AAR RESEARCH REPORT

Work performed by:

TTCI
Transportation Technology Center, Inc.

A SUBSIDIARY OF THE ASSOCIATION OF AMERICAN RAILROADS

THE COMPARATIVE WEAR PERFORMANCE OF PREMIUM AND BAINITIC RAIL STEELS UNDER HEAVY AXLE LOADS

REPORT NO. R-941

KEVIN SAWLEY
RAFAEL JIMENEZ

Association of American Railroads
Transportation Technology Center, Inc. (TTCI)
Pueblo, Colorado

OCTOBER 2000

WORK PERFORMED BY:

Transportation Technology Center, Inc.

A SUBSIDARY OF THE ASSOCIATION OF AMERICAN RAILROADS

REQUEST FOR FEEDBACK

Report No: ***R-941***

Report Title: The Comparative Wear Performance of Premium and Bainitic Rail Steels Under Heavy Axle Loads

To help us continue to improve the quality and value of AAR reports to our customers, we would appreciate it if you would take a few moments to complete this form. Please feel free to provide further comments in the space below or on additional pages. Thank you for your cooperation.

For each of the following questions, please rate this report on a scale of 1 to 5 where 1 is the lowest rating and 5 is the highest.

	Low 1	2	3	4	High 5
How important is the subject of the report to your organization?					
How effective is the content of the report in assisting your organization address the subject?					
How well are the conclusions supported by the research?					
How clearly is the report written?					
How clearly are the graphics and tables presented and explained?					
How would you rate the timeliness of the completion of this project?					
If you ordered this report, how promptly was your order processed?					

How could this report be improved?

NAME: ______________________________

TITLE: ______________________________

COMPANY: ______________________________

ADDRESS: ______________________________

____

TELEPHONE: ________________ FAX: ________________

Please mail or fax the completed form to:

Peggy L. Herman, Assistant Manager-Technology Transfer and Documentation Services, Transportation Technology Center, Inc., P. O. Box 11130, Pueblo, Colorado 81001

Facsimile Number (719) 584-0716

1. Report No.	2. Report Date	3. Period Covered
R-941	October 2000	1997-2000

4. Title and Subtitle
The Comparative Wear Performance of Premium and Bainitic Rail Steels under Heavy Axle Loads

5. Authors
Kevin J. Sawley and Rafael Jimenez

6. Performing Organization Name and Address	7. Type of Report
Association of American Railroads Transportation Technology Center, Inc. P.O. Box 11130 Pueblo, CO 81001	Research **8. Contract or Grant No.** DTFR 53-93-C-00001

9. Sponsoring Agency Name and Address	10. No. of Pages
U.S. Department of Transportation Federal Railroad Administration Washington, DC	57 **11. Number of References** 16

12. Supplementary Notes

13. Abstract

The Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads has conducted wear tests on a range of rail steels in a 5-degree curve at the Federal Railroad Administration's Transportation Technology Center (TTC). The tests have included six premium rail steels, supplied by five manufacturers, and an experimental bainitic steel developed by the Association of American Railroads working with the Oregon Graduate Institute. Bainitic steel offers higher levels of hardness and toughness than conventional pearlitic steel used in premium rails, which are nearing their limit of development. Historically, increased rail hardness has led to improved wear resistance, and laboratory wear tests have indicated that high wear resistance can be achieved with high hardness bainitic steels. In these track tests, however, the bainitic steel has shown poorer wear performance than the pearlitic steels but apparent improved resistance to rolling contact fatigue.

14. Subject Terms	15. Availability Statement
Rail, Wear, Pearlitic steel, Bainitic steel	Transportation Technology Center, Inc., a subsidiary of the Association of American Railroads P.O. Box 79780 Baltimore, Maryland 21279

AAR R&T Documentation

(blank)

EXECUTIVE SUMMARY

The Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads has conducted wear tests on a range of rail steels in a 5-degree curve at the Federal Railroad Administration's Transportation Technology Center (TTC). The tests have included six premium rail steels, supplied by five manufacturers, and an experimental bainitic steel developed by the Association of American Railroads working with the Oregon Graduate Institute. Bainitic steel offers higher levels of hardness and toughness than conventional pearlitic steel used in premium rails, which are nearing their limit of development. Historically, increased rail hardness has led to improved wear resistance, and laboratory wear tests have indicated that high wear resistance can be achieved with high hardness bainitic steels.

Tests were undertaken in Section 7 of the High Tonnage Loop (HTL) at TTC's Facility for Accelerated Service Testing. Section 7 is a reverse curve (nominal 4-inch superelevation with train operation at 1.7 inch over-balance), and consequently under normal operation has only partial lubrication carried over from wayside lubricators elsewhere in the loop. Throughout the tests, the heavy axle load train typically consisted of 4 locomotives and 75 gondola and tank cars with nominal car loads of 315,000 pounds. The train ran clockwise and counter-clockwise at a nominal speed of 40 mph, and applied between 3 and 5 million gross tons (MGT) of traffic weekly.

These tests were conducted during three test phases of the Heavy Axle Load program:

Phase III All the cars had improved-suspension trucks equipped with a mechanism to increase warp stiffness and shear pads between the bearing adapters and the side frames. These trucks offer much better curving behavior than standard three-piece trucks. Partial rail lubrication was applied.

Phase IV The same improved suspension cars were applied, but the rail was operated in the fully dry condition.

Phase V The cars were re-equipped with standard three-piece trucks, and partial lubrication was again applied to the rails.

The six premium head-hardened rail steels in the test curve had hardnesses in the range 341 to 378 Brinell hardness (HB). These hardness values were found using manually operated Brinell machines. An automatic machine was found to give hardness values typically 16 hardness points higher. Five of the premium steels had conventional pearlitic microstructures, while the sixth (a hypereutectoid steel) had marginally higher carbon content and consequently thicker carbide lamellae. In contrast, the bainitic steel had a carbide-free ferrite lath structure with hardness provided by a very fine lath size and a high dislocation density. All but one of the rails was supplied to the American Railway Engineering and Maintenance of Way Association (AREMA) 136-10 section (10-inch crown radius). The exception had a section with a flatter rail top and was probably supplied to the older 136-pound design that mandates a 14-inch crown radius.

Profile measurements were made after installation, and at intervals up to the final reported tonnage. Snap gages measured height loss on the high and low rail, and gage-face loss on the high rail measured 5/8 inch below the rail top. Measurements were also made of the high and low rail transverse profiles using a Miniprof™ machine. The Miniprof and snap gage measurements agreed well. To determine wear rates for all the steels (under partial lubrication and fully dry conditions) linear regression was used to relate cross-sectional area lost (A) to tonnage (MGT):

$$A = a.(MGT) + b \qquad (1)$$

High values of coefficient, *a*, indicate poor wear resistance, low values mean good resistance. In all cases, the correlation coefficient (R^2) was above 0.9.

Wear rates in the first two test phases were found to be low, and rates were seen to vary considerably between the different premium rail steels. Also, in these two phases the expected inverse relationship between hardness and wear rate in pearlitic steels was not observed. Consequently it is believed that these early wear results included effects due to initial profile shape and extent of decarburized layer. Sufficient wear to remove these transient effects had likely occurred by Phase V, and it is therefore considered that relative wear performance should be judged on the basis of the Phase V results.

Principal findings from this study are:

- With one exception, the as-supplied rails had transverse profiles in close conformity to the design profile (AREMA 136-RE, 10-inch crown radius). One manufacturer (Hayange) produced rail with a flatter top, probably to the old 136-RE design that mandates a 14-inch crown radius.
- For all rails, maximum wear was seen on the high rail, with only minimal wear observed on the low rail.
- The lowest rail wear rates were seen in Phase III (315,000-lb. cars equipped with improved suspension trucks, partial lubrication conditions), while the highest wear rates were seen in Phase V (315,000-lb. cars equipped with standard three-piece trucks, partial lubrication conditions). As individual wear rates increased through the three test phases, so the relative performance of the premium rails converged.
- For the six premium rail steels, there was no consistent relationship between hardness and wear rate in Phases III and IV. In contrast, in Phase V the expected relationship between bulk hardness and wear rate was observed. For each 1 percent increase in as-manufactured Brinell hardness, wear rate fell on average by 1.4 percent.
- J6 bainitic rail steel had the highest hardness and the highest wear rate of all the rails tested. This confirms that factors other than simple bulk hardness influence wear rate. This relatively poor wear resistance need not curtail the implementation of J6 rail if, as expected, the rail needs less grinding in revenue service.
- Statistical tests indicated no significant effect of fastener type on rail wear. Analysis also indicated that there was little, if any, effect of position-in-curve on rail wear.

Although the bainitic rail steel showed a higher wear rate than the premium rail steels, rail life is not simply related to wear resistance. Though most rails are replaced when wear limits are exceeded, in many cases much of the metal loss is caused by grinding to remove surface cracks, pits, and spalls. For premium rails, grinding is used to remove fatigue-damaged surface material, aiding the natural wear. Bainitic rail steel, with its higher hardness (which should equate to better fatigue resistance) and higher natural wear, still offers the possibility of longer rail life through a reduction in rail grinding. To test their performance under service conditions, trial bainitic rails have recently been installed in a 5.5-degree curve on the Norfolk Southern track near Roanoke, Virginia USA.

Table of Contents

List of Exhibits

1.0 INTRODUCTION

This report describes an experiment conducted by Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR), to measure the comparative wear performance of a range of modern rail steels. The rails examined include six conventional head-hardened premium grade steels supplied by five manufacturers, and an experimental high-hardness bainitic rail steel (coded J6) developed as part of the AAR's Strategic Research Initiative. The wear tests were conducted in a 5-degree curve at the Federal Railroad Administration's (FRA) Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center near Pueblo, Colorado USA.

Testing was performed in Section 7 of the High Tonnage Loop (HTL) at FAST, a nominal 5-degree curve that sees heavy axle loads (approximately 39 tons) applied by the heavy axle load (HAL) train. Section 7 is the only reverse curve in the HTL, and is often described as a dry-wear curve, since the high rail is not intentionally lubricated. In practice, as the HAL train is regularly turned, the high rail at Section 7 is contaminated with lubricant and in routine operation has a prevailing friction level of about 0.3 to 0.4. During the wear experiment, and principally to test the operation of improved-suspension trucks under non-lubricated conditions, both wayside lubricators were turned off and the HAL train was run with fully dry rail.

These tests were conducted during three test phases of the Heavy Axle Load program:

HAL Phase III: The HAL train was equipped with improved suspension trucks, and the rail had light contamination lubrication (friction 0.3 to 0.4).

HAL Phase IV: The HAL train was equipped with improved suspension trucks, but the rail was left in the non-lubricated condition (friction about 0.5).

HAL Phase V: The HAL train was equipped with standard three-piece trucks, but the rail had light contamination lubrication (friction 0.3 to 0.4).

Wear was measured using both manual gages to measure high- and low-rail height loss and high-rail gage wear, and the Miniprof™ system, which measures the full rail head profile. For the head-hardened steels, wear and profile measurements were measured over an accumulated tonnage of 317 million gross tons (MGT) of traffic. The J6 rails were installed after the head-hardened rails, and measured over a tonnage of 252 MGT.

