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Evaluation of Immediate Actions Taken to Deal with Cracking Problems Observed in Wheels of Rail Commuter Cars

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This report is the first in a series of engineering studies on railroad vehicle wheel performance. Preliminary studies are summarized, involving evaluation of actions taken to respond to high rates of crack occurrence observed in the wheels of certain multiple unit (MU) power cars used in commuter service. The conclusions of the studies were that the actions taken to address the observed problems were timely and appropriate. These actions were: (1) improvement of maintenance to prevent brake shoe misalignment and dispatching of cars with inoperative traction motors; (2) daily visual inspection of wheels to detect thermal cracks; and (3) immediate re-trueing of thermally cracked wheels with center tread cracks longer than 1/2 inch or rim edge cracks of any size.

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PREFACE

This report is the first of a series of engineering studies on railroad vehicle wheel performance. Preliminary studies are summarized, involving evaluation of actions taken to respond to high rates of crack occurrence observed in the wheels of certain multiple unit (MU) power cars used in commuter service. The conclusions of the studies were that the actions taken to address the observed problems were timely and appropriate. These actions were: (1) improvement of maintenance to prevent brake shoe misalignment and dispatching of cars with inoperative traction motors; (2) daily visual inspection of wheels to detect thermal cracks; and (3) immediate re-trueing of thermally cracked wheels with center tread cracks longer than 1/2 inch or rim edge cracks of any size.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

This report is the first of a series on the results of an engineering study of the effects of service loads on railroad vehicle wheels. The study was initiated in September 1991, in response to a request for assessment of contributing factors and corrective actions taken regarding high rates of crack occurrence in certain multiple unit (MU) powered cars used in commuter service. This report summarizes the results of preliminary studies conducted to assess MU wheel cracking problems and evaluate the corrective actions.

From the preliminary studies there also evolved a plan for longer term research to develop engineering models which could be used to evaluate safe limits or performance demand (weight carried per wheel, maximum speed, vehicle braking rate) as a function of wheel design, material selection, and manufacture, as well as percentage of braking effort absorbed through the wheel tread in service. These developments will be discussed in subsequent reports.

1.1 Background

Special inspections of commuter rail vehicles conducted by the Federal Railroad Administration (FRA) Office of Safety, beginning in the winter of 1990, revealed chronic problems of cracking in the wheels of powered MU cars operated by three railroads serving the Greater New York area. The car design types are similar, but the vehicle characteristics and wheel cracking features were found to have significant differences.

The highest rate of cracking was found in the wheels of moderate weight vehicles, operated at moderate speeds (80 mph), and equipped with blended dynamic braking to supplement the wheel tread brakes. The wheel cracks in this fleet, predominantly of thermal origin at the front rim edge, were attributed to maintenance problems: (1) dispatching of vehicles with inoperative traction motors, and thus also inoperative dynamic braking; and (2) inadequate tread brake unit refurbishment, leading to brake shoes riding over the front rim edge.

A comparable rate of cracking was found in the wheels of moderate weight vehicles, operated at high speed (100 mph), and equipped solely with tread brakes. The wheel cracks in this fleet, of thermal origin in the center tread position, were attributed to the demand for heat absorption through the tread imposed by high-speed operation without auxiliary brakes.

A lower rate of cracking with mixed thermal and mechanical origins was found in the third fleet. This fleet consists of heavy vehicles, operated at moderate speeds, and equipped with blended dynamic braking to supplement the tread brakes. The combination of vehicle weight, heat input to the wheel tread, and occasional maintenance problems were identified as the factors contributing to wheel cracks in this case.

The FRA Office of Safety directed that immediate actions be taken to address identified maintenance problems to which wheel cracking was attributed. Daily inspections and remedial actions for cracked wheels were also required. In view of the economic burdens thereby placed on the affected railroads, the FRA Office of Safety asked the Office of Research and Development, in the summer of 1991, for an engineering study to: (1) evaluate the effectiveness of the immediate actions; and (2) develop rational options for long-term solutions. The RSPA/Volpe Center was asked to participate in August.

The evaluation was started in September 1991 with a review of wheel maintenance records to confirm the general nature of the crack occurrence patterns. The frequency of re-trueing in some cases suggested that wheels were developing visible thermal cracks in a matter of weeks. Although there were no confirmed reports of fractures at that time, wheel service life appeared to be limited by the re-trueing necessary to remove crack indications.

Inquiry was also made through other FRA region offices to determine whether other railroads were experiencing similar problems. No comparable occurrence rates were found, although apparently isolated incidents of cracking were reported for some diesel-electric locomotives and unpowered coaches.

The inquiry covered one other fleet of similar MU cars located in the Greater Philadelphia Area. These vehicles were of moderate weight, operated at moderate speeds, some cars with and some without auxiliary braking. No significant incidence of wheel cracking has been observed in this fleet.

1.2 Inspection and Remedial Action Criteria

The federal safety standards for railroad freight cars define as defective any wheel whose "*... rim, flange, plate, or hub area ... has a crack or break,*" 49 CFR 215.103(d). "Cracked" is defined to mean "*... fractured without complete separation into parts, except that castings with shrinkage cracks or hot tears that do not significantly diminish the strength of the member are not considered to be 'cracked',*" 49 CFR 215.5(b). The federal safety standards for locomotives, under which MU cars are covered, contain essentially the same definition for a defective wheel due to cracking: any wheel with "*A crack or break in the flange, tread, rim, plate, or hub,*" 49 CFR 229.75(k).

The railroad industry also publishes standards[1] which, although established only for interchange freight service, are understood and applied to other services by railroad employees. In the 1980 edition of these standards, a cracked wheel is defined to be "*condemnable at any time*" if it contains "*Thermal cracks: transverse cracks in tread, flange or plate any length. ... ,*" Rule 41 - Section A. In the 1984 edition, the foregoing definition was qualified by the addition of the following language: "*Thermal or heat checks: Brake shoe heating frequently produces a fine network of superficial lines or checks running in all directions on the surface of the wheel tread. This is sometimes associated with small skid burns. It should not be confused with true thermal cracking and is not a cause for wheel removal.*"

Heat checking is recognized by experienced failure analysts as a phenomenon distinct from thermal cracking. In the absence of other effects, heat checks are believed at worst to progress to minor shelling or spalling [1], which can be detected and removed well ahead of any risk to operational safety. However, a recent analysis suggests that heat checks are unsafe if the affected wheel has also been subjected to rim stress reversal [2]. The interchange rules cannot supercede the federal safety standards, but the apparent conflict of definitions has led to disagreements between FRA inspectors and railroad inspectors about interpretation of wheel conditions in the field. The potential for misinterpretation is also accentuated by lack of field training for visual recognition.

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1 *Field Manual of the Interchange Rules*, Operations and Maintenance Department, Mechanical Division, Association of American Railroads, Washington, DC.

