The MacArthur Maze Fire: How Hot Was It? - 9223

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ABSTRACT

In 2007, a severe transportation accident occurred in Oakland, California in what is commonly known as the "MacArthur Maze" section of Interstate 580 (I-580). The accident involved a tractor trailer carrying gasoline that impacted an overpass support column and burst into flames. The subsequent fire burned for over 2 hours and led to the collapse of the overpass due to the loss of strength in the structural steel that supported the overpass. The US Nuclear Regulatory Commission (NRC) studied this accident to examine any potential regulatory implications related to the safe transport of radioactive materials, including spent nuclear fuel. This paper will discuss the details of the NRC's MacArthur Maze fire investigation.

NOMENCLATURE

Caltrans – California Department of Transportation
CHP – California Highway Patrol
NRC – United States Nuclear Regulatory Commission
SwRI – Southwest Research Institute

BACKGROUND

The accident occurred on Sunday morning, April 29, 2007, in an area commonly known as the "MacArthur Maze", a network of connector ramps that merge highways I-80, I-580, and I-880 in Oakland, California. The fire that eventually led to the overpass collapse started at about 3:38 a.m. when a gasoline tanker truck carrying 32,500 liters [8,600 gallons] 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 rolled onto its side and slid to a stop on the 50-foot-high ramp connecting westbound I-80 to southbound I-880.

The fire, fueled by the gasoline from the tanker, heated the steel girders to temperatures where the steel strength was reduced and was insufficient to support the weight of the elevated roadway. The I-580 overpass collapsed about 17 minutes after the fire started, based on surveillance video taken from a water treatment plant adjacent to the highway interchange. The main portion of the fire spread along a section of the I-880 roadway. Some of the gasoline went through the scupper drain on I-880 and burned on the ground around the support pillar. An aerial photograph of the area with the accident site identified is shown in Figure 1 [1]. A photograph of the scene after the fire was extinguished is shown in Figure 2[1] [2].

DETERMINING FIRE TEMPERATURES

The primary objectives of this work were to evaluate the structural materials exposed to the MacArthur Maze fire of April 29, 2007; estimate the maximum temperatures experienced by those materials during the fire event; and, to evaluate how this actual accident compares to the hypothetical accident condition fire exposure defined in Title 10 of the Code of Federal Regulations, Part 71, "Packaging and Transportation of Radioactive Material" [3]. The secondary objective of this work, which may be explored in a future paper, was to assess the potential impact of this accident on a radioactive material or spent nuclear fuel transportation package.

Examining Physical Evidence

Initial media reports of the MacArthur Maze accident cited sources at the scene estimating that the fire reached temperatures as high as 1,650°C [3,000°F]. This estimation was based on speculation as, to the NRC's knowledge, no direct temperature measurements were taken of the fire.

[1] The transverse support locations for the elevated roadway are referred to as "Bents" in Figure 2.

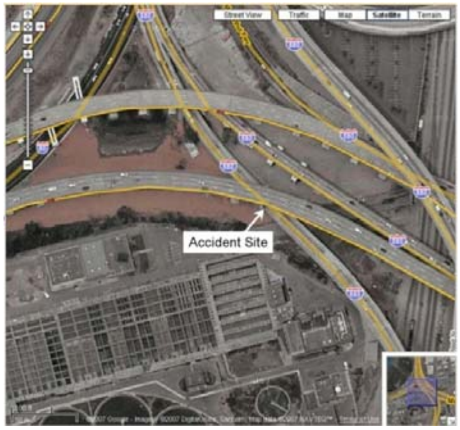


Fig. 1. Aerial photograph of I-880 and I-580 Interchange

Fig. 2. Postfire aerial view of the collapsed section of I-580 looking west. Picture from Caltrans http://www.dot.ca.gov/dist4/photography/images/070429

Review of the extensive photographic documentation compiled by Caltrans during the demolition and repair of the overpass as well as examination of the I-580 overpass girders after the demolition revealed no indications that any of the steel girders were exposed to temperatures where melting would be expected. Although the actual melting temperatures of steel alloys, including carbon steels, is 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]. Because no melting of the structural steel was observed, the determination of the maximum temperatures the girders were exposed to would have to be performed using other information. Other items that could aid in determining the fire temperature included melting of alloys used on the tanker truck, spalling of concrete, damage to paint, and solid-state phase transformations in the steel girders. Spalling of the concrete was observed on the surface of the I-880 roadbed, the actual extent of which was measured by Caltrans. Damage to the paint of the steel girders may serve as a useful indication of temperature especially with the extensive photographic documentation available from Caltrans. NRC and SwRI staff collected and analyzed samples from the steel girders and the tanker truck to estimate exposure temperatures.

Samples of the MacArthur Maze (I-580 Overpass)

Samples of the steel girders were collected and metallurgical analyses were conducted to determine the effect of the fire temperature on the microstructure of the materials. The approximate locations of the samples in the collapsed structure are shown in Figure 3 [2].