Section 2.0 of this report lists the rail steels examined and gives brief details of their microstructure and hardness. Appendix A gives in-depth information about the experimental bainitic J6 steel. The operating environment at the HTL is described in Section 3.0, along with the measured small-scale variations in curvature through the nominal 5-degree curve. The wear measurement methodology is described in Section 4.0, while results — with analysis — are given in Section 5.0 and Appendix D. Finally, the implications of the results are discussed in Section 6.0.

2.0 TEST STEELS

Exhibit 1 lists the code names of the seven rail steels tested and their manufacturers, and gives a brief description of their microstructures. According to the manufacturers' information, five of the six head-hardened steels had a fine pearlitic microstructure typical of rapidly cooled carbon-manganese steel. The only exception was the hypereutectoid steel produced by Nippon Steel Corporation (steel NSCHE), which was claimed to have a carbon content above the eutectoid level, with consequently thicker carbide lamellae.[1] The microstructure of the low-carbon bainitic steel (steel J6) was significantly different from the head-hardened steels. The steel had a carbide-free ferrite lath structure, with hardness provided by a very fine lath size and a high dislocation density. Full details of the J6 steel and its properties are given in Appendix A.

Manufacturers were asked to donate 136-pound section rails for test. The rails supplied had the profile descriptions given in Exhibit 1 and most appeared to have been made to the current American Railway Engineering and Maintenance of Way Association (AREMA) 136-RE, 10-inch crown radius.[2] The only exception was the

Hayange rails that had a flatter rail top. It is possible that these rails had been made to the older AREMA 136-RE profile that has a 14-inch crown radius.

Exhibit 1. Test Rail Steels with Nominal Microstructure

Rail steel	Manufacturer	Microstructure	Rolled rail section
HAYHH	Hayange	Fine pearlitic steel	136-RE
NKKTH37N	Nippon Kokan	Fine pearlitic steel	136BN
NSCDH37	Nippon Steel Corporation	Fine pearlitic steel	136-RE
NSCHE	Nippon Steel Corporation	Fine pearlitic steel	136-RE
PSTHH	Pennsylvania Steel Technologies	Fine pearlitic steel	136-10
RMSDHH	Rocky Mountain Steel Mills	Fine pearlitic steel	1360(BNSF)
J6	Pennsylvania Steel Technologies*	Carbide-free bainitic steel	136-10

** Produced for the Association of American Railroads*

Exhibit 2 shows the positions of rail hardness measurement for values shown in Exhibit 3. The Brinell hardness (HB) of each steel was measured 3/8 inch below the rail surface at positions specified in Reference 2 (Exhibit 2). Because of concerns over some of the early measured hardness values obtained and since the wear of pearlitic steels is commonly inversely linked to hardness, measurements were made by TTCI and at three independent laboratories accredited to undertake Brinell hardness testing. All results are shown in Exhibit 3. The table also lists, where available, the hardness values supplied by the manufacturers prior to rail installation. Brinell hardness maps made by TTCI for all the test steels are shown in Appendix B.

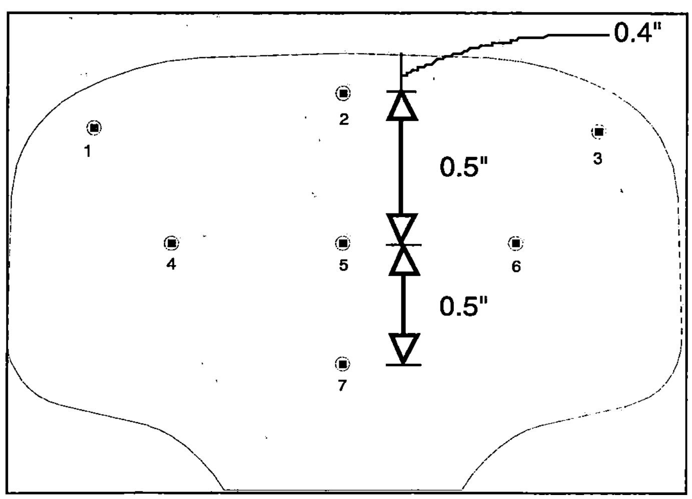


Exhibit 2. Positions of Rail Hardness Measurement for Values Shown in Exhibit 3

Exhibit 3. Measured Brinell Hardness Values for Test Rails

Rail steel	Position (Exhibit 2)	Hardness, HB					
		TTCI (Manual)	CMS* (Manual)	MTC* (Manual)	Average (Manual)	LTI* (Automatic)	Manufacturer Values
HAYHH	1	363	352	368	361	381	N/A
	2	363	363	363		371	
	3	363	352	363		380	
NKKTH37N	1	363	375	368	369	389	375**
	2	363	375	368		391	
	3	363	375	368		393	
NSCDH37	1	363	352	363	358	365	353
	2	363	375	356		376	
	3	341	352	356		372	
NSCHE	1	363	363	375	367	379	364
	2	363	363	375		382	
	3	363	363	375		382	
PSTHH	1	341	341	341	342	363	374†
	2	341	341	341		341	
	3	341	352	341		365	
RMSDHH	1	388	375	375	378	391	375**
	2	388	375	388		402	
	3	363	363	388		382	
J6	1	415	415	401	413	-	-
	2	415	415	415		-	
	3	415	415	415		-	

*CMS = Colorado Metallurgical Services.
*MTC = Metallurgical Testing Corporation.
*LTI = Laboratory Testing, Inc.
** Values converted from Vickers hardness measurements (reference 4).
† Value found by automatic Brinell measurement.

The Brinell hardness measurements made by TTCI and two of the independent laboratories, CMS and MTC, were made using manual Brinell machines. With these machines, the operator manually measures the diameter of the hardness indentation, along two orthogonal diameters, and translates the average diameter into a hardness value using standard tables. The TTCI, CMS, and MTC hardness values agree well with each other, and are consistent with most of the hardnesses quoted by the manufacturers. The measurements performed by LTI were taken using an automatic system. In this, a computer analyzes a camera image of the indentation and calculates an average diameter from 80 measurements of diameter. For all the rail steels, the automatic method consistently reported higher hardness values than the manual method, by an average of 16 HB. Since the automatic method measures more diameters, and does not rely on human measurements, it could be expected to give more accurate results. However, it should be stressed that the manual method is accepted for the relevant ASTM specification, and the CMS and MTC laboratories were accredited for Brinell hardness testing.[3] It is outside the scope of this project to decide between manual and automatic methods of measuring Brinell hardness.

The J6 bainitic-rail test zone consists of two 80-foot rails on the high side and one 80-foot rail on the low side of the curve. The six premium rail test zones consist of two 80-foot rails on the high side and two 80-foot rails on the low side. Although a small number of measurements are taken in an adjacent spiral section, all the results in this report are taken from measurement positions within the body of the 5-degree curve of Section 7 (4-inch superelevation).

The six head-hardened steels were flash welded into strings, using typical flash welding parameters for head hardened rail. These two strings were installed in Section 7 on August 26, 1997. The J6 rails were installed at a later date (February 19, 1998). At the time of reporting, the head-hardened rails had accumulated 317 MGT of traffic and the J6 rails had accumulated 252 MGT. Exhibit 4 shows the layout of the rails in the curve. Because of other test constraints, rails were laid on a variety of ties using a range of fasteners. Exhibit 5 details the ties and fasteners at and near the wear measurement locations. Possible tie and fastener effects on wear performance will be discussed in Section 5.0 of this report.

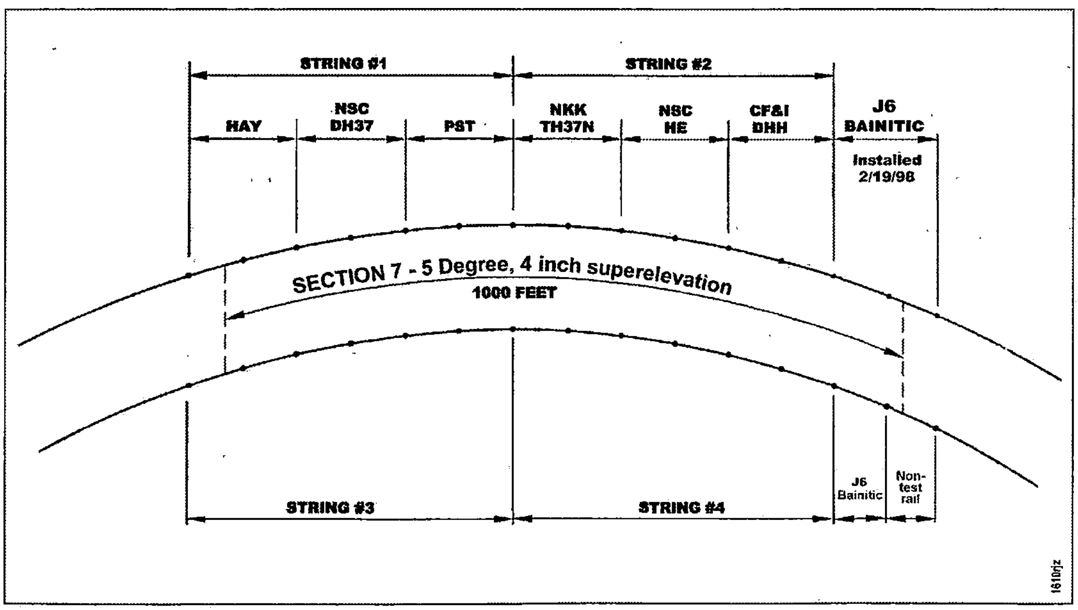


Exhibit 4. Layout of Test Rails in 5-degree Curve of Section 7

Exhibit 5. Tie and Fastener Types Under the Test Rails

Rail	Position (Tie Number)	Tie type**	Fastener type †
HAYHH	*		
	T25	Oak (±10 min.)	Cut spikes (±10 min.)
NKKTH37N	T265	Oak (±10 min.)	Lock-spiked e-clips (±10 min.)
	T318	Parallam (±10 min.)	Screw-spiked e-clips (±10 min.)
NSCDH37	T76	Oak ties (+10, -5)	Cut-spikes (+10, -5)
	T125	Laminated s. yellow pine (±10 min.)	Cut-spikes (±10 min.)
NSCHE	T365	Oak ties (+10, -4)	Double elastic spikes (+10, -4)
	T414	Reconstituted	Cut-spiked e-clips
PSTHH	T169	Laminated s. yellow pine (±10 min.)	Cut-spikes (±10 min.)
	T218	Oak (±10 min.)	Lock-spiked e-clips (±10 min.)
RMSDHH	T461	Plastic (±10 min.)	Screw-spiked e-clips (±10 min.)
	T514	Oak (±6)	Safeloks (±6)
J6	T561	Oak (±10)	Safeloks (+10, -2)
	T606	Oak (+10, -3)	Safeloks (+10, -3)

* Tie in spiral at entrance to Section 7 curve
** Numbers refer to extent of ties either side of measurement position.
† Numbers refer to extent of fasteners (by number of ties) either side of measurement position.