Under these circumstances, and with the agreement of the affected railroads, the FRA established the following policy with regard to the wheels of the MU cars. Daily visual inspection of wheels is required, under the provisions of 49 CFR 229.21(b). A wheel must be removed from service if the visual inspection reveals either: (1) any crack in the rim edge or flange region; or (2) cracks 1/2 inch or longer in the center tread region. Wheels with sufficient rim thickness remaining, after remedial action has been taken, may be returned to service. The remedial action consists of re-trueing, with sufficient material cut from the tread to remove all fluorescent magnetic particle or dye penetrant indications of cracking.

2. PRELIMINARY ENGINEERING STUDIES

Following the initial review of maintenance records, the Volpe Center contracted for several preliminary failure analysis tasks, which were carried out between October 1991 and December 1992. Approximate calculations were also undertaken in-house to obtain estimates of maximum wheel tread temperature to be expected under a variety of stop-braking conditions. The results of these studies are summarized in the following sections.

Table 1 indicates the range of performance demand variables found in the related MU car fleets. All fleets were originally equipped with 32-inch nominal diameter, reversed dish, straight plate wheels. Some of the railroads started to replace defective wheels with a recently developed "S" plate design during the preliminary study period, but this did not affect the failure analyses, since only straight plate wheels were sampled. Changes of wheel material class associated with the plate design change are noted. Table 2 summarizes the wheel material properties.

Table 1. MU Fleet Characteristics.

Railroad	Weight[a] (lb.)	Speed[b] (mph)	Braking rate[d] (mph/s)	Brake system[e]	Wheel class
"A"	140,000	80	3.2	T+D	L
"B"	164,000	80	3.0	T+D	L to A[f]
"C"	140,000	100	1.9	T	L to A[f]
"D"	140,000	80 or 95[c]	not reported	T+D	L
				T	B

[a]Maximum weight on the rails, per car.
[b]Maximum operating speed.
[c]Route dependent.
[d]Full service application.
[e]T - tread; D - blended dynamic.
[f]Change to A with adoption of "S" plate wheels.

2.1 Preliminary Estimates of Temperature

Rough estimates of tread temperature versus time were made by means of a one-dimensional model representing the radial heat transfer characteristics of a generic body. The rim was represented by ten equal lumped heat capacities connected by equal lumped conductivities. The innermost rim element was connected through another lumped conductivity to an eleventh lumped heat capacity representing the plate and hub. The

Table 2. Wheel Steel Properties.

Class	Carbon* (Wt%)	Rim Hardness* (BHN)	Yield strength (ksi)		Ultimate strength (ksi)	
			Rim	Plate	Rim	Plate
L	0.47 max	197-277	63	45	105	90
A	0.47-0.57	255-321	65	45	105	90
B	0.57-0.67	277-341	80	55	135	110
C	0.67-0.77	321-363	90	55	140	110

*Per AAR specification M-107.

outermost rim element was driven by a time-dependent heat source representing brake shoe friction and a temperature-dependent heat sink representing black-body radiation to the surroundings.[2]

The heat source description was based on the idealized scenario of braking at a constant deceleration rate from a defined initial speed to a full stop, with the effort assumed to be distributed evenly to eight wheel treads. For a vehicle of weight W travelling at an initial speed V, the total energy absorbed per wheel is obtained from the initial kinetic energy of the vehicle:

$$E = \frac{WV^2}{16g} \tag{1}$$

where g is the acceleration of gravity. The stopping time is $t = V / a$, where a is the braking rate, and the average power absorbed is then given by:

$$P = \frac{E}{t} = \frac{WaV}{16g} \tag{2}$$

Instantaneous power can be expressed as the product of force times relative speed. The speed of the wheel rim, relative to the brake shoe, is close to the instantaneous vehicle speed, which decreases linearly with time when the deceleration rate is constant. Therefore, the instantaneous power absorbed is for practical purposes the linear function of time illustrated in Figure 1.

2 Air stream convection cooling is also a significant heat sink in practice but was neglected in this approximate model.

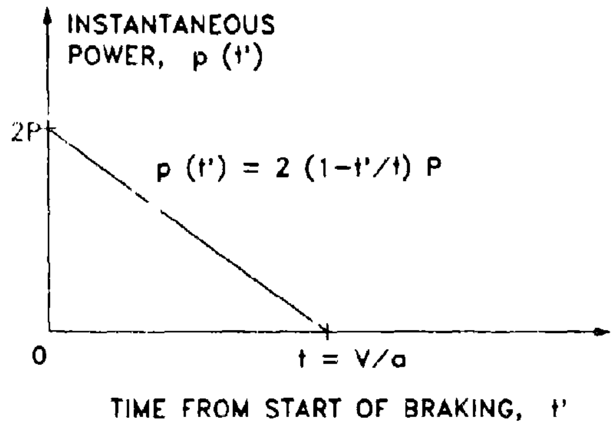

Figure 1. Power Absorbed Versus Time.

Typical stopping times for the combinations of maximum speeds and braking rates given in Table 1 vary from roughly 30 to 50 seconds. Finite difference calculations were performed for several cases using one-second time steps. Linear profiles of power versus time representing a 140,000 lb. vehicle were used, and the model was assumed to be initially at a uniform 90 $^{\circ}$F ambient temperature. Figure 2 summarizes the results, including for comparison, a similar case based on a 36-inch diameter wheel under a 263,000 lb. freight car braked at 1 mph/s from an initial speed of 80 mph.

The peak temperatures shown in Figure 2 are useful mainly as comparative indicators. Thus, actual tread temperatures should be affected strongly by both operating speed and braking rate, but only moderately by the relatively minor variations of MU car weight (see Table 1). Comparison of temperatures in the ten lumped elements at a fixed time revealed a steep gradient, suggesting that only the outer rim region would experience very high temperatures. The results also suggested that typical MU stopping profiles without the aid of dynamic braking could lead to tread temperatures in the tempering range of wheel steel.

