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Quantification of the Effectiveness of Low Solar Absorptivity Coatings for Reducing Rail Temperature

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George W. Ritter (Edison Welding Institute), Leith Al-Nazer (Federal Railroad Administration)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Edison Welding Institute (EWI)
1250 Arthur E. Adams Drive
Columbus, OH 43221

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13. ABSTRACT (Maximum 200 words)
Due to the thermal expansion properties of steel, the risk that a track will buckle increases as the temperature of the rails increase. Therefore, it is desirable to keep rail temperature as low as possible, especially on hot summer days. Empirical data and modeling has shown that on such days, the peak temperature of the rail could reach as high as (or slightly exceed) 35 degrees Fahrenheit above the peak ambient temperature. If the peak ambient temperature for a given day is 100 degrees Fahrenheit, for example, then the peak rail temperature can be expected to be approximately 135 degrees Fahrenheit, provided there is little cloud cover and no precipitation. This project’s objective was to quantify the effectiveness of various low solar absorption coatings for reducing rail temperature, thereby reducing the risk of track buckling. The results indicate that some of the coatings tested can significantly reduce the temperature of a rail when the coated rail is compared to the temperature of an uncoated rail. However, further studies are needed to ensure the durability of these materials when applied to in-service track.

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Track buckling, sun kink, rail neutral temperature, low solar absorption coating, thermal reflective coating

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

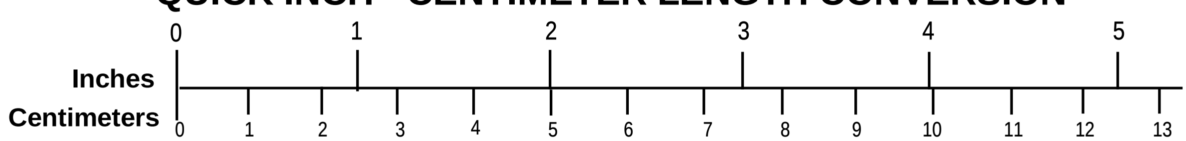
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Track buckles are a serious safety and economic concern for the railroad industry as they often result in a train derailment. Every summer, there are a number of track buckle (or "sun kink") derailments that cost the railroad industry millions of dollars. For example, in 2014, there were 14 track buckle-related derailments that resulted in over 23 million dollars in damages to track and equipment.

Continuous Welded Rail (CWR) is typically laid with a neutral temperature, called the rail neutral temperature (RNT). The target RNT varies by railroad and geographical location. Due to the thermal properties of steel, rail expands as its temperature increases. Therefore, when the rail temperature is below the RNT, the rail is in tension, and when the rail temperature is above the RNT, the rail is in compression. As the rail temperature increases above the RNT, more and more compression stresses are built up, and the potential for track instability and a track buckle (or lateral misalignment) increases.

With that in mind, this project's objective was to quantify the effectiveness of low solar absorptivity coatings for rail. If one or more of the coatings was effective, they could be applied to rail at locations which are prone to buckling and sun kink (as doing so would lower the rail temperature thereby decreasing the buckling risk). Due to past experience, railroads generally know where the high risk spots are for track buckles and they also know that most track buckles occur near fixed structures. At fixed points, such as grade crossings or open deck bridges, the rail is constrained and cannot move longitudinally along the track; therefore, such areas are prone to developing high compressive forces.

In the first phase, the project identified commercially available coatings to use in the study then test them on small steel plates. Next, the project applied five of the best performing coatings to four foot long rail samples instrumented with multiple thermocouples. The rails were placed outdoors, and the temperatures of each of the rails was monitored over a five month period and compared to the temperature of an uncoated rail.

Overall, the coatings had a significant impact on the temperature of the rails on which they were applied. Some of the coatings were more efficient at reducing rail temperature than others:

- Sherman-Williams® latex tan paints showed a slight reduction in maximum daily rail temperatures when compared to the maximum daily rail temperature of an uncoated rail.
- Precision Coatings® Reflect 3000, which is used in other civil engineering applications, such as on rooftops, proved to be more effective at reducing rail temperature than the Sherman-Williams® latex tan paints.
- The two inorganic coatings, namely EonCoat® and RailShield® Alkyd, were the best performers. Both of these coatings decreased maximum daily rail temperature by greater than ten degrees Fahrenheit when compared to the maximum daily temperature of an uncoated rail.

Future projects may apply one or more of these coatings to in-service rail to determine if they maintain mechanical integrity when exposed to the harsh railroad environment, which can cause

the deformation of rail under load and generate higher-frequency vibrations that may occur due to impact loads.

1. Introduction

1.1 Background and Objectives

Continuously Welded Rail (CWR) is laid with a neutral temperature, called the rail neutral temperature (RNT). The target RNT varies by railroad and geographical location. Typically, the target RNT is around 100 degrees Fahrenheit (° F).

Due to the thermal properties of steel, rail expands as its temperature increases. Therefore, when the rail temperature is below the RNT, the rail is in tension, and when the rail temperature is above the RNT, the rail is in compression. As the rail temperature increases above the RNT, more and more compression stresses are built up, and the potential for track instability and a track buckle increases.[1] Therefore, it is desirable to keep rail temperatures as low as possible, especially on hot summer days. Empirical data and modeling has shown that on such days, the peak temperature of the rail could reach as high as (or slightly exceed) 35° F above the peak ambient temperature. If the maximum ambient temperature for a given day is 100° F, for example, then the maximum rail temperature can be expected to be approximately 135° F, provided there is little cloud cover and no precipitation.

Track buckles are serious safety and economic concerns for the railroad industry since they often cause train derailments. Every summer, track buckle derailments cost the railroad industry millions of dollars. For example, there were 14 track buckle-related derailments in 2014 that led to more than $23 million worth of damage to tracks and other equipment.[2] Figure 1 shows a plot of the number of track buckle derailments that occurred each calendar year between 1990 and 2014.

[1] The theoretical foundations for this "buckling" phenomenon are put forth in introductory books on mechanics of materials, such as *Mechanics of Materials (Third Edition)* by Roy R. Craig and *Strength of Materials* by J.P. Den Hartog.

[2] These numbers were obtained by looking at the T109 cause code (Track Alignment Irregular – Buckled/Sunkink) incidents on FRA's safety data website (http://safetydata.fra.dot.gov/OfficeofSafety/Default.aspx). The costs only include direct damage to track and equipment; they do not include indirect costs, such as costs associated with lost revenue due to the track being out of service for a derailment clean-up.

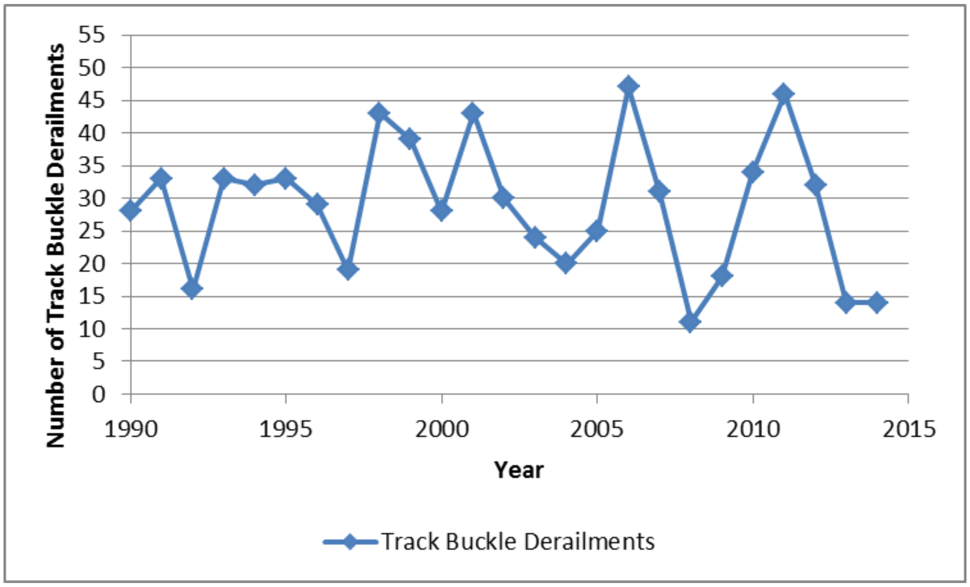

Figure 1. Number of track buckle derailments per year from1990 through 2014

As seen in Figure 1, there are significant variations in the number of track buckles from year to year. The project hypothesized that the variation of summer ambient temperatures from year to year caused the variation in track buckle derailments. To investigate this hypothesis, databases maintained by the National Oceanic and Atmospheric Administration (NOAA) were queried. NOAA maintains over 1200 weather stations throughout the United States in their Historical Climatology Network (HCN). A coding script was written to query the NOAA HCN database and extract the maximum daily temperature for each weather station for every day in July and August from calendar years 1990 through 2014. All the days from July and August for each site were averaged and after that, all the sites were averaged together. The result was a single data point for each year that represents the average maximum daily temperature for the contiguous United States. The red plot in Figure 2 shows the resulting average maximum daily ambient temperature, and the blue plot represents the number of track buckles in July and August for each calendar year.[3]

[3] Note that the blue plot in Figure 2 is not equivalent to the blue plot in Figure 1 as the blue plot in Figure 1 represents all the track buckles in the calendar year, whereas the blue plot in Figure 2 only represents the track buckles that occurred in July and August of the respective calendar year.