Profiles were measured using the Miniprof system on all the rails before traffic to provide baselines for later wear measurements. One profile was taken from each rail to give two high-rail and two low-rail profiles per rail steel. (Because one of the Hayange rails was installed in the entrance spiral, only one Hayange high-rail profile was analyzed for comparison with the other rails.) Appendix C shows these initial profiles compared to the design 136-10 profile. Also given for each rail steel are residual plots showing the differences between the measured and design profiles, plotted with respect to angle from the railhead top center. Note these differences are defined as the separation between each pair of profiles measured along lines normal to the design profile.

These residual plots illustrate the manufacturers' ability to roll rail to the design profile. Six of the test rails had as-rolled profiles acceptably close to the current AREMA

136-RE design profile. As already stated, the exception was the Hayange rail that had a relatively flat top and pronounced shoulders. As will be seen later, these high shoulders appear to have had an effect on performance; first, by limiting contact between the wheel flange and the high-rail gage face (reducing side wear), and second, by concentrating the wheel load on the high-rail gage corner top (causing cracks and spalls).

3.0 OPERATING ENVIRONMENT

Exhibit 6 shows the 2.7-mile High Tonnage Loop. The HTL has three 5-degree curves with 4 inches of superelevation, one 6-degree curve with 5 inches of superelevation, and tangent sections. The effects of heavy axle loads are examined by operating a HAL train, which normally consists of 70 to 80 315,000-pound (39-ton axle load) gondola and tank cars. The HAL train operates at night starting at 2200 hours and stopping at 0730 hours the following morning. It operates 4 days per week generating 3 to 5 MGT weekly. At a steady speed of 40 mph, the train runs at 1.7 inches over balance speed through the 5-degree, 4-inch superelevation rail wear test zone curve in Section 7. This curve is a reverse curve on the loop and is therefore less lubricated than the other curves, which receive high-rail lubrication from trackside lubricators at either end of Section 25.

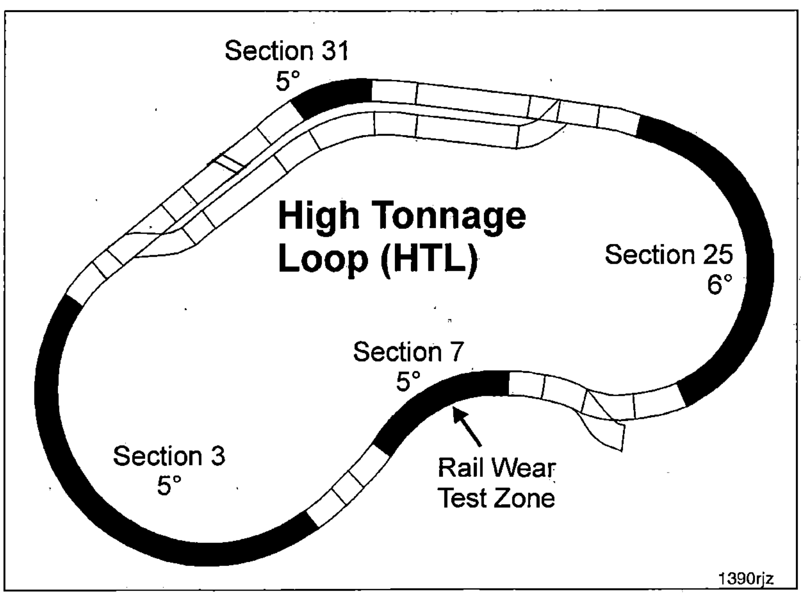


Exhibit 6. Layout of the High Tonnage Loop showing the Rail Wear Test Zone

Exhibit 7 summarizes operating conditions of the current rail wear test. When the premium rails were installed during Phase III testing in August 1997, the HAL train was equipped with improved suspension, warp-stiffened trucks with primary shear pads between the bearing adapters and the side frames. These provide the benefit of improved curving response with enhanced wheelset steering and resistance to warp. During Phase III, Section 7 was typically slightly contaminated with lubrication on the high rail. The low rail received light, indirect lubrication. The primary objective during Phase III testing was to compare the performance of new rail steels, including hypereutectoid and bainitic rail. During Phase IV testing, the same rails were measured for wear under the improved-suspension trucks but the HAL train ran on fully dry rail. During Phase V the HAL train was equipped with standard three-piece trucks and the rail again had lubricant contamination. While Section 7 has a nominal track curvature of 5 degrees, it was known that small variations in curvature occurred through the section. These variations in curvature were measured, and are shown in Exhibit 8 for the different rail steel locations. Curvature is seen to vary between 4.27 and 5.25 degrees.

Exhibit 7. Summary of Tonnages and Operating Conditions during Phases III, IV, and V of HAL Rail Wear Testing

Phase	Start Date	Tonnage (MGT)	Operating Conditions in Section 7
III 2nd Main Installation	August 1997	167	Improved trucks: Slight lube-contaminated high rail 0.35 to 0.40 μ Light indirect lube low rail
IV	January 1999	56	Improved trucks: Dry rail 0.5 to 0.55 μ
V	September 1999	In progress 94 MGT	Standard trucks: Slight lube-contaminated high rail 0.35 to 0.40 μ Light indirect lube low rail

Exhibit 8. Local Track Curvature at the Rail Positions

Rail Type	Average curvature (degrees)
HAYHH	4.27
NKK TH37N	5.25
NSC DH37	4.86
NSCHE	4.64
PSTHH	5.30
RMSDHH	4.80
J6	4.58

The Section 7 test zone is inspected weekly using a hi-rail Pandrol-Jackson 300 ultrasonic rail flaw detection vehicle.

4.0 MEASUREMENTS AND OBSERVATIONS

Two methods were used to measure wear in the test rails. First, the Miniprof system was used to measure the full transverse profiles of the rails. This system, shown in use in Exhibit 9, measures the profile from the lower gage corner to the lower field corner and describes the resultant profile by a series of x-y coordinate pairs. Results are stored on computer for subsequent analysis. Comparison of new and worn profiles enables the following wear parameters to be calculated using the Miniprof software (see Exhibit 10).

Area A:	Total area worn from the rail head cross section.
Height loss, W1:	Total vertical height loss from the rail top center.
Gage point loss, W2:	Gage face loss measured 0.47 inch down from the new rail top.
Gage corner loss, W3:	Gage corner loss measured on a line at 45 degrees to the vertical and passing through the new rail center.

The other measurement tools used were "snap" gages. These gages use simple analog dial gages to measure height loss at the rail top center and gage face loss 15.9 mm (5/8 inch) down from the worn rail top. These gages were used as backup to the Miniprof system. Exhibit 5 shows the rail measurement positions by tie number. Profile and gage measurements were made immediately after installation and at intervals thereafter. Exhibit 11 lists the accumulated tonnages at which measurements were made, and indicates the tonnage at which dry running commenced for both the head-hardened and J6 bainitic rails. Visual observations were made of rail condition at routine intervals.

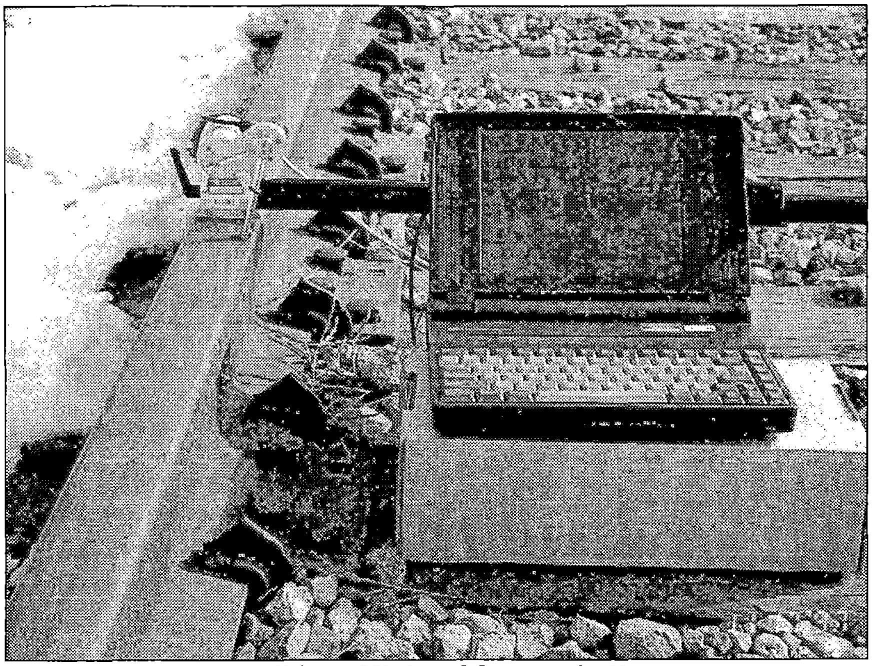


Exhibit 9. Miniprof System in Use

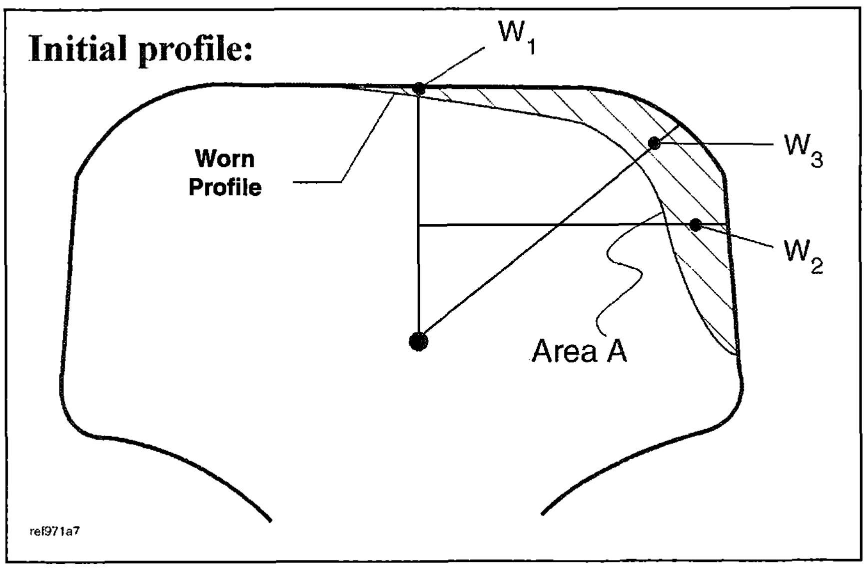


Exhibit 10. Illustration of Wear Measurements available from the Miniprof Software

Exhibit 11. Profile Measurements

Head-hardened rails		J6 bainitic rail
0 MGT: partial lubrication		0 MGT: partial lubrication
10 MGT		10 MGT
19 MGT		19 MGT
40 MGT		35 MGT
60 MGT		60 MGT
98 MGT		72 MGT
152 MGT		87 MGT
167 MGT: dry running starts		102 MGT: dry running starts
180 MGT		115 MGT
193 MGT		128 MGT
205 MGT		140 MGT
224 MGT: partial lubrication starts		159 MGT: partial lubrication starts
240 MGT		175 MGT
253 MGT		188 MGT
270 MGT		206 MGT
285 MGT		220 MGT
300 MGT		235 MGT
317 MGT		252 MGT