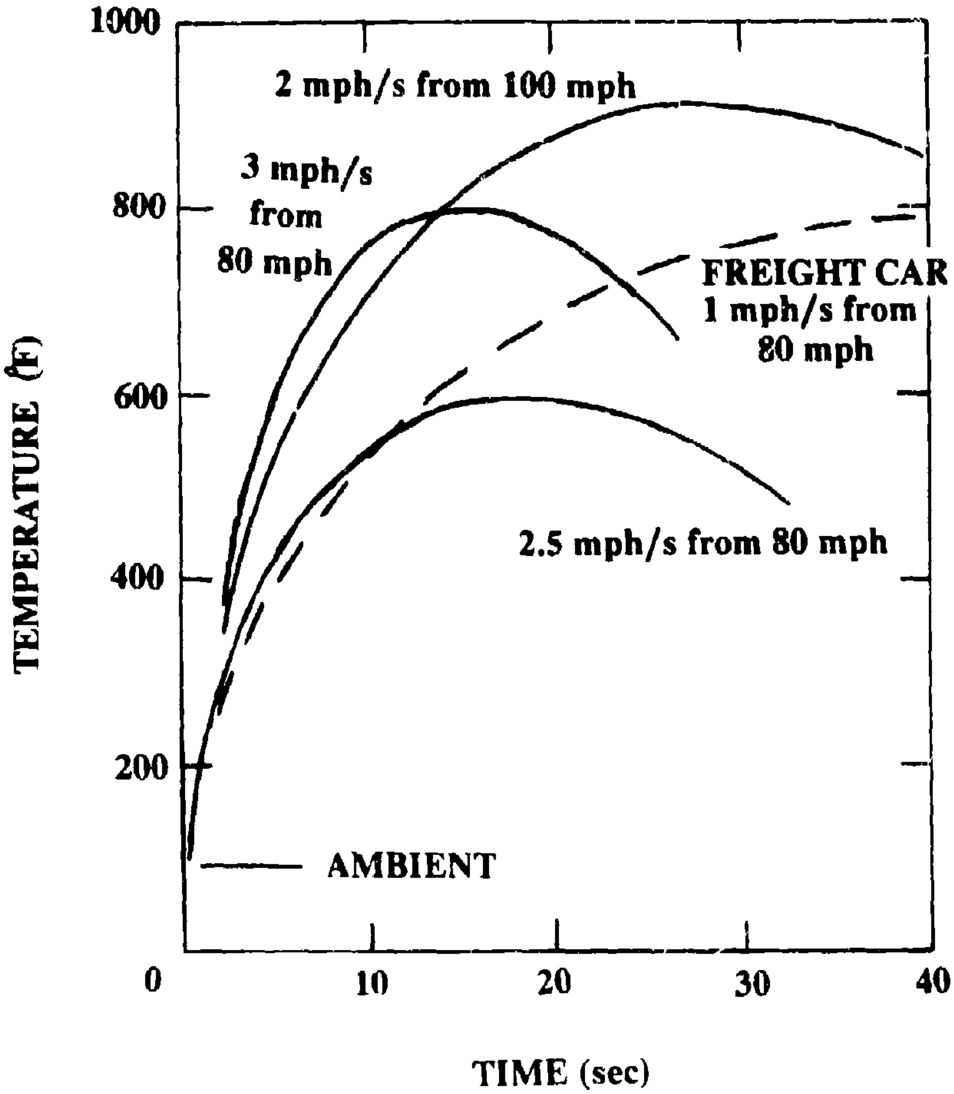

Figure 2. Approximate Estimates of Tread Temperature Versus Time.

2.2 Wheel "Peeling" Survey

A wheel "peeling" survey was undertaken to answer questions regarding the size, shape, and quantity of center tread cracks typically found by railroad inspectors. How deep were the cracks penetrating into the rim, and was the depth proportional to the visible length on the surface? Were any cracks buried, i.e., longer below the tread surface than on it? Were the cracks forming all at once, or in isolated groups (thus introducing the chance element of wheel rotation angle into visual detection)?

Two Class L straight plate wheels with thermal cracks provided by Railroad "C" were sacrificed to obtain quantitative data [3]. One wheel (from car # 1501) was selected from a group previously removed from service and had no history available. The second (from car #1419) was followed after re-trueing and was removed three weeks after being returned to service. Each tread surface was first surveyed with the aid of fluorescent magnetic particle inspection to locate the cracks and measure their visible lengths. Each wheel was then mounted on a vertical boring mill, and the outer inch of rim was cut away from the front face toward the flange to expose the crack shape and maximum depth.[3] A schematic of the rim region of a wheel section profile illustrates the process (Figure 3). When the cut face approached the crack ends, as indicated by their visible lengths on the tread, the milling was restricted to 0.01 to 0.05 inch per cut, until the first visible indications were observed on the cut face. Milling was then continued, at 0.1 inch per cut, with fluorescent magnetic particle inspection between each cut, until the cut face was below the region of maximum crack depth.

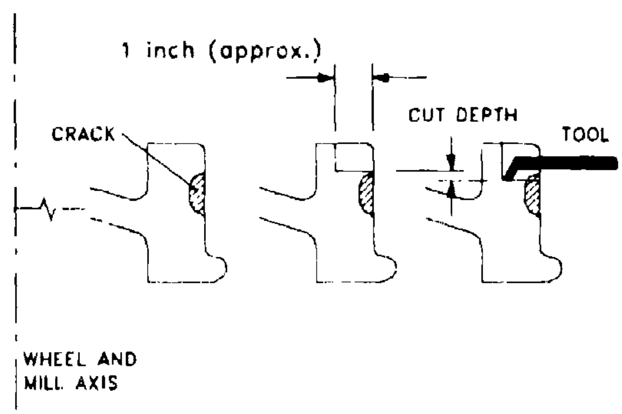

Figure 3. "Peeling" a Wheel to Expose Center Tread Thermal Cracks.

A representative sample of the cracks was marked, the visible length of each was measured before milling, and the depth of each was measured between each cut in order to determine its maximum depth. The wheel from car #1419 was found to have 69 center tread thermal cracks with visible lengths averaging 0.92 inch, in a band centered at 1.53 inches from the front rim face. The wheel from car #1501 had 160 center tread thermal cracks, of which only 76 were surveyed. In this case, the visible lengths averaged 0.65 inch, and the cracks were

3 Shop support was provided by the ORX Railway Corporation, Tipton, PA.

located in a band centered at 2.96 inches from the front rim face. All cracks were visible on the tread surface, and the visible length of each crack was also its maximum length. The cracks were well distributed around the circumferences of both wheels, although the car #1419 wheel had one 12-inch sector with no cracks. Heat checks, such as described in the 1984 edition of the AAR interchange rules (see Section 1.2) were generally visible between the thermal cracks. The combined populations included cracks with visible lengths ranging from 0.5 inch[4] to 1.15 inches. From the combined populations, 22 cracks marked and measured in the "peeling" process exhibited a rough proportionality between visible length and maximum depth, with no crack depth exceeding 1/3 inch (Figure 4).

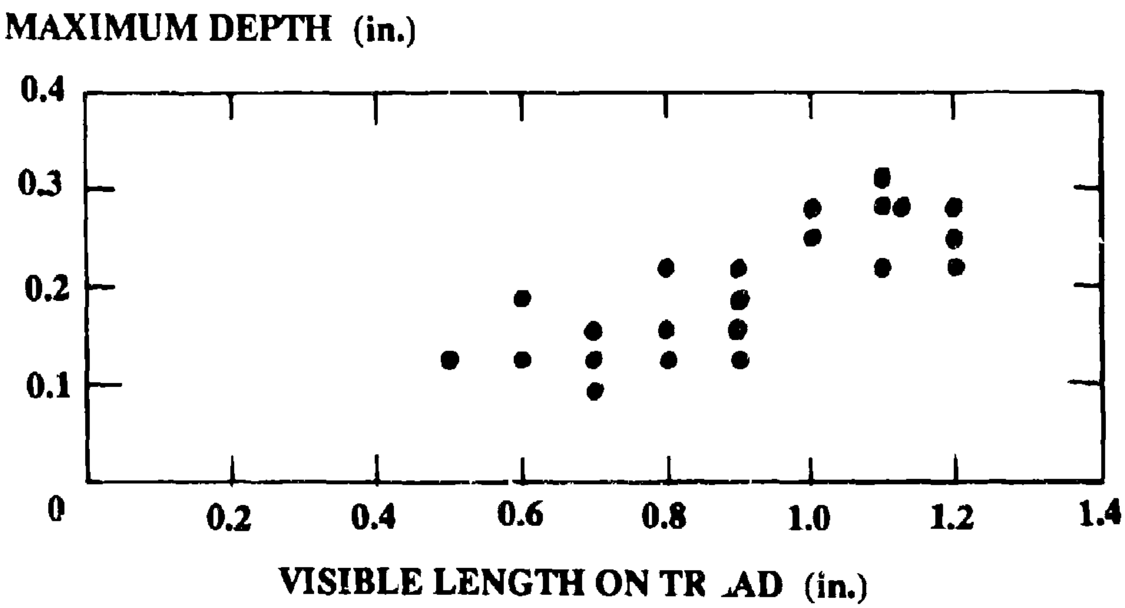

Figure 4. Visible Length Versus Maximum Depth.