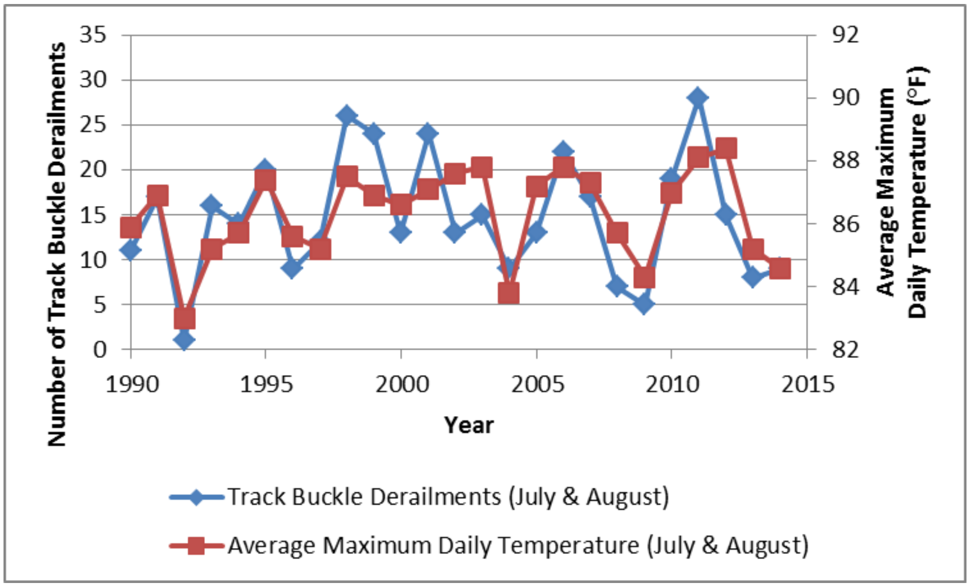

Figure 2. Number of track buckle derailments and the average maximum daily temperature for the contiguous United States for July and August of each year from 1990 through 2014

Figure 2 shows a strong correlation between the red and blue plots. The correlation coefficient was calculated and was found to be 0.77. Using a paired student's t-test, it can be shown that this correlation value is statistically significant given that there are 25 pairs of data points (one pair of data points for each year from 1990 through 2014). Figure 3 shows the same data presented in a scatter plot form. In scatter plot form, the correlation is evident as there is a clear linear trend line that can be fitted to the data points.

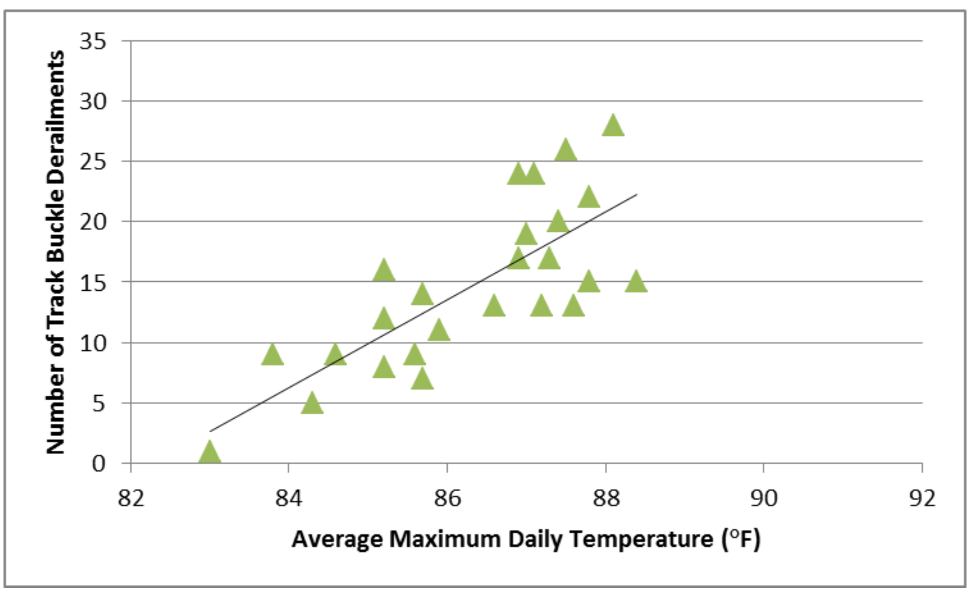

Figure 3. Average maximum daily temperature in the contiguous United States for July and August versus the number of track buckle derailments in July and August from 1990 through 2014

In Figure 3, it is evident that when the summer months of July and August have an average maximum daily ambient temperature in the low 80s, there are a low number of buckle derailments. Conversely, there are a significantly larger number of buckle derailments in years where the summer months of July and August have an average maximum daily temperature in the upper 80s. This data led to the assumption that the average maximum daily rail temperature increases as the average maximum daily ambient temperature increases. Also, it was hypothesized that a relatively small reduction (for example, 10° F) in maximum daily rail temperature may reduce the number of track buckle related derailments.

1.2 Objectives

This project's objective was to quantify the effectiveness of low solar absorptivity coatings for rail. If one or more of the coatings was found to be effective, they could potentially be applied to rail at locations which are prone to buckling, which would lower the rail temperature and reduce the risk of buckling. The high risk spots are for track buckles are known to railroads, which have past experience and are aware that most track buckles occur near fixed structures. At fixed locations, such as grade crossings or open deck bridges, the rail is constrained and cannot move longitudinally along the track; therefore, such areas are prone to developing high compressive forces.[4]

1.3 Organization of the Report

Section 2 of the report outlines the data collection effort and discusses the experimental steps that were taken. Section 3 contains the results from the data collection effort. Section 4 discusses potential future work and provides some concluding remarks.

[4] The effect of boundary conditions on physical systems is outlined in introductory books on boundary value problems, such as *Elementary Differential Equations and Boundary Value Problems (Tenth Edition)* by William E. Boyce and Richard C. DiPrima.

2. Data Collection

First, the team identified commercially available coatings to use in the study and tested all of the coatings on small steel plates. This effort is documented in Section 2.1.

Second, five of the best performing coatings were chosen and each coating was applied to four foot long rail samples instrumented with multiple thermocouples. The temperatures of each rail was monitored and compared to an uncoated rail. In addition, the effect of dirt and grime on the performance of the coating was considered. This effort is documented in Section 2.2.

2.1 Research and Identify Coatings and Perform Lab Tests

2.1.1 Identify Commercial Low-Solar Absorptivity Coatings

Objects are heated by absorption of infrared energy. The project's primary spectral region of interest spans 0.9 to 3.0 microns; this region contains infrared radiation primarily responsible for heat gain by solid objects. Therefore, literature and Internet searches were conducted to identify potential technologies or materials that could be useful for rejecting infrared radiation away from steel.

Two distinct commercial approaches were found. The first approach consists of coatings used in civil engineering for heat rejection; these coatings are mostly used on rooftops or structure walls in hot climates. Two specific products were chosen from this category for testing:

- Precision Coatings' Reflect 3000 Coating ® and DTM 1300 Primer System
- Nutech's NXT Cool Zone Coating ® and Nutech Metal Primer

In late 2013, these two products ranged in price from $40 to $50 per gallon.

The second approach employed research by the National Aeronautics and Space Administration (NASA) into heat rejection for satellites and spacecraft. The NASA-based technology uses small, hollow ceramic spheres called microballoons to reduce the infrared reflectance of a paint material and improve its heat rejection. They are commercially available under the name Hytech Additive Microballoons®. In this study, the microballoons were mixed with high performance architectural Sherwin-Williams® paint (although other paints could have been substituted). Retail pricing for the Sherwin-Williams® paint was approximately $100 in late 2013. One-half pound of the microballoons should be added to a gallon of paint, and the approximate cost for one-half pound of microballoons was $13.