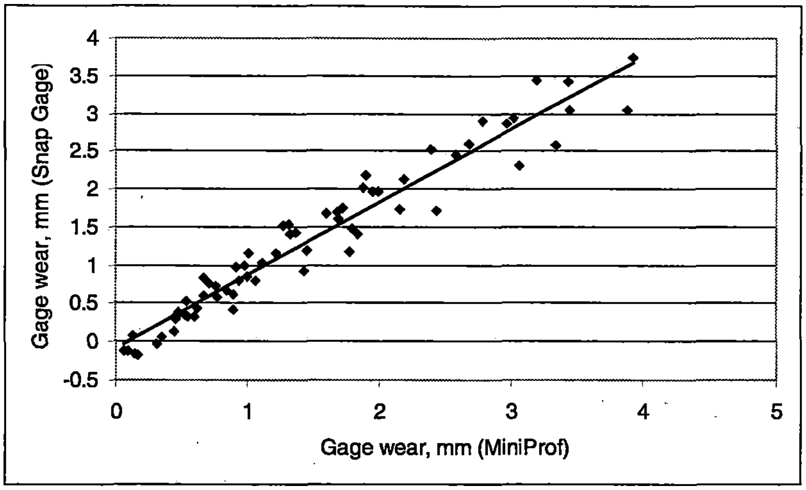
5.0 RESULTS AND ANALYSIS

This section presents data generated through the experiment and examines the possible effects on rail wear of:

- Changes in lubrication practice
- Tie/fastener system used
- Minor variations in track curvature
- Variations in rail hardness

For all the rails, head height loss over the period of the test has been relatively low — especially on the low rails. Most wear has occurred on the high-rail gage face, as shown in the illustrations in Appendix D that compare the final (premium rail: 317 MGT; bainitic rail: 252 MGT) high-rail worn profiles to the initial profiles (0 MGT). Exhibit 12 compares high-rail gage face wear measurements produced by the Miniprof machine (the W_2 measurement, taken approximately 1/2 inch below the as-new rail profile top) and the snap gage (taken approximately 5/8 inch below the new rail top).

Good agreement is seen between the two forms of measurement. For this reason, the wear rate analyses that follow will use the Miniprof wear measurements.



(Note: 1 mm = 0.04 inch)

Exhibit 12. Relationship between Gage Face Wear Measured by the "Snap Gage" and by the Miniprof System

For ease of description in the exhibits that follow, the rail names given in Exhibit 1 will be abbreviated to refer only to the manufacturer. The exceptions are the bainitic rail, which will be referred to as J6, and the two Nippon Steel Corporation rails that will be referred to as NSCDH and NSCHE.

5.1 WEAR RATE ANALYSIS

Exhibits 13 to 16 summarize the high-rail wear results obtained from the Miniprof measurements. They show, respectively, the effect of accumulated tonnage on cross sectional area lost (measurement A), head height loss (measurement W_1), gage face loss (measurement W_2), and gage corner loss (measurement W_3) (refer to Exhibit 10). Each point in these graphs is an average of the two measurements taken at each of the test high rails. The only exception is the Hayange data, where only one high rail was installed. Each Exhibit includes vertical lines separating the three test phases. These appear at different positions for the J6 and premium rails only because the J6 rails were installed after the premium rails.

Exhibit 13 shows the total cross sectional area lost during the test. It can be seen that the wear rate (shown by the slope of each individual graph) has increased from Phase III to Phase IV to Phase V. Of the premium rails, the NSCDH rail and the Hayange rail show the least wear at the end of test, followed by the NSCHE, NKKTH, and RMSDHH – which all show similar performance. Of the premium rails, the PSTHH rail shows the most wear. The J6 shows worse wear performance than the premium rails, although this is accentuated in Exhibit 13 by the later start to the J6 test, which emphasizes the acceleration in wear caused by dry running. Nevertheless, the J6 rail shows more wear after 252 MGT than all the premium rails after 317 MGT.

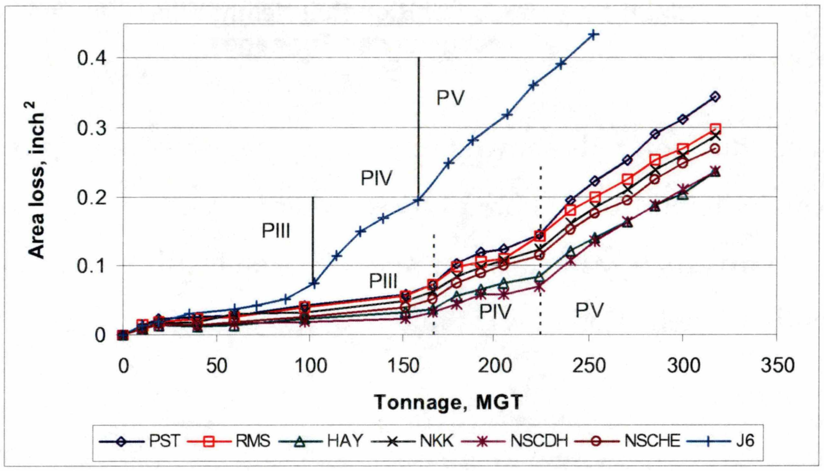


Exhibit 13. Variation of High-Rail Cross Section Area Wear (A) with Accumulated Tonnage
PIII, PIV, and PV = the test phases for the J6 and premium rails

Exhibit 14 shows the effect of accumulated tonnage on metal worn from the high-rail top. During Phase III (improved suspension truck with partial rail lubrication) wear on the high-rail top was virtually nonexistent for all the test rails. Wear is seen to start with the advent of dry running, and has continued after the introduction of standard trucks with partial rail lubrication. However, rail top wear is minimal even after 317 MGT of traffic, nowhere exceeding 0.035 inch (0.9 mm) for the premium steels. The relatively high degree of scatter in the measurements illustrates the difficulty of matching new and worn rails in the vertical direction when wear is limited.

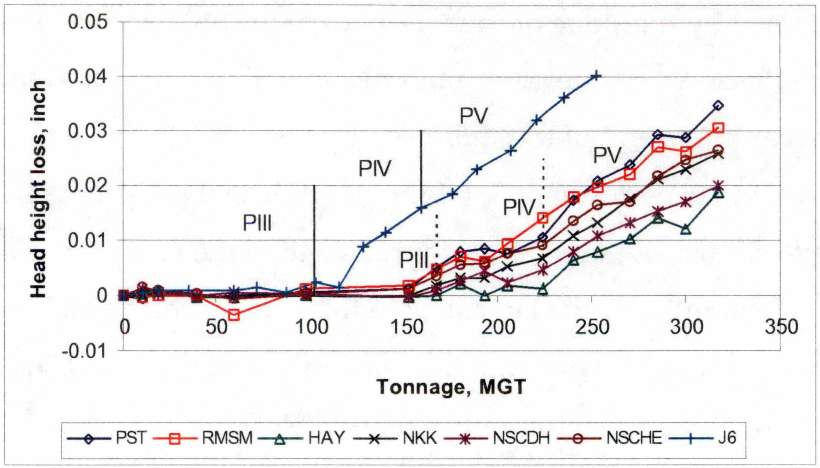


Exhibit 14. Variation of High-Rail Height Wear (W_1) with Accumulated Tonnage

As expected, the high rails showed much more gage face and gage corner wear. This is seen in Exhibits 15 and 16. In both of these, wear increases from Phase III to Phase IV to Phase V. Approximately linear wear rates are seen in all three test phases, although there is a trend of a reduction in wear rate with increasing tonnage in Phase IV (dry running).

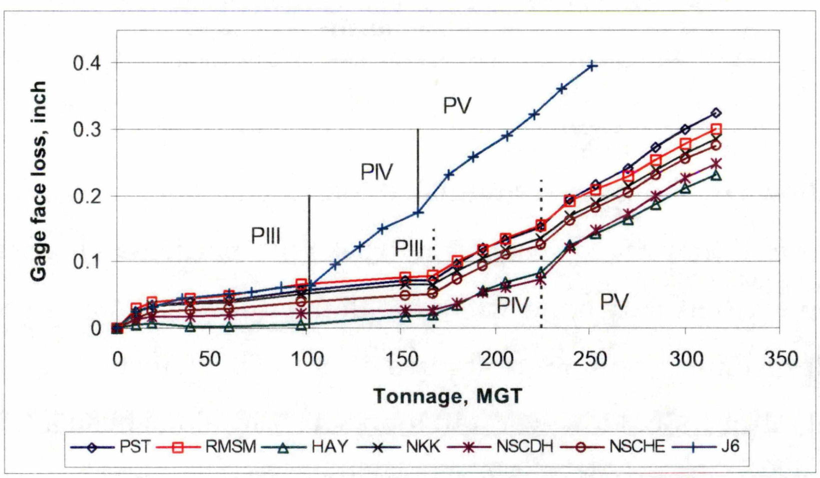


Exhibit 15. Variation of High-Rail Gage Face Wear (W_2) with Accumulated Tonnage

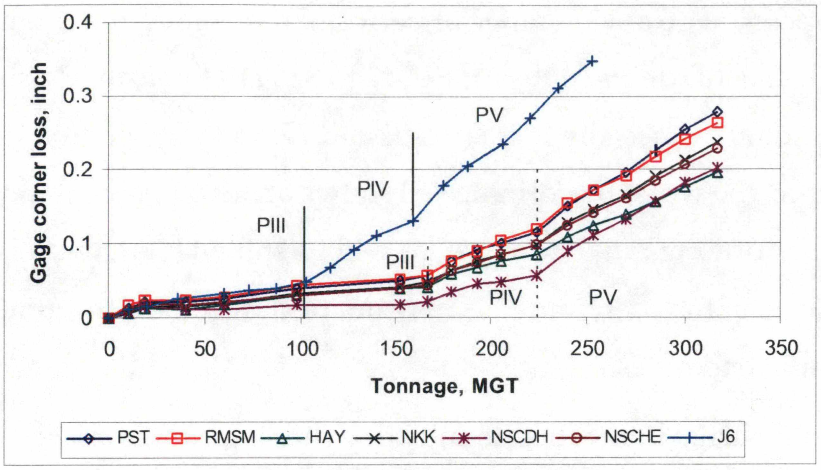


Exhibit 16. Variation of High Rail Gage-Corner wear (W_3) with Accumulated Tonnage

Finally, Exhibit 17 compares the high-rail and low-rail height losses (measured at the rail center-line) at the end of the test period for all seven-test rail steels. As can be seen, the amount of wear on the low rails after 317 MGT (premium rails) and 252 MGT (bainitic rail) is minimal.

Exhibit 17. Height Losses (measured at the rail center line) at the End of the Test Period

Final Tonnage	Rail Steel	High-Rail Height Loss* Inch (mm)	Low-Rail Height Loss* inch (mm)
317 MGT	HAY	0.019 (0.48)	0.018 (0.45)
	NKK	0.026 (0.66)	0.021 (0.53)
	NSCDH	0.020 (0.51)	0 015 (0.38)
	NSCHE	0.026 (0.66)	0.024 (0.62)
	PST	0.035 (0.89)	0.027 (0.68)
	RMS	0.031 (0.79)	0.021 (0.54)
252 MGT	J6	0.040 (1.02)	0.025 (0.63)

** Miniprof measurement results*

5.1.1 General Wear Performance of Test Rail Steels

Exhibits 13 to 16 illustrate a number of general features of the wear test:

- The J6 bainitic rail steel, despite being significantly harder than the premium rails, exhibits the highest wear rates during all three-test phases. Reasons for this will be considered later.