2.3 Saw Cutting Tests

A new Class L straight plate wheel and the mate to the car #1501 wheel discussed in Section 2.2 were also subjected to destructive saw cutting to provide displacement data for estimation of residual stresses in the rim.[5] The car #1501 mate wheel contained center tread

4 Center tread thermal cracks do not become visually identifiable as such until the visible length reaches about 1/2 inch.

5 Shop support was provided by the Norfolk Southern Railroad Research Laboratory, Alexandria, VA.

thermal cracks similar to those observed in the "peeling" survey. The procedure for measuring the displaced cut profile was improved by means of moire instrumentation [4], but the method used to estimate the residual stresses from the displacement data was the same as that developed by the Association of American Railroads for an earlier program of research on freight car wheels [5].

When a wheel is radially cut, the kerf either opens or closes, depending upon whether the cut is passing through material which is under tensile or compressive hoop stress. The basic procedure for determining the wheel condition, established by the railroad industry, relies on a clip-gauge extensometer to measure the kerf opening or closing at the tip of the flange, as the cut is being made. The movable part of the saw table is also instrumented, with a linear voltage-displacment transducer (LVDT), to measure the radial depth of the cut. The cut depth and kerf response are recorded as a "clip-gauge curve" on an XY plotter.

Figure 5 reproduces one of the two clip-gauge curves obtained from each wheel. In each case, the entire curve ABC was divided into two segments by stopping the saw briefly at B and repositioning the plotter pen, in order to keep the entire record on one page. The new wheel, Figure 5(a), exhibited a strong kerf closure which continued as the cut entered the rim/plate fillet region. The discontinuity near the midpoint of segment AB reflects jamming of the saw by the kerf closure. (A wedge was temporarily inserted behind the blade to allow continuation of the cutting.) A mild trend toward kerf opening appeared as the cut entered the plate. Conversely, the car #1501 mate wheel exhibited only a weak kerf closure, Figure 5(b), and the trend reversed toward kerf opening when the cut reached the inner rim region.

Moire applied to the flat areas on the front and back rim faces of each wheel was used to measure the kerf displacement profiles when the cut was stopped at roughly two thirds of the way through the rim thickness. A three-dimensional finite element model was prepared for each wheel[6] and was used to reconstruct the rim hoop stress. Steep gradients were found, with maximum compressive stresses (at the tread surface) of 42 ksi in the new wheel and 28 ksi in the car #1501 mate wheel. The retention of some compression in a used wheel was encouraging, since compressive stress tends to close and delay the growth of cracks. However, the saw cut tests did not provide the data necessary to reliably determine the depth below tread at which a crack would encounter tensile hoop stress.

Following the tests, an additional cut was made in the new wheel to remove a radial slice approximately 1/2 inch thick, and several 4 - 6 inch rim blocks were flame cut from the car #1501 mate wheel. These pieces were sent to laboratories for metallurgical testing and examination.

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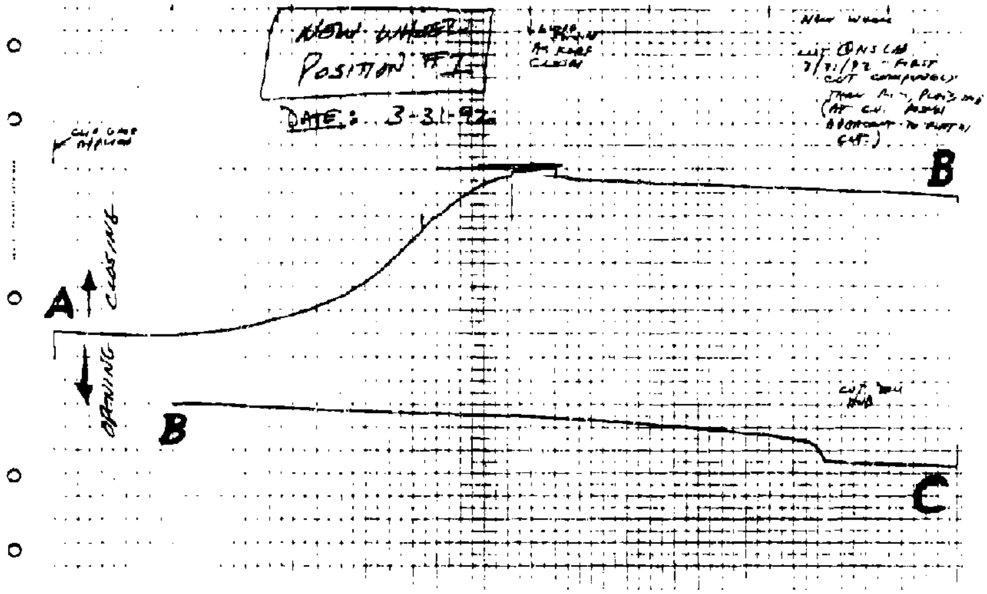
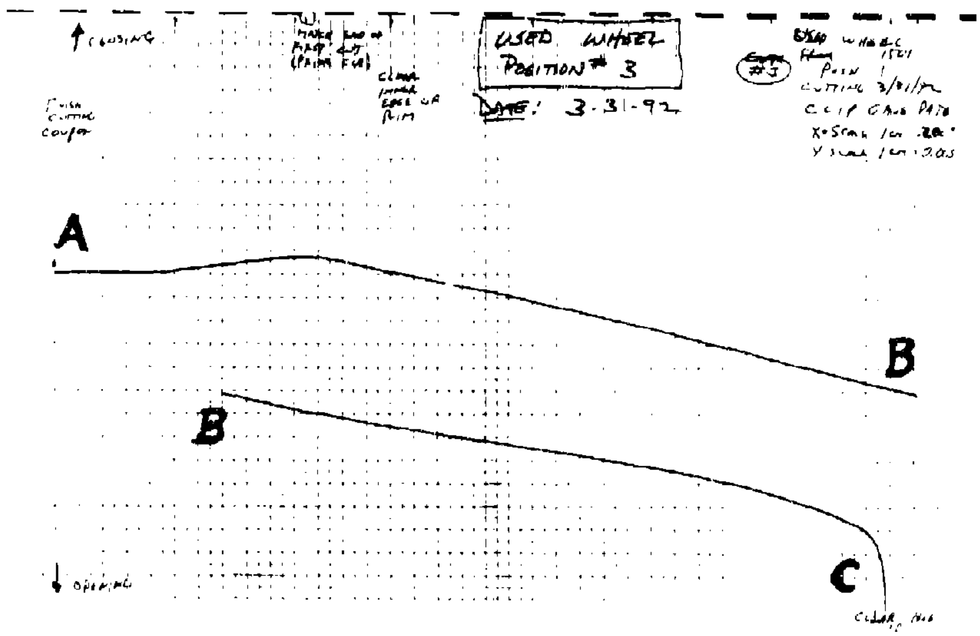
6 Separate models were required to represent the actual rim thicknesses: 2.5 inches for the new wheel and about 1.5 inches for the car #1501 mate wheel.



