-Welded Appearance With Porosity and no Evidence of Ferrite and Pearlite

specimens, providing a sufficient sample to conduct thermal exposures to determine the effect of exposure conditions on the weld microstructure. Multiple specimens were sectioned from the sample and exposed in an oven at temperatures ranging from 550 to 900 °C [1,022 to 1,652 °F] for 3 hours followed by cooling in laboratory air. Table 3-3 shows the thermal exposure conditions and the results of the analysis. Microstructures of the specimens are shown in Figures 3-18 to 3-20. It is apparent that no transformation of the weld occurred at temperatures of 750 °C [1,382 °F] or less. At a temperature of 800 °C [1,472 °F], the microstructure of the weld was mainly dendritic, but some small amount of pearlite were also present. In Sample NRC 9-8 exposed at 850 °C [1,562 °F], the microstructure contains more pearlite but was not fully transformed. After exposure to 900 °C [1,652 °F], the weld was fully transformed to a ferrite and pearlite microstructure.

Figure 3-19 shows the microstructure of the plate and the weld after exposure to temperatures of 650 to 900 °C [1,202 to 1,652 °F]. The microstructural distinction between the weld and the plate was apparent at temperatures of 800 °C [1,472 °F] or less. At 900 °C [1,652 °F], the weld was fully transformed and the distinction between the weld and the plate was reduced and limited to the differences in grain size between the two regions. Higher magnification images of specimens exposed to 800 to 900 °C [1,472 to 1,652 °F] for 3 hours are shown in Figure 3-20. The microstructure of the welds in the specimens exposed to 850 or 900 °C [1,562 or 1,652 °F] appeared to be similar to the microstructures observed in welds in specimens NRC 3 and NRC 4.

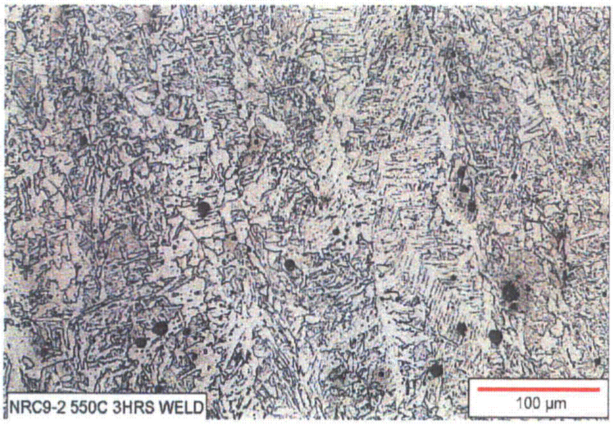
3.4 Metallurgical Analysis of the Bridge Girder Stiffeners Base Metal

The microstructure of the low carbon steel used consisted of a mixture of ferrite and pearlite consistent with the composition of low carbon steels. Grain size influences mechanical properties. Typically, structural steels such as A533 that are designed to function at ambient temperatures are processed to yield a fine-grain structure. For structural steels, this microstructure is preferable for fatigue resistance, toughness, and low nil ductility temperature (American Society for Metals, 1978b).

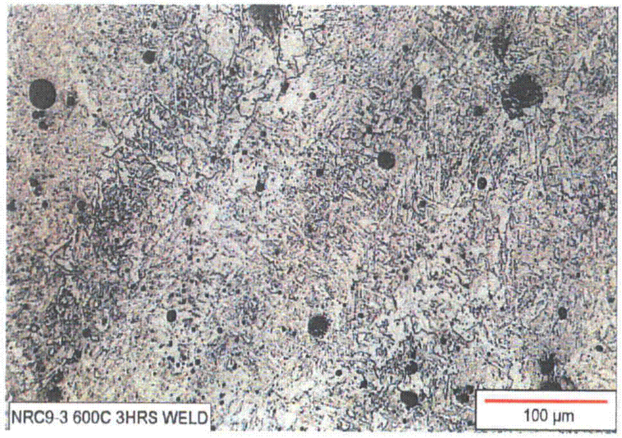
Thermal exposures of low carbon steels to temperatures above 815 °C [1,500 °F] result in an increase in grain size that can reduce toughness at higher temperatures and result in an increase in the nil ductility temperature (McIntyre and Ashbaugh, 1996).

Although the relationship between thermal exposures and the microstructure of some carbon steels is known, no specific information exists on the relationship between grain size and exposure temperature for ASTM A7 steel. To determine the relationship and assess the temperature at which the girders were exposed, specimens from the girder stiffeners were sectioned and exposed to temperatures in the range of 700 to 1,200 °C [1,292 to 2,192 °F]. Stiffener sections were chosen because they are most likely to be better witnesses to the exposure temperature in the hottest regions of the fire. Stiffeners were uniformly positioned along the length of all of the girders. Specimens from Sample NRC 9 were known to be at a lower temperature owing to the location of this material during the fire. The maximum temperature for this material was certainly less than 300 °C [572 °F] based on the appearance of the paint. Therefore, the starting microstructure in the specimens sectioned from NRC 9 was expected to be equivalent to the microstructure of a typical stiffener prior to the fire. In contrast, Sample NRC 3 was exposed to elevated temperatures during the fire and the microstructure of this material may have been altered as a result of the thermal exposure.

Table 3-3. Microstructure Analysis of Thermally Exposed Specimens From Sample NRC 9. Thermally Exposed Specimens Were Placed in an Oven at Temperature for 3 Hours and Cooled in Laboratory Air.		
NRC Sample Number	**Thermal Exposure Temperature**	**Microstructure**
NRC 9-1	None	As-deposited weld metal with dendritic and equiaxed grains
NRC 9-2	550 °C [1,022 °F]	As-deposited weld metal with dendritic and equiaxed grains
NRC 9-3	600 °C [1,112 °F]	As-deposited weld metal with dendritic and equiaxed grains
NRC 9-4	650 °C [1,202 °F]	As-deposited weld metal with dendritic and equiaxed grains
NRC 9-5	700 °C [1,292 °F]	As-deposited weld metal with dendritic and equiaxed grains
NRC 9-6	750 °C [1,382 °F]	As-deposited weld metal with dendritic and equiaxed grains
NRC 9-7	800 °C [1,472 °F]	Partially transformed with dendritic and equiaxed grains and small regions of pearlite
NRC 9-8	850 °C [1,562 °F]	Mostly transformed weld metal with significant ferrite with pearlite
NRC 9-9	900 °C [1,652 °F]	Fully transformed microstructure consisting of ferrite with pearlite



(A)



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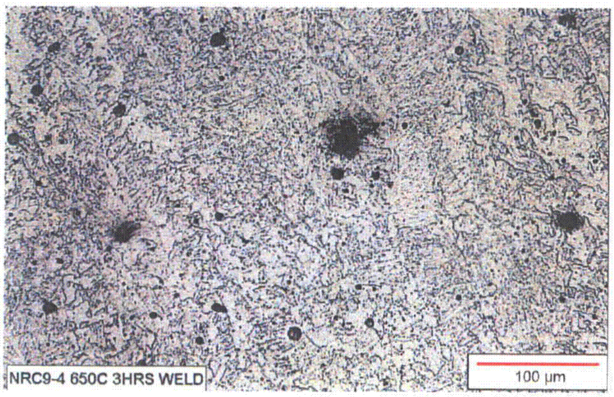

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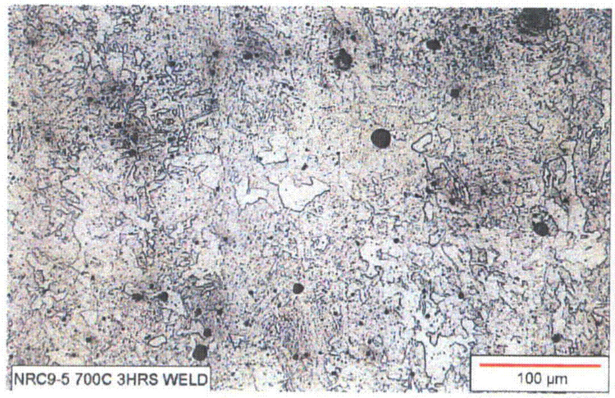
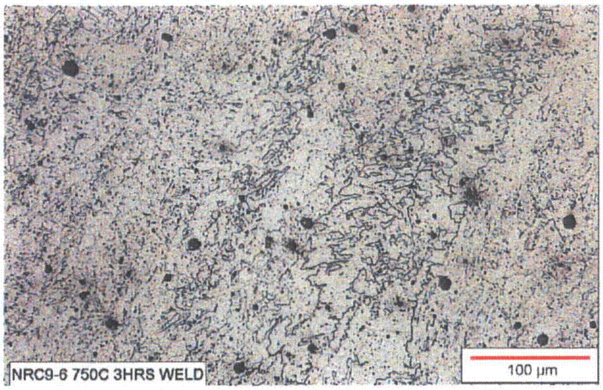
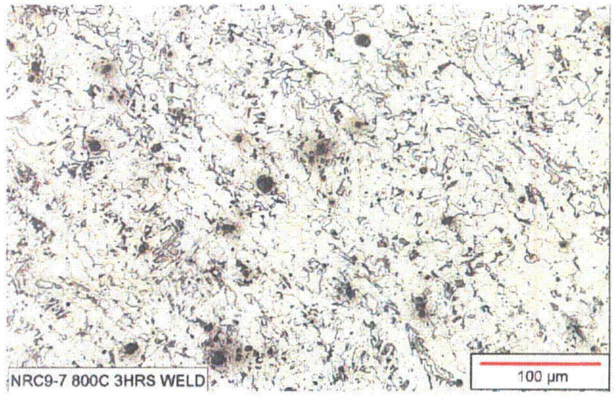