- There appears to be a wide range of performance among the premium rail steels, which all have hardness in the range 342 to 378 HB (measured using the manual Brinell method), especially in Phases III and IV. In terms of area lost, after 317 MGT traffic, the worst performing rail shows about 45 percent more wear than the best performing rails. However, as will be shown later, the relative performance of the premium rails may not be judged best by comparison of the total wear at end of test.
- Going from partial lubrication to fully dry running causes a large increase in wear for all the steels — as does the introduction of standard three-piece trucks to replace the improved suspension trucks. Estimated friction during dry running was about 0.5, while that in partial lubrication was 0.3 to 0.4. This confirms the great benefits to wear resistance offered even by limited lubrication.
- Initial profile shape has a significant effect on the position of rail wear. The Hayange rail had a much flatter rail top than the other steels and relatively proud gage corners. This as-manufactured profile concentrated wear on the gage corner, and tended to reduce wear on the rail top and gage face. Because of possible profile effects, the use of cross section loss to compare wear performance may be better than the use of point measurements such as gage face loss or head height loss, especially for high rail wear in curves.

5.1.2 Linear Regression Wear Analysis

Linear regression analysis of the high-rail cross-section wear loss data shown in Exhibit 13 was used to assess the rate of wear in the three test phases. In this analysis, cross section lost (A) is related linearly to accumulated tonnage (MGT) by the equation:

$$A = a.MGT + b \qquad (1)$$

where, *a* and *b* are coefficients of the regression. The coefficient R^2 is a measure of the correlation between A and MGT. R^2 coefficients near 1 indicate very good correlation. The limits over which the analyses were done were chosen as follows:

Premium steels:

- **Phase III analysis**: A lower tonnage limit of 40 MGT was chosen to discount potential effects of initial profile shape on wear. The upper limit was chosen to be 152 MGT to avoid the upturn in wear that was seen just before dry running started at 167 MGT.
- **Phase IV analysis**: A lower tonnage of 180 MGT was chosen to limit possible wear transient effects when moving from partial lubrication wear to dry wear. The upper limit was set at 224 MGT.
- **Phase V analysis:** A lower tonnage of 240 MGT was chosen to limit possible wear transient effects when moving from improved suspension trucks to standard trucks. The upper limit was set at 317 MGT.

J6 bainitic steel

For the same reasons as above, the regression limits were set at 35 to 87 MGT (Phase III), 115 to 159 MGT (Phase IV), and 175 to 252 MGT (Phase V).

Exhibit 18 gives results of these high-rail wear regression analyses. The correlation coefficients indicate a high correlation between cross section loss and accumulated tonnage, especially for Phase V. Exhibit 19 expresses the results normalized to the steel with the best wear resistance in each phase (lowest value of "a").

Exhibit 18. High-rail Wear Regression Analyses (cross section loss) in Phases III to V

Rail steel	Hardness (HB)**	Phase III		Phase IV		Phase V	
		a*	R^2	a*	R^2	a*	R^2
HAY	361	0.194	0.998	0.628	0.985	1.444	0.997
NKK	369	0.243	0.935	0.873	0.993	1.632	0.999
NSCDH	358	0.084	0.996	0.507	0.917	1.643	0.997
NSCHE	367	0.220	0.998	0.879	0.995	1.557	0.996
PST	342	0.324	0.990	0.879	0.979	1.936	0.997
RMS	378	0.312	0.993	0.973	0.902	1.530	0.998
J6	413	0.403	0.945	1.773	0.965	2.409	0.999

** Units are in^2 per 1,000 MGT*
*** Measured by manual Brinell method*

Exhibit 19. Relative Wear Rates in Phase III to V

Rail steel	Hardness (HB)*	Relative Wear Rates (best=1)		
		Phase III	Phase IV	Phase V
HAY	361	2.31	1.24	1
NKK	369	2.89	1.72	1.13
NSCDH	358	1	1	1.14
NSCHE	367	2.62	1.73	1.08
PST	342	3.86	1.73	1.34
RMS	378	3.71	1.92	1.06
J6	413	4.80	3.50	1.67

** Measured by manual Brinell method*

The main conclusions from the wear analysis are:

- There is a wide disparity in wear performance in Phases III and IV. This is especially the case in Phase III. In both these phases (improved suspension trucks with partial lubrication followed by dry running), the NSCDH rail steel shows by far the best wear resistance. The reasons for the outstanding apparent performance of NSCDH and the wide range of premium rail performance are not known, but may include:
  - Inherent differences in steel performance. This is unlikely as large variations in wear performance have historically been associated with much larger differences in hardness than those seen in Exhibit 3.
  - Effects of as-manufactured profile differences. Apparently small changes in rail profile can have large effects on contact stress; hence, on wear. However, with the exception of the Hayange rail, all the premium rails had very similar as-manufactured profiles.
  - Differences in the thickness of the decarburized layer present at the rail surface. All rails have a thin surface layer, which is depleted in carbon. This is a consequence of the manufacturing process, and therefore varies from manufacturer to manufacturer. This layer has a hardness that is low at the surface and gradually rises to the bulk hardness value and a ductility that is likely to be higher than the bulk material. The layer can, therefore, be expected to have wear properties different from the bulk material. The decarburized rail layers present in the test premium rails were thin, typically about 0.02 inch (0.5

mm, defined as the depth at which the hardness reached 95 percent of bulk hardness). The only exception was the Rocky Mountain Steel Mills rail that showed minimal loss of hardness at the surface. For comparison, at the end of Phase III the typical premium rail gage corner loss varied from about 0.016 to 0.04 inch (0.4 to 1.0 mm), while the respective Exhibits were 0.022 to 0.06 inch (0.6 to 1.5 mm) by the end of Phase IV. Thus effects due to the decarburized layer should have been minimal in Phase V, and possibly minimal in Phase IV.

- With improved suspension trucks, changing from partial lubrication to dry running (Phase III to Phase IV) has produced a large increase in wear — by a factor ranging from 2.71 to 6.06 (average 3.87). The introduction of dry running, however, appears to have narrowed the range of wear performance. This is unusual in that earlier work at FAST has indicated that lubrication causes the wear resistance of different steels to converge.[5] The effect of the gradual elimination of the decarburized layer on wear rate during Phases III and IV is unclear.
- The introduction of standard three-piece trucks (Phase V) has accelerated rail wear and caused the performance of all the premium rails to converge. The premium rail gage corner loss at the end of Phase V (317 MGT) ranged from 0.2 to 0.26 inch (5.1 to 6.6 mm); well beyond the level at which profile or decarburized layer effects should still be operative. It is, therefore, believed that the Phase V wear results are a truer reflection of the relative wear performance of the test rail steels.
- For all three test phases, Exhibit 20 shows the effect of bulk hardness on wear rate ($in^2/1,000$ MGT, normalized by track curvature) for the six premium rail steels. During Phases III and IV there is no consistent effect of hardness on wear rate. Conversely, a clear trend of decreasing wear with increasing hardness is seen in Phase V. These results support the arguments that transient effects have influenced wear performance in Phases III and IV.

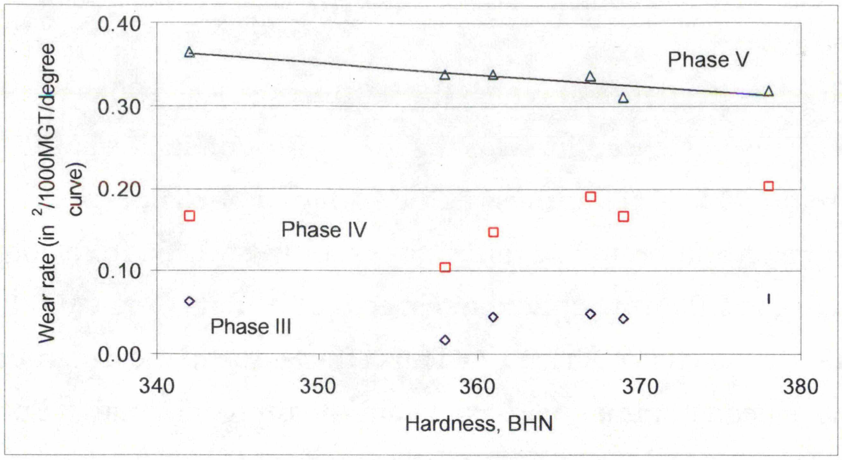


Exhibit 20. Effect of Hardness on Normalized Wear Rate in Phases III to V

- The J6 bainitic steel was the hardest tested and it consistently gave the highest wear rate during all three test phases. This result confirms that hardness alone is not an adequate predictor of wear resistance. Possible reasons for the higher wear rates of J6 will be discussed later.
- Finally, the wear lives of the premium rails in each phase can be estimated assuming that rails are replaced for wear when about 35 percent of the head has worn away. In Phase III, lives range from 5,200–20,000 MGT, in Phase IV the values are 1,700-3,300 MGT, and in Phase V the range is 870–1,160 MGT. These Exhibits show the beneficial effect of improved suspension trucks on rail wear.

5.2 POSSIBLE POSITION-IN-CURVE EFFECTS ON WEAR

Early in the test, there was concern that wear may be affected by the position of a rail within the curve. This is why local track curvature was measured (see Section 3.0). To test for any effect, Exhibit 21 plots normalized wear rate (in^2/1,000 MGT normalized by track curvature) against position in curve. (The Hayange steel was laid at one end of the curve with the J6 steel at the other end.) The partial lubrication results do not suggest that position-in-curve affects rail wear rate. However, the dry-running results do show a trend of low wear at one end of the curve leading to high wear at the other end, although this is accentuated by the J6 performance.

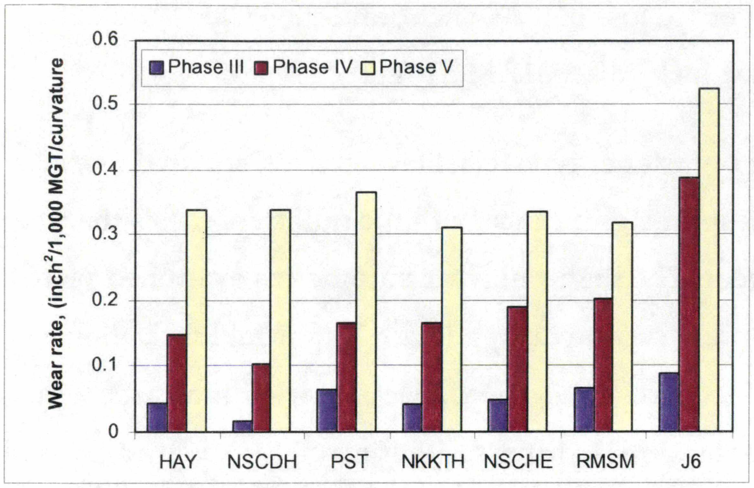


Exhibit 21. Variation of Normalized Wear Rate with Position in Curve

If there is a position-in-curve effect it is likely to lead to increased wear at either end of the curve. This is because trucks entering the curve may take some distance to achieve their optimum curving position. Since the train runs both clockwise and counterclockwise, this effect would be seen at both ends of the curve. To examine this, a simulation of wear within the test curve was undertaken using the NUCARS dynamic modeling program. Using new rail profiles, and wheel profiles and vehicles typical of those used in the heavy axle load train, the program calculated wear indices (a measure of the degree of wear expected) for the high and low rails through the curve and with the vehicle traveling in both directions. Dry and lubricated conditions were examined.