Besides the first two approaches (microballoons and coatings from civil engineering applications), three inorganic based coatings were also included because it was believed that they may have beneficial solar absorption properties:

- EonCoat®
- RailShield® Alkyd
- RailShield® Latex

Bulk pricing for EonCoat® falls is approximately $125 per gallon. The two RailShield® products are still experimental, but they could be commercialized in the future.

Except for EonCoat® and RailShield®, the coating systems are available in a variety of colors. In general, lighter colors were selected for this study. In addition, each product comes with a preferred method of application. For example, the best approach to applying Precision Coatings® and Nutech® products is:

1. Gritblast the steel
2. Apply a matching primer
3. Apply two coats of the topcoat product

However, application in the field would involve minimal surface preparation in order to apply the coating quickly and efficiently, and extra coating operations require more material and labor costs.

Therefore, a test matrix was developed to manage different levels of treatment complexity as the team tested coatings on steel plates. The test matrix is shown in Table 1.[5]

[5] The RailShield® products are not included in Table 1 because they were not available at the beginning of the study for infrared testing on small steel plates.

Table 1. Matrix of test cases for lab testing of steel plates

Supplier	Material System	Surface Preparation and Application		
		Primer	**First Coat**	**Second Coat**
	Bare Steel			
	Rusty Steel			
Precision Coatings®	Reflect 3000 Coating		✓	
		✓	✓	
		✓	✓	✓
Nutech®	NXT Coating		✓	
		✓	✓	
Hytech® Additive Balloons	Balloons only		✓	
	Mixed with Sherman-Williams® Tan Paint		✓	
	Mixed with Sherman-Williams® Gray Paint		✓	
Sherman-Williams® Paint	Tan Paint		✓	
	Gray Paint		✓	
EonCoat		*Provided by manufacturer*		

2.1.2 Preparation of Steel Plate Samples

Small steel plates were used for lab testing rather than full size rails. The Precision Coating® primer and topcoat materials arrived thinned for spray and they were applied to several of the steel plate samples with a simple spray apparatus. For normal applications, a syphon gun with atomizer cap works very well. Both the Precision Coating® primer and coating contain solvents, so the syphon gun and equipment must be cleaned with paint thinner. The Precision Coating® materials are low volatile organic content (VOC), but cannot be considered waterborne. The RailShield® products can also be applied using a syphon gun.

All other materials are waterborne. The Nutech® system is quite viscous and was applied best using rollers. The Hytech® microballoons dispersed easily into the Sherman-Williams® paints using a high shear mixer blade and electric drill. The coating was then applied using rollers. After three weeks standing, there was no evidence that the microballoons had separated from the paint. EonCoat® was applied by the manufacturer using a two-component spray system with an in-head mixing apparatus.

2.1.3 *Infrared Reflectance Spectroscopy*

Infrared spectroscopy is typically used for characterizing molecular structure. However, the instrumentation can also measure heat reflection (or absorption) versus infrared wavelength. For the project's purposes, the region of interest is 0.9 to 3.0 microns. This technique uses a mirror to bounce a broadband infrared beam onto a surface at an angle of 60 degrees. Any energy not absorbed by the surface is reflected onto a corresponding mirror that collects the specular reflectance at a similar angle of 60 degrees. The reflectance is then directed into the infrared detector. The input energy is known and the output energy is measured, thus giving a gauge of the amount of infrared energy absorbed by the sample. This relatively simple experiment can be used to gauge the relative effectiveness of coatings applied to the steel surface.

A photograph of the infrared test apparatus is shown in Figure 4. The infrared beam enters from the port on the right and is deflected by a mirror up onto the inverted, coated plate. The reflected light is gathered and transmitted through the port into the IR measuring devices.

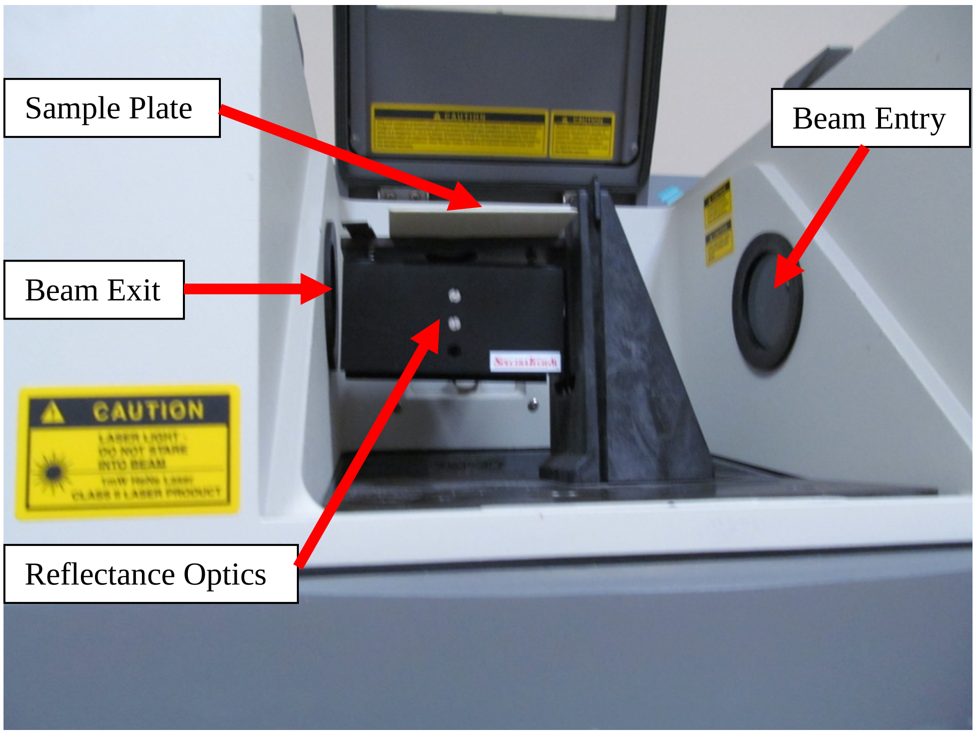

Figure 4. Inverted sample plate on reflectance optics for IR spectrum

However, the simplicity of the device leads to some difficulties. In addition to the reflections outlined above, there is also *scattered* reflection which occurs at angles less than or greater than 60 degrees. That energy will *not* be detected because it is not reflecting at 60 degrees. Scattered energy is energy not being absorbed and the equipment setup in Figure 4 cannot differentiate between the two types of reflection. Since the instrument interprets a reduced signal level as absorption, it is possible to rank the performance of a coating incorrectly.

An example of this anomaly is shown in Figure 5. Bare steel and gritblasted steel were both tested. Their surfaces differed in roughness, with the gritblasted sample expected to have more diffuse reflectance. As was stated previously, the detector cannot discriminate between diffuse reflectance and absorption, so the gritblasted sample appeared to have greater absorption. However, later testing (see Subsection 3.1.2) showed that the two samples have equivalent thermal performance.

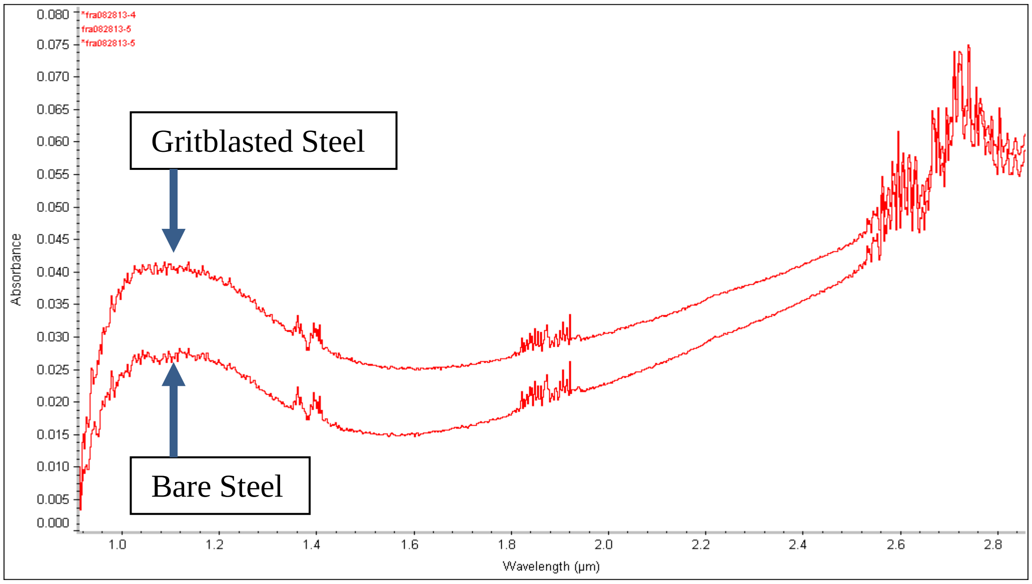

Figure 5. IR reflectance spectra of gritblasted steel and bare steel

2.1.4 Measurement of Heat Gain Under an Infrared Heat Source

In these tests the steel plates were scaled up to 8 inches by 12 inches by 0.75 inches. These plates were coated on one side with the subject material. When they had dried for several days, they were irradiated for 24 hours using a sun-spectrum heat lamp (ExoTerra PT2144) which provided the "natural" infrared distribution of sunlight that had travelled through the atmosphere.