(D)

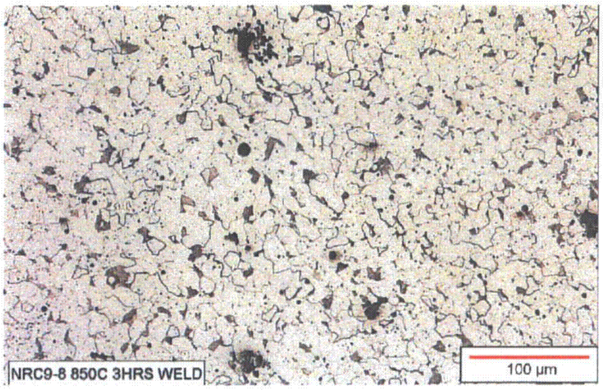
Figure 3-18. Microstructure of Welds on Specimens NRC 9-2 to NRC 9-9 After Thermal Exposure for 3 Hours at Temperatures of 550 to 900 °C [1,022 to 1,652 °F]. (A) NRC 9-2, 550 °C [1,022 °F]; (B) NRC 9-3, 600 °C [1,112 °F]; (C) NRC 9-4, 650 °C [1,202 °F]; (D) NRC 9-5, 700 °C [1,292 °F].



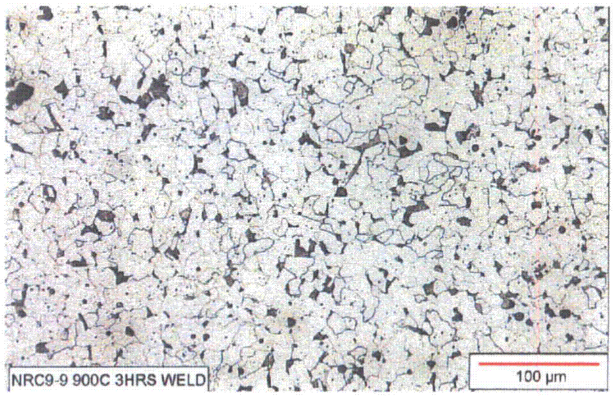
(E)



(F)



(G)



(H)

Figure 3-18 (continued). Microstructure of Welds on Specimens NRC 9-2 to NRC 9-9 After Thermal Exposure for 3 Hours at Temperatures of 550 to 900 °C [1,022 to 1,652 °F]. (E) NRC 9-2, 750 °C [1,382 °F]; (F) NRC 9-7, 800 °C [1,472 °F]; (G) NRC 9-8, 850 °C [1,562 °F]; and (H) NRC 9-9, 900 °C [1,652 °F].

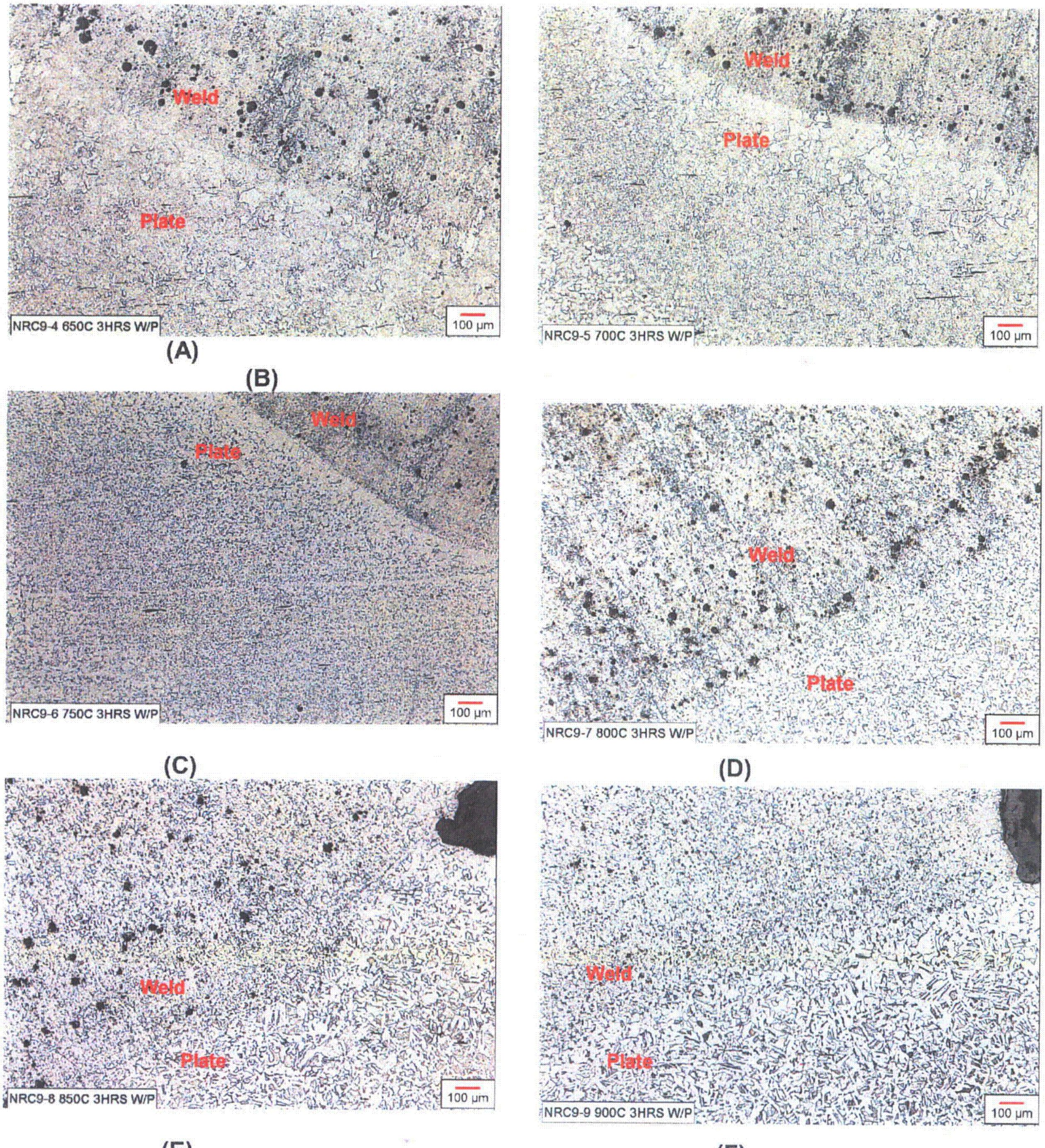
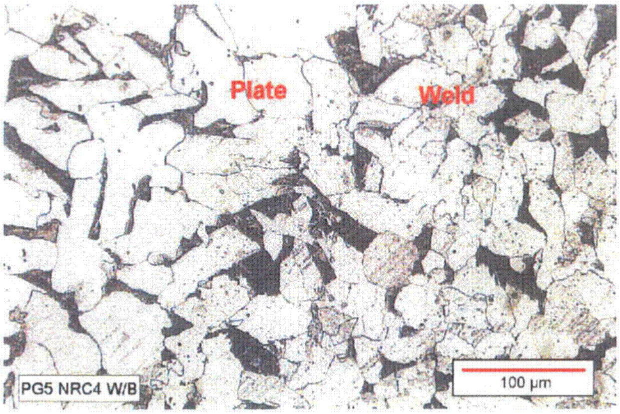
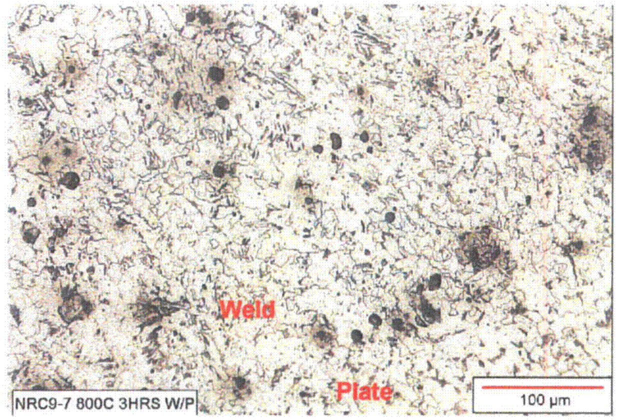


Figure 3-19. Microstructure of Welds and Plate Sections on Specimens NRC 9-4 to NRC 9-9 After Thermal Exposure for 3 Hours at Temperatures of 650 to 900 °C [1,202 to 1,652 °F]. (A) NRC 9-4, 650 °C [1,202 °F]; (B) NRC 9-5, 700 °C [1,292 °F]; (C) NRC 9-6, 750 °C [1,382 °F]; (D) NRC 9-7, 800 °C [1,472 °F]; (E) NRC 9-4 to NRC 9-9 After Thermal Exposure for 3 Hours at Temperatures of 650 to 900 °C [1,202 to 1,652 °F]; and (F) NRC 9-9, 900 °C [1,652 °F].