The NUCARS simulation indicated higher wear rates at each end of the curve, but this was confined only to approximately the first ten feet of rail. There was no variation in wear predicted through the remainder of the curve. Further, the increase in wear was small, on the order of 17 percent (dry condition) and 5 percent (partial lubrication). This was not sufficient to explain the wear variations shown in Exhibit 20. It is concluded that there is not a significant effect of position-in-curve on wear.

5.3 POSSIBLE TIE/FASTENER EFFECTS ON WEAR

The rails in Section 7 were laid on a range of tie types using several fastening systems, as described in Exhibit 5. This raised the question of whether wear was affected by the tie/fastening system. Analysis indicated that premium rails laid with elastic type fasteners had an average loss of 0.295 $inch^2$, and those laid with cut-spikes had an average loss of 0.262 $inch^2$, after 317 MGT (end of Phase V).

Possible effects of fastener type (elastic versus cut spike) on wear were examined using Student's t-test for significance with the null hypothesis that there is no effect of fastener type on wear. The high-rail wear parameters examined were total cross section loss at 317 MGT, and wear rate during Phase V (partial lubrication, standard trucks). A confidence level of 95 percent was used. Because wear increases with track curvature and possibly decreases with hardness, significance tests were also applied to wear parameters normalized by curvature and hardness. No statistically significant effect of fastener type on wear of the premium rails was found.

5.4 EFFECT OF RAIL HARDNESS ON PREMIUM RAIL WEAR

Numerous studies have indicated that, for pearlitic rail steels, wear resistance increases as hardness increases.[6,7] This seems to be a real effect, at least when large variations in hardness are studied, although there is some evidence that wear resistance may not increase continuously with hardness. Laboratory tests on a series of pearlitic steel specimens indicated that wear was independent of hardness in the range of 370 to 445 Vickers (equivalent to 350 to 420 HB).[8] The present results for Phase V, however, confirm the expected effect of hardness on wear, see Exhibit 20. (As already argued, the Phase III and IV results may not be a true reflection of rail wear performance.) In Phase V, each 1 percent increase in Brinell hardness produces a decrease in wear of about 1.4 percent.

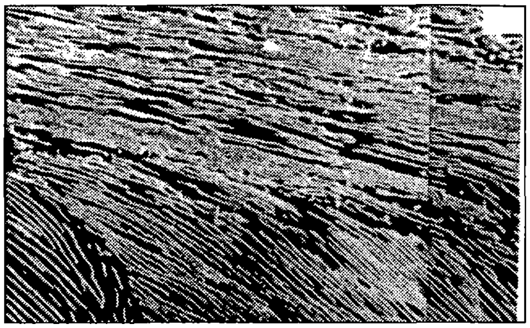
5.5 THE RELATIVE PERFORMANCE OF BAINITIC AND PEARLITIC STEELS

The J6 bainitic rail steel had lower wear resistance than any of the pearlitic rail steels tested despite having higher hardness. This raises two questions. First, what is the cause of the lower wear resistance? Second, does the lower wear resistance rule out the use of J6 rail in revenue service?

Hardness has traditionally been used to estimate the wear resistance of pearlitic rail steels. This does not mean that high hardness is the direct cause of good wear resistance. In pearlitic steels, wear resistance increases as carbon content rises and as pearlite spacing falls. (Pearlite is composed of alternating lamellae of iron and iron carbide, and has a lamellar spacing, which varies with the temperature of formation as the rail cools after rolling. As cooling rate is increased pearlite spacing is decreased, hence the increased hardness seen in head-hardened rail.) Increasing carbon raises the volume fraction of iron carbides, which are hard and tend to align themselves to the worn surface. This alignment is illustrated in Exhibit 22. This enriched layer of hard carbide itself is likely to confer wear resistance.

The effect of pearlite spacing is subtler in that it affects the way that the carbide lamellae deform in rolling contact.[9] The evidence is that thick carbides (above 4.0×10^{-6} inch) tend to fracture under high deformations; whereas, thin carbides (below 0.4×10^{-6} inch) almost always deform plastically without fracture.[10] To put these numbers into context, standard rail steel (300 HB) has a typical average pearlite spacing of about 6×10^{-6} inch, while head-hardened rail has a typical spacing of about 3×10^{-6} inch.[11] However, pearlite spacing is not constant, and is likely to vary in an approximately normal manner about these average spacings. Hence, the thin carbides in head-hardened steel are more likely to deform without cracking than are the thicker carbides in standard rail steel. The precise way in which wear particles form is not known, but it is reasonable to assume that microstructures where the carbide lamellae crack under deformation (to form cavities) are likely to have poorer wear resistance than microstructures whose carbides deform plastically.

Thus, in pearlitic steels, good wear resistance is given by high carbon content and low pearlite spacing (achieved by the head-hardening process), both of which act to increase hardness. In confirmation of the secondary effect of hardness on wear, Hirakawa and others increased the hardness of pearlitic steel samples by reducing the tempering temperature but did not increase wear resistance in laboratory tests.[12]


(a) Worn Surface Microstructure

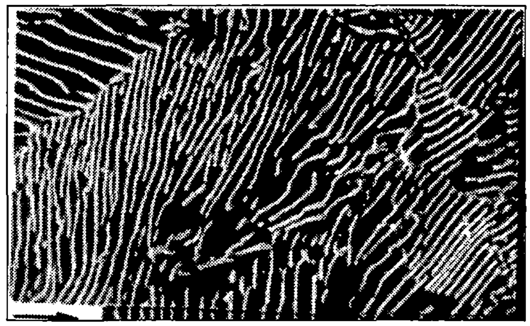

(b) Bulk Microstructure

Exhibit 22. The Effect of Wear Deformation on Pearlitic Microstructure

Low carbon bainitic steels (such as J6) are different from conventional pearlitic steels in that they have few, if any, carbides. Strength is produced by a very fine and heavily dislocated lath microstructure. Thus, these steels cannot develop a carbide-enriched worn surface layer. Further, since work-hardening is enhanced by the presence of a second phase (such as carbide), low carbon bainitic steels can be expected to work-harden less than pearlitic steels. The consequence of this is that while bainitic steel can start with a higher bulk hardness than pearlitic steel, the bainitic work-hardened worn surface may be softer than the pearlitic worn surface. Such an effect has been seen in laboratory wear tests.[13] The implication is that wear resistance may relate better to the hardness of the worn surface than to bulk hardness. Since high carbon pearlitic steels tend to work-harden to the same degree, worn hardness is approximately proportional to bulk hardness, thereby leading to the observed relationship between wear resistance and bulk hardness.

Recent work indicates that wear is related to ratcheting of the steel at the worn surface.[14,15] In ratcheting, each passage of the wheel causes a small increment of deformation to produce the highly deformed structure shown in Exhibit 22a. The rate of ratcheting is controlled by the ratio of contact stress (P_0) to shear yield stress (k). At high values of P_0/k (high P_0 or low k) ratcheting and wear are rapid. Conversely, at low values of P_0/k (low P_0 or high k) ratcheting and wear are low and may reach zero. In such a case all deformation is elastic. Bulk shear yield stress is related to (but may not be proportional to) tensile strength and hardness, but the worn surface shear yield stress will depend on the degree of work-hardening.

The conclusion is that while pearlitic steels may start with a relatively low shear yield stress, they work-harden during rolling contact to produce a relatively high shear yield stress. In contrast, bainitic steels such as J6 are likely to start with a higher shear yield stress (although this has not been measured) but are less likely to work-harden during rolling contact. Bainitic steels may therefore need to have a much higher manufactured strength (and hardness) than pearlitic steels to match the wear resistance of pearlitic steels. Based on laboratory work, bainitic steels are likely to need hardness at least 70 to 80 HB above current premium steels to match their wear resistance. This implies bainitic hardness of at least 450 HB and possibly 500 HB.

Regarding the second question, the lower wear resistance of the J6 steel need not be a barrier to implementation. Current premium rails have good wear resistance, but they are prone to surface damage such as cracks, pits, and spalls. It is believed, but not proven, that the reduced wear allows more time for fatigue damage to accumulate in the surface layers. This damage is routinely removed by grinding, which can be viewed as accelerating the natural wear produced by wheel/rail contact. Reducing the hardness of pearlitic steel would increase the natural wear, but would also tend to increase the rate of surface fatigue. The J6 bainitic steel has a higher wear rate than premium pearlitic steel, but is also harder and is likely to have improved resistance to fatigue. Thus the J6 steel may need less (or even no) grinding in revenue service. That is, its higher wear rate may substitute for the artificial wear supplied by grinding. Again, this potential attribute needs to be confirmed.

Whether the J6 rail will be more economic than premium rail in a given situation depends on its natural wear rate, and its need for grinding. The relationship between natural wear, grinding, and life can be illustrated using data from grinding test sites on Canadian National (CN) Railway.[16] Two of these sites have been ground at intervals of about 11 MGT since installation in 1995. They have now accumulated over 200 MGT. Detailed profile measurements allow estimates to be made of the metal removed by natural wear and by grinding to remove surface defects. Exhibit 23 shows these estimates of metal loss and also gives the predicted rail wear life, assuming rail is replaced when 35 percent of the head section has been lost. (Note, this value of 35 percent is for illustration and is not the rail wear criterion used by CN. It should also be noted that the past rate of grinding at these sites might not necessarily continue in the future.) Exhibit 23 also shows the effect of changed wear and grinding rates on rail life for two scenarios:

- Rail steel with a 25 percent increase in natural wear and a 50 percent decrease in rail grinding wear
- Rail steel with a 100 percent increase in natural wear and a 75 percent decrease in rail grinding wear

Exhibit 23. Estimated Effect of Natural Wear and Grinding Wear on Rail Life

Case		7.1-degree Curve		4.0-degree Curve	
		High rail	Low rail	High rail	Low rail
Measured performance	Natural wear	0.154 in^2	0.060 in^2	0.115 in^2	0.090 in^2
	Grinding wear	0.439 in^2	0.587 in^2	0.363 in^2	0.499 in^2
	Total wear	0.593 in^2	0.647 in^2	0.478 in^2	0.589 in^2
	Wear life*	**465 MGT**	**426 MGT**	**576 MGT**	**468 MGT**
25 percent higher wear 50 percent less grinding	Natural wear	0.192 in^2	0.075 in^2	0.144 in^2	0.112 in^2
	Grinding wear	0.219 in^2	0.293 in^2	0.181 in^2	0.249 in^2
	Total wear	0.411 in^2	0.368 in^2	0.325 in^2	0.361 in^2
	Wear life*	**670 MGT**	**749 MGT**	**848 MGT**	**763 MGT**
100 percent higher wear 75 percent less grinding	Natural wear	0.308 in^2	0.120 in^2	0.230 in^2	0.180 in^2
	Grinding wear	0.110 in^2	0.147 in^2	0.091 in^2	0.125 in^2
	Total wear	0.418 in^2	0.267 in^2	0.321 in^2	0.305 in^2
	Wear life*	**659 MGT**	**1032 MGT**	**858 MGT**	**903 MGT**

Based on rail replacement at 35 percent head loss.