Table I describes the samples that the NRC and SwRI staff collected during a site visit to Oakland, CA on June 13, 2007. Some of the girders from which samples were taken are shown in Figures 4 and 5. Additional information from other materials, such as the samples collected from the tanker truck, were also used to estimate temperature.

Samples from the plate girders were obtained from the structures near Bents 18 through 20. Samples obtained near the connection to Bent 20 showed some signs of fire damage to the latex paint. 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, damage to the latex paint was variable. On the outermost I-580 girder located the greatest distance from the I-880 road bed, the latex paint was mostly intact retaining its original gray color.

Between Bent 18 and Bent 19, the plate girders from I-580 were in contact with the I-880 roadway. Significant beam distortion is apparent as a consequence of heating, the resultant weakening of the steel structure, and the load of the concrete structure. No paint was noted on these beam sections. Based on this observation, it was determined that the plate girder section designated as Plate Girder 5 in Figure 4, and shown in detail in Figure 5, was originally located between Bent 18 and Bent 19 where the I-580 overpass was in contact with the I-880 road bed. Originally, the plate girder was approximately 122 cm [48 in] high. As shown in Figure 5, the end of Plate Girder 5, that was believed to be closest to Bent 19, buckled as the result of a loss of strength at elevated temperature and the subsequent impact with the I-880 road bed.

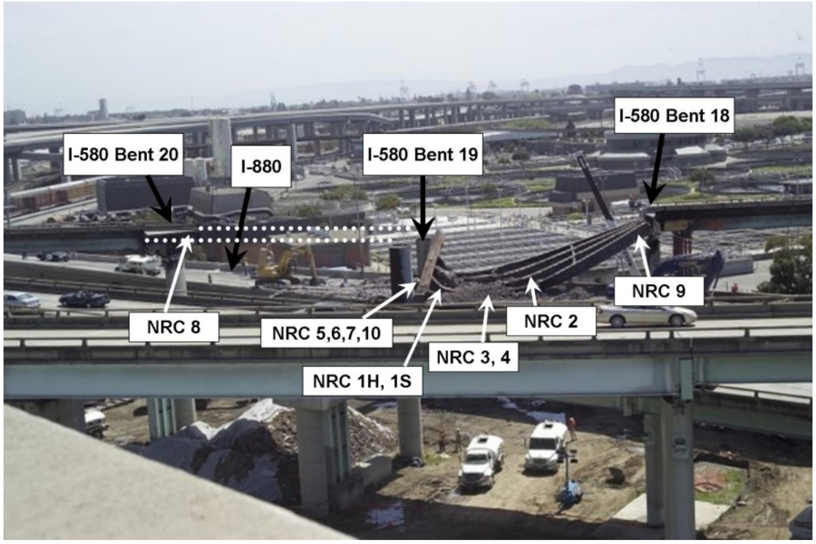


Fig. 3. View of damage during demolition looking southwest. Bent 18, 19, and 20 and approximate locations of collected specimens are indicated. Dotted lines represent pre-accident overpass structure that was demolished and removed prior to this photograph. Original picture from Caltrans website http://www.dot.ca.gov/dist4/photography/images/070430/index2.html

Table I. 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.
NRC 1S	Plate Girder 3 with stiffener near Bent 19. Specimen contained weld metal.
NRC 2	Plate Girder 4 with Butt Weld. Specimen contained weld metal.
NRC 3	Plate Girder 5 likely located between Bent 18 and Bent 19 with stiffener heavy distortion. Specimen contained weld metal.
NRC 4	Plate Girder 5 likely located between Bent 18 and Bent 19 with stiffener medium distortion. Specimen contained weld metal.
NRC 5	Box Beam Cap 7 lower plate with side and weld. Specimen contained weld metal.
NRC 6	Plate Girder found attached to Box Beam Cap 8 with reduction in area.
NRC 7	Rivet head located in Box Beam Cap 8.
NRC 8	Plate Girder 10 Near Bent 20 Web and plate with weld. Specimen contained weld metal.
NRC 9	Plate Girder 12 with stiffener near Bent 18. Specimen contained weld metal.
NRC 10	Flakes peeled off of plate girder angles on Box Beam Cap 8.

ANALYSIS OF MATERIAL SAMPLES

Samples collected were analyzed using traditional metallurgical methods. To minimize the effects of obtaining samples, 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. It was determined that the altered material from the cutting operation should be 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 from the initial cutting of the specimens would be limited to a narrow region near the torch cut edge. The metallurgical sections were placed in epoxy mounts. The sections were prepared using progressively finer grinding papers followed by polishing. 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.

Fig. 4. Girders at the Caltrans storage yard.

Fig. 5. Photograph of Plate Girder 5 believed to be between Bent 18 and Bent 19.

