Derailment of Canadian National Freight Train M33371 and Subsequent Release of Hazardous Materials in Tamaroa, Illinois

February 9, 2003

Railroad Accident Report

NTSB/RAR-05/01

PB2005-916301
Notation 7686

National Transportation Safety Board
Washington, D.C.

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Adopted January 25, 2005

National Transportation Safety Board
490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2005. ***Derailment of Canadian National Freight Train M33371 and Subsequent Release of Hazardous Materials in Tamaroa, Illinois, February 9, 2003.*** **Railroad Accident Report NTSB/RAR-05/01. Washington, DC.**

Abstract: About 9:04 a.m. central standard time on February 9, 2003, northbound Canadian National freight train M33371 derailed 22 of its 108 cars in Tamaroa, Illinois. Four of the derailed cars released methanol, and the methanol from two of these four cars fueled a fire. Other derailed cars contained phosphoric acid, hydrochloric acid, formaldehyde, and vinyl chloride. Two cars containing hydrochloric acid, one car containing formaldehyde, and one car containing vinyl chloride released product but were not involved in the fire. About 850 residents were evacuated from the area within a 3-mile radius of the derailment, which included the entire village of Tamaroa. No one was injured during the derailment, although one contract employee was injured during cleanup activities. Damages to track, signals, and equipment, and clearing costs associated with the accident totaled about $1.9 million.

The safety issues addressed in the report are the effect of bond wire welding on rail integrity and inconsistent instructions regarding the exothermic welding of bond wires.

As a result of its investigation of this accident, the Safety Board makes recommendations to the Federal Railroad Administration; ERICO Products, Inc.; and the American Railway Engineering and Maintenance-of-Way Association.

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Executive Summary

About 9:04 a.m. central standard time on February 9, 2003, northbound Canadian National freight train M33371, traveling about 40 mph, derailed 22 of its 108 cars in Tamaroa, Illinois. Four of the derailed cars released methanol, and the methanol from two of these four cars fueled a fire. Other derailed cars contained phosphoric acid, hydrochloric acid, formaldehyde, and vinyl chloride. Two cars containing hydrochloric acid, one car containing formaldehyde, and one car containing vinyl chloride released product but were not involved in the fire. About 850 residents were evacuated from the area within a 3-mile radius of the derailment, which included the entire village of Tamaroa. No one was injured during the derailment, although one contract employee was injured during cleanup activities. Damages to track, signals, and equipment, and clearing costs associated with the accident totaled about $1.9 million.

The National Transportation Safety Board determines that the probable cause of the February 9, 2003, derailment of Canadian National train M33371 in Tamaroa, Illinois, was Canadian National's placement of bond wire welds on the head of the rail just outside the joint bars, where untempered martensite associated with the welds led to fatigue and subsequent cracking that, because of increased stresses associated with known soft ballast conditions, rapidly progressed to rail failure.

The safety issues addressed in the report are as follows:

- The effect of bond wire welding on rail integrity, and
- Inconsistent instructions regarding the exothermic welding of bond wires.

As a result of its investigation of this accident, the Safety Board makes recommendations to the Federal Railroad Administration; ERICO Products, Inc.; and the American Railway Engineering and Maintenance-of-Way Association.

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Factual Information

Accident Synopsis

About 9:04 a.m. central standard time[1] on February 9, 2003, northbound Canadian National (CN)[2] freight train M33371, traveling about 40 mph, derailed 22 of 108 cars in Tamaroa, Illinois. (See figure 1.) Four of the derailed cars released methanol, and the methanol from two of these four cars fueled a fire. Other derailed cars contained phosphoric acid, hydrochloric acid, formaldehyde, and vinyl chloride. Two cars containing hydrochloric acid, one car containing formaldehyde, and one car containing vinyl chloride released product but were not involved in the fire. About 850 residents were evacuated from the area within a 3-mile radius of the derailment, which included the entire village of Tamaroa. No one was injured during the derailment, although one contract employee was injured during cleanup activities. Damages to track, signals, and equipment, and clearing costs associated with the accident totaled about $1.9 million.

Figure 1. Post-derailment wreckage.

[1] Unless otherwise noted, all times are given in central standard time.

[2] In July 1999, the Canadian National Railroad purchased the Illinois Central Railroad and became the Canadian National/Illinois Central (CN/IC) Railroad. In November 2003, about 10 months after the Tamaroa accident, the CN/IC was redesignated the Canadian National or CN. For the purposes of this report, the railroad will be referenced throughout by the designation "CN."

Accident Narrative

Train M33371 was a regularly scheduled northbound freight train that operated between Memphis, Tennessee, and Chicago, Illinois. The train changed crews in Fulton, Kentucky, for that portion of the trip between Fulton and Centralia, Illinois. On the day of the accident, because of the hazardous materials in its consist, the train was designated a "key train."[3] The crew that boarded the train in Fulton consisted of an engineer and a conductor. The conductor would stay with the train until it reached Centralia, Illinois, a timetable distance of 152.4 miles. The engineer would stay on the train only until it met with a designated southbound train at a siding. At that point, the engineers of the two trains would swap trains, with the engineer of the southbound train taking over train M33371 and operating it northbound to Centralia. Train M33371 departed Fulton at 3:33 a.m. on February 9, 2003, with 2 locomotives and 89 cars. On the day of the accident, train M33371 met the designated southbound train at Anna, a siding about 17.7 miles south of Carbondale, Illinois, and about 72.6 miles south of Centralia. The southbound train went into the siding track while train M33371 stayed on the single-track main line. The two engineers conversed, as was the normal routine, before exchanging trains. The engineer who was now operating train M33371 stated that after the crew change, he had a clear signal at Anna and proceeded northward at 6:50 a.m. He said he and the conductor noted no problems with the operation of the train as it continued northward.

Train M33371 made a scheduled stop at Carbondale Yard to pick up an additional 19 freight cars. At the yard, the conductor inspected the cars, and after the additional cars were coupled to the rest of the train, an air brake test was performed. No exceptions were noted during the inspection or brake testing.

While the train, which now consisted of 76 loads and 32 empties, was still in the Carbondale Yard waiting to depart, southbound CN train 348 passed, followed by northbound Amtrak train 58, the City of New Orleans. After the Amtrak train had passed, the engineer of train M33371 received signal indications from the dispatcher authorizing him to proceed northward, after which the train departed Carbondale.

The engineer stated that as train M33371 was passing through Tamaroa, about 26 miles north of Carbondale, he felt a "tug" and noted that the train movement slowed. He said that a moment later, about 9:04, he felt a surge, and the train brakes went into emergency.[4] The engineer said he could see dust and debris, and he radioed the train dispatcher. The engineer notified the dispatcher that the train had derailed and that the train was a key train.

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[3] The Association of American Railroads classifies as a *key train* any train with 5 tank car loads of a poison inhalation hazard (PIH) (hazard zone A or B) or 20 car loads or intermodal tank loads of a combination of a PIH (hazard zone A or B), flammable gas, Class 1.1 or 1.2 explosives (class A), or environmentally sensitive chemicals. A key train is restricted to a maximum speed of 50 mph.

[4] Data from the event recorder on the lead locomotive indicated that the train was traveling about 40 mph when the brake application occurred and that the train came to rest within about 30 seconds.

The engineer stated that the conductor had started to get off the lead locomotive when he “saw vapors” on his (west) side and they both observed “dust” on the engineer’s (east) side. The conductor then decided to stay on the locomotive as they looked through the train consist and the hazardous material instruction sheets provided for each hazardous material carried on the train. After about 5 minutes, the crewmen attempted to determine which cars were involved. They noticed a fire and told the dispatcher. About this time, a CN supervisor was heard on the radio, and the crewmen informed the supervisor that they had observed a fire. The conductor dismounted the lead unit and cut the two locomotives from the train. They moved the locomotives about 2 1/2 miles north to a road crossing and awaited further instructions.

The CN supervisor arrived at this location and transported the conductor back to the derailment site to meet with emergency personnel and to exchange information concerning the cars and the hazardous materials involved in the accident. Another supervisor arrived and transported the crewmen to a hospital for toxicological testing; he later transported the crewmen to Centralia, where they went off duty at 6:50 p.m.

Emergency Response

The Perry County Sheriff’s Office reported receiving the first 911 call about 9:04 a.m.; the office then called the Du Quion Emergency Services and Disaster Agency. The Tamaroa Fire Department responded directly to the scene. The State police were on the scene shortly after that, and police and fire department personnel began to evacuate the residents of homes near the tracks to the Tamaroa Community Center. About 140 residents were sheltered at the community center.

The Du Quion emergency services coordinator arrived on the scene at 9:30 a.m. He identified the hazardous materials involved in the derailment as hydrochloric acid and methanol, and he ordered the call-up of all disaster agency personnel. By this time, several State, county, and city fire and police departments were involved in the evacuation of all residents from the middle of Tamaroa. By 12:00 noon, vinyl chloride was determined likely to be involved in the derailment, and the evacuation perimeter was expanded to a 3-mile radius from the accident site, an area encompassing about 850 people and the entire village of Tamaroa.