(A)



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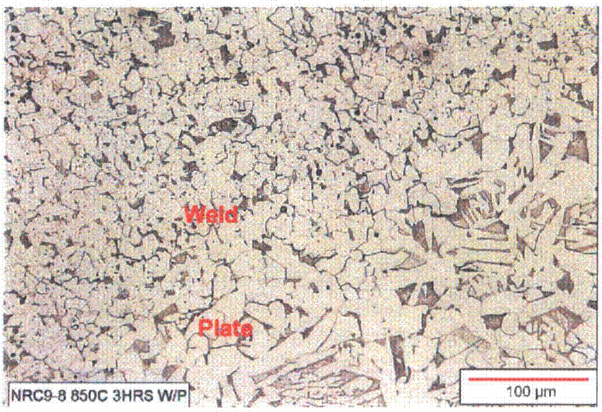

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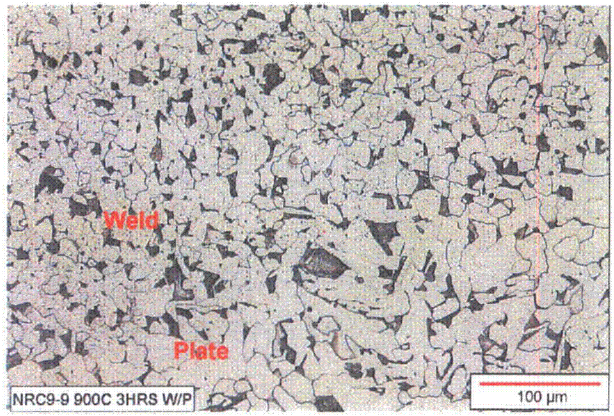


(D)

Figure 3-20. (A) Microstructure of Sample NRC 4 and the Microstructure of Welds and Plate Sections on Specimens NRC 9-7 to NRC 9-9 After Thermal Exposure for 3 Hours at Temperatures of 800 to 900 °C [1,472 to 1,652 °F]. (B) NRC 9-7, 800 °C [1,472 °F]; (C) NRC 9-8, 850 °C [1,562 °F]; and (D) NRC 9-9, 900 °C [1,652 °F]. The Amount of Pearlite and Ferrite in the Weld Increases With Temperature. At 900 °C [1,652 °F], the Microstructure of the Weld Appears To Be Similar to the Microstructure of the Plate.

Specimens from NRC 9 were exposed under isothermal conditions in a laboratory oven. The exposure temperature was measured and recorded. After the 2-hour isothermal exposure, the oven temperature was gradually reduced to a temperature of 700 °C [1,292 °F] and then allowed to slowly cool after the oven was turned off. After exposure, the specimens were placed in metallurgical mounts, polished, and etched to reveal the microstructure. Examination of the microstructure was conducted using a metallurgical microscope at magnifications from 50× to 1,000×. The grain size of the specimens was determined using the comparison method described in ASTM E112 (ASTM International, 2008a) either using templates or an optical reticle with an Olympus PME3 metallurgical microscope.

The conditions of exposure and the resulting grain size are shown in Table 3-4. For the as-received condition of NRC 9, the grain size was ASTM 8. For NRC 3, the initial grain size of the as-collected specimen was much larger and measured to be between ASTM 4 and 5. Microstructures of the specimens are shown in Figure 3-21.

An important variable that influences the microstructure was the cooling rate of the material. For low carbon steels such as ASTM A7, the microstructure should be a mixture of ferrite and pearlite up to about 727 °C [1,340 °F]. Between 727 and 850 °C [1,340 and 1,562 °F], the microstructure is expected to be a mixture of ferrite and austenite. Above 850 °C [1,562 °F], the microstructure should be completely austenitic. While the grain size is a function of temperature, upon cooling, the microstructure transitions from either austenite or a mixture of austenite and ferrite back to ferrite and pearlite (American Society for Metals, 1978a,c). Rapid cooling will result in smaller grain sizes. Because the cooling rate for the structure was not known, the thermally exposed specimens were cooled slowly at 50 °C/hour [122 °F/hour] through the phase transformation regions from 900 to 700 °C [1,652 to 1,292 °F]. Specific tests on the effect of the cooling rate on the microstructure were not conducted; however, the effect of a fast cooling rate was apparent in the comparison of the microstructures in Figure 3-22. The as-received Samples for NRC 3 and NRC 9 are shown for comparison. Specimen sections from both NRC 3 and NRC 9 that were thermally exposed at temperatures of 900 and 1,000 °C [1,652 and 1,832 °F] and cooled in ambient laboratory air are also shown in Figure 3-22. This rapid cooling rate did not allow for sufficient time for grain growth after phase transformation. As a result, the final microstructure of the laboratory-air-cooled specimens and the as-received condition of Sample NRC 9 was similar and has a much smaller grain size compared to the slow-cooled specimens. A plot of the grain size as a function of thermal exposure conditions is shown in Figure 3-23.

Although the cooling rate for the actual structure was not known, it is expected that the cooling rate was slow owing to the nature of the fire and the overpass collapse. The large size of the girders, limited use of water on the fire, and the insulating effects of the concrete around the girders would be expected to prevent rapid cooling. Based on the grain size of the thermally exposed and slow-cooled specimens from NRC 9, a grain size between 4 and 5 is expected at a temperature of approximately 980 to 1,020 °C [1,796 to 1,868 °F].

In addition to the evaluation of the grain size, decarburization may also occur at elevated temperatures as a result of the reaction of oxygen with the carbon in the steel. The extent of decarburization may be dependent on several factors including the temperature of exposure and the exposure atmosphere because the presence of oxygen is necessary to react with the carbon in the steel. Characterization of the decarburized region on the as-collected and thermally exposed samples is also included in Table 3-4.

Table 3-4. Grain Size for As-Received and Thermally Exposed Samples				
Sample	**Thermal Exposure Conditions**	**Cooling Procedure**	**ASTM Grain Size**	**Decarburized Zone µm [mils]**
NRC 3-1	None (as received)	None (as received)	4–5	0 [0]
NRC 3-2	850 °C [1,562 °F] for 3 hours	Lab air cooled	8	Not measured
NRC 3-3	900 °C [1,652 °F] for 3 hours	Lab air cooled	8	Not measured
NRC 3-7	1,000 °C [1,832 °F] for 3 hours	Lab air cooled	8	Not measured
NRC 9-13	None (as received)	None (as received)	8	0 [0]
NRC 9-14	850 °C [1,562 °F] for 3 hours	Lab air cooled	8	Not measured
NRC 9-15	900 °C [1,652 °F] for 3 hours	Lab air cooled	8	75 [3]
NRC 9-19	1,000 °C [1,832 °F] for 3 hours	Lab air cooled	8	170 [6.7]
NRC 9-27	700 °C [1,292 °F] for 2 hours	Oven cooled to room temperature	8	Not measured
NRC 9-28	800 °C [1,492 °F] for 2 hours	Cooled 50 °C [122 °F]/hr to 700 °C [1,292 °F]; oven cooled to room temperature	8	100 [4]
NRC 9-29	900 °C [1,652 °F] for 2 hours	Cooled 50 °C [122 °F]/hr to 700 °C [1,292 °F]; oven cooled to room temperature	5	100 [4]
NRC 9-30	1,000 °C [1,832 °F] for 2 hours	Cooled to 900 °C [1,652 °F] in 1 hour; cooled 50 °C [122 °F]/hr to 700 °C [1,292 °F]; oven cooled to room temperature	4	180 [7]
NRC 9-31	1,100 °C [2,012 °F] for 2 hours	Cooled to 900 °C [1,652 °F] in 1 hour; cooled 50 °C [122 °F]/hr to 700 °C [1,292 °F]; oven cooled to room temperature	4	500 [19.7]
NRC 9-32	1,200 °C [2,012 °F] for 2 hours	Cooled to 900 °C [1,652 °F] in 1 hour; cooled 50 °C [122 °F]/hr to 700 °C [1,292 °F]; oven cooled to room temperature	3	1,350 [53.1]