(a) new wheel



(b) car #1501 mate wheel

Figure 5. Clip-Gauge Curves from New and Cracked Wheels [4].

2.4 Metallurgical Evaluation

One of the car #1501 mate wheel rim blocks was examined at the Massachusetts Institute of Technology (MIT) [6]. Two specimens, each containing a center tread thermal crack, were cut from the outer region of one of the rim blocks and broken in liquid nitrogen to expose the crack propagation surfaces. Adjacent specimens were cut from the same block for metallography and fracture toughness testing (Figure 6).

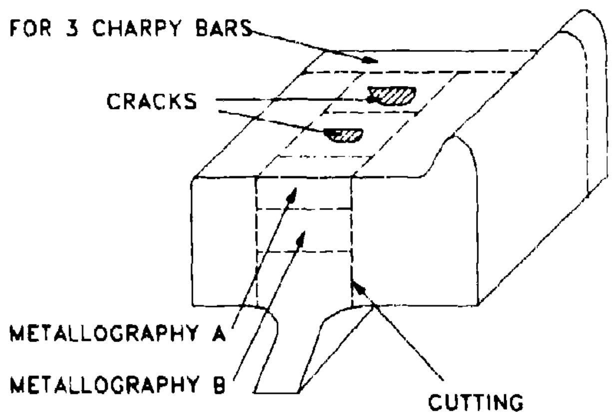


Figure 6. Specimen Locations (Car #1501 Mate Wheel) [6].

Examination and hardness testing of metallography specimen B revealed a normal pearlitic microstructure (Figure 7) hardened to approximately RC 35. This is the base material condition in the rim. Conversely, specimen A exhibited transformation to a spherodized microstructure with increased hardness from the tread surface to a depth of 0.02 inch (0.5 mm). Figure 8 illustrates the microstucture. Figure 9 additionally shows a zone of intense lateral shear deformation to a depth of 0.0008 inch below the tread. Figure 10 summarizes the results of microhardness measurements, showing the transition at the 0.5 mm depth.

Figure 11 illustrates the larger of the two thermal cracks which were examined. The rings which appear on the crack propagation surface consist of beachmarks and ridges, reflecting a process of slow fatigue crack growth influenced by shear. The ridges, which can be distinguished by shadows, result from small angles between the radial section and the actual planes on which the crack has grown. The alternation between positive and negative angles creates the ridge topography. Ridge topography has also been observed in the growth of transverse defects in rail heads subjected to regular reversals of traffic direction [7], as shown in Figure 12.

Examination of another rim block was made at MIT following an incident in June 1992, when a wheel was observed to fracture as it cooled under a railroad "B" MU car which had just entered the yard after a revenue run. Three incipient fractures were observed at a post-mortem inspection, and preliminary failure analysis indicated that this wheel had probably been subjected to dragging brakes just before the incident [8]. Figure 13 shows the crack propagation surface from one of the incipient fractures. No ridges are visible but three

Figure 7. Base Material Microstructure, from Specimen B (~ 1000X).

Figure 8. Spherodized Microstructure, from Specimen A (~ 1000X).

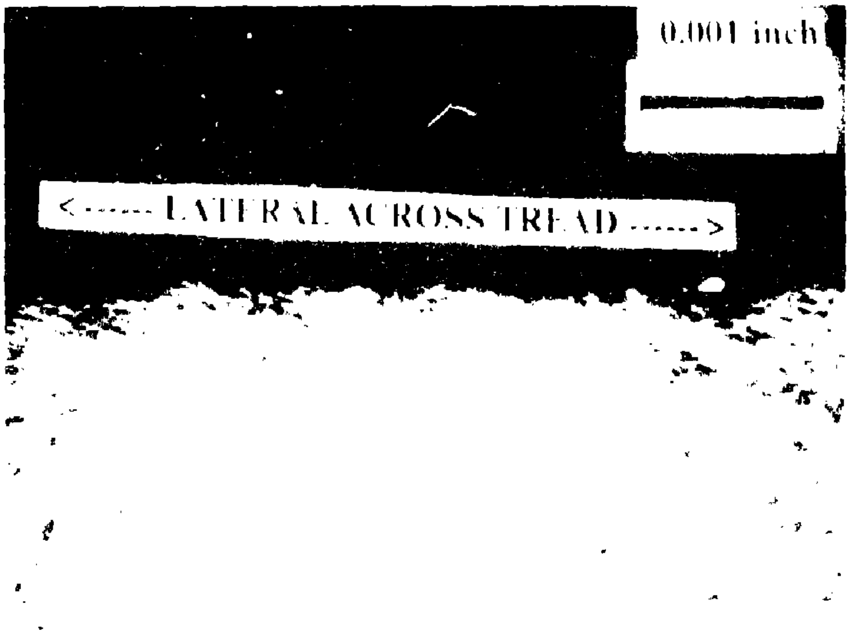


Figure 9. Plastic Deformation Near Tread Surface, from Specimen A (~ 1000X).

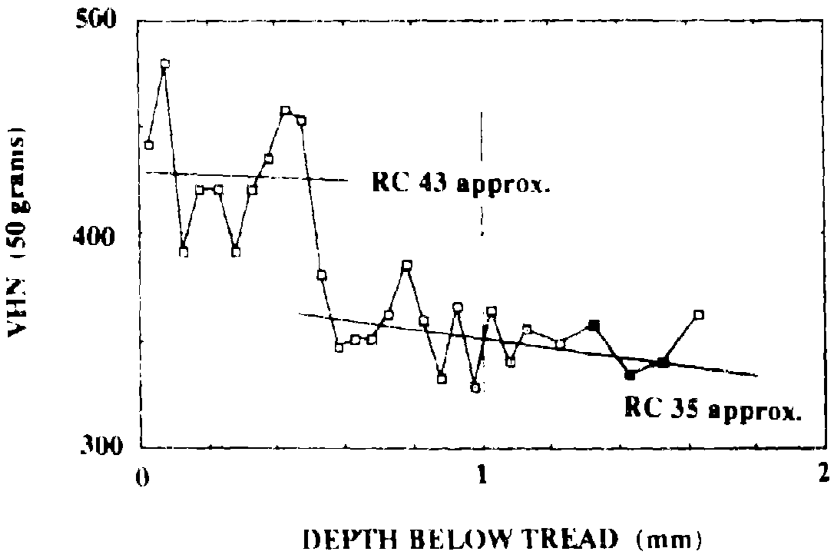


Figure 10. Hardness Profile from the Surface (Specimen A)

Figure 11. Thermal Crack from Car #1501 Mate Wheel (~ 5.6X) [6].