Six additional fire departments were assisting the Tamaroa Fire Department in the firefighting effort by 2:30 p.m. Hulcher Professional Services[5] hazardous materials personnel were on scene by 4:00 p.m. About 10:00 p.m., lime was brought in, and responders began using it to neutralize the hydrochloric acid.

[5] Hulcher Professional Services, Inc., was one of the companies contracted by CN to perform and coordinate emergency and initial response activities at the site.

The evacuation area remained the 3-mile radius throughout the next day, Monday, February 10. By 7:00 a.m., dirt was being applied to the methanol tank cars to smother the flames, and neutralization of the hydrochloric acid spill was continuing. The fire was extinguished by about 9:30 a.m. Fixed air monitoring stations were established around the site, and at 3:15 p.m., cargo transfer operations were started.

About 3:15 a.m. on Tuesday, February 11, as a damaged tank car containing methanol was being moved, an explosive re-ignition of methanol occurred. A Hulcher employee who was injured in the explosion was taken to the hospital and treated for a knee injury.

As progress was made in transferring material from the derailed cars, the evacuation area was reduced to a 1-mile radius of the site at 10:00 a.m. on February 11. The evacuation area was reduced to a 1/2-mile radius on February 12. By 8:50 a.m. on February 12, the material from all but one of the methanol tank cars had been transferred. At 6:00 p.m. on Thursday, February 13, Tamaroa residents, with the exception of those living in houses adjacent to the tracks, were allowed to return home.

At 7:00 a.m. on Friday, February 14, the tracks were opened and trains began moving through the area. At 8:00 a.m. on February 15, the order requiring the evacuation of the remaining homes was lifted.

Injuries

No one was injured during the derailment. A contract employee of Hulcher Professional Services was injured on February 11, as a result of a methanol vapor explosion that occurred during the cleanup of the derailed cars. The employee was taken to Marshal Browning Hospital in Du Quoin for treatment and observation. He was released on February 12 with a brace on his left knee.

Damage

Track damage started just south of the derailment site, about 89 feet north of a switch and right-hand turnout that connected the CN track to track owned by the Union Pacific Railroad (UP). Damage extended along the CN main track for about 800 feet through a left-hand switch for the CN house track.[6] In addition, about 400 feet of UP track was destroyed. This accounted for about $90,000 in track damages and $30,000 in signal equipment damages.

[6] The *house track* was a stub track that was used to set out freight cars that needed mechanical attention or as a place where track maintenance equipment could be parked.

All 22 derailed cars were destroyed. Damage to railroad equipment was $925,000. The loss of lading totaled $353,000. The cost of environmental damage and cleanup exceeded $500,000. Total damages were about $1.9 million.

Wreckage

The 28th through 49th cars of train M33371 derailed and piled up; most were positioned approximately perpendicular to the track in accordion fashion. Seventeen loaded tank cars containing hazardous materials and two containing hazardous material residue derailed. Of the 19 tank cars that derailed 5 were Department of Transportation (DOT) class 105 pressure tank cars that had protective head shields on each end, and 14 were DOT class 111 general service tank cars.

The five pressure tank cars were transporting vinyl chloride, a highly flammable and reactive gas that is also a known human carcinogen. One pressure tank car was breached. The breach involved a puncture by a pointed, rigid object that penetrated both the 1/2-inch-thick steel head shield and the 1/2-inch-thick steel tank head. The 6-inch-long puncture was 2 inches wide at its widest point.

Of the 14 general service cars that derailed, 2 cars contained phosphoric acid and 2 cars contained hydrochloric acid solution, both of which are corrosive liquids. Three cars contained formaldehyde solution (with methanol), and seven cars contained methanol (two residue), both of which are flammable liquids. Seven of the general service tank cars were breached. Of these, four cars contained methanol, two cars contained hydrochloric acid, and one car contained formaldehyde. Two of the seven cars, a methanol tank car and a formaldehyde tank car, had minor leaks through damaged fittings. The three other tank cars containing methanol lost product through damage to their heads: two had head punctures, and one had a localized area that was severely crushed and torn. One of the two tank cars containing hydrochloric acid solution had a puncture in its side shell. The second tank car containing hydrochloric acid lost product through a compromised section of the tank shell.

Operations Information

The main track was owned, inspected, maintained, and operated by CN, which had designated it as class 5 track.[7] Given this track designation, the single main track had a maximum allowable operating timetable speed of 79 mph for passenger trains, 70 mph for loaded container trains, and 60 mph for other freight trains. (The accident train was restricted to 50 mph because it was designated a key train.)

[7] Railroads determine at what class they will operate various segments of their track. As the class designation increases, the track must meet increasingly higher Federal standards for construction, maintenance, and inspection. Federal regulations also establish maximum speeds for each class of track.

Typical train counts through Tamaroa included four Amtrak passenger trains, eight manifest freight trains, two unit grain trains, and two local freight trains per day. Train traffic for the 12 months preceding the accident accounted for an annual gross tonnage of 35.2 million gross tons.

Postaccident Inspections

Equipment

The train equipment that had not derailed was inspected, and no preexisting defects or exceptions were noted. The derailed and damaged cars were also inspected, and no obvious preaccident defects or exceptions were noted. Based on car position and marks on equipment, investigators determined that the 28th car was the first car in the train to derail.

Point of Derailment

The track was completely destroyed in the area of the derailment; however, Safety Board investigators studied and excavated the footprint of the derailment[8] and determined that the point of derailment was on the east rail of the main track at an insulated joint plug[9] at milepost 279.95. The joint plug appeared on visual inspection to contain rail fatigue defects and was broken into four segments, one of which contained the intact insulated joint. The south end of the segment containing the insulated joint exhibited evidence of receiving rail-end batter;[10] the north end exhibited trailing rail-end batter.[11]

[8] The *footprint* comprised any and all visible evidence, including marks on the ties, marks on the track components and the rail, car and truck component positions, and broken track components.

[9] Railroad tracks in centralized traffic control territory have numerous electronic circuits that detect the presence of trains. These circuits use the rails as conductors of a low-voltage electrical current of a designated frequency, often referred to as “code.” To separate the different segments of track circuits, certain lengths of rail must be electrically insulated from adjacent segments. This electronic separation is accomplished by the use of an *insulated rail joint*, which employs special joint bars and fasteners that electrically isolate the joined rail segments. Typically, when an insulated joint must be replaced, the old joint, along with several feet of rail on each side of the joint, is cut from the track. The cut-out section is then replaced with a manufactured *joint plug*, which is a relatively short section of rail that contains within its length a pre-assembled insulated rail joint. The joint plug is bolted or welded in place.

[10] *Receiving rail-end batter* is a deformation of the rail head that occurs when an oncoming train wheel strikes the end of rail that has become higher than the adjacent rail.

[11] *Trailing rail-end batter* occurs when a train wheel rolls over the rail head end and drops onto the end of a rail section that has become lower than the adjacent rail.

Fatigue cracking appeared to have originated at two exothermic bond wire welds.[12] (See figure 2.) Each of the three welds on either side of the insulated joint contained a single track bond wire. One wire was for the electronic track circuit code, the second wire was for an audio frequency circuit, and the third wire was for future use with a grade crossing predictor circuit.

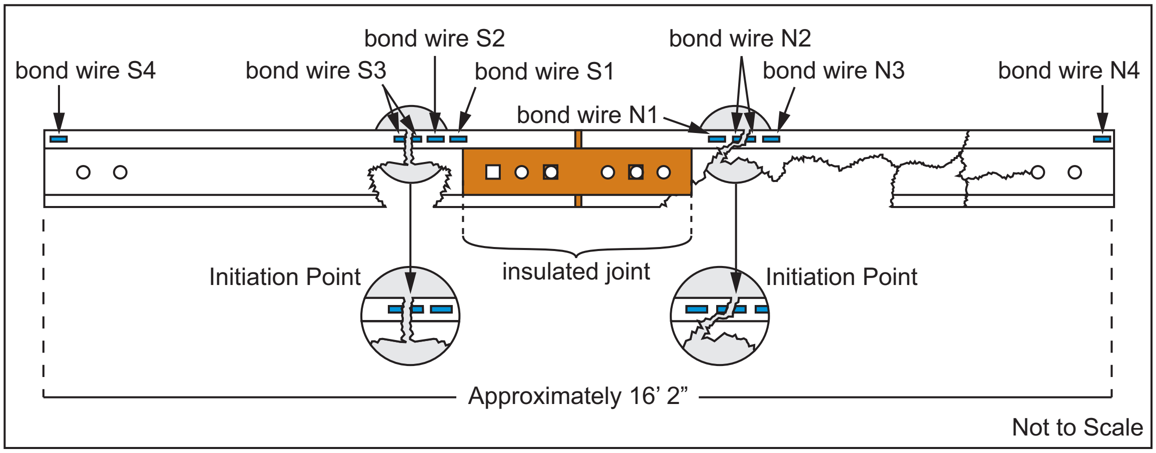

Figure 2. Illustration of the insulated joint plug that failed at Tamaroa showing fracture locations. Three exothermic bond wire welds had been made at the head of the rail on either side of the insulated joint. (Letter designations indicate north or south portions of the plug.)

The insulated joint plug was manufactured by Allegheny Rail Products, a Division of L. B. Foster Company, in April 2002.