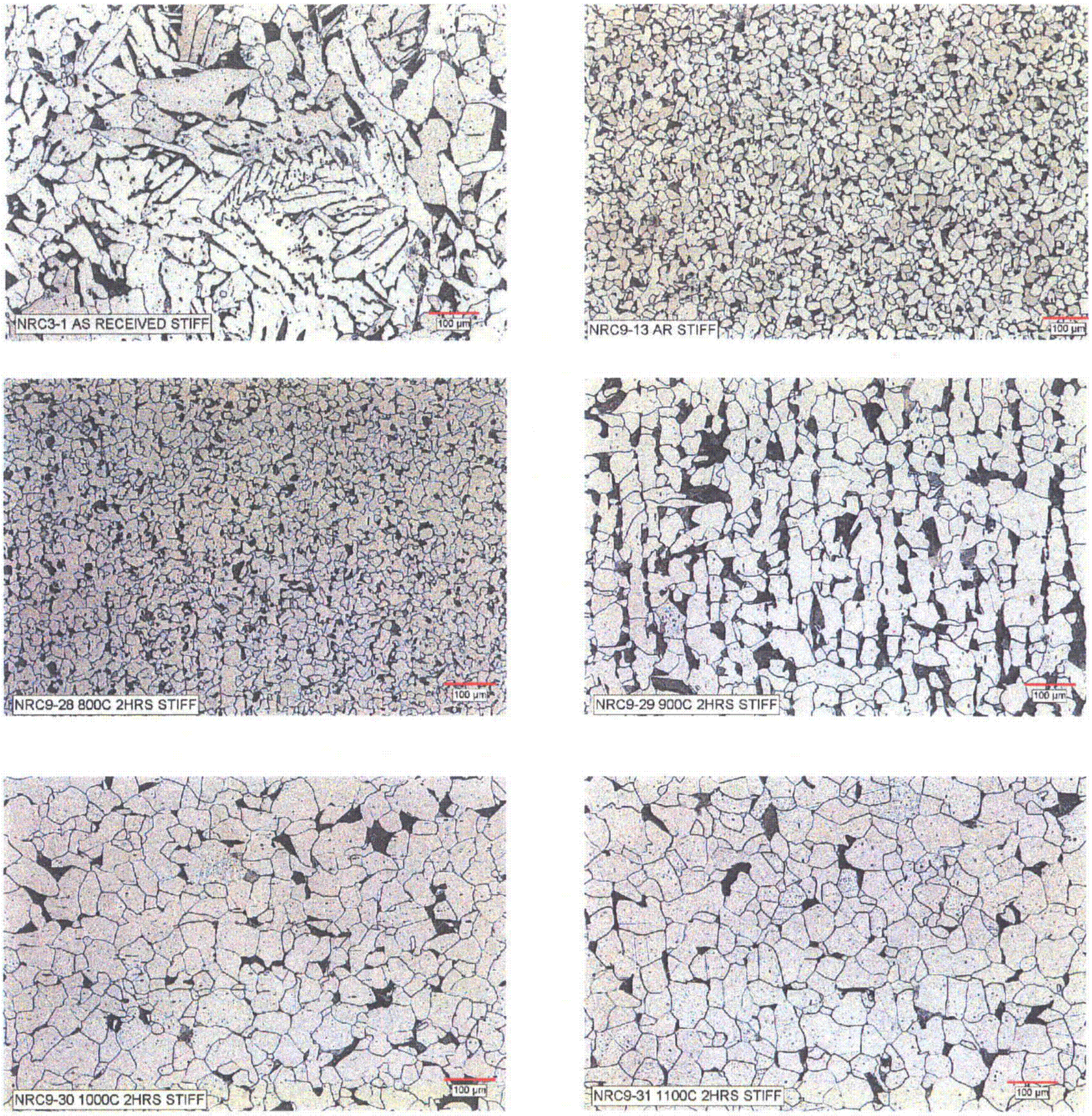


Figure 3-21. Microstructure of As-Received NRC 3, As-Received NRC 9, and NRC 9 Specimens Slow Cooled After Thermal Exposure at 800; 900; 1,000; and 1,100 °C [1,492; 1,652; 1,832; and 2,012 °F]

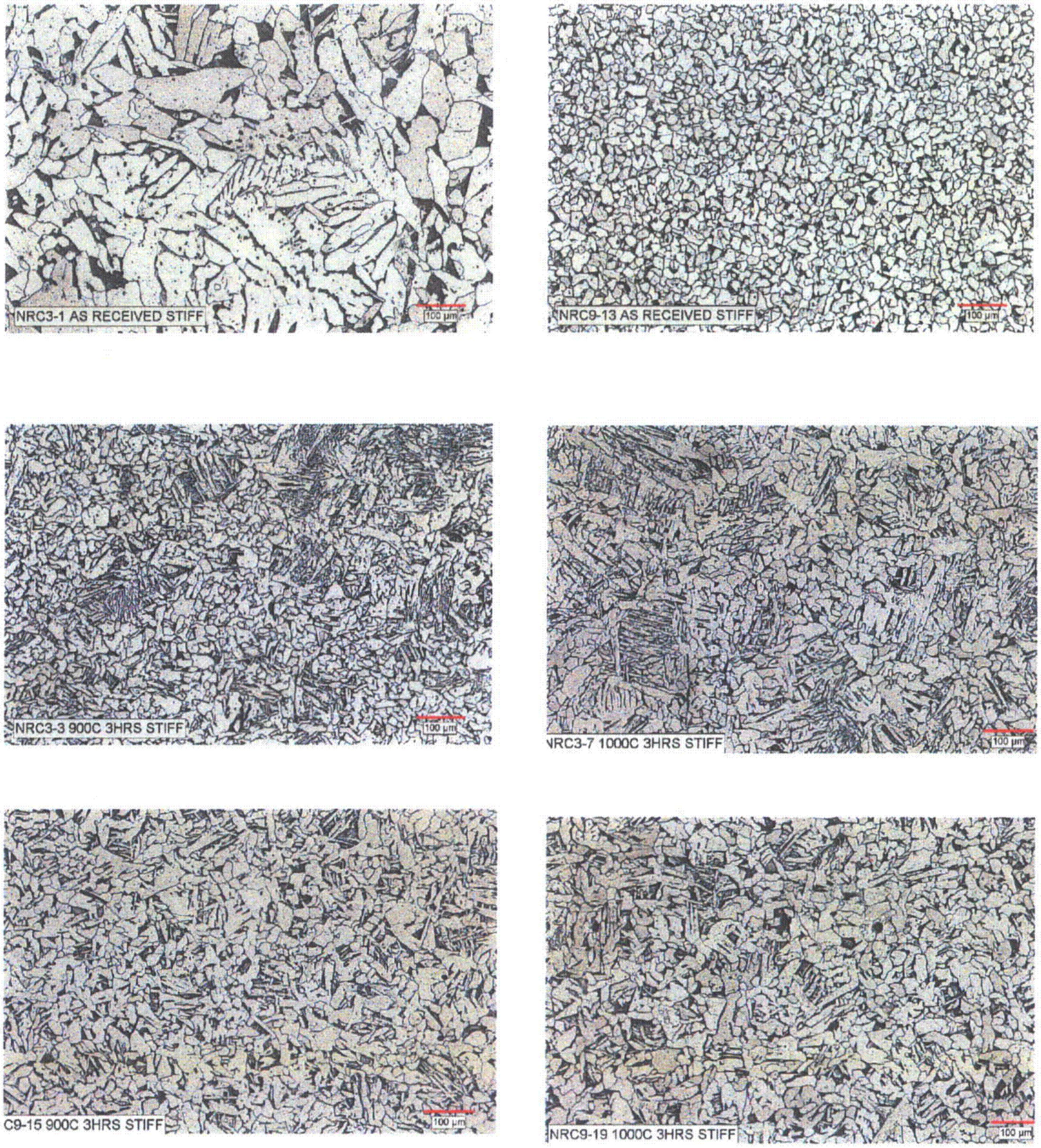


Figure 3-22. Microstructure of As-Received NRC 3, As-Received NRC 9, and NRC 9 Specimens Air Cooled After Thermal Exposure at 700; 800; 900; and 1,000 °C [1,292; 1,492; 1,652; and 1,832 °F]

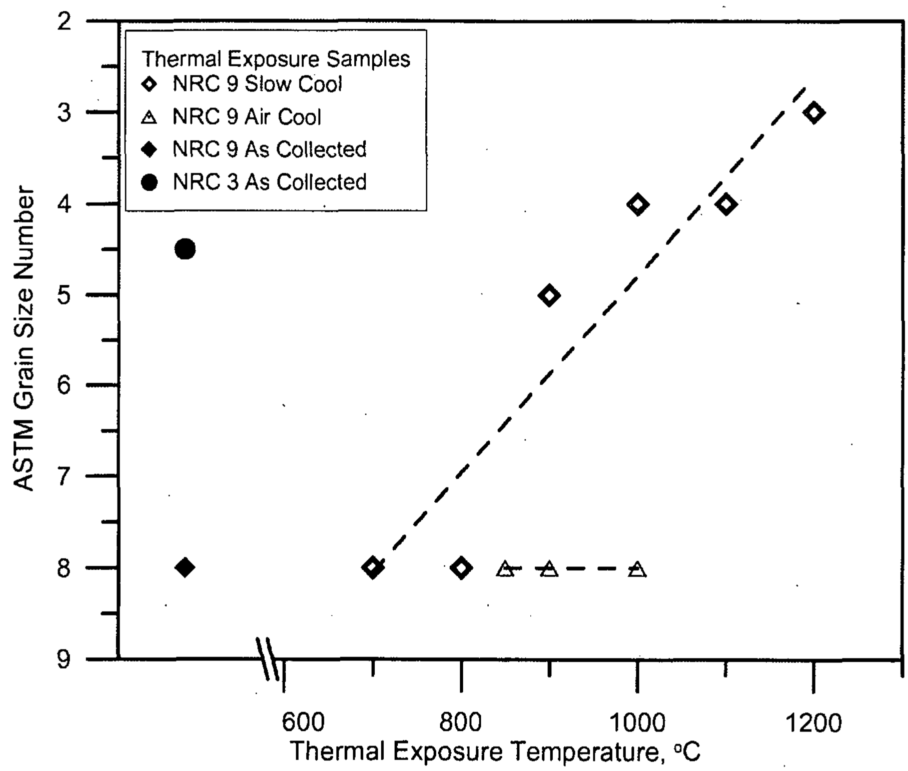


Figure 3-23. ASTM Grain Size as a Function of Thermal Exposure Conditions

Photographs of the edges of the specimens showing the decarburized regions (light-colored regions) are shown in Figure 3-24. The as-collected sample had no appreciable decarburized zone. Some decarburization was observed after exposures above 800 °C [1,492 °F]. Samples exposed at 1,000 °C [2,012 °F] had a slightly larger decarburized zone. At 1,100 and 1,200 °C [2,012 and 2,192 °F], the decarburized zone increased significantly and was 10× larger after the exposure at 1,200 °C [2,192 °F] compared to 900 °C [1,652 °F].