It was determined that the examination of welds in the girder sections could provide information on the temperature of the steel structure during the fire. Given the size and materials of construction, the welds in the girders would not be expected to have undergone postweld heat treatment. Therefore, in the original 'as-built' state, the microstructure of the welds would exhibit characteristics of as-deposited weld metal, which is typically a dendritic microstructure consisting of primarily ferrite with carbide precipitates, whereas the plate sections would be expected to have an equilibrium structure consisting of ferrite and pearlite based on the phase diagram for Iron-Carbon alloys. Compositional analyses indicate that the weld metal and base metal both contain approximately 0.2 percent carbon (Table II), which is consistent with the ASTM A7 steel.

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 [4]. Such fast cooling rates are not expected for the as-welded condition. It should be noted that phase diagrams are based on cooling from elevated temperatures. Using such diagrams may not accurately predict transformations under either isothermal conditions or under conditions where an equilibrium phase is not present. While specific information on the kinetics of low carbon steels is not readily available, heating of the as-deposited weld metal to sufficiently high temperatures should result in a phase transformation to an equilibrium microstructure consisting of pearlite and ferrite. Based on the composition of the welds in the 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. For the hypoeutectoid composition containing 0.2 percent carbon, the transformation is initiated at approximately 725°C [1,337°F] and is fully austenitic above 840°C [1,544°F] based on the phase diagram for iron-carbon alloys [5].

Table II. Compositional Analysis of Weld and Base Metals

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

Analysis of As-Received Samples

A summary of the analysis results for selected samples is shown in Table III. Efforts were focused on the analysis of girder sections that were believed to be located close to the fire (i.e., near Bent 19) as well as samples that were known to be in much cooler locations such as near Bent 18. The microstructure of the base alloy in the plate girder in Sample NRC 1S from Plate Girder 3 contained ferrite and pearlite that is expected for this material. The weld on this sample appeared 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.

While all the samples collected were analyzed, this paper will focus on samples NRC 3 and NRC 4, which provided the clearest indication of an elevated temperature exposure. Samples NRC 3 and NRC 4 were collected from Plate Girder 5, which was buckled during the fire. Sample NRC 3 was likely located closer to Bent 19 compared to Sample NRC 4.

Table III. Results of Microstructure Examination from Collected Samples

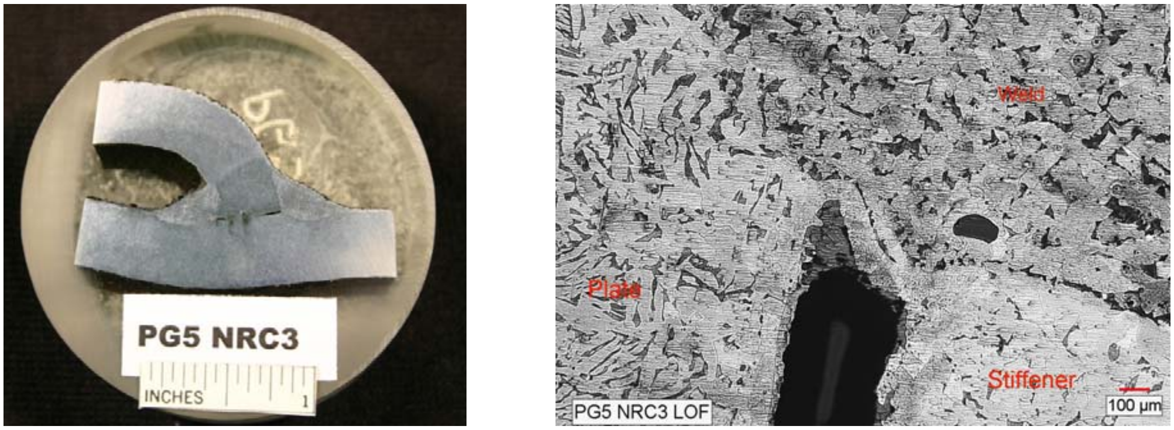
NRC Sample Number	Description	Results
NRC 1S	Plate Girder 3 with stiffener near Bent 19. Specimen contains weld metal.	Weld is as-deposited weld metal consisting of a dendritic microstructure with columnar and equiaxed grains. Some pearlite is also present. Web and plate are pearlite and ferrite.
NRC 2	Plate Girder 4 with butt weld. Specimen contains weld metal.	Weld is pearlite and ferrite. Plate is pearlite and ferrite.
NRC 3	Plate Girder 5 likely located between Bents 18 and 19 with stiffener heavily distorted. Specimen contains weld metal.	Weld is pearlite and ferrite. Plate and stiffener are pearlite and ferrite.
NRC 4	Plate Girder 5 likely located between Bents 18 and 19 with stiffener medium distortion. Specimen contains weld metal.	Weld is pearlite and ferrite. Plate and stiffener are pearlite and ferrite.
NRC 5	Box Beam Cap 7 lower plate with side and weld. Specimen contains weld metal.	As-deposited weld metal with a dendritic microstructure with columnar and equiaxed grains; web and plate are pearlite and ferrite.
NRC 8	Plate Girder 10 near Bent 20. Web and plate with weld. Specimen contains weld metal.	Weld is as-deposited weld metal with dendritic microstructure with columnar and equiaxed grains. Web and plate are pearlite and ferrite.
NRC 9	Plate Girder 12 with stiffener near Bent 18. Specimen contains weld metal.	Weld is as-deposited weld metal with dendritic microstructure with columnar and equiaxed grains. Plate and stiffener are pearlite and ferrite.