Track Geometry Measurements

Track geometry measurements were recorded for 30 stations south of the point of derailment. Each station was 15 feet 6 inches apart. All 30 station measurements were taken in an unloaded state with any evidence of rail and tie movement added to the unloaded measurements. Station 1 was closest to the point of derailment, and Station 30 was farthest away. Stations north of the point of derailment could not be measured because the track was destroyed. All geometry measurements were then compared with the Federal requirements for class 5 track.

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[12] In the case of insulated joints, *bond wires* are used to connect the rails to the signal circuitry. Bond wires are relatively short, flexible, stranded wires with terminals at each end. One end is attached to the rail near the end of the track circuits, usually at or near the insulated joint bars; the other end connects to track circuit wires that are typically routed underground from the rail(s) to a nearby signal case that houses various components of the signal system. Bond wires are most often attached to the rails by *exothermic welding*, which is discussed in more detail later in this report.

Standard gage measurement is 56 1/2 inches between the rail heads. Gage measurements on non-disturbed Tamaroa track ranged from 56 3/8 inches to 56 5/8 inches. Title 49 *Code of Federal Regulations* (CFR) 213.53 allows a minimum gage of 56 inches and a maximum gage of 57 1/2 inches.

Track surface parameters were measured. The largest cross-level[13] deviation measurements revealed a 3/4-inch variation from level at station 2. The 49 CFR 213.63 track surface chart indicates that the maximum allowable deviation for cross level is 1 inch. The maximum variation for track warp[14] was 7/8 inch between stations 2 and 4. According to the track surface chart, the maximum allowable deviation for track warp is 1 1/2 inches. The track profile measurement revealed a maximum deviation of 3/4 inch between stations 1 and 2. The track surface chart indicates that the maximum allowable deviation for track profile is 1 1/4 inches.

Walking Track Inspection

On February 9, 2003, investigators conducted a walking track inspection to the north and south of the derailment area (milepost 279.95) between milepost 278.9 and milepost 281.2. During the walking inspection, spot measurements and observations were made for compliance with class 5 track standards. No exceptions were noted during the inspection.

Preaccident Track and Signal Condition and Maintenance

Preaccident Track/Signal Condition

The CN track foreman and the CN signal maintainer characterized the point of derailment as typically having muddy track conditions; however, all evidence of this muddy track condition was destroyed in the derailment. The signal maintainer stated:

> My personal opinion is that they had trouble … keeping the Alleghenys up high enough that … the mud in the water [would not be] able to work the joints …. There was a lot of … mud pumping, there. It seemed to be a trouble spot. Anytime the tampers would come down there, [there would be] mud on my signals … where [the tampers] would be pumping mud.

The signal maintainer added that mud at the joint seemed to put extra tension on the signal bond wires, especially in freezing weather, when the mud would become hard and "tug on the wire" as trains traversed the joint. He stated that the mud also affected the insulated joint by placing greater tension on it until the insulation started pulling away around the joint bar area. He stated that in the 13 months he was responsible for this territory, he was called one time for an open track wire at that location. He said he had to dig in the mud to find the broken wire that caused the problem.

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[13] *Cross level* refers to the relative heights of the two rails.

[14] *Warp* is the measured difference in cross level between any two points less than 62 feet apart.

The signal maintainer stated that he inspected insulated joints on his territory at least once a month. He said he checked all bonds in nonwelded joints once every 3 months. He also stated that any time he made a monthly switch inspection, he checked all the bonds at that location.

The signal maintainer's personal logbook records for January 2003 contained a notation of a problem with the track in the area of the subsequent derailment that included poor tie and ballast conditions and subzero temperatures. He stated that the poor surface caused the track to dip down in the area where the derailment would occur, and that mud in that area squirted on the signal mast and junction base.

The signal maintainer was asked if he recalled telling anybody about the poor tie and ballast condition and pumping mud. He stated that he had mentioned his concern about this location to the track supervisor on more than one occasion, most recently in late 2002. He stated that to his knowledge, no action was taken to correct the problem.

The last train to travel over the derailment site before the accident was Amtrak train 58, the *City of New Orleans*. The engineer of Amtrak train 58 stated that the train was traveling in a northward direction at about 78 mph when it passed through Tamaroa about 5:00 a.m. on February 9. The engineer stated that his train rode as it always did. He stated that there was a stretch of rough track between milepost 280 and the "graveyard crossing" at milepost 279.1, and that "If you're drinking a cup of coffee, you got to get a hold of it."

The train 58 engineer stated that in December 2002, while operating an Amtrak train in a southward direction, he told the CN train dispatcher that the track in the derailment area rode rough and asked that a speed restriction be placed on the track. He said the roughest section was between milepost 279.4 and milepost 280. He stated that he believed a speed restriction was put in place but that it had been removed before his next trip. He said that during that next trip, because of his concerns about the ride quality of the train, he operated at a slightly reduced speed. He stated that the train rode significantly better than it had before he reported the rough track condition.

Replacement of Tamaroa Insulated Joint Plug

A CN welder for the Centralia Subdivision installed the insulated joint plug at the derailment site on January 23, 2003. (See figure 2.) The welder said that one of the two joint bars[15] at an insulated joint was cracked. A new Allegheny insulated joint plug was delivered to the site, and the welder cut out the section of rail containing the defective insulated joint and replaced it with the Allegheny plug (which included a new, pre-assembled insulated joint). The new joint plug was not welded into place but was installed with standard 115-pound, 36-inch-long joint bars. The welder stated that he did not field-weld the insulated joint plug into the main track because the temperature was about 10° F

[15] *Joint bars* are steel bars used to fasten together the ends of rails in a track. They are used in pairs and are designed to fit closely in the space between the rail head and rail flange (fishing space). They are held in place by track bolts. Joint bars are also called angle bars, rail joint bars, or splice bars. Joint bars at insulated joints are insulated from the rail to prevent current flow between the joined rail sections.

at the time of installation, and such cold conditions affect the weld preparation process. Besides the welder, a welder helper, a track foreman and his laborer, the track inspector, and a signalman all participated in the plug replacement.

Insulated Joint Plug at St. Johns

About 2 1/2 weeks before the accident at Tamaroa, a CN signal maintainer, while conducting his monthly inspection on January 23, 2003, discovered a broken rail at a signal bond wire weld at St. Johns station (milepost 285.45 on the Centralia Subdivision of the Gulf Division, about 5 1/2 miles from the derailment). The rail failure was in an Allegheny insulated joint plug at the St. Johns switch. (See figure 3.) No information was available to indicate how long the existing welds had been in place or whether there was any additional flexing of the rail due to inadequate underlying ballast support.

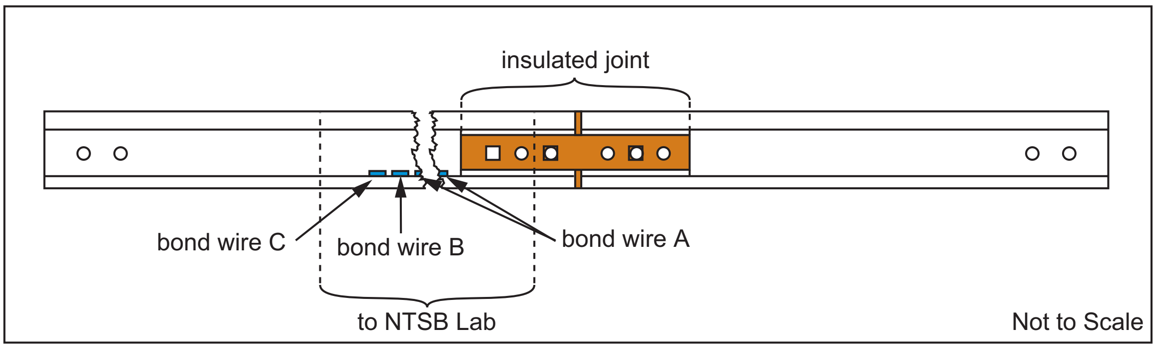

Figure 3. Illustration of insulated joint plug that failed at St. Johns showing fracture locations. Three bond wire welds had been made to the base of the rail outside the joint bar.

In the vicinity of the rail fracture, exothermic bond wire welds had been made on the base of the rail just outside the confines of the insulated joint bars. The top of the field side (outside) of the rail base contained three bond wire welds. The fracture appeared to emanate from an area near one of these welds, about 1 inch from the end of the insulated joint bars. Portions of the bond wire weld closest to the joint bars were present on both sides of the fracture.[16]

Railroad signal systems rely on a low-voltage current introduced into the rails to detect the presence of trains and to set signal aspects to provide train separation. The same current also makes it possible for signal systems to detect an "open" circuit, such as occurs in the case of a broken rail. But at St. Johns, because the bond wire connected to the signal circuit remained attached to the rail even after the fracture occurred, the signal system did not detect the break. The CN signal maintainer who found the broken rail at St. Johns told

[16] After the Tamaroa accident, a 12-inch portion of the St. Johns track was removed from both sides of the separation, with the remains of insulated joint bars attached, and sent to the Safety Board Materials Laboratory for further examination. The results of the examination appear in the "Tests and Research" section of this report.

investigators that the signal system had displayed a *clear* signal, even though the broken rail had allowed a 5-inch separation in the continuous welded rail (CWR).[17]

Welding Signal Bond Wires Onto Insulated Joint Plugs at St. Johns and Tamaroa

Welding Signal Bond Wires. CN procedures called for signal bond wires at a rail joint to be welded to rails using an exothermic welding process. In a typical exothermic welding process, a chemical reaction is achieved with heavy metal oxides, such as iron or copper oxide, using aluminum as a reducing agent. When ignited, the oxides and aluminum powder react within a few seconds to produce the necessary welding heat. The resultant superheated molten metal is so hot—in excess of 2200° C (about 4000° F) for steel—that the contacting surface layers of the materials to be joined melt and form a permanent bond.