Note that the environment inside the laboratory oven where the exposures were conducted was likely to be significantly different from the fire exposure involving a hydrocarbon fuel fire. The environment resulting from the combustion of a hydrocarbon fuel is expected to be depleted in oxygen and contain possibly both soot and incomplete combustion products that may alter the kinetics of decarburization. Because of this uncertainty, an exposure temperature based on decarburization cannot be estimated.

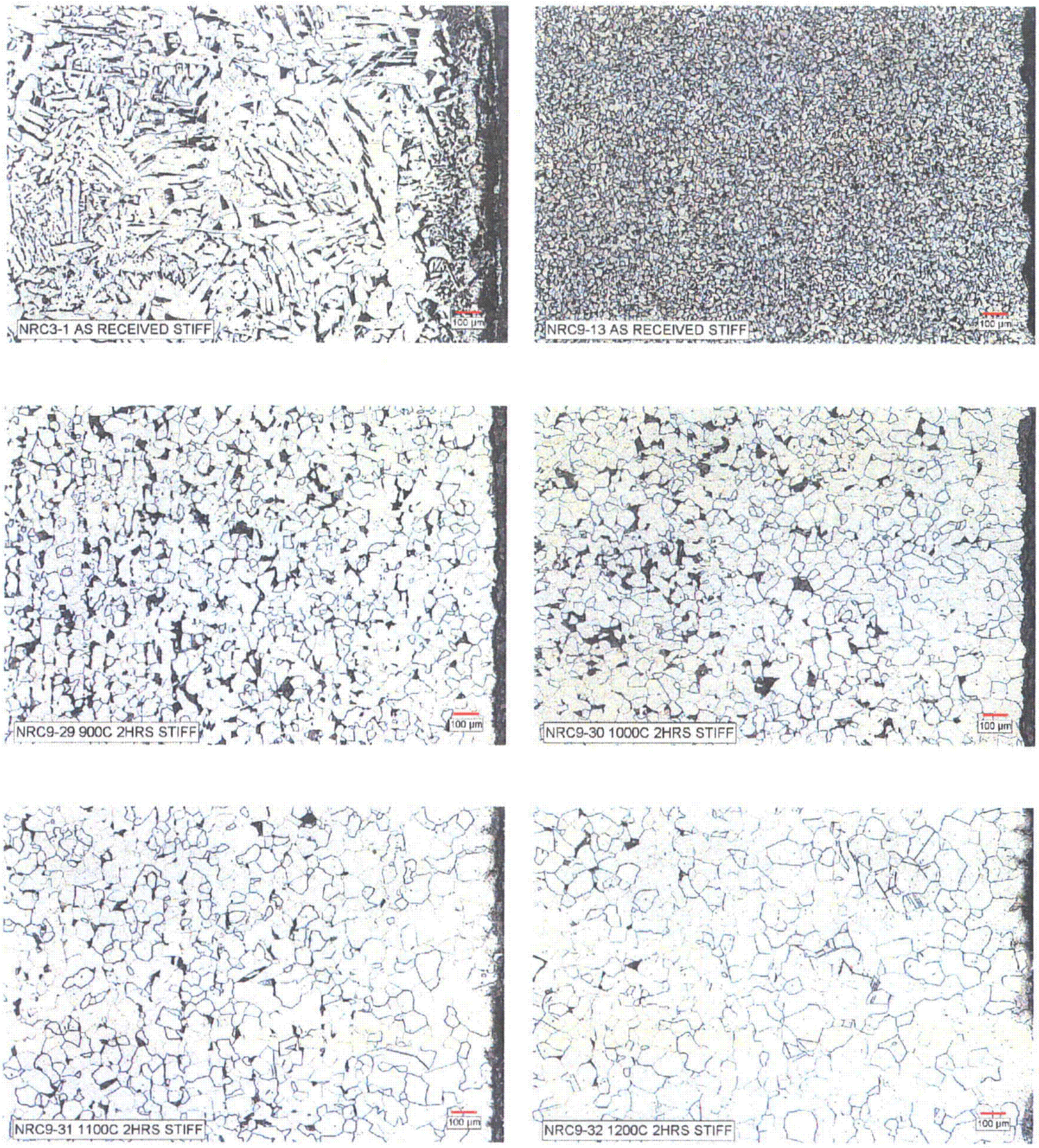


Figure 3-24. Microstructure of the As-Received NRC 3 Sample, As-Received a Sample, NRC 9 Samples Slow Cooled After Thermal Exposure at 900; 1,000; 1,100; and 1,200 °C [1,652; 1,832; 2,012; 2,192 °F]. The Edge of the Samples Is Uniformly Positioned on the Right Edge of Each Photograph (American Society for Metals, 1978b).

4 ANALYSIS OF THE TANKER TRUCK SAMPLES

On March 19, 2008, staff from SwRI and the NRC inspected the tanker truck involved in the accident and collected selected samples for analysis. The truck involved in the single vehicle crash was a model year 2001 Freightliner 3-axle tank truck with a model year 2000 Weld-It 2-axle pull tank trailer. An overall view of the truck remains is shown in Figure 4-1. A variety of materials were collected from the truck remains including glass, aluminum alloys, steel, copper, brass, and stainless steel. Descriptions of the samples are shown in Table 4-1.

Figure 4-1. Overall View of the Tanker Truck After Recovery From the Accident Site

Table 4-1. Description of Collected Tanker Truck Samples

Sample Identification	Description
Truck Sample 1	Front tire cord from left side of vehicle
Truck Sample 2	Tire cord from number 5 axle on right side of vehicle
Truck Sample 3	Brake pad located near rear of vehicle
Truck Sample 4	Rim component sample from number 5 axle
Truck Sample 5	Spring located near rear of truck
Truck Sample 6	Large bolts (3) located on frame and near engine
Truck Sample 7	Grade 5 bolt located on frame
Truck Sample 8	Copper wire ground strap located on frame
Truck Sample 9	Copper wire battery cable
Truck Sample 10	Copper wire electrical system wiring located on frame
Truck Sample 11	Fitting with brass located on engine
Truck Sample 12	Bolt from engine passenger side with steel wire and melted aluminum
Truck Sample 13	Aluminum screen from radiator
Truck Sample 14	Aluminum rim from dual wheel axle
Truck Sample 15	Aluminum tank section
Truck Sample 16	Glass mirror from passenger side
Truck Sample 17	Stainless steel mirror support bracket

4.1 Aluminum Alloys

Aluminum samples collected included parts of the rims, part of the tank section, a screen from the engine radiator, and a section of the gas tank. Although significant portions of these samples remained intact and, as such, aided component identification, all of the aluminum alloy samples also displayed signs of partial or localized melting. A portion of the selected samples was sectioned, polished, and analyzed using a scanning electron microscope (Amray model 1642T) with an energy dispersive spectrometer (Kevex) to determine composition and melting point (Table 4-2). Because the alloys contain several alloying elements, the determination of the melting point was estimated using binary phase diagrams for the major elements. Most of the alloys contain multiple phases and are not eutectic compositions; each material has a solidus temperature, where a liquid phase is in equilibrium with a solid phase, and a liquidus temperature above which the alloy is in a liquid phase (i.e., no solid phase exists). Based on the appearance of the specimens, it is likely that at least some portions of the materials reached the liquidus temperature. Photographs of the several samples collected are shown in Figure 4-2.

Truck Sample 12 was unique because it had multiple materials including a steel bolt, a strand of steel wire, and an aluminum alloy that may have been from a component or bracket that was attached to the engine. The composition of the aluminum sample is included in Table 4-2. Figure 4-2 shows that only the aluminum alloy melted. Similarly, Truck Sample 10, originally located on the truck frame, contained copper wire covered with aluminum that was melted and resolidified. The aluminum composition was determined to contain a significant amount of copper and thus has a low liquidus temperature of 590 °C [1,094 °F]. As shown in Figure 4-2, the small gauge copper wire showed no indication of melting.

Based on the compositional analysis of the aluminum alloys, the liquidus temperature ranged from 590 °C [1,094 °F] to 720 °C [1,330 °F]. Melting was clearly apparent in all samples, indicating the temperature in some locations reached values of 720 °C [1,330 °F]. Because very large portions of the thin-walled tank were not melted, the temperature in these areas was below 570 °C [1,058 °F].

4.2 Copper Alloys

Copper used for electrical system wiring was found throughout the remains of the truck. Large sections of copper wiring that were likely the battery cables were observed in the engine compartment. Copper ground straps were found on the frame of the tanker truck. Smaller gauge wiring that would be expected for signal and marker lights was also found in many locations on the tanker truck frame. None of the copper wires found displayed signs of melting. A brass fitting was also found attached to the engine block. The location of this sample was located approximately 10 cm [4 in] from Truck Sample 12 that had aluminum which melted during the fire. The brass sample did not display indications of melting. Photographs of the copper-based alloy samples are shown in Figure 4-3.