The samples were irradiated at a standoff distance of 6.75 inches, which corresponds to an irradiance of about 120W over the surface of the steel plate. The temperature in the bottom center (opposite the side being irradiated) was measured for approximately 24 hours. The test setup is shown in Figure 6.

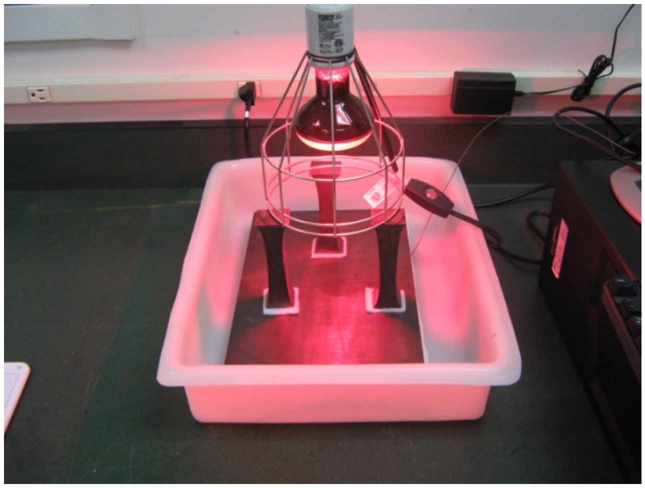

Figure 6. Lab testing of steel plate heat gain under an IR heat source

Samples tested included the following:

- Bare steel
- Rusted steel
- Sherwin-Williams® tan paint
- Sherwin-Williams tan paint with Hytech® microballoons
- Sherwin-Williams tan paint with doubled amount of Hytech® microballoons
- Sherwin-Williams gray paint with Hytech® microballoons
- Nutech® single coat
- Precision Coating Reflect® single coat
- Precision Coating Reflect® double coat over primer
- EonCoat®
- RailShield® Alkyd
- RailShield® Latex

2.1.5 Adhesion Testing

In an eventual field application in a railroad environment, it is important that a coating be durable and it should solidly adhere to the rail. Therefore, adhesion of the coatings to the steel plates was measured using sample choices drawn from Table 1. Not all the combinations were tested, but at least one variant of each type was tested. Those selected were:

- Sherwin-Williams tan paint with Hytech® microballoons
- Sherwin-Williams gray paint with Hytech® microballoons

- Nutech® single coat
- Precision Coatings Reflect® single coat
- Precision Coatings Reflect® primer and double coat
- EonCoat®
- RailShield® Alkyd

The test used bonded pull rods, which were directly attached to the coating surface with a bonding adhesive. The rods were 1.125 inches in diameter and produced a circular attachment area very close to 1.0 square inches. Adhesive squeeze onto adjoining areas of coating was minimized by using masking tape with circular cutouts. Once cured, the excess adhesive was scored around the base of the attached rod, as is shown in Figure 7. Five tests were performed on each system and the pull tests were performed at 0.05 inches per minute.

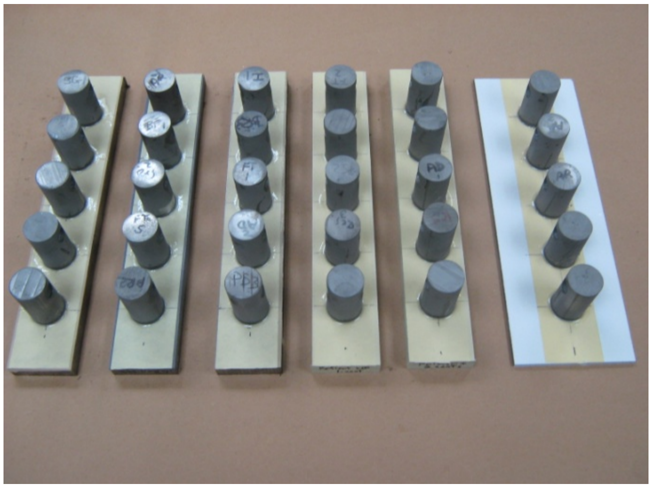

Figure 7. Masked steel plates with rods bonded in place

2.2 Apply Better-Performing Coatings to Rail Samples and Perform Outdoor Tests

Five of the better-performing coatings were selected for outdoor testing:

- Sherwin-Williams® tan paint
- Sherwin-Williams® tan paint with Hytech® microballoons
- Precision Coatings® Reflect 3000 single coating
- EonCoat®
- RailShield® Alkyd

In addition, an uncoated rail was used as a control.

Five thermocouples were affixed to each rail prior to coating; they were placed into small drilled holes and secured with epoxy adhesive. The epoxy adhesive was modified with boron nitride filler to improve thermal conductivity. In total, there were 30 thermocouples placed on the six rails, and a thirty-first thermocouple was used for monitoring ambient air temperature. The placement of the thermocouples on a rail section is shown in Figure 8.

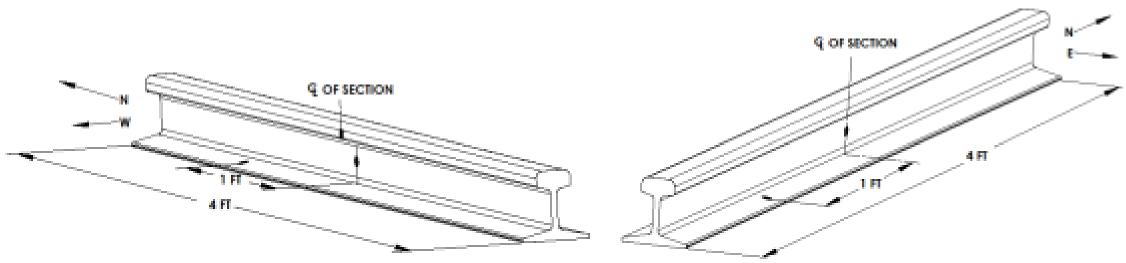

Figure 8. Placement of thermocouples on rail segments for outdoor testing

The rails were coated on both sides of the base and web. In addition, one side of the head was coated. The second side of the rail head and the top of the rail head were *not* coated because it was assumed that wheel-wear would remove the coatings quickly from the areas. The coatings were applied at Edison Welding Institute (EWI) except for EonCoat® which was applied by the vendor. The plain Sherman-Williams® tan paint and the Sherman-Williams® tan paint with Hytech® microballoons were both roller-applied. The Precision Coating® Reflect 3000 and the RailShield® Alkyd were spray-applied.

Figure 9 shows a prepared rail with the masking removed. The thermocouples were attached before the coating was applied, so the rail steel temperature underneath the coating would be measured (rather than the coating's temperature).

Figure 9. Rails coated for outdoor testing

Ultimately, the rails were placed on a platform where they could be exposed to direct sunlight much of the time. The setup of the rails is shown in Figure 10. The order of the rail samples starting from the bottom in Figure 10 and moving towards the top is as follows:

- Precision Coatings® Reflect 3000
- Sherwin-Williams® tan paint

- Uncoated rail
- Sherwin-Williams® tan paint with Hytech® microballoons
- EonCoat®
- RailShield® Latex

Figure 10. Placement of rails on test platform

Ballast would be expected to be somewhat heat-reflective and could potentially reflect solar radiation onto the rails. Since ballast is heavy and difficult to move around, a sheet of white-painted plywood was used instead of ballast. The white-painted plywood could be expected to reflect some solar radiation back onto the rail in a similar manner as ballast. It is to be noted that the bottom of the base of the rail sections was not painted. The ties were placed at standard spacing (approximately 20 inches apart). In addition, foam insulation blocks were placed on the ends of each rail to prevent heat from entering or leaving the rail at those locations.