Figure 6 (A) shows a specimen from Sample NRC 3 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 each other. Figure 6 (B) 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 specimen from Sample NRC 4 is shown in Figure 7. The microstructure of the weld, plate, and stiffener consists of ferrite and pearlite. Similar to Sample NRC 3, the weld on Sample NRC 4 shows no signs of any dendritic structure that was likely to be present after welding. The stiffener welds in both Samples NRC 3 and NRC 4 are fully transformed and practically indistinguishable from the plate.

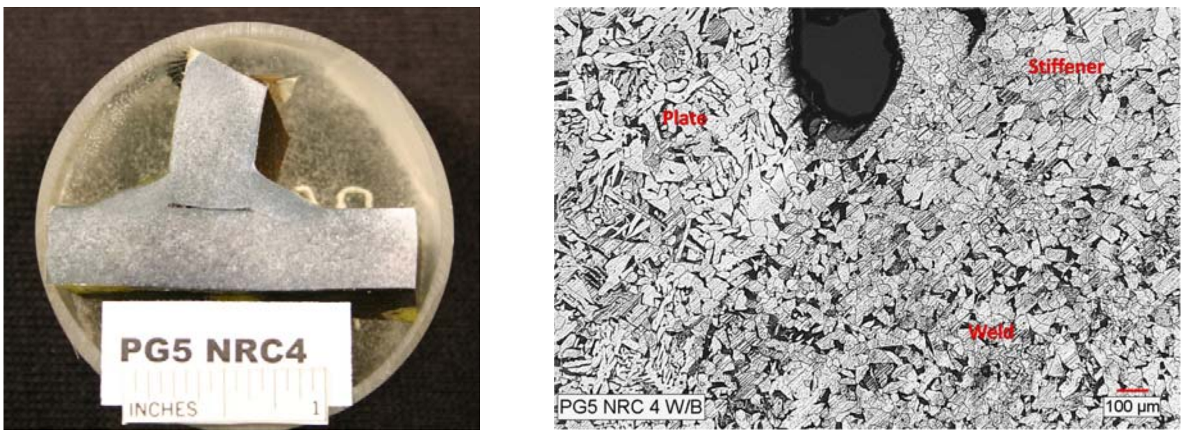
Analysis of Thermally Exposed Specimens

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 specimens so that a sufficient sample was available on which to conduct thermal exposures to determine the effect of exposure conditions on the microstructure of the weld. 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 a period of 3 hours followed by cooling in laboratory air. Table IV shows the thermal exposure conditions and the results of the analysis.



(A) (B)

Fig. 6. Metallurgical specimen from Sample NRC 3 after mounting, polishing, and etching (A). Microstructure of stiffener fillet weld, plate girder, and stiffener (B).



(A) (B)

Fig. 7. Metallurgical specimen from Sample NRC 4 after mounting, polishing, and etching (A). Microstructure of stiffener fillet weld, plate girder, and stiffener (B).

Table IV. Microstructure Analysis of Thermally Exposed Specimens from Sample NRC 9.

Specimen 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

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 is mainly dendritic, but some small amount of pearlite is also present. In Specimen NRC 9-8, exposed at 850°C [1,562°F], the microstructure contains more pearlite but is not fully transformed. After exposure to 900°C [1,652°F], the weld is fully transformed to a ferrite and pearlite microstructure.

Figure 8 (B, C, and D) shows the microstructure of the plate and the weld after exposure to temperatures of 800 to 900°C [1,472 to 1,652°F] along with the microstructure of a specimen from Sample NRC 4 (A). The microstructural distinction between the weld and the plate is apparent at temperatures of 800°C [1,472°F] or less. At 900°C [1,652°F], the distinction between the weld and the plate is reduced and limited to the differences in grain size between the two regions. The microstructure of the welds in the specimens exposed to 850 or 900°C [1,562 or 1,652°F] appears to be similar to the microstructures observed in welds in specimens taken from Samples NRC 3 and NRC 4.