Table 4-2. Compositional Analysis and Estimated Solidus and Liquidus Temperatures for Aluminum Alloys Obtained From the Tanker Truck									
Truck Sample	Composition, Weight Percent							Estimated Solidus	Estimated Liquidus
	Al	Si	Cu	Zn	Mg	Fe	Mn		
4	73	22	2.6	1.5	—	0.7	—	577 °C [1,071 °F]	720 °C [1,330 °F]
14	97.5	0.2	—	—	2.3	—	—	610 °C [1,130 °F]	650 °C [1,200 °F]
15	93.4	0.3	—	—	5.3	0.4	0.6	570 °C [1,058 °F]	640 °C [1,184 °F]
12	74.8	14.4	3.0	2	—	4	1.1	577 °C [1,071 °F]	600 °C [1,112 °F]
10	68.1	3.9	22.7	3.5	—	0.6	—	548 °C [1,018 °F]	590 °C [1,094 °F]

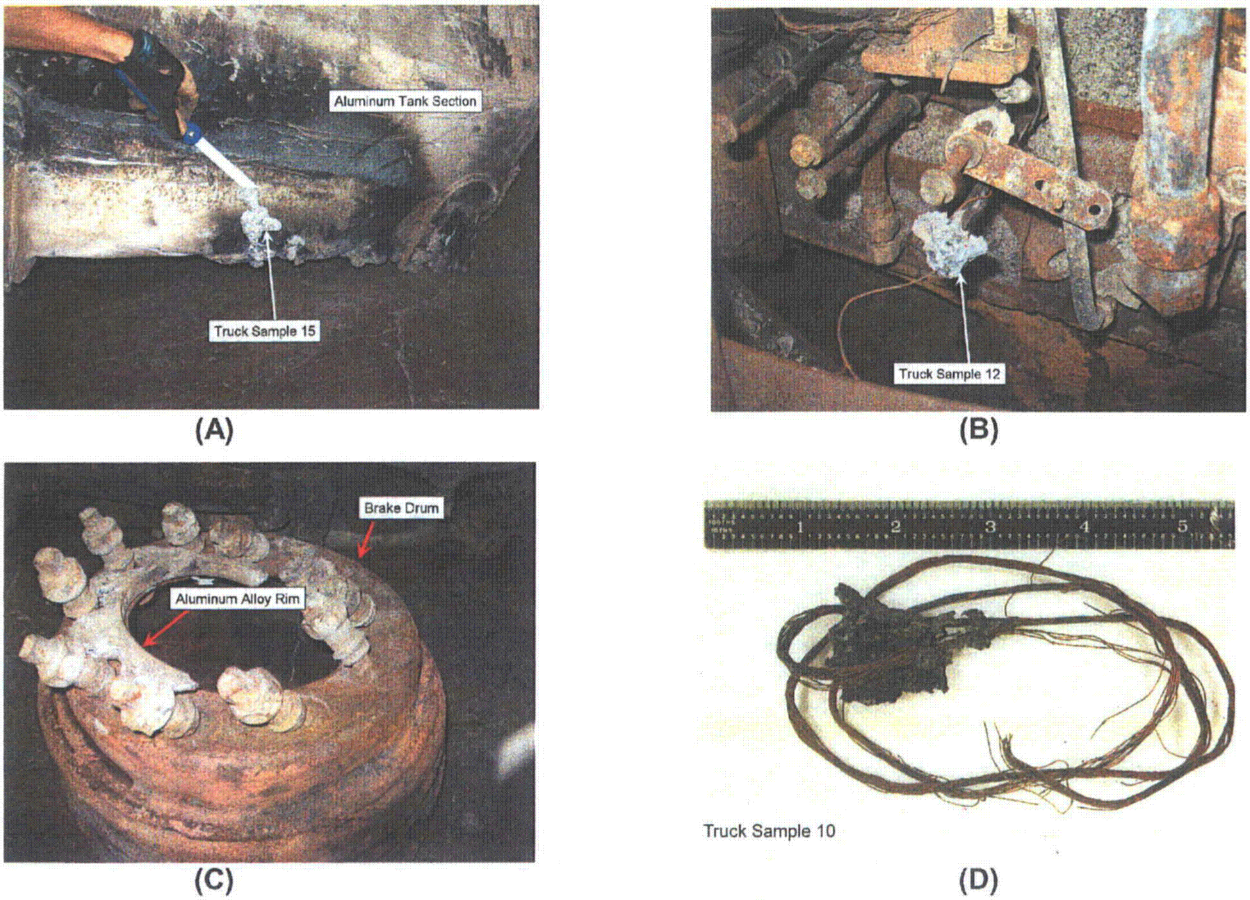
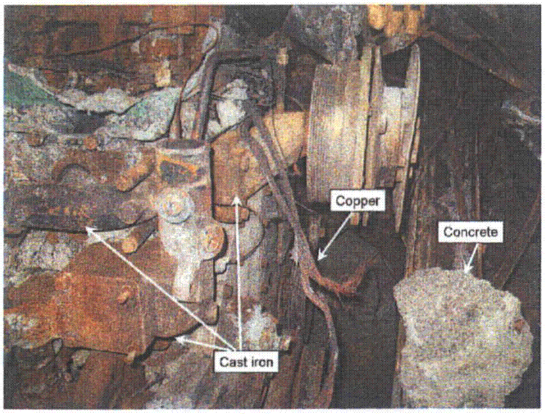
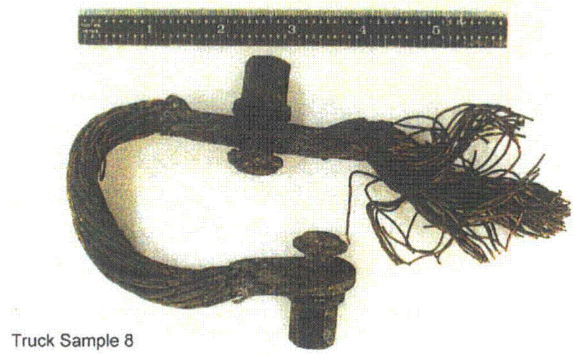


Figure 4-2. Photographs of the Collected Aluminum Alloy Samples. (A) Truck Sample 12 Collected From the Passenger Side of the Engine, (B) Truck Sample 15 Is a Portion of the Aluminum Tank That Had Melted, (C) Truck Sample 14 Is the Remains of a Partially Melted Aluminum Wheel, and (D) Truck Sample 10 Is a Section of Copper Wire Partially Covered With Aluminum.



(A)



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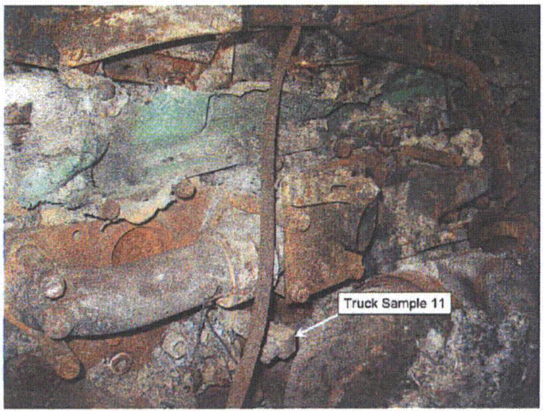


(C)

(D)

Figure 4-3. Photographs of Copper Alloy Materials Collected From the Tanker Truck. (A) Battery Cable in the Engine Compartment, (B) Ground Strap Found on Tanker Truck Frame, (C) and (D) Brass Fitting Located on Passenger Side of the Engine.

Collected samples were prepared using standard metallurgical practices and analyzed to determine composition using a scanning electron microscope with an energy dispersive spectrometer. The composition of the materials is included in Table 4-3.As expected, the copper wiring was pure copper, consistent with the compositional specifications for copper wire (ASTM International 2008b,c). Some silicon contamination was noted on Truck Sample 11, which is believed to be from the pulverized concrete that covered the truck after the overpass collapse. The melting point of pure copper is 1,084 °C [1,983 °F]. As copper wiring was found on many locations along the truck frame, it is apparent that near the truck, the temperature during the fire did not exceed the melting point for copper. The solidus temperature for the brass fitting is 903 °C [1,657 °F], and the liquidus temperature is 930 °C [1,706 °F] based on the copper and zinc concentration. Small amounts of lead are typically added to improve machining but are not expected to significantly alter the solidus or liquidus temperature. As the brass fitting showed no indications of melting the temperature near the engine compartment is estimated to be less than 903 °C [1,657 °F].

Table 4-3. Composition and Melting Point of the Recovered Copper Alloy Samples							
Truck Sample	Composition, Weight Percent					Solidus Temperature	Liquidus Temperature
	Cu	Zn	Pb	Fe	Si		
8	100	—	—	—	—	1,084 °C [1,983 °F]	1,084°C [1,983 °F]
9	100	—	—	—	—	1,084 °C [1,983 °F]	1,084 °C [1,983 °F]
10	99.8	—	—	—	0.18	1,084 °C [1,983 °F]	1,084 °C [1,983 °F]
11	61.8	35.7	2.24	0.23	—	903 °C [1,657 °F]	930 °C [1,706 °F]

4.3 Iron-Based Alloys

The majority of the materials in the tanker truck were iron-based alloys. These include mainly steel and cast irons but also some stainless steel. Most of the cast iron materials were large sections such as the engine block and the transmission case and were not collected for analysis. Note, however, that cast iron has a lower melting point than carbon steels. Depending on the type, cast irons melt at temperatures in the range of 1,177 to 1,260 °C [2,150 to 2,300 °F] (McIntyre and Ashbaugh, 1996; American Society for Metals, 1978c). No indication of cast iron melting was observed.