The data collection system (located in the white box in Figure 10) sampled thermocouple readings every hour throughout the exposure time. Data was downloaded periodically for storage and analysis.

2.2.1 Application of Mud on Grime on Rail Samples

After three months exposure (April through June 2014), the outdoor trials were modified slightly by the weekly addition of a mud-oil slurry to mimic dirt and grime accumulating on the rails. The slurry was made from dirt, used motor oil, detergent, and water. This was applied liberally with a brush approximately once a week from July through August 2014.

3. Results and Data Analysis

3.1 Results of Lab Testing

3.1.1 Results of Infrared Reflectance Spectroscopy

Figure 11 shows a composite overlay of the spectra measured for the coating systems. The plots with larger values represent higher absorbance and hence are lower performance materials, and the plots with lower values represent lower absorbance and hence are better performing materials.

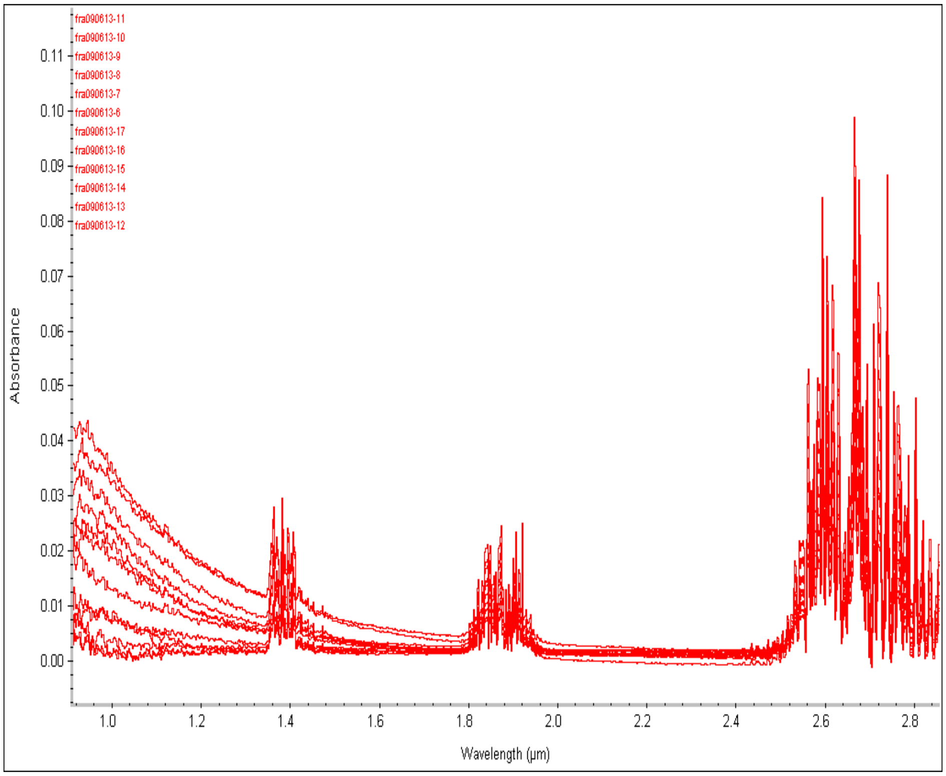

Figure 11. Composite spectral comparison of IR reflectance of coatings and surfaces

The plots shown in Figure 11 from bottom (better performing) to top (lesser performing) are listed in order as follows:

- Nutech® NXT coating
- Sherman-Williams® gray paint with Hytech® microballoons
- Precision Coatings® Reflect 3000 (one coat, no primer)
- Sherman-Williams® tan paint with Hytech® microballoons
- Precision Coatings® Reflect 3000 (two coats with primer)
- Gritblasted steel

- Precision Coatings® Reflect 3000 (one coat with primer)
- Bare steel
- Rusted steel
- EonCoat®

The peaks in Figure 11 at 1.4 microns, 1.9 microns, and 2.7 microns are from water, paint resin, and water (again), respectively. The best coatings show absorption near zero across the entire bandwidth of the testing from 0.9 microns to 1.3 microns, which constitutes the leftmost portion of Figure 11.

These results suggested that the commercial coatings from Precision Coatings® Reflect 3000 and Nutech's® NXT coating should perform well, along with Sherman-Williams® paints with Hytech® microballoons added. The results for EonCoat were not encouraging at this stage. The RailShield® materials were not available for testing at this stage of testing.

3.1.2 Results of Heat Gain Under an Infrared Heat Source

Samples tested were as follows:

- Bare steel
- Rusted steel
- Sherman-Williams® tan paint with Hytech® microballoons
- Sherman-Williams® tan paint with doubled amount of Hytech® microballoons
- Sherman-Williams® gray paint with microballoons
- Nutech® NXT coating (single coat)
- Precision Coatings® Reflect 3000 (single coat)
- Precision Coatings® Reflect 3000 (double coat over primer)
- EonCoat®
- RailShield® Alkyd
- RailShield® Latex

The measurement metric used to quantify performance was the temperature gain which is the final temperature (after approximately 24 hours of exposure to the IR heat source) minus the initial temperature (before exposure to the IR heat source). This metric is shown in Figure 12 for the coatings tested.

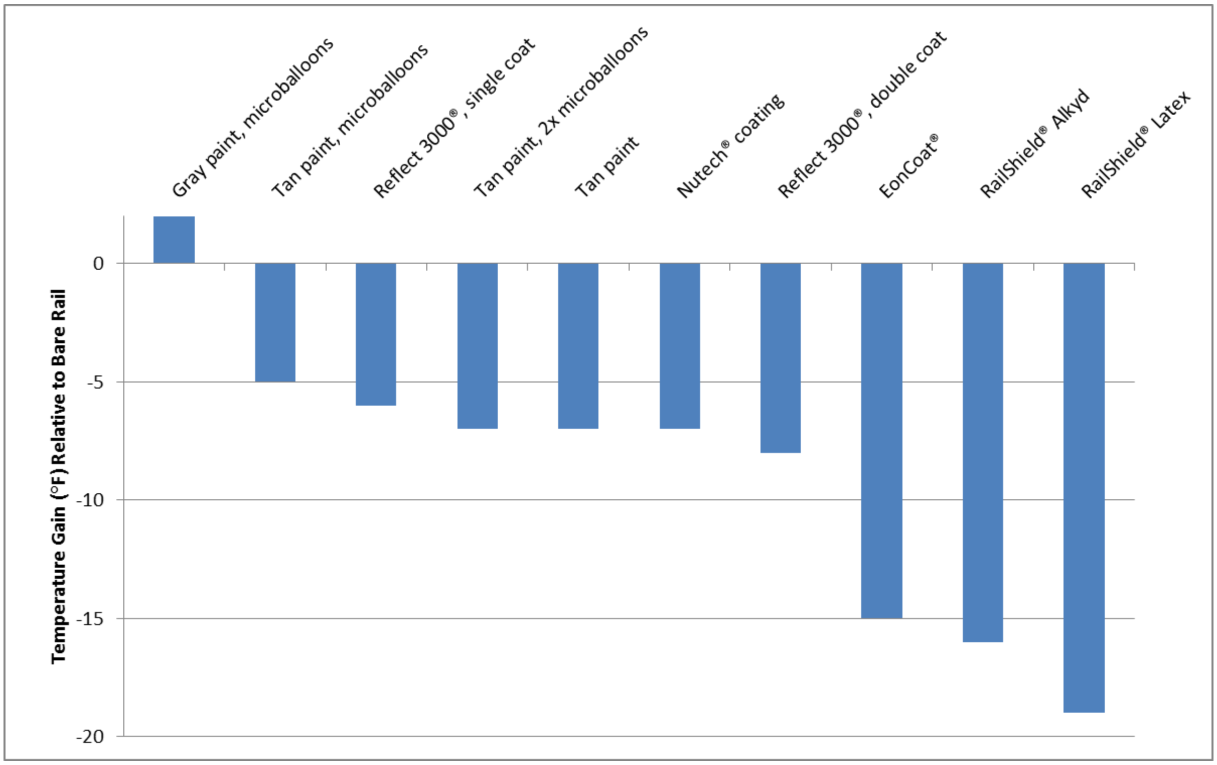

Figure 12. Temperature gain relative to uncoated rail

The data presented in Figure 12 indicates that most of the coatings provided some resistance to temperature gain under the IR heat source.[6] The data shows that EonCoat® and the two RailShield® products were the only coatings that provided a reduction of greater than 10° F relative to the uncoated rail.