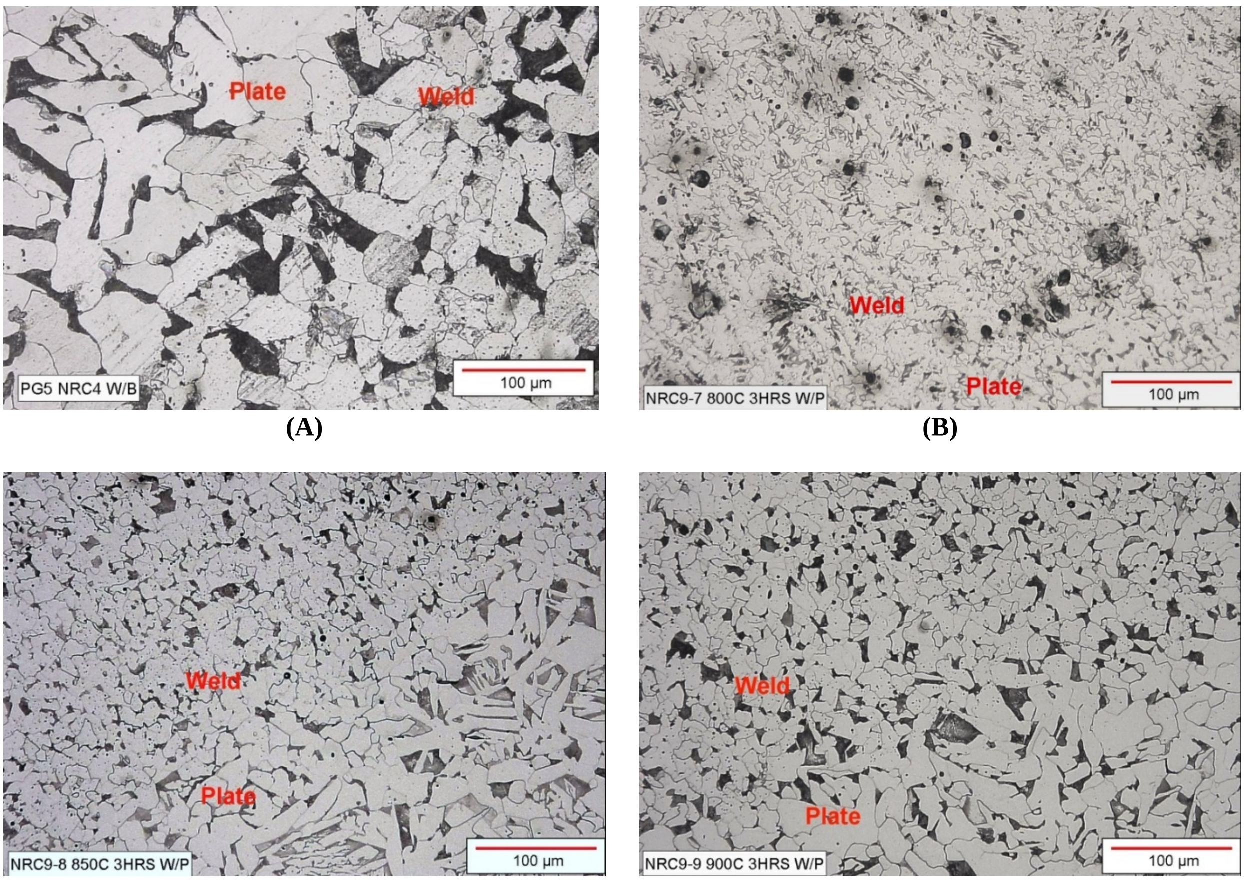


Fig. 8. (A) Microstructure of Sample NRC 4; (B) Microstructure of Specimen NRC 9-7, 800°C [1,472°F]; (C) Microstructure of Specimen NRC 9-8, 850°C [1,562°F]; and (D) Microstructure of Specimen NRC 9-9, 900°C [1,652°F].

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 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 [6].

Thermal exposures of low carbon steels to temperatures above 815°C [1,500°F] result in an increased grain size that can reduce toughness at higher temperatures and result in an increased nil ductility temperature [7].

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 were most likely the best 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.

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 [8] either using templates or an optical reticle with an Olympus PME3 metallurgical microscope.

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 as between ASTM 4 and 5.

An important variable that influences the microstructure is the cooling rate of the material. For low carbon steels such as ASTM A7, the microstructure is 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 a mixture of ferrite and austenite. Above 850°C [1,562°F] the microstructure is 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 [5,9]. 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 cooling rate on microstructure were not conducted; however, the effect of a fast cooling rate is apparent when comparing the microstructures of the samples. 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. This rapid cooling rate does 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 is 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 9.

Although the cooling rate for the actual structure is 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 likely prevented 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].

Analysis of the Tanker Truck Samples

On March 19, 2008, staff from SwRI and NRC inspected the tanker truck involved in the accident and collected selected samples for analysis. A variety of materials were collected including glass, aluminum alloys, steel, copper, brass, and stainless steel. Descriptions of the samples are shown in Table V. Photographs of the truck remains are shown in Figure 10.