To carry out the procedure, the signal maintainer uses a special mold that holds the bond wire against the rail where the two are to be joined. After placing one end of a bond wire into the mold and placing a retaining disk at the bottom of the crucible of the mold to contain the powder mixture, the signal maintainer pours oxide powder into the mold crucible and covers it with a layer of starting powder. He then ignites the mixture using a spark lighter. The molten oxide material burns through the retaining disk and flows downward in the mold, where it contacts the bond wire and the rail, melting them locally and then fusing them upon cooling.

Because the exothermic welding system requires no external power source and is highly portable, quick, effective, and relatively inexpensive, it is widely used among railroads. ERICO Products, Inc., (ERICO) of Cleveland, Ohio, and four other companies are known to manufacture exothermic bond wire welding systems for the U.S. rail industry. Each company provides its own mold designs[18] and powders. ERICO provides the equipment, supplies, and guidance for the Cadweld® exothermic welding process that CN used at the St. Johns and Tamaroa sites.

Bond Wire Welding at St. Johns and Tamaroa. A CN signal inspector used the Cadweld exothermic welding process to weld the signal bond wires onto the insulated joint plugs at both St. Johns and Tamaroa.

About 9:30 a.m. on January 23, 2003, the signal inspector's supervisor called him and said the track crew needed a signal maintainer to bond the signal wires to the insulated joint plug being installed to replace the broken rail of the insulated joint plug at St. Johns. Because a signal maintainer was not available, the signal inspector did the work. He stated that about 2 weeks before installing the new bonds, he had received oral instructions that signal bond wires should be welded to the web of the rail,[19] but he did not receive written

[17] *Continuous welded rail* is rail that has been welded together into lengths exceeding 400 feet.

[18] A different mold fixture is used depending on whether the bond wires are to be welded to the head, web, or base of the rail.

[19] The *web* is the vertical section of rail between the rail head (top) and the rail base (bottom).

instructions to that effect. The signal inspector said he told the supervisor on January 23 that he did not have the mold he would need to weld the bond wires to the web. (He subsequently told accident investigators that many other signal maintainers and inspectors did not have the equipment needed to install bonds in the rail web as directed.) He asked his supervisor for instructions and was told to use what he had at hand. After cleaning the head of the rail with an electric grinder, the signal inspector used a rail bonding mold assembly to bond wires to the rail head. He finished about noon.

Also on January 23, track personnel called the signal inspector to bond the new insulated joint plug at Tamaroa. (This was the joint at which the derailment occurred about 2 1/2 weeks later.) The signal inspector used the same grinder to clean the head of the rail, then he put three Cadweld bonds on the rail head on each side of the joint just outside the limits of the joint bars.[20]

Preaccident Track Inspections

CN had last inspected the track that encompassed the point of derailment (milepost 279.95) on February 8, 2003. The track inspection was conducted, via a Hy-Rail vehicle,[21] by the relief track inspector as he traversed the track in a northward direction. No track defects were reported in the derailment area or for the entire inspection trip between mileposts 285 and 258. The relief track inspector had also inspected that area on the 2 previous days, February 6 and 7, with no track defects noted.

Investigators reviewed CN track inspection records for the period between February 2002 and February 8, 2003. Class 5 track standards under 49 CFR 213.233 require the track to be inspected twice a week; the CN track inspectors stated that they usually inspected the track area three times per week. No records were found of inspections for the week of March 3 through March 9, 2002, and for the week of April 28 through May 4, 2002. In addition, there was no inspection record for one inspection for each of following 3 weeks: February 17 through 23, 2002; February 24 through March 2, 2002; and August 11 through 17, 2002.

On May 8, 2002, an Illinois Commerce Commission track inspector inspected the track in the area of the derailment on behalf of the Federal Railroad Administration (FRA). The closest defect to the point of derailment the inspector noted was at the house track switch (at milepost 279.9). At this location, he noted an insufficient fastener condition in a 39-foot-long track segment, and he noted that ties were needed. The fastener condition was repaired on the same day, and the area supervisor stated that some switch ties were replaced in the switch about 2 weeks later and again in November 2002.

[20] Railroad officials have told the Safety Board that bond wire welds are typically placed outside the limits of joint bars because of concerns that the welding could damage to the joint insulating material and because bond wires placed away from the bars are less likely to be damaged by track maintenance equipment. (A manufacturer of insulated joints has told the Safety Board that bond wire welding does not damage the joint insulation.)

[21] A *Hy-Rail vehicle* is a highway vehicle, usually a pickup truck, fitted with wheels that allow it to travel along the tracks.

A rail defect detector car had been operated over the derailment site on November 15, 2002, to ultrasonically test the rail for internal defects. The closest rail defect detected had been at milepost 282.49, about 2 1/2 miles south of the derailment area.

The CN track geometry inspection vehicle was operated from north to south over the area of the derailment on November 19, 2002. Between milepost 279 +3,188 feet and milepost 280 +655 feet, six deviations were found, resulting in the lowering of the track classification from class 5 to class 4. The deviations included one cross-level deviation that measured 1 1/4 inches and five profile deviations (four locations that measured 1 3/8 inches and one that measured 1 5/8 inches). Per 49 CFR 213.63, the maximum allowable cross-level deviation is 1 inch for class 5 track and 1 1/4 inches for class 4 track. The maximum allowable profile deviation is 1 1/4 inches for class 5 and 2 inches for class 4.

Slow Order History

Prior to the accident, two slow orders had recently been issued in the area of the derailment. The first slow order was related to the deviations noted by the CN track geometry car on November 19, 2002. The slow order restricted freight and intermodal train speed to 60 mph. This slow order was removed as a result of repair work by December 2, 2002, and track speeds were returned to original timetable speeds. The second slow order was issued on February 7, 2003, at the house track switch. The speed restriction was issued for one train at 25 mph because of tamping maintenance in the area of a switch.

Exothermic Bond Wire Welding

Federal Regulations

Title 49 CFR Part 213, “Track Safety Standards,” does not contain guidance on rail bonding. Part 236, “Rules, Standards, and Instructions Governing the Installation, Inspection, Maintenance, and Repair of Signal and Train Control Systems, Devices, and Appliances,” does not specify placement of track circuit connectors on the head, web, or base of the rail.

Title 49 CFR 236.51, Track Circuit Requirements, subpart (a)(1), requires that track relay controlling signals shall be in a de-energized position when a rail is broken, except that it shall not be a violation of this requirement if a track circuit is energized when a break occurs between the end of rail and track circuit connector (bond). The regulation does not specify the location or placement of the track circuit bond in relation to the joint bars.

Railroad Exothermic Welding Policies, Practices, and Experience

Safety Board investigators contacted railroad engineering personnel from a variety of passenger and freight railroads, the FRA, and ERICO and inquired about their policies and experiences regarding exothermic bond wire welding.

The Amtrak deputy chief engineer of communication and signals stated that Amtrak drills holes in the rail web and inserts pin bonds to connect track circuit wires.[22] Exothermic bond wire welding is used within the area of the joint bars to provide track continuity. Amtrak's director of engineering tests and standards stated that Amtrak does not allow exothermic bond wire welding to the rail web because of anecdotal evidence that such welding creates martensite[23] that could lead to rail failures. Amtrak had no records of rail failures that had been caused by exothermic bond wire welding.

The principal engineer for signals for the Long Island Railroad stated that his company uses exothermic bond wire welding for both track circuit wires and bonding wires within the joint bars instead of drilling holes in the rail web and inserting pin bonds to connect track circuit wires. The Long Island Railroad principal engineer for track maintenance stated that rail defects caused by exothermic welds to rail heads would be noted on the ultrasonic/induction internal rail inspections records but not with a separate code. Therefore, without looking at each report, he could not determine the number of rail defects the Long Island Railroad had found at such weld sites. The railroad did not keep records to reflect service failures from exothermic welding, and the engineer was not aware of any rail failures that had been caused by exothermic bond wire welding at the rail web.

The Burlington Northern Santa Fe Railroad (BNSF) assistant vice president of signals stated that BNSF uses exothermic bond wire welding for both track circuit wire welding and joint wire welding. Track wires are installed on the rail web, and joint wires are welded on the rail head.[24] For new construction projects, track wire comes preinstalled, via pin brazing,[25] on the rail web. The BNSF director of rail stated that he did not maintain records of either rail service failures or defects detected by internal inspection that were caused by exothermic bond wire welding. He estimated that the number of rail failures caused by exothermic welding was low.