The EonCoat® material is completely inorganic, but all he other coatings all have organic binders as the paint base along with inorganic additives for heat reflection or control.[7]

3.1.3 Results of Adhesion Testing

The results for the pull-off tests are shown in Table 2.

[6] It is an interesting anomaly that the Sherman-Williams® gray paint with Hytech® microballoons actually led to a slight increase in rail temperature relative to the uncoated rail.

[7] From the discussion in Section 3.1.1 and the IR spectra in Figure 11, recall that organic binders used in paints absorb IR radiation at approximately 1.9 microns and 2.7 microns.

Table 2. Results of pull tests on coated steel plates

Coating Pull Strength in lb-f							
Sample	SW DTM, Gray with Microballoons	SW DTM, Tan with Microballoons	Nutech	Reflect 3000, Clean, 1-coat	Reflect 3000, Clean, Prime, 2-coats	EonCoat®	RailShield®-Alkyd
1	726	1038	0	0	941	9	659
2	396	1226	705	462	2046	8	1130
3	509	1011	766	0	408	6	631
4	473	854	554	1880	6	6	633
5	492	692	717	996	576	7	447
AVE	519	964	548	668	795	7	700
ESD	123	202	317	792	776	1	255
Failure Mode	Paint pull off	Paint pull off	Paint pull off; some peel back	Adh failure on paint surface	Adh failure on paint surface	Coh pull off	Mixed adh, coh

The Sherman-Williams® paints and Nutech® coating were largely pulled off the steel surface. The adhesive being used did not bond well to the Precision Coatings® Reflect 3000 coating, which resulted in the coating remaining mostly intact as shown in Figure 13. This was unforeseen but suggests the coating has a slippery surface, which may help to shed dirt and water. EonCoat® experienced a cohesive failure mode as shown in Figure 14, which suggests that EonCoat® may be susceptible to mechanical failure in service. RailShield® Alkyd showed a mix of adhesive and cohesive failure but appears to have a fairly high internal strength.

Figure 13. Results of pull-off tests for Precision Coatings® Reflect 3000

Figure 14. Results of pull-off tests for EonCoat®

3.1.4 Down-Selection of Coating Systems for Outdoor Trials

The overall purpose of this work was to select coating systems for outdoor exposure over a substantial time period in various weather conditions. The primary goal was to monitor thermal performance, but another issue is the durability of the coatings in withstanding weather and other environmental conditions.

EonCoat® showed good ability to reduce temperature gain, but its strength characteristics do not appear to match those of the other coatings. If any of the coatings fail mechanically, they cannot continue to effectively shield the rail from solar radiation.

The best performing paint-like coating was Precision Coatings® Reflect 3000 system, when applied as recommended. Proper application entails using a primer coat and two top coats. This is not likely to be adopted by the railroad industry due to complexity and cost considerations. However, one coat of Reflect 3000 is potentially effective but other coatings show similar performance. There was no appreciable difference in thermal performance between the unmodified Sherman-Williams® tan paint and the Sherman-Williams® tan paint with Hytech® microballoons added.

The Nutech® material cannot be sprayed and neither can the Sherman-Williams® paints. Precision Coatings® Reflect 3000 sprays easily as does the RailShield® Alkyd coating. EonCoat® is also spray-applied. The other coatings would be roller-applied.

Based on all these considerations, the materials selected for outdoor testing were:

- Sherman-Williams® tan paint
- Sherman-Williams® tan paint with Hytech® microballoons
- Precision Coatings® Reflect 3000
- EonCoat®

- RailShield® Alkyd

An uncoated rail was also chosen for outdoor testing to serve as a control.

3.2 Results of Outdoor Testing

Outdoor testing began on April 7, 2014 and ended on August 24, 2014. In total there were 135 days with complete data sets. The outdoor testing took place in Columbus, OH (approximately 40° N latitude). At the summer solstice, Columbus receives 15 hours of daylight. The outdoor test bed was placed with the rail axes oriented north-south and was positioned to minimize shading from the adjacent buildings and trees. Thermocouple data was sampled and recorded once an hour and was downloaded on a periodic basis for analysis.

It was found early on that the temperatures measured by the five thermocouples throughout a given rail varied little from each other point-to-point. This suggests that for future work a single thermocouple at the web or head of the rail might suffice.

3.2.1 Overall Thermal Performance of Coatings

Table 3 shows the average of the relative maximum daily temperature compared to an uncoated rail for each of the five materials included in the outdoor testing phase. For example, the first row states that the maximum daily temperature of the rail with Sherman-Williams® tan paint was 4° F lower on average than the maximum daily temperature of the uncoated rail. The coatings are listed in order from worst performing to best performing.

Table 3. Summary results from outdoor testing

Coating	Average Temperature Relative to Uncoated Rail (°F)
Sherman-Williams® Tan Paint	-4.1
Sherman-Williams® Tan Paint with Hytech® Microballoons	-4.8
Precision Coatings® Reflect 3000	-7.7
RailShield® Alkyd	-11.6
EonCoat®	-13.7

As can be seen from the numbers presented in Table 3, both the plain Sherman-Williams® tan paint and the Sherman-Williams® tan paint with Hytech® microballoons were the poorest performers with average temperatures of 4.1° F and 4.8° F below the temperature of the uncoated rail, respectively. The Precision Coatings® Reflect 3000 had better results with an average maximum daily temperature 7.7° F less than the uncoated rail. The two best performers were the inorganic coatings, namely RailShield® Alkyd and EonCoat®. Both of these coatings had average maximum daily rail temperatures that were greater than 10° F below that of the uncoated rail. For a more detailed look into the daily maximum temperatures, see Appendix A which shows plots of the maximum daily temperature for each of the five coatings as well as the uncoated rail.

In Table 3, these averages were obtained by considering all the days in the testing period from April 7 through August 24, even cooler, overcast days. On such days, there is less difference between an uncoated rail and a coated rail simply because the effect of solar radiation is diminished on overcast days. Therefore, the numbers presented in Table 3 would decrease (in other words the coatings would appear to perform better) if only hot, sunny days were being considered.

Figure 15 is a complete day of data (not just the maximum daily temperature) for the uncoated rail and the rails that were coated with EonCoat® and RailShield® Alkyd. This data was recorded on July 11, 2014 and represents one of the hottest days during the data collection period.

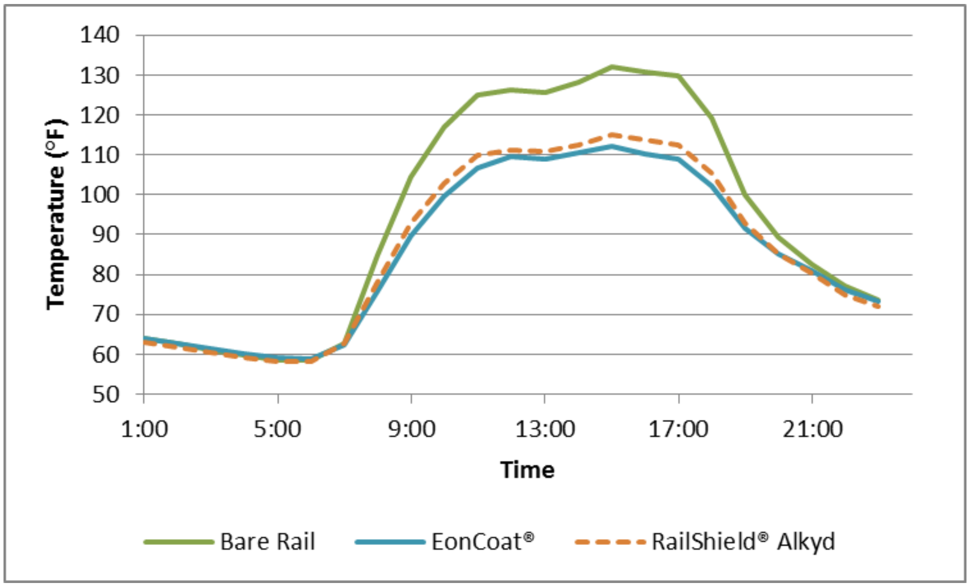

Figure 15. Rail temperatures from July 11, 2014

3.2.2 Effect of Dirt-Grime Slurry on Thermal Performance of Coatings

From July 1, 2014 onward, a dirt-grime slurry was applied to each of the rails weekly. This was done in order to mimic the accumulation of dirt and grime on in-service rails. The middle column in Table 4 shows the relative average maximum daily temperature when compared to an uncoated rail for the month of June (before application of the dirt-grime slurry). The rightmost column shows the relative average maximum daily temperature for the combined months of July and August after the application of the dirt-grime slurry.