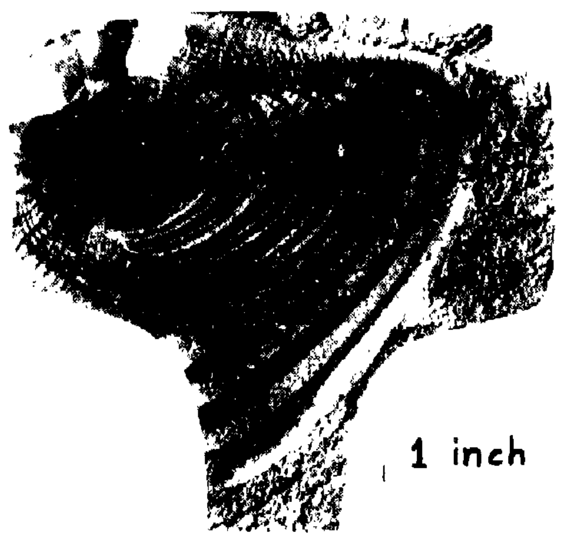


Figure 12. Detail Fracture Grown in a 136 RE Rail at the Transportation Test Center. Traffic was reversed approximately once per million gross tons.

Figure 13. Thermal Crack Nearing Limit of Fatigue Life ([illegible] 2.5X).

beach marks are present (A,B,C). The appearance of the surface between beach marks indicates possible fast propagation. This point remains to be evaluated by means of high-magnification fractography.

Charpy bars were machined from a specimen of the car #1501 mate wheel rim block (see Figure 6) and tested at room temperature to provide data for estimation of the wheel steel fracture toughness. The fracture toughness of carbon steel alloys can be estimated from the empirical formula [9]:

[illegible]

where [illegible] (psi, in.[illegible]) is the fracture toughness, [illegible] 3 x 10[illegible] (psi) is Young's modulus for steel, and C (ft lb.) is the energy absorbed by specimen fractured in the Charpy test. Table 3 summarizes the test results and estimated fracture toughness values.

Specimens from the new wheel were subjected to combined high temperature and rapid plastic compression, followed by air cooling, in a Gleeble testing machine at the Oregon Graduate Institute of Science & Technology [10]. Figure 14 illustrates the schematic temperature-strain time profile, which was designed to approximate the outer rim environment. The rapid heating rate and air cooling were chosen to simulate temperature-

Table 3. Wheel Steel Fracture Resistance [6].

Quantity	Test #1	Test #1	Test #3	Average	Std. Dev.
C (ft.lb.)	14.0	15.4	15.6	15.0	0.87
K_{IC} (ksi$\sqrt{\mathrm{in.}}$)	45.8	48.1	48.4	47.4	1.4

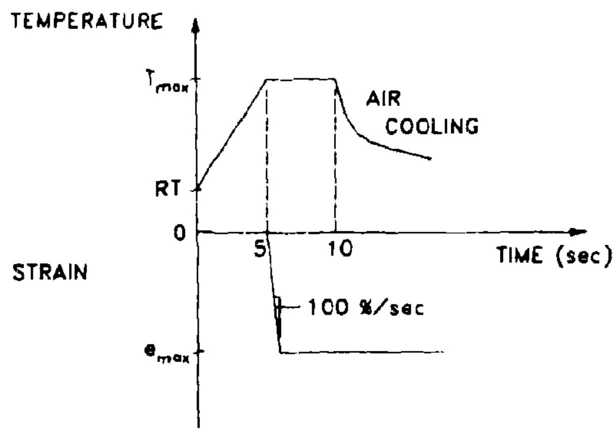


Figure 14. Specification for Gleeble Tests.

time histories in the range expected for outer rim material subjected to stop-braking. One cycle of large plastic strain was imposed to approximate the effects of wheel/rail contact on the hot outer rim region. (Repeated strain cycling was not an available testing option.)

Table 4 summarizes the test matrix. Specified nominal values of peak temperature T_{max} and compressive strain e_{max} are listed in the upper and left margins, respectively. Actual temperatures achieved were within 1 ^{0}F of the specified values. Actual strains achieved are given in the body of the table. Metallographic examination of the specimens is in progress at MIT [11]. Completed examinations are noted in the body of the table by the symbols S, for observation of spherodized microstructure similar to that shown in Figure 8, or P for undisturbed pearlitic microstructure.

2.5 Finite Element Heat Transfer Model

The results of the preliminary tread temperature estimates (Section 2.1) demonstrated the need for a detailed model capable of predicting temperature distributions in the wheel profile section under transient conditions. Accordingly, the Volpe Center began development of finite element models for 32-inch diameter straight and "S" plate wheels, using the

Table 4. Gleeble Test Matrix and Results.

T_{max} (°F) / e_{max} (%)	1100	1150	1200	1250	1300	1350	1400
1	0.8 P		3.4 P		3.2 P		5.2 S
5	0.8	4.6	6.6	20.6 S	10.0	13.2	12.8
10	4.2		14.6		14.0		15.8
20	13.6 P	12.0 P	19.2 P	22.0	20.8 P	16.0 S	16.0 S

TOPAZ2D computer program [12]. A later report in this series describes the models and validation in detail. However, two results obtained from the straight plate model are relevant to the work discussed in this report.

2.5.1 Evaluation of temperatures measured after fracture

When the wheel fracture was discovered by railroad "B" in June 1992, hub temperature measurements were made on all wheels of the affected car and its mate, within 70 to 90 minutes of the initial observation. The hubs of the wheels on the affected car were found to be uniformly hotter than those on the mate car, suggesting a significant difference of energy absorbed by the respective wheel treads.

The heat transfer model was used to compute hub temperatures for two scenarios. In the first case, the wheel was assumed to be heated by the energy input of stopping a 155,000 lb. vehicle from 80 mph at 3 mph/s (representing assumption of load by the tread brakes upon dynamic brake failure), and was then allowed to cool for 66 minutes. In the second case, the wheel was assumed to be heated by drag-braking at the rate of 29 Hp for 20 minutes, followed by cooling for 72 minutes. The brake shoe was assumed to be properly aligned in both cases.

Table 5 summarizes the measured and calculated hub temperatures. The measured temperature range for the affected car (#8814) exceeds the range predicted for stop-braking with loss of dynamic brakes but is less than the range predicted for drag-braking. This result confirms that the car #8814 wheel treads were subjected to abnormally high braking energy input.

2.5.2 Effect of overhanging brake shoe

The heat transfer model was also used to perform transient analyses of stop-braking for comparison of the effects associated with properly aligned and overhanging brake shoes. In the overhanging case, the lateral width of the heat input zone was assumed to be about half the nominal value. The models were otherwise identical, representing a 140,000 lb. vehicle stopping at 2 mph/s from 80 mph.

Table 5. Measured and Calculated Hub Temperatures.