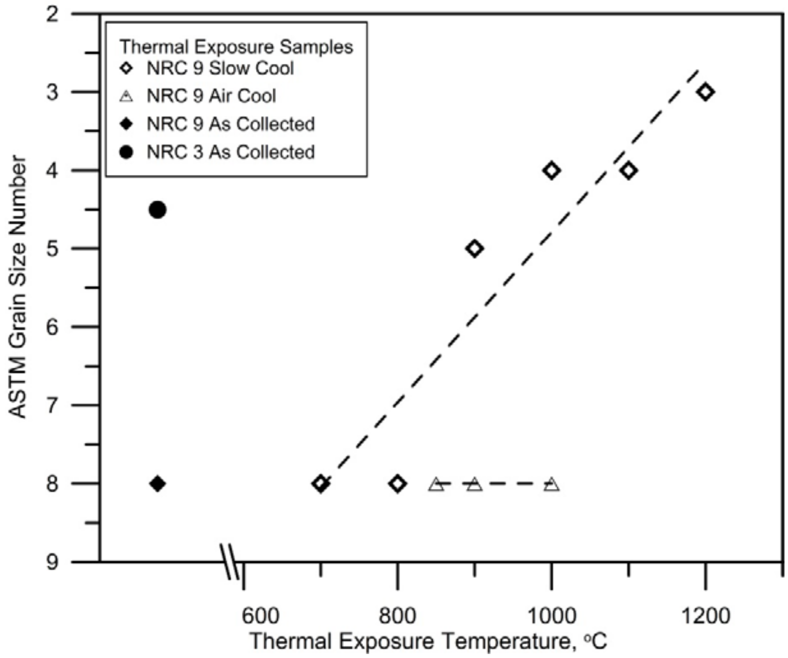


Fig. 9. ASTM grain size as a function of thermal exposure conditions.

Table V. 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 #5 axle on right side of vehicle
Truck Sample 3	Brake pad located near rear of vehicle
Truck Sample 4	Rim component sample from #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 and melted aluminum
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

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 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 VI).

(A)

(B)

Fig. 10. Photographs of the tanker truck remains at the accident site (A) and at the Caltrans storage facility (B).

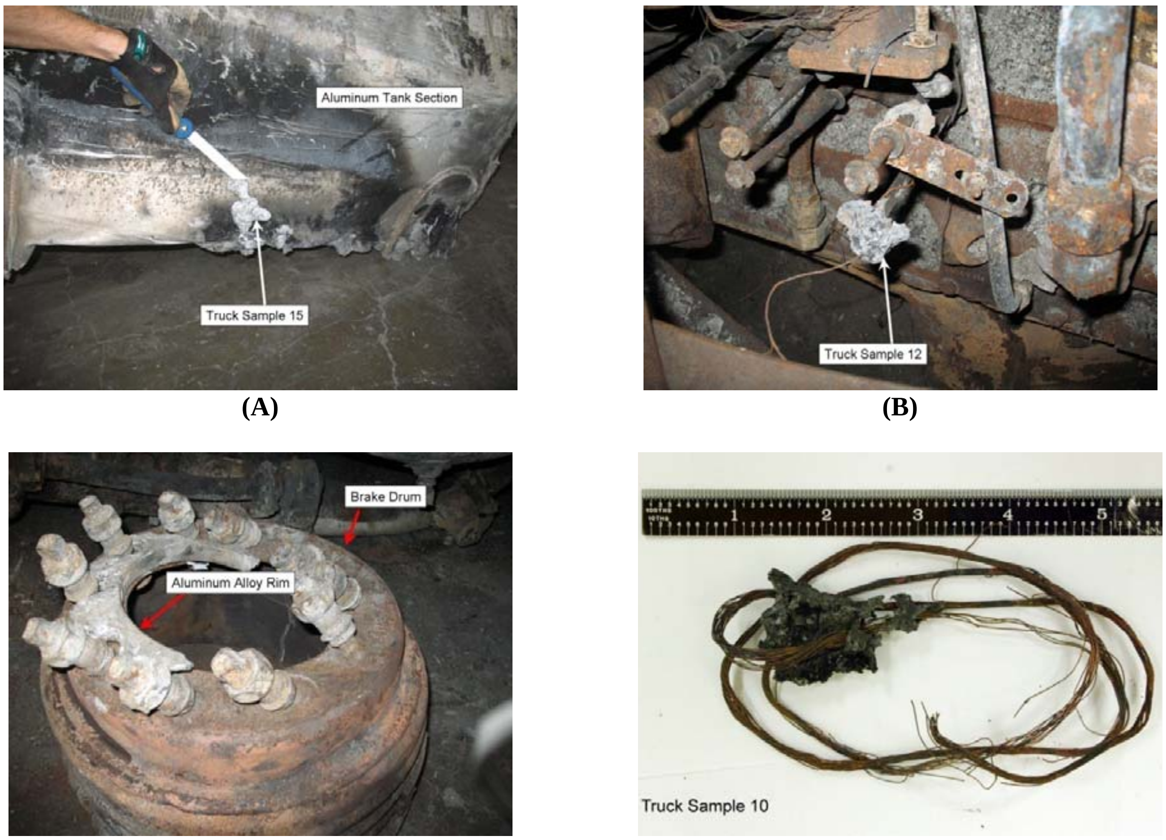
Table VI. Compositional Analysis and Estimated Solidus and Liquidus Temperatures for Aluminum Alloys Obtained from the Tanker Truck

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]

Because the alloys contained 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 11.

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 VI. Figure 11 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 11, the small gauge copper wire showed no indication of melting.

Based on the compositional analysis, 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].