Table 4. Relative average maximum daily temperatures before and after application of dirt-grime slurry

Coating	Relative Average Maximum Daily Temperature in June Before Application of Dirt-Grime Slurry (°F)	Relative Average Maximum Daily Temperature in July After Application of Dirt-Grime Slurry (°F)
Sherman-Williams® Tan Paint	-4.0	-3.6
Sherman-Williams® Tan Paint with Hytech® Microballoons	-5.2	-4.1
Precision Coatings® Reflect 3000	-8.0	-6.9
RailShield® Alkyd	-12.0	-10.6
EonCoat®	-14.2	-11.8

As can be seen from the data presented in Table 4, there is an increase in the relative maximum temperature after the application of the dirt-grime slurry. In other words, the performance of the coatings appears to degrade slightly with accumulation of dirt and grime. A t-test was performed in order to determine if this apparent degradation in performance was statistically significant given the June sample and the July-August sample for each coating. The results of those t-tests are shown in Table 5.

Table 5. Results of t-tests to determine statistical significance of perceived performance degradation due to application of dirt-grime slurry

Coating	p-Value from One-Tailed t-Test
Sherman-Williams® Tan Paint	0.1795
Sherman-Williams® Tan Paint with Hytech® Microballoons	0.0004
Precision Coatings® Reflect 3000	0.0872
RailShield® Alkyd	0.0703
EonCoat®	0.0085

Assuming a p-value below 0.05 is statistically significant, the degradation in performance of the Sherman-William® tan paint with Hytech® microballoons and the degradation in performance of EonCoat® were both statistically significant. The t-test results for the other three coatings had p-values above 0.05 which indicates that the degradation in performance is not statistically significant. However, the p-values for the Precision Coatings® Reflect 3000 and the RailShield® Alkyd were both only slightly above the threshold of 0.05. Therefore, since four out of the five coatings were near or under the 0.05 p-value threshold, it can be stated tentatively that there was a statistically significant different in performance after application of the dirt-grime slurry.

Investigating the effect of dirt and grime accumulation on the performance of the coatings was not originally planned. This application of the dirt-grime slurry was done after receiving feedback from interested third parties who wanted to know if there was any degradation in the performance of the coatings due to accumulation of dirt and grime.

If the effect of dirt and grime was considered in initial test planning, it would have been more effective to include two rails with each coating in the study; the first rail with Coating XYZ, for example, would be kept clean and the second rail with Coating XYZ would have the dirt-grime slurry applied through the entire outdoor testing period. This would eliminate the effect of weather parameters (ambient temperature, solar radiation, etc.) as variables and would represent more of an “apples-to-apples” comparison of the effect of dirt and grime on the performance of the various coatings.

The way the study was actually conducted, by adding the dirt-grime slurry half-way through the outdoor testing period, introduces additional complications because the weather parameters are not equivalent before the application of the dirt-grime slurry (in April through June) and after the application of the dirt-grime slurry (in July and August).

3.2.3 Overall Mechanical Performance of Coatings

Photographs of the rails were taken at the end of the outdoor exposure period and they can be found in Appendix B. Most of the coatings visually appeared to maintain their mechanical integrity relatively well. However, the EonCoat® did show some signs of alligator cracking and a little spalling.

4. Conclusions and Recommendations

Overall, the coatings had a significant impact on the temperature of the test rails, but some of the coatings were more efficient at reducing rail temperature than other coatings. While Sherman-Williams® latex tan paints showed a slight reduction in maximum daily rail temperatures when compared to the maximum daily rail temperature of an uncoated rail, a second coating called Precision Coatings® Reflect 3000, which is used in other civil engineering applications such as on rooftops, proved to be more effective at reducing rail temperature than the Sherman-Williams® latex tan paints. However, the two best performers were the inorganic coatings EonCoat® and RailShield® Alkyd. Both of these coatings decreased maximum daily rail temperature by greater than 10° F when compared to the maximum daily temperature of the uncoated rail.

The application of a dirt-grime slurry did appear to degrade the thermal performance of the coatings slightly. However, they still performed well overall. For example, even after the application of the dirt-grime slurry, the two best performers, EonCoat® and RailShield® Alkyd, still had an average maximum daily rail temperature that was greater than 10° F below that of the uncoated rail.

In potential future work, one or more of these coatings may be applied to in-service rail so it can be determined if they maintain mechanical integrity when exposed to the harsh railroad environment (including deformation of the rail under load as well as higher-frequency vibrations that may occur due to impact loads).

References

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Craig, Roy R. *Mechanics of Materials (Third Edition)*. John Wiley & Sons, 2011.

Hartog, J.P. Den. *Strength of Materials*. Dover Publications, 1961.

Appendix A – Plots of Maximum Daily Temperature from Outdoor Testing

This appendix features maximum daily temperature plots for the five coated rails as well as the uncoated rails. Presenting all the data in a single plot would result in a "busy" plot that would be hard to read. Therefore, the data is presented in three separate plots:

- Figure 16 shows the maximum daily temperature for the rail coated with Sherman-Williams® tan paint and the rail coated with Sherman-Williams® tan paint with Hytech® microballoons.
- Figure 17 shows the same plot for the rail coated with Precision Coatings® Reflect 3000.
- Figure 18 shows a third plot for the rails coated with EonCoat® and RailShield® Alkyd.

The data shown in each of the plots encompasses the entire duration of outdoor testing from April 7, 2014 to August 24, 2014.

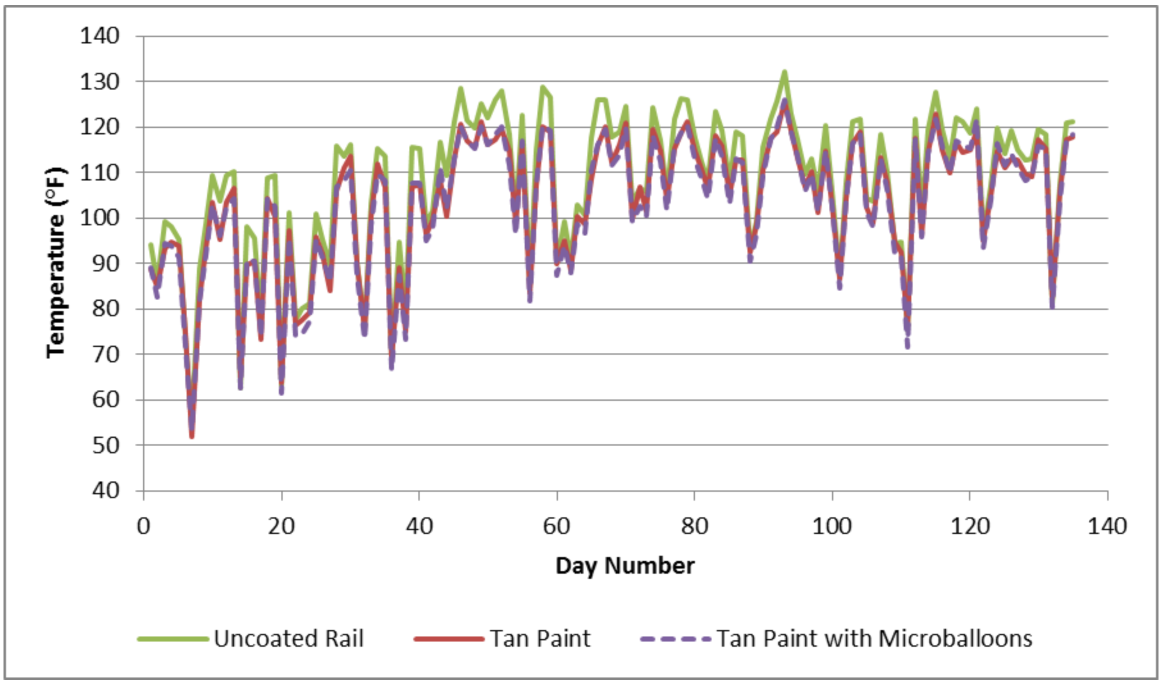

Figure 16. Maximum daily temperature for rail coated with Sherman-Williams® tan paint and rail coated with Sherman-Williams® tan paint including Hytech® microballoons