It is seen that increased natural wear can lead to increased rail life providing the need for grinding is reduced sufficiently. (Reduced grinding also leads directly to decreased rail maintenance costs.) The extent to which new steels such as the J6 bainitic steel can economically replace premium rails needs to be judged on purchase cost and on performance in revenue service trials. The first such trial began December 1999 on Norfolk Southern in a 5.5-degree curve between Roanoke and Bluefield. The J6 rail will be compared directly with premium rail manufactured by Pennsylvania Steel Technologies.

5.6 VISUAL OBSERVATIONS OF SURFACE DETERIORATION

During Phases III and IV of testing (improved suspension trucks with partial lubrication and dry running) very little surface deterioration was seen on the premium and J6 bainitic rails. Some very fine gage-corner cracks were seen on the premium rails, and minor spalls developed on the Hayange high-rail gage corner. It is most probable that these spalls on the Hayange rail formed as a consequence of the relatively flat rail top that allows the gage corner to stand proud (refer to Appendix C).

The introduction of standard three-piece trucks in Phase V led to an increase in defects on the surface of the premium high rails. Isolated areas of pitting and minor spalling had developed by 317 MGT on all the premium rails. Examples of this damage are shown in Exhibit 24. It is not known to what extent this damage, if left unground, will affect rail integrity and life. In contrast, to date (252 MGT) very little deterioration has been seen on the J6 bainitic steel high rails. Minimal deterioration has also been seen on the low rails (both premium and bainitic) under test.

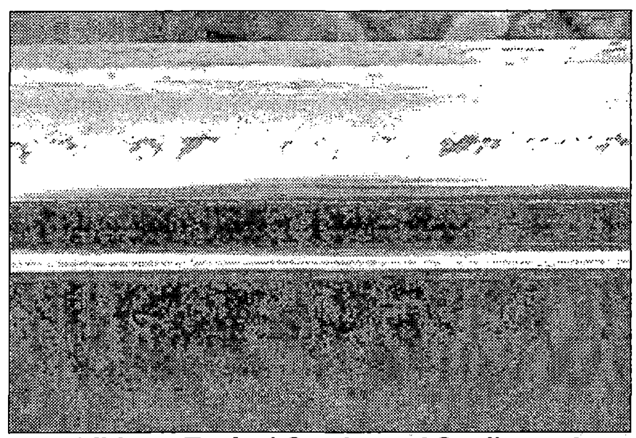


Exhibit 24. Typical Cracks and Spalls on the High-Rail Gage Corner of Premium Rails

Finally, all the premium rails show evidence of deformation. On the low rails this shows as a relatively wide running band centered on the rail top. On the high rails, deformation appears as a lip on the field side of the rail top formed by the action of shear stresses caused by gage spreading lateral forces. Due to its higher yield strength, the bainitic rail shows a narrower low-rail running band and no such high-rail lip.

6.0 CONCLUSIONS

- Four of the manufacturers produced rail with head profiles very close to the design profile (AREMA 136-RE, 10-inch crown radius). The fifth manufacturer (Hayange) produced rail with a flatter top, probably to the older 136-RE design that mandated a 14-inch crown radius.

- In Phase III (315,000-lb. cars equipped with improved suspension trucks, partial lubrication conditions), there was significant difference in the wear rates of the six premium rail steels tested. In terms of loss of cross section, the lowest wear rate was .84 x 10^{-4} inch^2 per MGT, and the highest was 3.24 × 10^{-4} inch^2 per MGT.
- In Phase IV (the same cars under fully dry running), wear rates rose by an approximate factor of four. Also, the differences between the premium rails narrowed but were still significant.
- In Phase V (315,000-lb. cars equipped with standard three-piece trucks, partial lubrication conditions), wear rates of all the steels increased yet again. However, the wear performance of the premium rail steels converged still further. It is concluded that performance of the premium rail steels in Phases III and IV may be unduly influenced by initial profile and decarburized layer effects, and that the Phase V results should be used to judge the service wear performance of the rails.
- For the six premium rail steels, there was no consistent relationship between hardness and wear rate in Phases III and IV. In contrast, the expected relationship between bulk hardness and wear rate was observed in Phase V. For each 1 percent increase in hardness, wear rate fell on average by 1.4 percent.
- The J6 bainitic rail steel had the highest wear rate of all the rails tested despite having the highest bulk hardness. This confirms that while wear may be inversely related to hardness for steels with common microstructures, hardness alone is not the sole predictor of relative wear for steels with different microstructures. That is, some factor other than simple bulk hardness influences wear rate. This relatively poor wear resistance need not curtail the implementation of J6 rail if, as expected, the rail needs less grinding in revenue service.
- Although there was an indication that rails laid with cut spikes wore marginally less than rails laid with elastic fastenings, statistical tests indicated that the difference was not significant. Analysis also indicated that there was little effect of position-in-curve on rail wear.

References

1. K. Uchino, M. Ueda, K. Kutaragi, and K. Babazono, "Development of Hypereutectoid Steel Rail for Heavy Haul Railways," 39th MWSP Conference Proceedings, ISS, Vol. XXXV, 1998, pp. 1047-1055.

2. American Railway Engineering and Maintenance of Way Association, *Manual for Railway Engineering*, Vol. 1, Chapter 4.

3. American Society for Testing and Materials, "Brinell Hardness of Metallic Materials," ASTM Standard E.10, Vol. 03.01, 1993.

4. Metals Handbook, Desk Edition, eds. H. E. Boyer and T. L. Gall, ASM, 1985, p. 160.

5. R. K. Steele and T. J. Devine, "Wear of Rail/Wheel Systems," Conference Proceedings, Contact Mechanics and Wear of Rail/Wheel Systems, Vancouver, July 1982, pp. 293-315.

6. P. Clayton, "Predicting the Wear of Rails on Curves from Laboratory Data," *Wear*, Vols. 181-183, 1995, pp. 11-19.

7. J. S. Hannafious, "Results of Rail Wear Tests at FAST," 1st Annual AAR Research Review, Pueblo, Colorado, November 1995, pp. 35-41.

8. J. Kalousek, D. M. Fegredo and E. E. Laufer, *Wear*, Vol. 105, 1985, p.199.

9. E. E. Laufer, D. M. Fegredo, and J. Kalousek, "The Effect of Microstructure on Wear in Standard and Head-Hardened Rails in Heavy-Haul Service," Proceedings 3rd International Heavy Haul Conference, pp. 176-192.

10. G. Langford, "Deformation of Pearlite," Met. Trans, Vol. 8A, 1977, pp. 861-875.

11. A. J. Perez-Unzueta, "Wear Resistance of Pearlitic Rail Steels," Ph.D. Thesis, University of Sheffield, England, 1992.

12. K. Hirakawa, K. Toyama, S. Suzuki, and A. Hamazaki, "Effects of Chemical Composition and Microstructure on Wear Properties of Steels for Railroad Wheel," Proceedings, 2nd International Heavy Haul Conference, Colorado Springs, Colorado, 1982, pp. 646.

13. J. E. Garnham, "The Wear of Bainitic and Pearlitic Steels," Ph.D. Thesis, University of Sheffield, England, 1995.

14. H. Ghonem and J. Kalousek, "Surface Crack Initiation due to Biaxial Compression/Shear Loading," Proceedings, 2nd International Conference on Contact Mechanics and Wear of Rail/Wheel Systems, Rhode Island, 1986, pp. 338-360.

15. A. Kapoor, "Wear by Plastic Ratcheting," *Wear*, Vol. 212, 1997, pp. 119-130.

16. K. J. Sawley, "North American Rail Grinding: Practices and Effectiveness," AAR Research Report R-928, Association of American Railroads, September 1999.

APPENDIX A:

PRODUCTION AND PROPERTIES OF J6 BAINITIC RAIL STEEL

Table of Contents

1.0. INTRODUCTION

Although rail steel making has changed from acid Bessemer to basic open hearth to basic oxygen, and continuously cast steel has largely replaced ingot stock, rail chemistry has changed little this century. Almost all modern rails are today made from plain carbon-manganese steels that are little different in concept from rails made over the last hundred years. Rail manufacturers have, however, made major improvements in rail cleanness and quality. Sophisticated inspection procedures ensure that modern rail steels are produced almost wholly free of defects. Wear resistance has also been greatly improved in two ways. First, higher carbon contents (typically 0.75 to 0.80 weight percent) have been used to produce fully pearlitic steel. Second, both alloying (for example using chromium) and heat treatment (off-line and on-line processes [1-3]) have been used to refine the pearlite structure. Increased carbon content and pearlite refinement both act to increase hardness; moreover, for pearlitic steels, increasing hardness has generally been shown to lead to increasing wear resistance.

However conventional pearlitic rail steels have now been developed to hardness levels approaching 400 Brinell (HB), and further increases in hardness are difficult to achieve. Thus, pearlitic steels may be reaching their limit of wear resistance. Although hypereutectoid steels are being developed, and these may further improve the wear performance of pearlitic steel, it is prudent to consider whether other steel structures can offer benefit as rail materials.[4]

Because bainitic and martensitic steels offer higher hardness than pearlite, many studies have examined the wear resistance of these steels in rolling/sliding contact. Clayton and others have reviewed literature on the wear of bainitic steels.[5] Most laboratory rolling/sliding wear studies have indicated that, at a given hardness, bainite is inferior to pearlite, but few studies have adequately characterized the bainitic structure. This may be important since the term 'bainite' covers a number of different microstructures, from the classical upper and lower bainite to the carbide-free structures found in lower carbon steels.[6,7] It may be that wear resistance is related to the type of bainite in a way not yet known.

Results from track tests of bainitic rails are both limited and mixed. Heller and Schweitzer reported tests with 0.07 weight percent carbon (270 to 345 HB) and 0.3 weight percent carbon (390 to 460 HB) rails installed on a 6-degree curve, with 76.4 kips axle load traffic traveling at 45 km/h (28 mph).[8] The conclusion was that bainitic rails wore faster than pearlitic rails of the same hardness. Results reported by de Boer and others are from 0.4 weight percent carbon bainitic rails installed in a 6-degree curve on a Norwegian iron ore line.[9] The bainitic rails had a hardness of 415 HB, and reportedly lasted about 50 percent longer than 360 HB head hardened pearlitic rail before reaching their wear limit. There is thus some evidence that bainitic steels have the potential to give good wear resistance in wheel/rail contact, but the important microstructural or material property factors that control wear are not known. This lack of knowledge makes the design of wear-resistant bainitic steels difficult.