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

Fig. 11. Photographs of the collected aluminum alloy samples. (A) Truck Sample 15: portion of the aluminum tank that had melted; (B) Truck Sample 12: collected from the passenger side of the engine; (C) Truck Sample 14: remains of a partially melted aluminum wheel; (D) Truck Sample 10: section of copper wire partially covered with aluminum.

Copper Alloys

Copper used for electrical system wiring was found throughout the remains of the truck. Large sections of copper wiring, 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 examined 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 12.

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 VII. As expected, the copper wiring was pure copper, consistent with the compositional specifications for copper wire [10,11]. 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 was estimated to be less than 903 °C [1,657 °F].

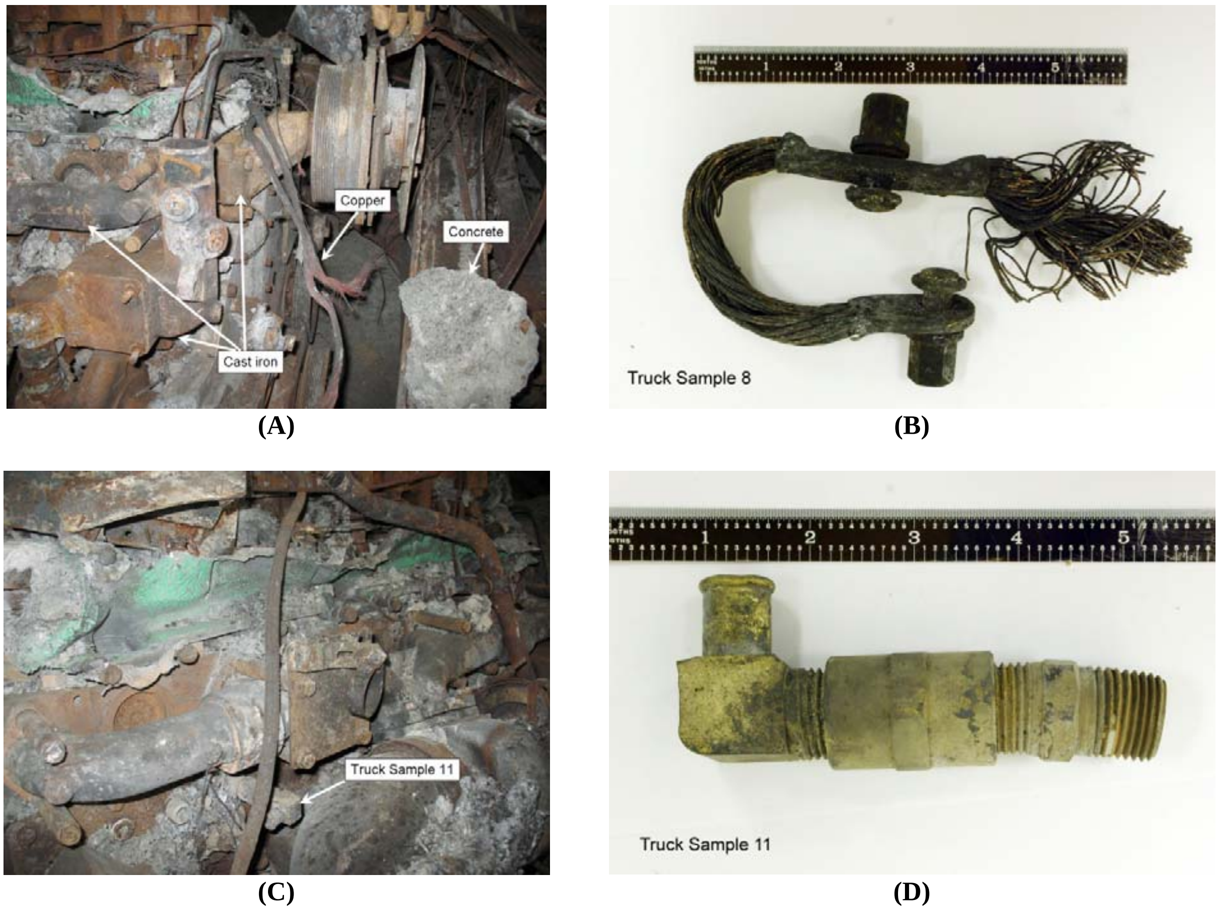


Fig. 12. Photographs of copper alloy materials collected from the tanker truck. (A) battery cable in the engine compartment; (B) ground strap found on tanker truck frame; (C) and (D) brass fitting located on passenger side of the engine.

Table VII. 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]

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] [5,7]. 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 1535°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.

Truck Frame

Onsite observation of some of the steel components, such as the vehicle frame, revealed the formation of oxide scale. 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] [7]. 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].

Stainless Steel Bracket

A stainless steel rearview mirror bracket was determined to be Fe–19Cr–9Ni, which is 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. 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]. Electrolytic etching of the sample was conducted in an oxalic acid solution. The grain boundaries examined were typical of a non-sensitized 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].