A large number of steel materials were observed including structural components such as the vehicle frame, suspension components, engine components, and hardware. Pure iron melts at 1,535 °C [2,795 °F]. The melting temperature is dependent on alloy composition, but carbon steels have melting temperatures of approximately 1,516 °C [2,760 °F]. Inspection of the truck revealed many small steel components that were easily recognized, such as springs, fasteners, studs, and tire cords, that showed no signs of melting. Recovered tire cords were >99 percent iron, with small concentrations of manganese and silicon, along with carbon that cannot be analyzed using an energy dispersive spectrometer. The melting point of the tire cord would be expected to be similar to that for low carbon steel.

4.3.1 Truck Frame

Onsite observation of the some steel components such as the vehicle frame revealed the formation of oxide scale. A photograph of the scaling is shown in Figure 4-4. Scaling temperatures for steel are dependent on steel composition. Carbon steels are expected to scale at a temperature of 482 °C [900 °F], whereas scaling of 5Cr-0.5Mo will occur at 621 °C [1,150 °F] (McIntyre and Ashbaugh, 1996). Although the composition of the truck frame was not analyzed, it is expected to be a carbon steel with a scaling temperature of less than 500 °C [930 °F].

4.3.2 Stainless Steel Bracket

A stainless steel mirror bracket (Figure 4-5) was determined to be Fe–19Cr–9Ni, which was consistent with the composition of Type 304 stainless steel that has a melting temperature of 1,454 °C [2,650 °F]. The bracket suffered mechanical damage, however, no indication of melting was observed.

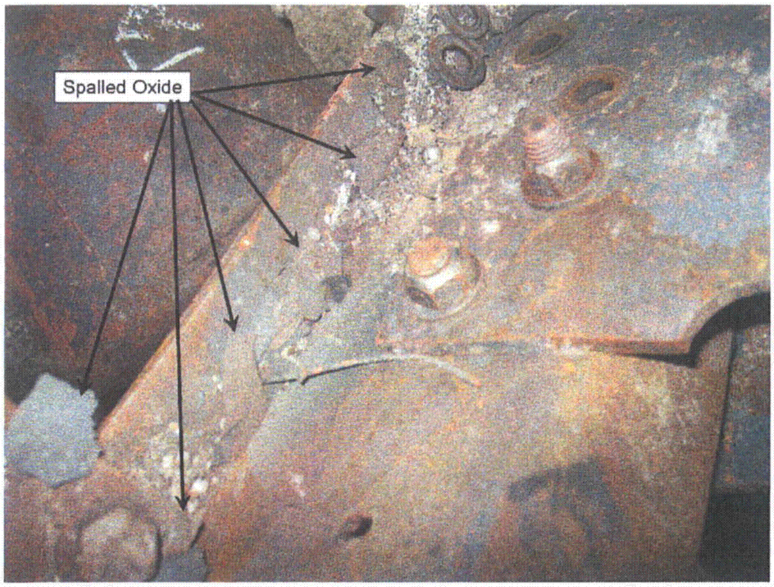
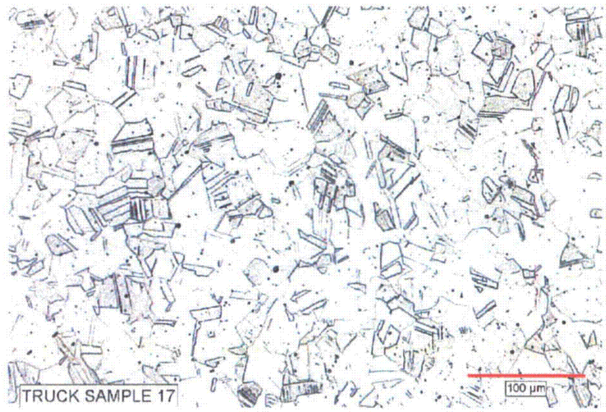


Figure 4-4. Spalled Oxide From the Carbon Steel Frame



(A) (B)

Figure 4-5. (A) Photograph of the Stainless Steel Support Bracket and the Material, (B) Microstructure and the Microstructure of the Stainless Steel Material

A sample of this material was sectioned, polished, and etched to reveal the microstructure. Sensitization of 300 series stainless steels is known to occur at temperatures above approximately 540 °C [1,000 °F]. The microstructure of the specimens is also shown in Figure 4-5. Electrolytic etching of the sample was conducted in an oxalic acid solution. The grain boundaries were typical of a nonsensitized stainless steel and did not display the typical "ditched" appearance of a chromium-depleted, sensitized microstructure. The absence of sensitization suggests that the stainless steel material was not exposed to temperatures at or above 540 °C [1,000 °F].

4.3.3 Steel Fasteners

Truck Sample 6 was collected from the frame of the tanker truck and was likely originally located under the tank. The bolts were stamped with markings consistent with SAE Grade 8 (SAE International, 1999). Grade 8 hardware specifications require a minimum 130,000 psi [890 MPa] yield strength; 150,000 psi [1035 MPa] tensile strength; and a core Rockwell hardness of C33 to C39 (SAE International, 1999; ASTM International, 2008d). The bolt was sectioned, and the hardness was measured using a Wilson Rockwell Series 500 Model B544T hardness tester. The as-collected sample had a core hardness of B93.8±1.1 (approximately Rockwell C16). The as-collected hardness was well below specification and corresponds to a material with a tensile strength of approximately 98,000 psi [675 MPa]. Although a control specimen of the hardware that was not exposed to the fire was not available for comparison, the Grade 8 hardware was likely heated to well above the minimum tempering temperature resulting in a reduction in strength and hardness.

To estimate the temperature that the bolt was exposed to during the fire, several new Grade 8 bolts were obtained and characterized. All of the unused bolts, which had vendor stamps JY, TY, and WT, were within specifications and had hardness values between Rockwell C33 and C39. Compositional analysis of the bolts was conducted using a scanning electron microscope with a energy dispersive spectrometer. This analysis was limited to elements with an atomic number greater than sodium, so the concentration of carbon was not determined. The analysis was conducted to verify that the composition of all the hardware was similar (with the exception of the carbon content) and was not used to determine whether the hardware met compositional specifications. The results of the analyses are shown in Table 4-4. Note that the composition of the hardware will have an effect on hardness and strength after thermal exposure. In general, the addition of manganese, chromium, and molybdenum increases hardenability, and steels with additions of these alloying elements usually require higher tempering temperatures (American Society for Metals, 1978b). The compositional analyses shown in Table 4-4 indicate that one of the bolts collected from the truck (Truck Sample 6) is most similar to bolt WT. Truck Sample 6 has slightly more manganese and molybdenum whereas Bolt WT has higher chromium. Although slight differences were noted, the hardenability of all the bolts was expected to be similar.

The bolt samples were sectioned and exposed to temperatures ranging from 400 to 800 °C [752 to 1,472 °F] for 2 hours. Samples exposed at temperatures above 400 °C [752 °F] were oven cooled to 400 °C [752 °F] prior to removal from the oven and air cooled to room temperature. The hardness of the samples was measured after oxide scale removal.

Table 4-4. Composition of Steel Bolts

Sample	Fe	Mn	Cr	Mo	Si	Al
Truck Sample 6	98.01	0.85	0.30	0.38	0.46	—
Bolt WT	97.75	0.71	0.98	0.28	0.27	—
Bolt TY	97.33	0.77	1.04	0.41	0.37	0.08
Bolt JH	97.87	0.73	1.08	—	0.32	—

Hardness scales can be converted, but converted values are subject to error at the low and high end of a particular scale. Although conversions between the B and C scales is generally not recommended owing to the reduced accuracy in the conversion (ASTM International, 2008e), the measured Rockwell B scale values were converted to the Rockwell C scale to allow comparison over the entire range of thermal exposures. Measured hardness values are shown in Figure 4-6. The effect of temperature on hardness was apparent for the new Grade 8 bolts. Although all of the new bolts had slight compositional differences, the hardness as a function of temperature was similar. At temperatures below 500 °C [932 °F], the hardness of the Grade 8 bolts was not significantly altered. At higher temperatures, the hardness was a function of exposure temperature. The as-collected hardness of Truck Sample 6 was Rockwell B93.8 ± 1.1 or equivalently Rockwell C16. Data from the bolts JH, TY, and WT suggest an exposure of approximately 720 °C [1,328 °F] for 2 hours would result in a similar reduction in hardness comparable to the as-collected condition of Truck Sample 6. At 800 °C [1,472 °F], the hardness of the bolts was less than Rockwell B82 or equivalently Rockwell C5. Figure 4-6 also shows the effect of thermal exposure on sections of the Truck Sample 6. Most significant was the substantial decrease in hardness observed after the exposure at 800 °C [1,472 °F]. Based on the data shown in Figure 4-6, it was estimated that Truck Sample 6 was exposed to a temperature in the range of 700 to 750 °C [1,292 to 1,382 °F].

The microstructure for several of the bolt samples is shown in Figure 4-7. The microstructure of the bolt WT consists of tempered martensite in the as-received condition that was expected with the hardness and minimum tensile strength requirements of SAE Grade 8 hardware. Truck Sample 6 had a microstructure that contained spheriodial pearlite, which is expected in alloy steels at temperatures at or above 700 °C [1,292 °F] followed by slow cooling (American Society for Metals, 1978b). Thermally treated samples of bolt WT did not have pearlite at temperatures below 700 °C [1,292 °F]. After thermal exposure at 800 °C [1,492 °F], the microstructure of bolt WT had significant amounts of pearlite. The observed changes in the microstructure as a function of thermal exposure temperature were in line with the hardness data and suggest that Truck Sample 6 was exposed to a temperature above 700 °C [1,292 °F] but less than 800 °C [1,492 °F].