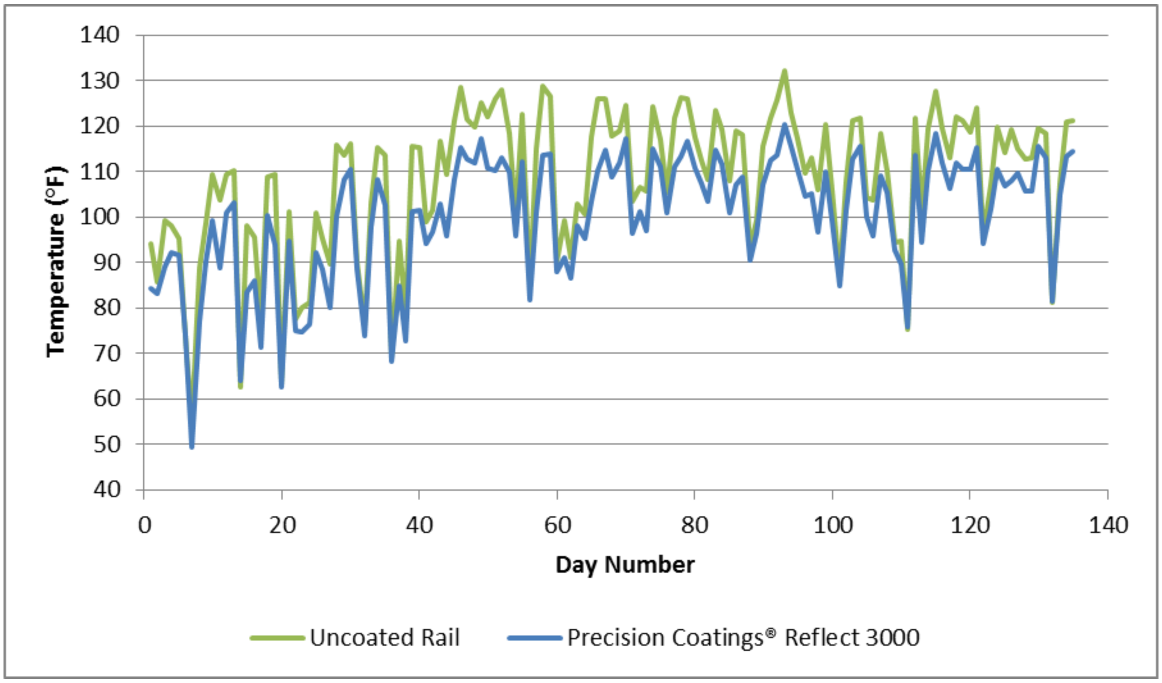

Figure 17. Maximum daily temperature for rail coated with Precision Coatings® Reflect 3000

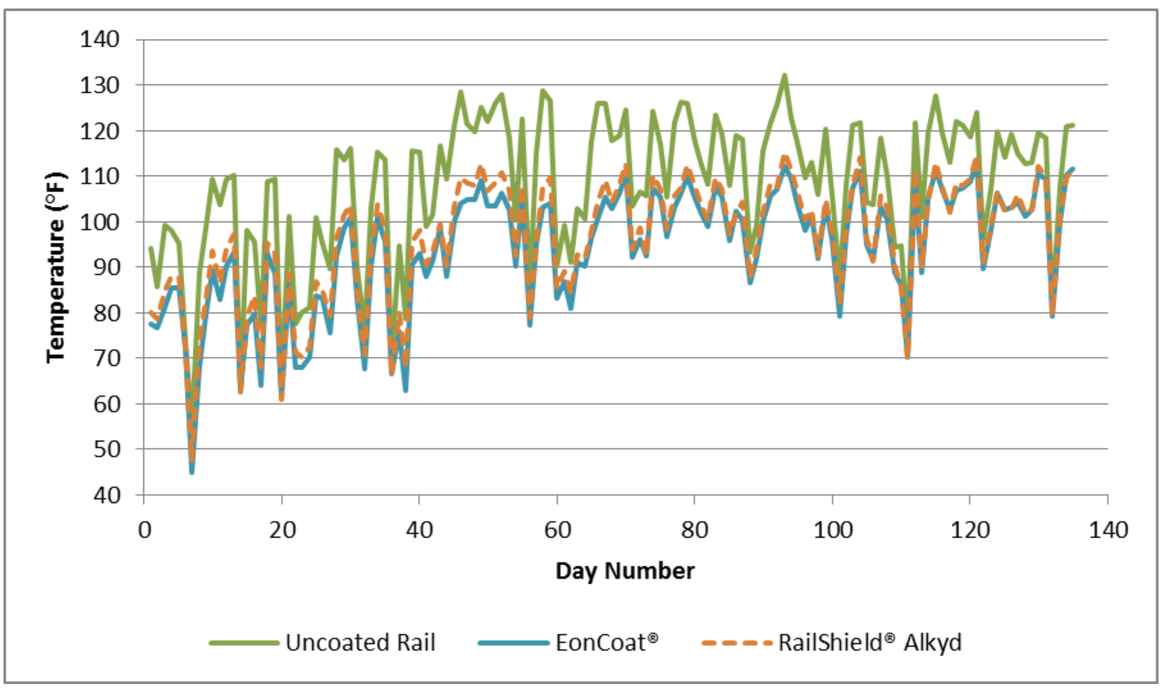

Figure 18. Maximum daily temperature for rail coated with EonCoat® and rail coated with RailShield® Alkyd

Appendix B – Photographs Documenting Mechanical Performance of Coatings

The photographs in this appendix were taken after 135 days of outdoor exposure and were taken of the west-facing side of each coated rail.

Figure 19. Rail coated with Sherman-Williams® tan paint at conclusion of outdoor testing

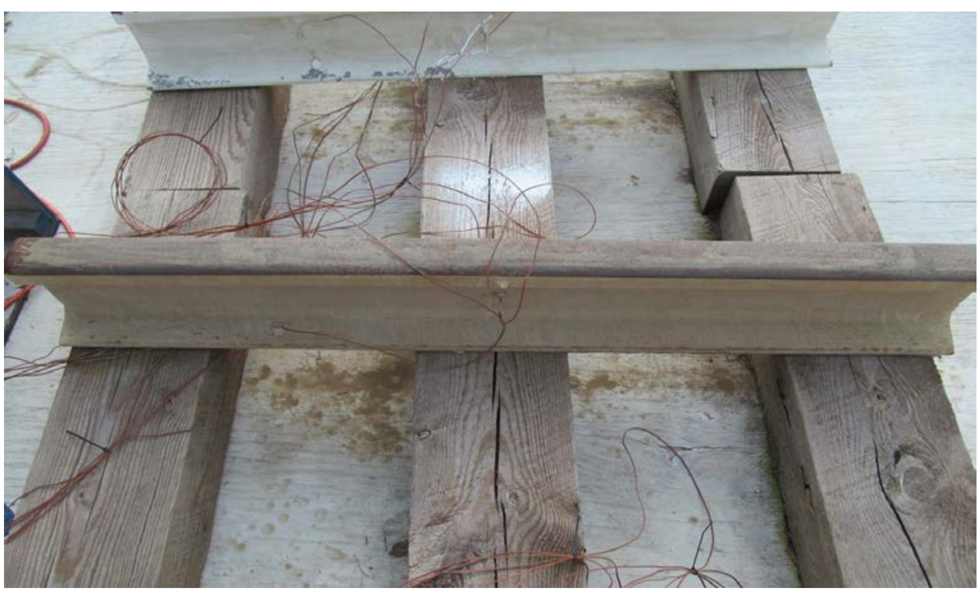

Figure 20. Rail coated with Sherman-Williams® tan paint and Hytech® microballoons at conclusion of outdoor testing

Figure 21. Rail coated with Precision Coatings® Reflect 3000 at conclusion of outdoor testing

Figure 22. Rail coated with EonCoat® at conclusion of outdoor testing

Figure 23. Rail coated with RailShield® Alkyd at conclusion of outdoor testing

Abbreviations and Acronyms

CWR	Continuously Welded Rail
FRA	Federal Railroad Administration
HCN	Historical Climatology Network
IR	Infrared
NASA	National Aeronautics and Space Administration
NIR	Near Infrared Region
NOAA	National Oceanic and Atmospheric Administration
RNT	Rail Neutral Temperature
VOC	Volatile Organic Content