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 [12]. Grade 8 hardware specifications required 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 [12,13]. 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 is 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 which resulted 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 it cannot be used to quantify the concentration of carbon. 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 VIII.

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 [6]. The compositional analyses shown in Table 8 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 is 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.

Conversion of hardness scales is possible but 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 [14], the measured 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 13.

Table VIII. 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	—

The effect of temperature on hardness is apparent for the new Grade 8 bolts. Although 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 is not significantly altered. At higher temperatures, the hardness is 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 13 also shows the effect of thermal exposure on sections of the Truck Sample 6. Most significant is the substantial decrease in hardness observed after the exposure at 800°C [1,472°F]. Based on the data shown in Figure 13, it is estimated that Truck Sample 6 was exposed to a temperature in the range of 700 to 750 °C [1,292 to 1,382 °F] in the MacArthur Maze fire.

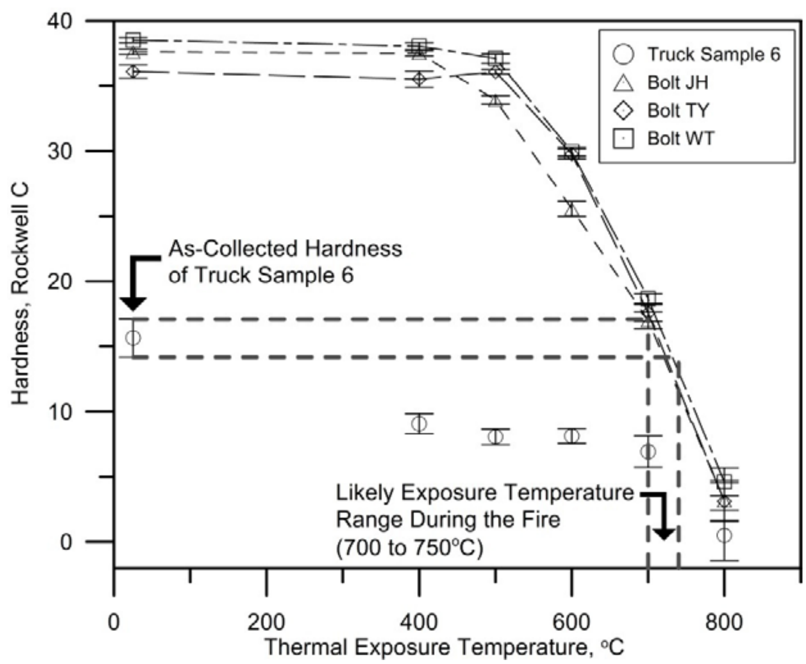


Fig. 13. Effect of exposure temperature on the hardness of Truck Sample 6 and commercially available Grade 8 bolts.

Additional Information

The damage to the paint on the steel girders may also indicate the temperature [7]. Photographs taken during demolition and the condition of the girders observed in the Caltrans storage yard clearly indicate that the paint was destroyed on girders closest to the fire. For the thermally exposed samples described in this paper, discoloration and significant damage of the paint was observed after the exposure at 550°C [1,022°F]. After exposure, the paint appeared to be a yellow-green color. At 700°C [1,292°F], the paint was completely destroyed. At higher temperatures, the specimen was covered with a dark gray oxide layer.

The girders supporting the span from Bent 19 to Bent 18 had varying levels of paint degradation, due to the fire, as the distance away from the fire source (the tanker truck) at Bent 19 increased. This indicates that fire was spread along the length of the I-880 roadbed. On the outermost girder (greatest distance from I-880) the latex paint was intact at Bent 18 suggesting a temperature less than 200°C [392°F]. Damage to the latex and lead based paint observed on innermost girders (closest to I-880) at distances of approximately 3 meters [10 feet] from Bent 18 suggests that the temperature in this area approached 700°C [1292°F].

CONCLUSIONS AND FUTURE WORK

Fire temperatures can be estimated using information collected from phase transformations in the welds and grain size of the steel girders, damage to paint on the steel girders, and the observed condition of the tanker truck materials. Samples were collected from the I-580 steel girders and the truck remains and analyzed. A limited number of thermal exposures were conducted to determine the effect of temperature on the microstructure of structural welds.

At the hottest locations, the temperatures witnessed by the steel girders were above 850°C [1,562°F] based on the microstructure of welds, and close to 1,000°C [1,832°F] based on grain size of samples 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. At locations away from the fire, microstructural evidence and the condition of the paint used to protect the steel girders suggest that temperatures were much lower. At Bent 18 or Bent 20, no alteration of the welds, due to extensive heating, was observed.

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 720°C [1,328°F] and less than 930°C [1,706°F]. Results obtained from the analysis of the overpass and truck samples are consistent with modeling results, indicating the hottest gas temperatures during the fire were located above the I-880 roadway near the steel girders of the I-580 overpass.

The insights gained from the materials analyses can be used to validate a computer fire model of the MacArthur Maze fire and further investigate the potential affects that a fire of this magnitude and duration could potentially have had on an NRC certified over-the-road radioactive material transportation package.

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