The CSX Transportation (CSX) engineer of field services stated that the CSX does not track rail defects or rail service failures caused by exothermic bond wire welding. He said he did not recall any major occurrences attributed to that type of rail defect or failure. The CSX uses exothermic bond wire welding on the head of the rail for both joint wire bonds and track circuit wire bonds.

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[22] This process involves drilling holes into the rail web at the neutral axis and pressure-fitting bond wire connections.

[23] *Martensite* is a hard and brittle crystal structure that occurs as a result of very rapid cooling (quenching) of heated steel (at about 1000º C or 1832º F per minute). Subsequent reheating of the steel to about 400º C (752º F) and holding it at this temperature for a time (tempering) produces a strong and tough steel with lower hardness and brittleness.

[24] *Track wires* are those wires that carry current to and from a trackside signal device or component. *Joint wires* are those that directly connect two sections of rail at a non-insulated joint. The presence of joint bars on either side of a joint preclude the welding of joint wires onto the rail web.

[25] *Pin brazing* is an alternative method of making electrical connections, including bond wire connections, to rails. Research conducted by Stanley Railroad Products, Inc., on the effects of high-temperature pin brazing on steel identified martensite to a depth of 1.5 millimeters (.059 inch) at pin-brazed welds.

The UP general director of derailment prevention stated that because of split rail web defects that were detected during internal rail inspections, the UP has examined its practice of exothermic bond wire welding to the rail web. The split web problems occurred primarily on the heavy-haul lines when multiple applications of exothermic bond wire welds were made near the same spot. The UP still uses exothermic bond wire welding for existing track. For new track components, such as insulated joint plugs, frogs, switch points, and stock rails, the company specifies that the component manufacturer install bonds using a low-temperature pin brazing process that does not create martensite. The UP does not track service failures from exothermic bond wire welding, but it notes on inspection reports those rail defects attributed to exothermic bond wire welding found during internal rail inspections. However, because these rail defects are not coded separately, each inspection report must be examined to determine the number of defects caused by exothermic welding.

The FRA staff director, Track Division, stated that the agency does not have a cause code[26] for derailments caused by rail failures resulting from exothermic bond wire welding and cannot quantify the number of rail defects caused by exothermic bond wire welding. For the FRA, if a derailment occurs as a result of a rail failure caused by an exothermic bond wire weld, it should be reported in a general category of “Other” for types of broken rails. CN reported the rail service failure at Tamaroa to the FRA under the “Other” code of rail failures. Specifically, it was reported as cause code T 299, “Other Rail and Joint Bar Defects.”

A spokesperson for ERICO stated that his company does not maintain a database of rail failures attributable to exothermic welded wire bonds. However, ERICO stated that when rail breaks have occurred in the area of the exothermic weld, they were most often attributed to the following:

- Application to an area that is not recommended, for example, rail head bonds applied outside the confines of a joint bar, or other rail bonds not applied at the neutral axis[27] of the rail web.
- Aggressive grinding before bonding that has left visible scratches in the rail.
- Failure to properly clean and protect the rail area where the bond will be applied, resulting in an unsatisfactory bond and necessitating repetition of the process.
- Re-bonding that overlaps an earlier bond.

[26] A *cause code* is a database number that is assigned to a specific derailment cause.

[27] The *neutral axis* of a beam is an imaginary line in the cross section of a beam at which tensile or compressive stress and strain are essentially zero. For a 115-pound rail section that is 6 5/8 inches high, the neutral axis is 2.98 inches from the bottom of the rail base.

Industry Guidance

The American Railway Engineering and Maintenance-of-Way Association (AREMA)[28] *Manual for Railway Engineering* gives the following recommended practices at Chapter 4, "Rail," Part 4, Section 4.1, "Application of Rail Bonds":

> The application of pin connected bonds or welded bonds to the outer side of the rail head, within the limits of the joint bars for standard bonding and outside of joint bars for special work where not practicable to apply them within the joint bar limits, is good practice.

In addition, the AREMA *Communications and Signals Manual*, Part 8.1.32, "Recommended Design Criteria for Copper Based Exothermically Welded Type Non-Propulsion Rail-Web Bonds and Track Circuit Connections," states, in part:

> The following shall be considered when installing exothermically welded type rail web bonds:
>
> 1. Size, bond type, length and terminal type.
>
> 2. For quality and safety, molds, bonds, exothermic welding material and installation equipment (welder, frame, clamps) shall be from the same manufacturer.
>
> 3. Follow bond manufacturer's installation, removal, and reinstallation procedures.
>
> 4. Bond terminals shall be installed on the neutral axis of the rail. (Ref. AREMA *Manual for Railway Engineering*, Chapter 4, "Rail").

The AREMA *Communications and Signals Manual*, Part 8.6.40, "Recommended Instructions for Application of Head-of-Rail Type Welded Bond," Section C5, recommends that bonding not be performed when moisture or lubricants are present on the molds, weld metal, or rail surface.

The AREMA Railroad Engineering Manual, Section 2.1, addresses the specifications for steel rails. Section 2.1.4.1, "Standard AREMA Chemistry of Rail," Part (b) "Hardness of Standard Chemistry of Rail Steel," limits the contents of martensite. Note 4 states that "no untempered martensite shall be present within the rail."

In an April 26, 1999, letter to ERICO, a CN manager who was also chairman of the joint bars subcommittee of Committee 4 of AREMA stated that Section 4.1, Chapter 4, of the AREMA Railroad Engineering Manual ("Application of Rail Bonds") was too general and that it needed a major revision to make it more specific. The letter asked ERICO for suggested language that could be added to the AREMA manual.

[28] AREMA is an industry association that sets recommended standards of practice for railroad construction and maintenance. AREMA's stated purpose is "The development and advancement of both technical and practical knowledge and recommended practices pertaining to the design, construction, and maintenance of railway infrastructure."

ERICO replied on May 10, 1999, with the following eight suggestions:

- Exothermically welded connections to the rail are to be made in accordance with the manufacturer's recommended procedures. Since the welded connection is part of a system, it is very important to have the bonds, weld metal, molds, and frames supplied by the same manufacturer.
- The exothermic weld metal shall be an alloy that is designed to weld to rail steel.
- Under no condition shall weld metal containing tin be used to make welded connections to the rail.
- The weld metal shall have a minimum tensile strength of 39,000 pounds per square inch.
- Bonds are to be exothermically welded to the head of the rail only within the confines or limits of the splice plate or joint bars.
- The maximum size bond, to be welded to the head of the rail within the confines of the splice plate [joint bars], shall be 250MCM cable with factory-formed terminals.
- Connections or bonds welded to the rail outside the confines of the splice plate or joint bars shall be welded to the web of the rail at the neutral axis.
- The maximum size bond to be welded to the web of the rail shall be 500MCM cable with a factory-formed terminal.

The CSX engineer of field services, who chairs the rail subcommittee of AREMA's Committee 4, told the Safety Board that the issue of exothermic bond wire welding had been raised at a meeting of the rail subcommittee, but the procedure had not been perceived as a problem. The suggestions from ERICO were never disseminated by AREMA in either its Railroad Engineering Manual or its *Communications and Signals Manual*.

The AREMA *Communications and Signals Manual* illustrates, at Part 8.1.30, figure 8130.1, a bond wire positioned on the rail head directly above a joint bar. Although ERICO's application standard for exothermic welds states that a weld should never be applied over a location that contains an earlier weld, unless the weld is within the confines of a joint bar, the company's Cadweld instructions did not include reference to the placement of bond welds in relation to joint bars.

ERICO's Cadweld preparation instructions for rail web bonds did not contain the rail-drying requirement found in its Cadweld preparation instructions for rail head bonds, even though both applications require the same pre-weld preparation. ERICO's Cadweld rail web bond preparation instructions did not contain a requirement that molds be clean and dry, although ERICO provides such a requirement in its preparation instructions for bonds at rail heads.

Interaction Between Track Structure and Exothermic Welds

After the Tamaroa accident, ERICO evaluated the interaction between the track structure and exothermic bond wire welding. This evaluation included developing a description of engineering facts on exothermic bonds applied to rail and a spreadsheet comparative analysis of track operating loads and stresses based on known track conditions. The company noted that railroad operational conditions have changed over the years and stated that two conditions in particular—increased axle loads and the introduction of CWR—have raised rail stress levels. The company stated that the introduction of CWR has become the most significant stress component because the increased tensile loading that occurs during cold weather is greater in CWR than in jointed rail. As noted in its May 10, 1999, letter to CN, ERICO states that for design safety, exothermic welded wire bonds outside the confines of joint bars should be applied only to the neutral axis of the rail web. It further states that bonds made in rail between joint bars should be made at the center of the rail head. These are normally the locations of lowest combined stress.

ERICO submitted to the Safety Board the results from a finite element analysis.[29] The company determined that the highest tensile stresses are in that portion of a rail head just outside the confines of joint bars. The higher stresses are caused by the change in rail stiffness from the additional steel in the joint bar. ERICO contends that this stress condition, combined with uneven tie support and thermal and other stresses, make the portion of a rail head just outside the confines of joint bars a likely site for the initiation of fatigue cracking.