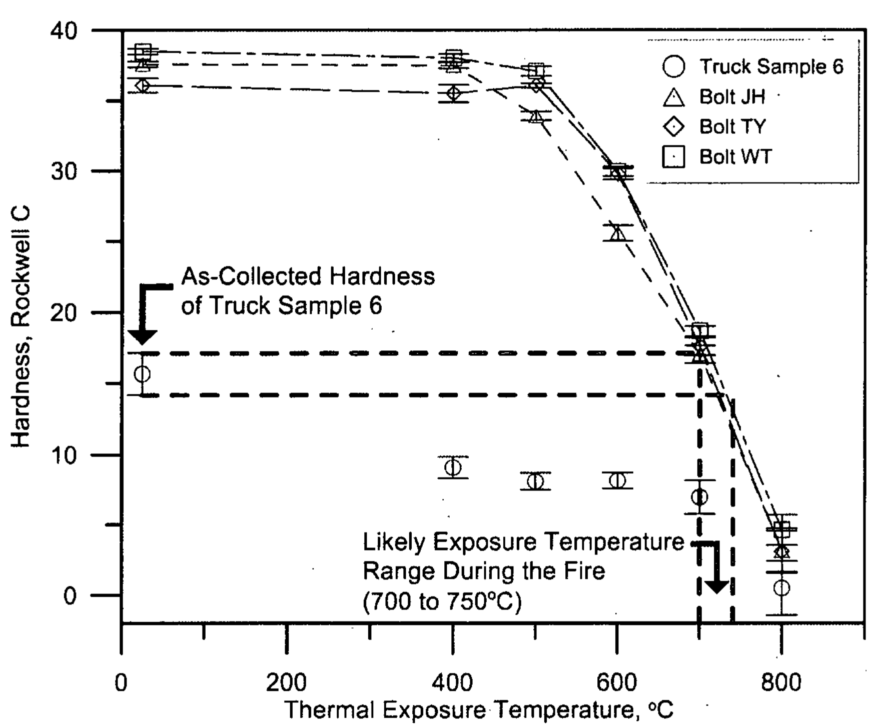
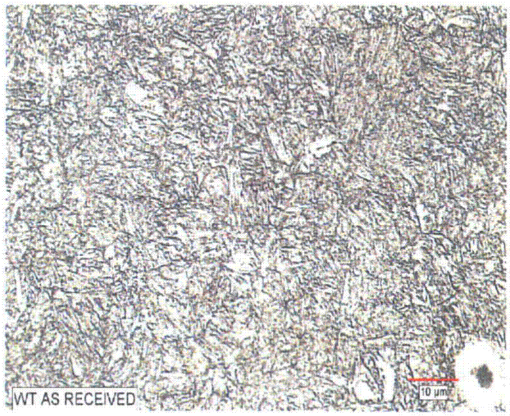
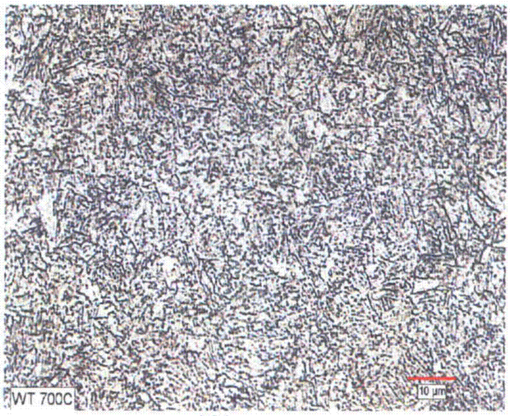


Figure 4-6. Effect of Exposure Temperature on the Hardness of Truck Sample 6 and Commercially Available Grade 8 Bolts

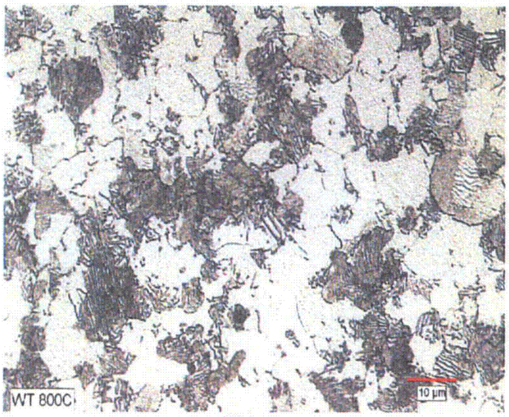
(A)



(B)



(C)



(D)

Figure 4-7. Microstructure of (A) Truck Sample 6 Showing Tempered Martensite (Light Gray) With Pearlite Precipitates (Dark Gray); (B) As-Received Sample of Bolt WT Showing Only Tempered Martensite; (C) Bolt WT After Thermal Exposure at 700 °C [1,292 °F] for 2 Hours Showing Tempered Martensite With Small Pearlite Precipitation, and (D) Bolt WT After Thermal Exposure at 800 °C [1,492 °F] for 2 Hours Showing Extensive Pearlite Precipitation

5 SUMMARY AND CONCLUSIONS

Temperatures during the April 29, 2007, MacArthur Maze fire were estimated after collecting and analyzing samples from the overpass structure and the tanker truck. Phase transformations in the welds of the steel girders, changes to the grain size of the girder steel, and damage to paint on the steel girders were used to estimate the temperature of the Interstate (I)-580 overpass structure. The melting point of and metallurgical changes to the tanker truck samples were used to estimate temperatures near the truck. In addition to the analysis of the collected samples in the as-received condition, a limited number of thermal exposures were conducted to determine the effect of temperature on the collected samples.

At the hottest locations, the temperatures witnessed by the steel girders were above 850 °C [1,562 °F] based on the microstructure of welds obtained from Plate Girder 5 (Samples NRC 3 and NRC 4), which was believed to be located between Bent 18 and Bent 19 and in contact with the I-880 roadway after the collapse. The temperature distribution cannot be determined owing to the limited number of samples available and the uncertainty of the original sample location. Near the Box Beam Cap at Bent 19 (Sample NRC 1S), only partial transformation of the weld microstructure was observed, suggesting a maximum temperature of 800 °C [1,472 °F]. At Bent 18 or Bent 20, no alteration of the welds was observed. The grain size of the base metal of Plate Girder 5 was measured and compared to the grain size of samples from Plate Girder 12 that were thermally exposed samples at temperatures from 700 to 1,200 °C [1,292 to 2,192 °F]. Based on the grain size comparison, Plate Girder 5 was estimated to have reached temperatures between approximately 980 and 1,020 °C [1,796 and 1,868 °F] during the fire.

Other evidence that may be used to estimate temperature includes the damage to paint used to protect the steel girders. Note that systematic tests of separate paint specimens to determine the temperature at which paint discoloration is expected were not conducted. Based on observations of specimens prepared for microstructural characterization, significant discoloration of the paint was observed at a temperature of 550°C [1,022°F]. Complete destruction of the paint was observed at a temperature of 700°C [1,292°F] for 3 hours. The observation that the paint on the girders near Bent 18 was still in the natural gray color is evidence that the temperature in this location was much cooler than the temperatures in the vicinity of the fire.

Materials collected from the tanker truck suggest that a significant range of temperatures was present near the truck. Spalling of the iron oxides on the truck frame indicates an exposure of at least 500 °C [932 °F]. Partial melting of aluminum alloys from the tanker truck indicates exposure temperatures of 590 to 720 °C [1,094 to 1,328 °F]. Hardness and microstructure of hardened steel fasteners suggest an exposure temperature between 700 and 750 °C [1,292 and 1,382 °F]. Several alloys were found that did not melt during the fire including brass, copper, and cast iron, which have melting points of 930, 1084, and >1,177 °C [1,706, 1,983, and >2,150 °F], respectively, indicating the exposure temperatures for these components was less than the melting temperature for these alloys.

Based on the samples collected and the results of thermal exposures, the temperature of the I-580 overpass is estimated to range from 850 °C [1,562 °F] to approximately 1,000 °C [1,832 °F]. Near the truck, the maximum exposure temperature is estimated to be at least 590 °C [1,094 °F] and less than 930 °C [1,706 °F]. Results obtained from the analysis of the overpass and truck samples are consistent with results obtained in the fire model developed for the MacArthur Maze accident, indicating the hottest gas temperatures during the fire were located above the I-880 roadway near the steel girders of the I-580 overpass.

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10. SUPPLEMENTARY NOTES

C. Bajwa, NRC Project Manager

11. ABSTRACT *(200 words or less)*

On April 29, 2007, a gasoline tanker truck carrying 32,500 L [8,600 gal] crashed while heading south along Interstate (I) 880 in Oakland, California. The single-vehicle accident occurred in the MacArthur Maze, which is a network of connector ramps that merges I-80, I-580, and I-880. The resulting fire led to the collapse of the I-580 overpass, directly above I-880, approximately 17 minutes after the fire started. The main objective of the work reported here was to examine samples collected from the collapsed overpass and tanker truck and estimate the temperatures reached during the fire. Based on a comparison of the samples collected from hot regions of the fire and test samples that were thermally exposed, the girders close to the fire reached a minimum temperature of 850°C [1.562 °F]. Based on the information obtained from the materials analyses, the temperature of the samples collected near the tanker truck on the I-880 road bed was between 590 and 930°C [1,094 and 1,706 °F]. The 1-580 girders located directly above the fire where hot gases accumulated and where direct flame impingement occurred reached a temperature between 850 and 1,000 °C [1,562 and 1,832 °F].

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