Case	Mate car measured	Stop-braking model	#8814 measured	Drag-braking model
Temperature range (°F)	105 107	115 120	155 163	200 212

Figures 15 and 16 illustrate the computed temperature distributions at the respective times when the peak tread temperatures are attained. Note that the peak value for the overhanging case is almost twice the nominal value. Note also that the overhanging case leads to temperatures which, according to the metallurgical investigation results, are high enough to spherodize the microstructure.

3. DISCUSSION

Inspections of wheel cracks and tracking occurrence rates in the affected MU fleets has shown that thermal cracks are the main concern at the present time. This is consistent with past experiences of wheel cracking in the railroad industry. The preliminary study results have highlighted several important factors, but a number of questions remain to be answered.

3.1 Performance Demand Factors

Of the three major performance demand factors, operating speed and braking rate are the most influential. The wheel tread is at risk of reaching extreme temperatures, if not unloaded by auxiliary braking, when stops are made from speeds of 80 mph or higher at rates of 2 mph/s or faster.

Dynamic braking is a practical and useful auxiliary method for the electric MU cars, but the actual benefit achieved depends on the blending characteristics. Most systems in use today apparently have a short delay, of the order of one second, between tread brake application and dynamic brake application. The proportion of effort diverted to the dynamic brake is then a function of the vehicle speed. Deviation of actual function from the nominal profile may be sufficient to have significant effects on tread temperature. Further study is required with realistic specifications for blending as a function of speed.

The effect of vehicle weight on tread temperature is secondary, mainly because the MU fleets have a narrow range of weights. The mechanical effects remain to be evaluated. Although the heavier weights do not imply unduly high wheel/rail contact pressure under pure rolling conditions, Johnson has noted that the addition of tractive or braking effort can increase the tendency of the outer rim to deform under weight [13]. This tendency can be further exacerbated by a decrease of yield strength when the outer rim is hot.

3.2 Maintenance and Operational Factors

Contact area between the tread and brake shoe should be treated as a variable, but little quantitative information is available about actual contact area under the shoe pressure load corresponding to full service brake cylinder pressure. Contact width is the more important aspect, since wheel rotation distributes the heat input to the entire tread circumference, regardless of shoe length.[7] Even a slight amount of overhang tends to place the shoe against a part of the wheel with a dissimilar profile: a recipe for reduced contact area. Therefore, extreme tread temperatures should be expected if brake shoes are misaligned, even when vehicles are stopped from moderate speeds with dynamic brakes fully functional.

Dynamic brakes cannot function if motors are inoperative. With the equipment now in service, failure of the motor on one axle cuts out power and dynamic braking from the truck. The lost braking effort must either be redistributed to treads, or the vehicle stopping distances must increase. If redistribution occurs, the combination of extra energy and variation of

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7 From the design viewpoint, however, a longer shoe might be less prone to reach temperatures at which the binder resin begins to break down.

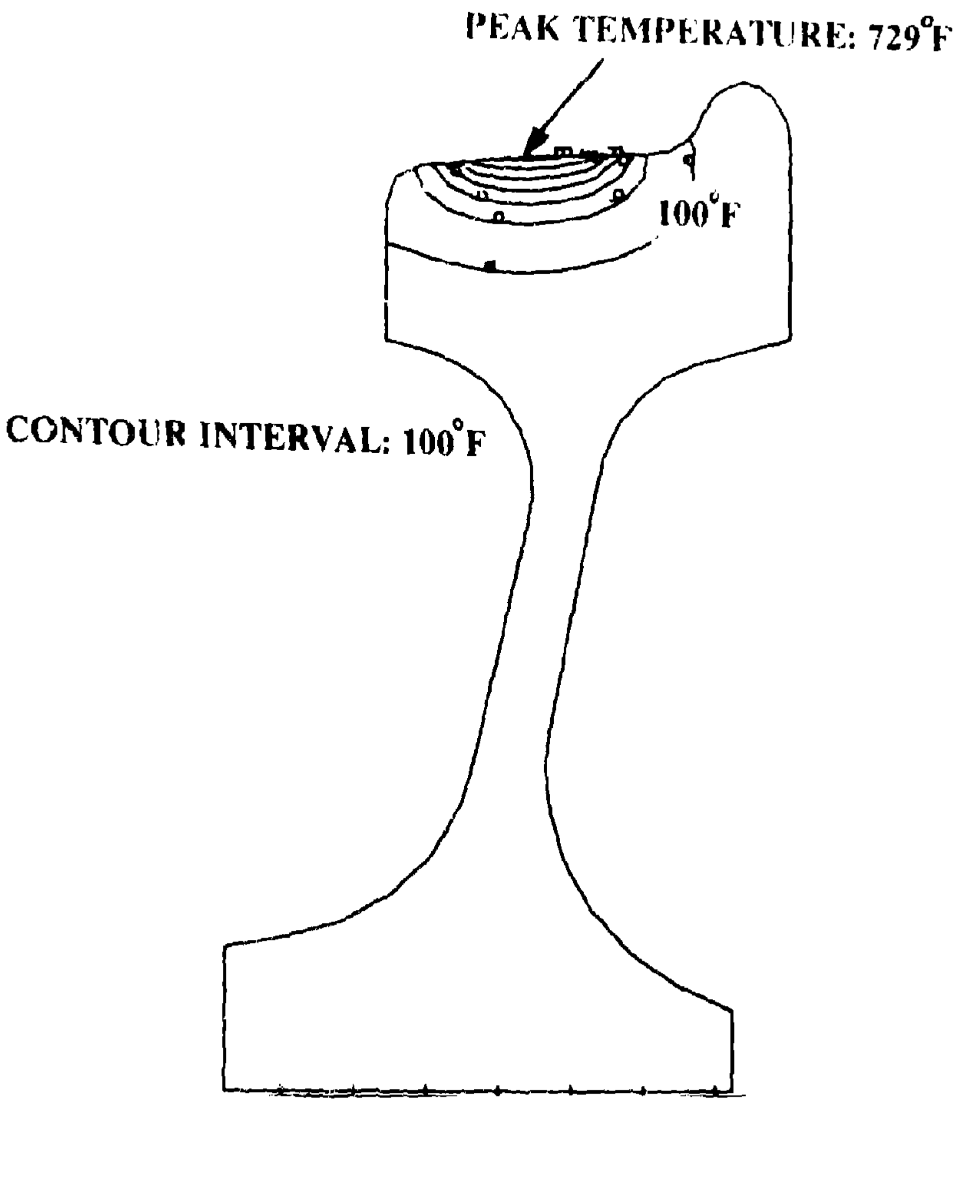

Figure 15. Temperatures Attained with Shoe Correctly Aligned.