CN Experience with Exothermic Bond Wire Welding

The CN division engineer stated:

> We had noticed some [rail] breakage on areas that we have either base-bonded or head-bonded with Cadweld bond … and we have looked at a couple of different methods, and one method that we looked [at] … was welding to the web, as close to the neutral as you can get it, or going to what is a newer procedure, pin brazing. So in November …, I instructed the managers of the signals communication to have his people start going to Cadweld bond on the web and … to purchase pin-brazing outfits ….

On November 7, 2002, in response to some previous rail failures, the CN division manager of signals and communication for the Gulf Division issued a maintenance bulletin directing that the practice of applying rail bonds to the head or the base of the rail be stopped immediately. Further instructions required that all bonding be done on the neutral axis of the rail with the use of pin-brazing kits.

The division engineer added that bonding onto the rail web was required for specialty track work near switches, signals, and grade crossings. He also stated that he

[29] *Finite element analysis* is the simulation of a physical system (geometry and loading environment) by a mathematical approximation of the real system. Using interrelated building blocks called elements, a real system with infinite unknowns is approximated with a finite number of unknowns.

believed that martensite was the cause of previous rail breakage. He said CN had done some testing at the interface between the bond and the parent rail material and had discovered martensite.

The division engineer also stated that ATRONA Metallurgical Services, Inc., conducted a metallurgical weld analysis on a previous CN Cadweld rail failure. ATRONA concluded:

> Welding heated the local welded regions of the surface of the base metal to temperatures above 1400º F and changed the pearlitic/ferritic original base metal's microstructure to predominantly martensitic. This was possible because the local welded surfaces were not pre-heated prior to welding or were not pre-heated to a high enough temperature. The relatively large mass of the rail effectively quenched the near melted and melted surface and solidified these surfaces very rapidly causing hardness to be dramatically increased.

The division engineer stated that internal rail testing on the CN system showed that 327 rail defects (usually cracks) had been caused by exothermic bond wire welding between January 1, 2000, and December 31, 2003. A total of 63,849 internal rail defects were recorded over the same period. CN was able to retrieve the number of exothermic bond wire welding rail defects because CN maintains a specific code for this type of defect in its database. However, service failure records did not specify which, if any, failures had occurred at the site of bond wire welds. For example, CN would not have recorded the St. Johns rail failure as a rail failure caused by exothermic bond wire welding, even though the investigation showed that this was the cause of the failure.

In the early 1990s, CN management became concerned about the traces of martensite found in the heat-affected zones at bond points. These concerns led to the testing of exothermic bond wire welds installed on the Alberta District portions of the Edison and Wainwright Subdivisions since March 1992 (Service Test MR-9210).

Service Test MR-9210 restricted application of exothermic connections to the neutral axis of the rail to avoid the higher stress areas in the rail head and base. The exothermic bond wire welding on the web of the rail was made during the period between March 1992 and July 1994 (before the purchase of the Illinois Central Railroad by CN). Based on the test results, on October 7, 1994, CN restricted the use of exothermic bond wire welds to applications not involving rail joints. Engineering personnel of the Illinois Central said they were not made aware of the CN test results or restrictions after the 1999 merger of the two railroads.

Tests and Research

Tamaroa Rail and Joint Bars

Seven pieces of rail and six joint bars (two joint bars from each end of the rail plug and two from the insulated joint) were recovered from the accident site and transported to the Safety Board Materials Laboratory in Washington, D.C., for metallurgical examination. Representatives from CN, the FRA, Rocky Mountain Steel (the rail manufacturer), L. B. Foster Company (the insulated joint plug manufacturer), and ERICO (the exothermic bond wire welding system manufacturer) were present during the laboratory examination.

The rail specimens were identified as having come from the point of derailment at milepost 279.95. A preliminary examination and matching of fracture faces determined the location of the received pieces in the assembled insulated joint. As the track was laid in a north/south direction, the north and south ends of the rail were identified.

Fracture features on the broken rail indicated that the various fractures in the rail pieces initiated from two separate locations in the head of the rail, one location just outside each end of the joint bars at the insulated joint. The cracking from each origin area separated into multiple branches, and some pieces away from the origin areas were not recovered.

Detailed examination revealed the presence of fatigue cracking at both of the fracture origin areas. The fatigue cracking initiated from bond wire welds on the field side of the rail head and propagated from the field side toward the gage side of the head. Although the exact extent of the fatigue regions could not be determined, most of the fracture features in the rail head and the web and base portions of the rails were consistent with overstress fracture in these regions.

Examination of the broken field side joint bar at the south end of the insulated joint plug showed that the joint bar fractured primarily due to overstress, originating from a small fatigue crack at the bottom of the bar. No evidence of any type of defect was noted at the fatigue origin area. The gage side joint bar at the south end of the insulated joint was intact but slightly bent.

Tamaroa Signal Bond Wires and Welds

Visual examination showed that the eight bond wire welds in the insulated joint assembly[30] contained varying degrees of porosity. Sectioning of the bond wire welds as part of the Materials Laboratory examinations revealed three welds with a single heat-affected zone below all the weld material, three welds with two heat-affected zones below the weld material, one weld with a heat-affected zone below only a portion of the weld material, and one weld that was missing most of the weld material and had a single heat-affected zone that was split by a fracture. The maximum depth of the heat-affected zones varied between 0.032 inch and 0.058 inch. Some of the welds also displayed a loss of weld material, a loss of portions of the heat-affected zone at the weld/rail interface, and cracks propagating within the heat-affected zones. Both of the fatigue origin areas were at welds on the side of the rail head. Portions of the heat-affected zones were missing from these two welds. The shape of the missing portions matched the shape of the cracks observed within other heat-affected zones. The extra etching required to reveal the microstructure of

[30] At the same time the welder placed the three welds on either side of the insulated joint, he also welded bond wires at the ends of the plug to provide continuity between the new plug rail and the existing rail. The insulated joint plug thus had a total of eight bond wire welds.

the heat-affected zones, the microstructure of the heat-affected zones, and the hardness in the heat-affected zones—in the 60 to 66 HRC[31] range—indicate that the heat-affected zones were hard and brittle and consisted mostly of untempered martensite. In comparison, a high-speed steel, designated "M2" and used to produce metal cutting tools, has a hardness of 63 to 65 HRC, and untempered martensite in a steel with 0.80 percent carbon (such as the rail in this accident) is about 67 HRC.[32]

Demonstration Cadweld Welds

Many iron-based alloys that are brought to a high temperature then quenched (quickly cooled) become hard but brittle. Reheating the same metal to a lower temperature "tempers" it, making it slightly less hard but much less brittle. Cadweld literature describes this two-step process of quenching and reheating and states that Cadweld exothermic welding (which has no reheating step) produces a quenched and tempered thermal cycle that reduces the material's hardness and increases its toughness. The literature suggests that the tempering is produced by two possible sources, (1) the flow of heat from the very hot weld nugget to the rail or (2) the relatively slow rate of cooling of the martensitic layer. The process literature states that "while the degree of tempering … is not large, it is sufficiently high to reduce the brittleness …."

After the accident, under controlled laboratory conditions, a representative from ERICO applied three Cadweld exothermic bond welds to the head of a rail.[33] The rail and mold were preheated as specified, and the resultant welds were of a uniform shape. Sectioning of these welds showed a distinct lack of porosity and that two of the three welds displayed a significant heat-affected zone below the weld material, while one displayed a heat-affected zone below about 50 percent of the weld material. The extra etching required to bring out the structure in the heat-affected zones and their high hardness—in the same 60 to 66 HRC range as the insulated joint welds—were consistent with untempered martensite. The maximum depth of the heat-affected zones was between 0.037 inch and 0.043 inch, which was similar to the size of the heat-affected zones in the Tamaroa bond wire welds.

St. Johns Rail Fracture

The Safety Board's Materials Laboratory examined the three St. Johns rail bond wire welds. All were at the top of the rail base, which, like the rail head, is a highly stressed portion of the rail. The rail fracture was found to have been caused by fatigue cracking that initiated in the bond wire weld closest to the end of the joint bar. Sectioning of this weld showed the presence of a heat-affected zone from a previous weld location (a re-bond). The heat input associated with the second weld apparently tempered a portion of the untempered martensite associated with the original weld. The fatigue cracking that led to the rail fracture initiated at the toe of the brittle heat-affected zone associated with the more recent weld and propagated perpendicularly through the tempered heat-affected zone into the rail base. The orientation of this weld was transverse to the rail and to the other

[31] Hardness, Rockwell "C" scale.

[32] *Metals Handbook*, Desk Edition, 1985, p. 29-9, Figure 4.

[33] A section of the rail from the insulated plug involved in the accident was used for this test.

two welds. The microstructure of the heat-affected zones beneath the other welds was consistent with untempered martensite.

All the St. Johns welds displayed severe porosity and dissimilar heat-affected zones. The proportions of the St. Johns welds suggest that they were made with a mold that was different from the mold used for the previously examined Tamaroa welds.

Postaccident Developments

On February 19, 2003, the CN division manager issued a maintenance bulletin giving details about bond wire welding. The maintenance bulletin stated, in part:

> The suspected cause of the recent derailment on the Centralia Subdivision is a Cadweld bond to the head of the rail at a glued insulated joint location.
>
> Therefore effective immediately, Cadweld bonds will only be applied to the web of the rail. The only exceptions are as follows. One is in jointed rail territory where head to head bonds may be used as the joint bars provide a degree of broken rail protection. The other exception is in special track work components such as the heel of a frog. In these circumstances it is recommended that the Division Manager of S&C be consulted.
>
> Due to the undesirable microstructure (martensite) left by Cadweld bonding, it is highly recommended that each Division make plans to migrate as soon as possible from Cadweld bonding towards pin brazing.

Since the issuance of the February 19, 2003, maintenance bulletin, CN has used only the pin-brazing process.

As has been noted in the report, an Allegheny insulated rail joint at St. Johns (milepost 285.5), similar to the one in the Tamaroa derailment area, had been installed on January 23, 2003, and the signal bond wires were exothermically welded on the rail head, contrary to the November 7, 2002, maintenance bulletin that had prohibited the practice. On February 19, 2003, Safety Board investigators informed the CN track supervisor of the similarities between the insulated joint at Tamaroa that appeared to have failed and the one at St. Johns. The CN track supervisor told investigators that he would have the insulated joint changed out, and it was replaced on February 27, 2003. The bond wires were pin brazed onto the web of the replacement rail at or near the neutral axis.

Environmental Response

The leaking tank cars discharged methanol, vinyl chloride, formaldehyde, and hydrochloric acid. Remediation activities consisted of open excavation, removal of contaminated soil, and groundwater investigation. Six groundwater-monitoring wells were installed to monitor possible transient migration of the spill contaminants though the soil. Several shallow residential wells also were monitored. No contaminants related to the derailment were detected through any of the monitoring efforts.

Analysis

The Accident

CN train M33371 was a regularly scheduled northbound freight train. There was nothing remarkable about the train makeup, which at the time of the derailment was 2 locomotives, 76 loaded cars, and 32 empties.

As the train approached Tamaroa on the morning of February 9, 2003, the crew was operating the train at a recorded speed of 40 mph, about 10 mph below the maximum authorized speed of 50 mph. Without warning, shortly after 9:00 a.m., the 28th through 49th cars in the train derailed, and the train emergency brakes automatically applied. When the train crew realized that the train had derailed, they quickly notified the train dispatcher that the derailed train contained hazardous materials, and that some material had been released and started a fire.

State and local emergency response organizations arrived at the scene quickly and provided timely and effective response actions. Because of the derailment of 19 hazardous materials cars, about 850 residents were evacuated from the area within a radius of 3 miles around the derailment, which included the entire village of Tamaroa. The Safety Board concludes that the response to the accident by emergency personnel and the train crew was timely and effective, and enhanced the safety of the community.

Investigators studied and excavated the footprint of the derailment and determined that the point of derailment was on the east rail of the main track of an Allegheny insulated joint plug at milepost 279.95.

Track Condition and Maintenance

The point of derailment was characterized by at least two CN track maintenance employees as an area that was “pumping” mud. As long as the track movement that caused the pumping did not exceed the dimensions set forth in 49 CFR 213.63, “Track Surface,” track inspectors would not record a track surface defect for this condition. In addition, postaccident measurements did not reflect a track surface defect at or approaching the point of derailment. But mud pumping would indicate that the track bed, ballast, and ties were not fully supporting the track structure under load. Without this support, the rail would be subject to significant flexing with each passage of a train, and this flexing would greatly increase the stress on the rail. The Safety Board concludes that the known soft ballast condition in the area of the insulated joint increased the amount of rail flexing in that area which, in turn, significantly increased stresses in the rail.

The Gulf Division engineer determined that some past rail failures on the division had been caused by untempered martensite created by Cadweld exothermic bond wire welding at the rail base and rail head. In response to this finding, the division signals manager, on November 7, 2002, issued instructions that, for work typical of the insulated joint plug installation at Tamaroa, signal bond wires were to be welded only at the neutral axis of the rail web. Signal maintenance employees were told to use Cadweld equipment to weld the wires to the web until new pin-brazing equipment was purchased.

In January 2003, insulated joint plugs were replaced at Tamaroa and St. Johns. At that time, not all CN signal maintenance employees had been provided with the correct equipment, either for Cadweld welding to the rail web or for pin brazing. When the bond wire welding was conducted at Tamaroa and St. Johns (for the replacement plug), the signal inspector was instructed to use what he had available. Because he did not have the equipment necessary to place welds at the neutral axis of the rail, he was authorized by his supervisor to exothermically weld the bond wires to the head of the rail at both locations. The Safety Board therefore concludes that the placement of the bond wire welds at Tamaroa, which was authorized by a CN signals supervisor, was not in accordance with the company's exothermic bond wire welding policy that had been promulgated 2 months before.

Rail Failure

Laboratory examination of the rail from the area of the derailment revealed the presence of untempered martensite at the weld points for the signal bond wires. These weld points were thus hard and brittle, and their presence on the rail head—a high-stress area—likely contributed to the development of fatigue cracking at those sites. The Safety Board concludes that fatigue cracks developed in the rail from areas of untempered martensite at points where bond wires had been exothermically welded to the rail head.

The fatigue cracking was likely accelerated by abnormal flexing of the rail under load as a result of inadequate underlying track support. The likelihood of such abnormal flexing was indicated by a CN signal maintainer's statements that, under wet conditions, mud would be pumped from underneath the joint and splashed onto nearby signal equipment. This suggests that during the passage of a train's wheels, the track would flex downward, then spring back after passage of the wheels, then flex downward again as the next set of wheels loaded the joint. Thus, as a train passed over the joint, any mud and water on the track bed would alternately be drawn into and then discharged from the depressions under the ties. The fatigue cracking on both sides of the insulated joint and the fatigue cracking of the field side joint bar at the south end of the joint plug found during the postaccident inspection suggest significant rail flexing at the joint. The Safety Board concludes that the increased stresses due to the flexing of the rail in the area of the insulated joint caused the propagation of the cracks that had originated in areas of untempered martensite at the rail head, causing the rail to fail only 17 days after installation.

Examination of Welding Procedure Documents

A review of ERICO guidance documents applicable to bond welds revealed some omissions and contradictions that, if the instructions in these documents were used to direct the welding process, could affect the integrity of the weld or the steel at the weld site.

For example, effective bond welding requires that the rail be dried before application of the bond wires. However, ERICO's Cadweld preparation instructions for rail web bonds did not contain the rail-drying requirement found in its Cadweld preparation instructions for rail head bonds, even though both applications require the same pre-weld preparation. AREMA's *Communications and Signals Manual*, Part 8.6.40, Section C5, also recommends that bonding not be performed when moisture or lubricants are present on the molds, weld metal, or rail surface. Further, ERICO's Cadweld rail web bond preparation instructions did not contain a requirement that molds be clean and dry, although ERICO provides such a requirement in its preparation instructions for bonds at rail heads, and such a requirement is appropriate for all applications.

To reduce stresses in the weld areas, bond welds at the rail head must be placed above the joint bars. The Cadweld rail head bond instructions, however, illustrate the fixture on a rail head without any reference to the joint bars. In contrast, the AREMA *Communications and Signals Manual*, at Part 8.1.30, figure 8130.1, properly illustrates a bond wire positioned on a rail head directly above a joint bar. Thus, the Safety Board concludes that ERICO's exothermic bond wire welding application literature was not entirely consistent with recommended industry practices.

ERICO's Cadweld instructions did not warn against placing a rail head bond outside the confines of a joint bar, despite the fact that ERICO's own May 10, 1999, list of items to include in AREMA guidance included the statement that "bonds are to be exothermically welded to the head of the rail only within the confines or limits of the splice plate or joint bars." ERICO's Cadweld instructions also did not specifically warn against putting a bond weld outside the confines of the joint bar on the rail base, although in its May 10, 1999, guidance to AREMA, ERICO stated that "bonds welded to the rail outside the confines of the splice plate or joint bars shall be welded to the web of the rail at the neutral axis." (In the case of the broken St. Johns insulated joint plug that was replaced in January 2003, the exothermic bond wire welds were made both outside the confines of the joint bar and on the rail base with equipment supplied by ERICO.)

The Safety Board's document review also revealed that some ERICO guidance literature contained statements that were proven inaccurate by the results of the demonstration welds that ERICO made as part of the accident investigation. Specifically, although the Cadweld process literature stated that the Cadweld process produces a quenched and tempered thermal cycle that tempers the steel and reduces its hardness sufficiently to result in reduced brittleness, Safety Board examination of eight bond wire welds from Tamaroa and three welds from St. Johns found heat-affected zones with structures consistent with untempered martensite. Analysis of a failed CN Cadweld weld performed for CN by a metallurgical testing laboratory also revealed an untempered martensitic structure beneath the weld. Finally, the hardness of the heat-affected zones in the demonstration welds that ERICO produced for the Safety Board was found to be near the maximum hardness associated with untempered martensite. The Safety Board therefore concludes that laboratory tests and examination of field welds indicate that little or no tempering of the affected steel occurs during the exothermic welding process. A re-bonded weld on the St. Johns rail did show a reduction in hardness and therefore a tempered martensite structure, suggesting that only a second heating process will truly temper the steels at exothermic welds.