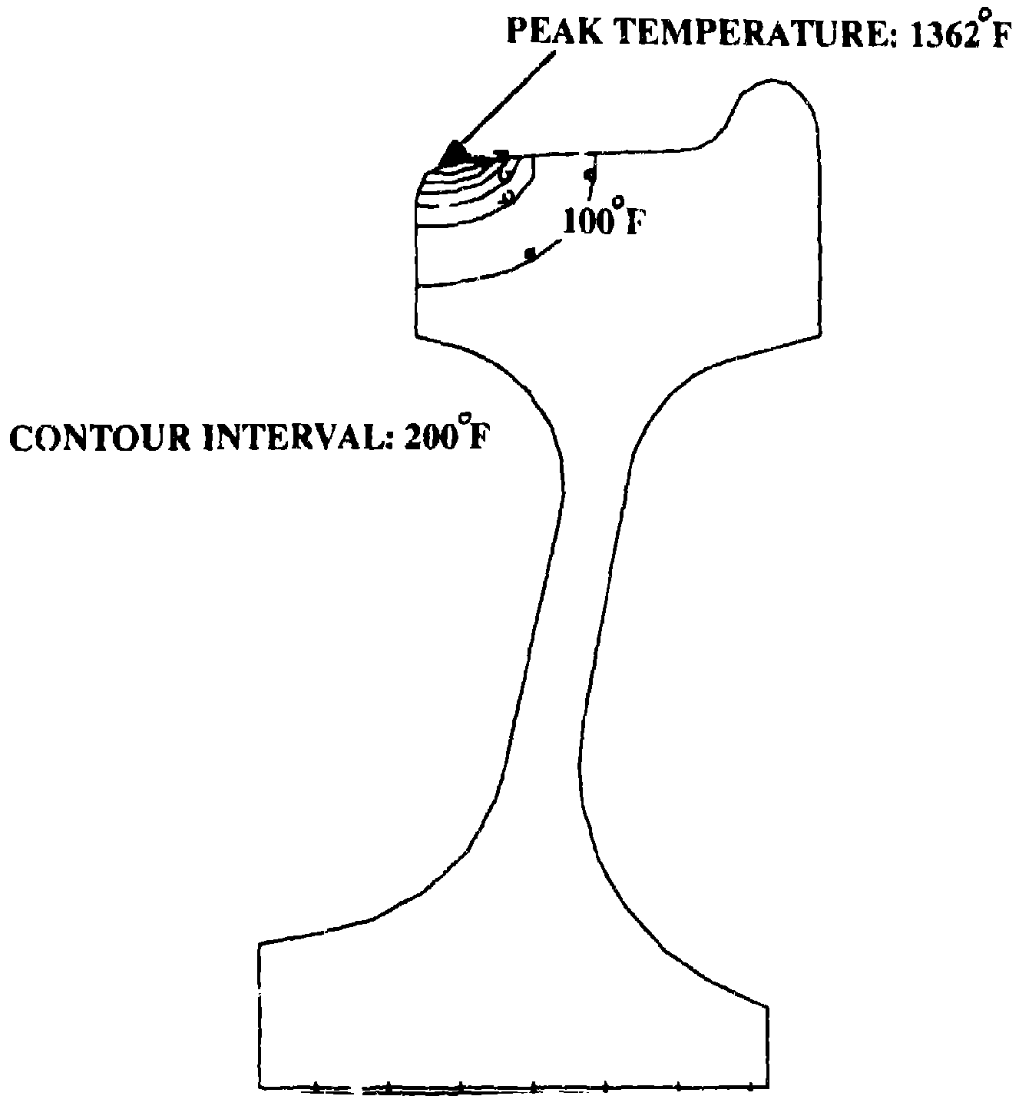

Figure 16. Temperatures Attained with Overhanging Shoe.

contact width creates risk. Motor failures will inevitably occur during revenue runs, so the risk cannot be totally avoided. However, it can be minimized as long as cars are not dispatched with known inoperative motors.

Drag-braking appears to be an important factor in incidents such as the wheel fracture mentioned earlier (see Sections 2.4 and 2.5). The problem is difficult to define because there is usually no evidence of malfunction when the system is tested after an incident[8], but is believed to result from partial release of the tread brakes on one car or one truck when the brake handle is returned to the lap position. Although such incidents are isolated, they are unpredictable, and the high risk of subsequent wheel failure is demonstrated by the repetition of fracture/arrest events evident in Figure 13. The first such event occurred when the original thermal crack was about 1/2 inch long on the tread surface. It is also important to note that similar behavior could occur if a wheel containing mechanically induced ("shear") cracks were later subjected to sticky tread brakes.

Two other questions have not yet been fully addressed. First, the variation of braking effort among the axles in a train is not fully known. Both unavoidable variations due to equipment tolerances and possible deviations due to improper maintenance should be defined. Second, the effect of frequent stops has not been fully quantified. Such conditions are inevitable in commuter operations, and peak tread temperatures are likely to be increased when the wheels do not have time to thoroughly cool between stops.

3.3 Material Behavior

The presence of spherodite is a good indication that a wheel tread has been subjected to direct thermal damage. Spherodite has been observed in test specimens subjected to plastic strain while heated to temperatures from 1350 to 1400 °F. For Class L wheel steel (0.47 % carbon maximum), the lower limit of the pearlite - austenite transformation range is about 1340 to 1430 °F (see [14], Figure 1.11). Thus, it appears that the spherodite forms at least in part by direct diffusion of carbon from the pearlite microstructure, suggesting that total time at elevated temperature may be an important factor.

The confinement of observable material effects also points to the existence of steep temperature gradients. Thus, it is likely that the thermal stresses are similarly confined, and hoop residual stress reversal is limited to a shallow layer.

3.4 Crack Behavior

The behavior of small center tread thermal cracks, in the absence of other unusual effects (drag-braking) is consistent with the hypothesis of shallow stress reversal due to stop-braking. This is demonstrated by the pattern of beach marks and ridges (Figure 11), which depict the rate of crack growth decreasing as the crack depth increases, whereas the lateral rate of growth is not so affected.

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8 As was the case for tests conducted after the wheel fracture incident.

However, the presence of ridges suggests that the overall rate of growth is quite rapid. The ridges in Figure 11 first become visible when the crack is about 0.1 inch long on the surface. There are eight ridges between this point and the maximum 0.8-inch length of this crack. If traffic reversal is the mechanism which creates the ridges, as has been demonstrated for fatigue cracking of rails, then the implied growth time is about three days of service (round trips with consist not wyed). Total crack growth time, i.e., from formation (as a small surface crack shorter than 0.5 inch) to a fully developed crack 0.8 inch long, would then likely be no more than a matter of weeks.

The apparent rapid formation and growth, followed by slowing down or even possibly arrest of propagation into the depth of the rim, suggests that the center tread thermal crack per se does not pose an immediate risk of wheel failure. However, the apparent ability of drag-braking to create conditions that re-accelerate the growth of these cracks means that they cannot be treated as nothing more than a minor maintenance problem.

4. CONCLUSIONS

The requirement, issued by the FRA Office of Safety, for immediate action to address maintenance problems in the MU fleets, involving misaligned brake shoes and/or dispatching of cars with inoperative traction motors, was both timely and appropriate.

The requirements, issued by the FRA Office of Safety, for daily visual inspection to detect thermally cracked wheels and for re-trueing before return of such wheels to revenue service, were prudent and well suited to address the known risks.

The policy, established by the FRA Office of Safety, requiring action on center tread cracks of 1/2 inch or longer on the surface, was a reasonable in the light of practical limitations on visual inspection of the center tread area. The preliminary studies show that the 1/2 inch length is prudent, in that there is little or no risk of immediate failure from smaller cracks.

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