At Chapter 4, "Rail," Part 4, Section 4.1, "Application of Rail Bonds," the AREMA Railroad Engineering Manual states:

> The application of pin connected bonds or welded bonds to the outer side of the rail head, within the limits of the joint bars for standard bonding and outside the joint bars for special work where not practicable to apply them within the joint bar limits, is good practice.

But, as can be seen in the Tamaroa accident, placing welds on the rail head at locations outside joint bars is never good practice. Untempered martensite at such locations may create fatigue cracking that can propagate especially rapidly if, as at Tamaroa, track conditions allow greater-than-normal rail flexing.

On May 10, 1999, ERICO sent AREMA recommendations for proper exothermic bond wire welding for inclusion in the AREMA Railroad Engineering Manual. Two of ERICO's recommendations addressed placement of the welds. First, ERICO stated that exothermic bond wire welded connections should only be placed on the rail head within the confines or limits of the joint bars. Second, ERICO stated that exothermic bond wire welded connections required outside of the joint bars should be welded to the rail web at the neutral axis. AREMA has not yet revised its manual to include this guidance. Therefore, the Safety Board concludes that the AREMA Railroad Engineering Manual does not adequately address the proper placement of exothermic bond wire welds.

Therefore, the Safety Board believes that ERICO should revise the instructions for its Cadweld welding systems to address the proper placement of exothermic bond wire welds, especially in the vicinity of joint bars, and to make users aware that these welds create untempered martensite that could, under certain conditions, lead to fatigue cracking and rail failure. The Safety Board further believes that AREMA should modify its Railroad Engineering Manual and/or its *Communications and Signals Manual* so both address the proper placement of exothermic bond wire welds and high-temperature pin-brazings and to include information that these welds and brazings create untempered martensite that could, under certain conditions, lead to fatigue cracking and rail failure.

Rail Failure Tracking

Reviewing its internal rail inspections for a 3-year period, CN found that 327 rail defects (0.5 percent of all CN rail defects)[34] on its system had been caused by exothermic bond wire welding. However, CN did not track the rail service *failures* that such welding may have caused. CN reported the rail service failure at Tamaroa (which caused the derailment) to the FRA under a catch-all code of "Other" rail failures.

The size and extent of the exothermic bond wire welding rail defect problem throughout the railroad industry cannot be evaluated, because most railroads and the FRA do not record which rail defects or rail service failures may have resulted from exothermic bond wire welding. Some railroads have stopped performing exothermic welding at the rail web because they were detecting internal rail defects caused by the weld.

The Safety Board concludes that because most current rail failure tracking methods do not record the cause of rail failures that may have occurred at locations where bond wires have been welded or brazed, no adequate evaluation can be made of the effects of these welds on rail integrity in the U.S. rail system. Therefore, to permit an evaluation of the effects of exothermic bond wire welding on rail integrity across the U.S. rail system, the Safety Board believes that the FRA should require in 49 CFR Part 213, "Track Safety Standards," that rail cracks originating from bond wire attachments be identified as rail defects and that information be collected on the methods and locations of those attachments. The Safety Board further believes that the FRA should require in 49 CFR Part 225, "Guide for Preparing Accident/Incident Reports," that derailments caused by rail cracks originating from bond wire attachments be reported with a specific cause code and that information on the methods and locations of those attachments be provided in the accident narrative.

Tank Car Survivability

In this accident, five tank cars containing vinyl chloride, a highly flammable and reactive gas, derailed. These cars were all pressure tank cars that had head shields and thicker tank walls than general service cars. Only one of the pressure tank cars was breached, the result of a relatively small puncture that likely occurred when the car struck the elevated end of a broken rail. Because of the speed of the derailing car and the small impact area, the tank was subjected to a concentrated force that the tank would not be expected to withstand.

Of the 14 general service tank cars that derailed, 7 failed. The failed cars contained materials that are rated less hazardous than the vinyl chloride carried in the pressure cars. Two tank cars leaked flammable liquids (methanol and formaldehyde) through damaged fittings. Four tank cars had punctures or tears in their heads or sidewalls, releasing flammable or corrosive liquids (methanol and hydrochloric acid, respectively). The

[34] These were defects that were corrected before they led to failures.

remaining tank car lost product through a compromised section of the shell. This damage likely occurred as a result of heat from the post-derailment fire that melted a portion of the tank's interior rubber liner and subjected the steel shell to the corrosive effects of the acid.

As a result of accident investigations and Safety Board safety recommendations, the DOT issued regulations requiring shelf couplers and head shields to reduce punctures on tank cars transporting liquefied flammable gases and anhydrous ammonia (a toxic nonflammable liquefied gas). In 1995, also as a result of safety recommendations, the DOT issued tank head puncture-resistance requirements for tank cars transporting any liquefied gas and tank cars constructed of aluminum or nickel and used to transport hazardous materials. Additionally, commencing in July 2006, certain other high-risk hazardous materials, such as those that are poisonous-by-inhalation or designated by the Environmental Protection Agency to pose unusual environmental and health risks, will have to be transported in pressure tank cars that perform better in accidents than general service tank cars that are authorized today.

Conclusions

Findings

1. The response to the accident by emergency personnel and the train crew was timely and effective, and enhanced the safety of the community.

2. Fatigue cracks developed in the rail from areas of untempered martensite at points where bond wires had been exothermically welded to the rail head.

3. The placement of the bond wire welds at Tamaroa, which was authorized by a Canadian National signals supervisor, was not in accordance with the company's exothermic bond wire welding policy that had been promulgated 2 months before.

4. The known soft ballast condition in the area of the insulated joint increased the amount of rail flexing in that area which, in turn, significantly increased stresses in the rail.

5. The increased stresses due to the flexing of the rail in the area of the insulated joint caused the propagation of the cracks that had originated in areas of untempered martensite at the rail head, causing the rail to fail only 17 days after installation.

6. ERICO Products, Inc., exothermic bond wire welding application literature was not entirely consistent with recommended industry practices.

7. Laboratory tests and examination of field welds indicate that little or no tempering of the affected steel occurs during the exothermic welding process.

8. The American Railway Engineering and Maintenance-of-Way Association Manual for Railway Engineering does not adequately address the proper placement of bond wire welds.

9. Because most current rail failure tracking methods do not record the cause of rail failures that may have occurred at locations where bond wires have been welded or brazed, no adequate evaluation can be made of the effects of these welds on rail integrity in the U.S. rail system.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the February 9, 2003, derailment of Canadian National train M33371 in Tamaroa, Illinois, was Canadian National's placement of bond wire welds on the head of the rail just outside the joint bars, where untempered martensite associated with the welds led to fatigue and subsequent cracking that, because of increased stresses associated with known soft ballast conditions, rapidly progressed to rail failure.

Recommendations

As a result of its investigation of the February 9, 2003, Canadian National freight train derailment at Tamaroa, Illinois, the National Transportation Safety Board makes the following safety recommendations:

To the Federal Railroad Administration:

Require in 49 *Code of Federal Regulations* Part 213, "Track Safety Standards," that rail cracks originating from bond wire attachments be identified as rail defects and that information be collected on the methods and locations of those attachments. (R-05-01)

Require in 49 *Code of Federal Regulations* Part 225, "Guide for Preparing Accident/Incident Reports," that derailments caused by rail cracks originating from bond wire attachments be reported with a specific cause code and that information on the methods and locations of those attachments be provided in the accident narrative. (R-05-02)

To ERICO Products, Inc.:

Revise the instructions for your Cadweld welding systems to address the proper placement of exothermic bond wire welds, especially in the vicinity of joint bars, and to make users aware that these welds create untempered martensite that could, under certain conditions, lead to fatigue cracking and rail failure. (R-05-03)

To the American Railway Engineering and Maintenance-of-Way Association:

Modify your Railroad Engineering Manual and/or your *Communications and Signals Manual* so both address the proper placement of exothermic bond wire welds and high-temperature pin-brazings and to include information that these welds and brazings create untempered martensite that could, under certain conditions, lead to fatigue cracking and rail failure. (R-05-04)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

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Adopted: January 25, 2005

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Appendix A

Investigation

The Safety Board was notified about 11:00 a.m. eastern standard time on Sunday, February 9, 2003, that a Canadian National/Illinois Central Railroad (as the Canadian National Railroad was then known) freight train had derailed and subsequently released hazardous materials that required the evacuation of residents of Tamaroa, Illinois. The Safety Board launched an accident investigation team to the site. The team included investigators for multiple disciplines: an investigator for operations and mechanical; an investigator for track, signals, and engineering; and an investigator for hazardous materials. Investigators from vehicle performance, hazardous material environmental response, and metallurgical analysis supported the continuing investigation in Washington, D.C. No Board Member was on scene.

Parties to the investigation included the Federal Railroad Administration, the Canadian National Railroad, the Brotherhood of Locomotive Engineers, and ERICO Products, Inc.

The Safety Board conducted interviews as part of its investigation. The interviews were held during the on-scene segment of the investigation, and more interviews were conducted at Canadian National's U.S. region headquarters in Homewood, Illinois, and at Safety Board headquarters in Washington, D.C.