Work to develop a bainitic rail steel with improved wear resistance over conventional head-hardened pearlitic steel was undertaken by workers at the Oregon Graduate Institute in collaboration with Transportation Technology Center, Inc. Financial support was from the Association of American Railroads. In the main part of the work, five steels, coded J1 to J5, were manufactured to study the effect of bainitic microstructure on wear resistance.[10,11] Results from these five steels led to the design and manufacture of a further steel, J6, expected and confirmed to have good wear resistance in laboratory tests.[12] This appendix outlines the chemistry, production and properties of the J6 bainitic steel.

2.0 STEEL PRODUCTION AND CHEMISTRY

Ellwood City Forge manufactured a 36-ton cast of steel to the J6 composition. The measured ladle chemistry is given in Exhibit A1, consistent with bainitic chemistry found in the public domain. The steel was made by electric furnace, vacuum degassed and ladle refined. Limited aluminum additions were made to control nitrogen and oxygen and protect the titanium and boron additions. High hardness steels are more susceptible to hydrogen cracking, and care is needed to control final hydrogen content. The AREMA rail specification does not specify hydrogen content, but the draft new European specification sets a maximum of 2.5 parts per million for the equivalent of premium rail steel.[13,14] Exhibit A1 shows that the steel making process has given a hydrogen level well within this limit.

Exhibit A1. Ladle Chemistry of J6 Bainitic Rail Steel

Carbon	Manganese	Phosphorus	Sulfur	Silicon	Nickel	Chromium
0.26	2.00	0.008	0.006	1.84	0.11	1.94
Molybdenum	Aluminum	Vanadium	Copper	Titanium	Boron	Hydrogen
0.44	0.033	0.009	0.17	0.04	0.0026	1.1

All values in weight percent, except hydrogen (parts per million)

The 28 inch x 36 inch ingots produced were forged to 16 inch x 24 inch section bars, approximate weight 12,000 lb. After forging, the bars were shipped to Pennsylvania Steel Technologies for re-heating and rolling to intermediate size before final rolling to AREMA 136-10 section rail. The rails were cooled naturally in air, with no use of the head-hardening process, and roller-straightened when cold. Eighteen rails were produced with lengths between 60 and 80 feet.

The microstructure and cleanness of the test rail was characterized at Oregon Graduate Institute using optical and electron microscopy. The microstructure consisted of lath bainite with no visible carbides, and was similar to the experimental J6 steel. There was no evidence of sulfur segregation. The rail samples included dispersed angular inclusions (most probably nitrides), with an estimated volume fraction of 0.16 percent, formed as a consequence of the need to protect the boron from nitrogen. The nitrides were small (typical length less than .0003 inch) and should not affect rail trials, but their avoidance should be considered for volume rail production. Sulfides were present at a volume fraction of 0.4 percent.

3.0 J6 RAIL STEEL PROPERTIES

The properties of the J6 rail steel were characterized in laboratory tests.

3.1 MECHANICAL PROPERTIES

Hardness was measured on a full transverse rail section using a manual Brinell hardness machine. The test rail had a near uniform hardness through the section, with typical Brinell hardness (HB) of 430 to 420 in the head, 415 in the web, and 420 in the foot. This even distribution confirms that the hardness of J6 steel is relatively insensitive to cooling rate, and that the bainitic structure can be achieved without the need for accelerated cooling such as that provided by the head-hardening process. The measured hardness values compare with the value of 422 HB found in the experimental cast of J6 steel. Premium rail has typical head hardness in the range 340 to 390 HB (produced by the microstructural refinement given by head hardening), with approximately 300 HB in the web and foot. Steel hardness appears important for rails as studies have shown that high hardness equates to good wear resistance, especially for pearlitic steels. Longitudinal measurements along the prepared rail top center showed no significant variation in hardness.

The tensile properties of the J6 rail were measured on smooth specimens (nominal gage diameter 0.35 inch) taken from the rail head, web and foot. Eight specimens were tested, and results are compared in Exhibit A2 with typical values for premium head-hardened rail.

Exhibit A2. Tensile Properties of J6 Rail Steel Compared with Typical Values for Premium Head-hardened Rail

		Yield strength (ksi)	Tensile strength (ksi)	Reduction of area (percent)	Elongation (percent)
J6 steel	Head 1*	146.0	203.3	6.4	5.0
	Head 2*	148.2	203.1	5.9	4.0
	Web 1*	130.3	210.2	22.4	12.1
	Web 2*	129.5	211.9	21.4	10.7
	Foot 1†	154.1	206.0	2.8	5.0
	Foot 2†	152.0	203.3	5.9	4.0
	Average	**143.4**	**206.3**	**10.8**	**6.8**
Premium		**125**	**175**	**-**	**11**

* Fractured through gage marks or within specimen width of gage marks.
† Fractured outside gage marks.

Tensile strength was consistent throughout the bainitic rail, with highest yield strength in the base and lowest yield strength in the web. The bainitic tensile and yield strengths were both higher than those found in premium rail. There is concern with the bainitic rail ductility values, which show wide scatter. Maximum values are high and indicate a material with inherently good ductility. However, the steel is hard, and likely to be more notch sensitive than premium steel. The low ductility values may reflect the effect of surface preparation, small surface-breaking inclusions, or gage marks. This needs more investigation.

3.2 FRACTURE TOUGHNESS

Resistance of J6 rail steel to sudden brittle fracture was assessed using V-notch Charpy specimens and compact tension fracture toughness specimens.

Charpy specimens were taken longitudinally from the head and base of the J6 rail and tested at temperatures in the range -25°F to +125°F. Results are shown in Exhibit A3, where they indicate a lower shelf energy of about 7 ft.-lb. This compares with a typical value of about 4 ft.-lb. for pearlitic rail.

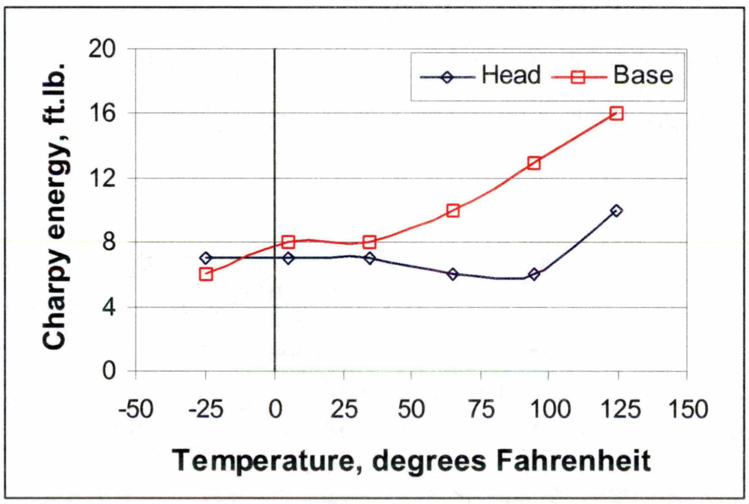


Exhibit A3. Charpy V-Notch Impact Data for J6 Steel

The compact tension fracture toughness specimens were taken horizontally from the head of the J6 test rail. Final specimen dimensions were 1.875″×1.800″×0.75″, with a notch root radius of 0.010 inch maximum. Comparison specimens were also taken from the head of a piece of unused premium rail steel. Metcut Research Associates, Inc. performed all tests at room temperature to the ASTM E399-90 specification. Results are shown in Exhibit A4, where the fracture toughness values are shown as valid (K_{1C}) or invalid (K_Q), along with any reasons for invalidity. Two of the premium rail specimen tests were invalid under specification ASTM E399-90. However, one test (Premium-1) was only marginally invalid and has been included in the average value.

The J6 steel has fracture toughness approximately 23 percent above that measured in the premium steel. Since critical crack size to fracture rises as the square of the toughness, this indicates that J6 rail ought to be able to sustain larger cracks than premium rail before failing by sudden brittle fracture.

Exhibit A4. Fracture Toughness Results for J6 Steel and Premium Steel

Steel	Fracture toughness		Reasons for invalidity
	K1C ksi.in$^{1/2}$	KQ ksi.in$^{1/2}$	
J6-1	46.7	-	
J6-2	47.7	-	
J6-3	46.5	-	
Average	**47.0**		
Premium-1	36.9*	36.9	a. Fatigue pre-crack stress intensity exceeded requirements b. Fracture load ratio exceeded requirements
Premium-2		34.8	
Premium-3	39.0		
Average	**38.0**		
* Marginally invalid			

3.3 RESIDUAL STRESS

The bainitic rails were roller-straightened and there was concern that their higher strength would lead to higher residual stresses, with a consequent increased risk of sudden rail failure. Residual stress was determined by two methods: web saw cutting, and strain-gage saw cutting.

At a rail end, the web of roller-straightened rail generally has a vertical residual tensile stress. The AREMA web saw cut test consists of cutting through the web longitudinally along the neutral axis and measuring the change in rail height produced by the relaxation of residual stress. Relaxation gives an increase in head height, which must not exceed 0.148 inch for a 24-inch long rail cut for a length of 16 inches (2/3 of total length). Because of equipment limitations the maximum length of rail that could be cut was 18 inches. Consequently, an 18-inch J6 rail was cut a length of 15 inches. At the 12-inch mark (2/3 total length) the opening was 0.062 inch, while at the full cut of 15 inches the opening was 0.081 inch—well below the 0.148-inch limit. The evidence is that the J6 rail would have passed the AREMA criterion if a 24-inch sample had been used.

Longitudinal stress was also measured by fixing strain gages to the head, web, and base of a test rail, and relieving strain by cutting round the gages under flood lubrication. The strain relaxation measured by each gage gave the value of residual stress at that point when multiplied by the modulus of elasticity (30,400 ksi). Measurements were made on two samples, each 3 feet long. Exhibit A5 shows the values of longitudinal stress produced. Also shown are values of residual stress documented for UIC60 section premium rail of hardness 340 HB and 370 HB.[15] The UIC60 section rail has a height of 6.77 inches, compared to AREMA 136 rail with a height of 7.31 inches. To allow comparison of stresses, in Exhibit A5 the UIC60 total height has been re-scaled to 7.31 inches. There are two points to note. First, the tensile residual stresses in the head and base of the J6 rail are no higher than those measured in premium rail. Second, the stress pattern in the J6 web is significantly different from that in the premium rail. The pattern was repeatable, and is believed to be authentic as the test method has been used on other rails with consistent results. The cause of the different behavior is not known. However, the evidence is that the residual stresses present in the J6 rail are not likely to be more damaging, in terms of sudden fracture, than those present in premium rail.

3.4 WEAR TESTS

Rolling/sliding wear tests were undertaken in an Amsler machine using 1.38-inch diameter cylindrical specimens taken from J6 rail and premium rail. Specimens were taken horizontally from the rail head, and were rolled against specimens machined from a North American Class C wheel. In all cases, the wheel steel specimens had higher peripheral speeds than the rail specimens.

Tests were performed at calculated Hertzian contact stresses of 177 ksi and 246.5 ksi, at a fixed creepage of 35 percent. This value of creepage is much higher than values known to occur between wheel and rail in service, but was chosen because it has been shown to produce severe wear in laboratory tests with pearlitic rail steels. Observations indicate that such wear occurs on the dry gage face of high rails in sharp curves under heavy-axle freight traffic.[16] In laboratory tests, severe wear is characterized by a break-in period, after which large pieces of wear debris are produced. This debris leads to surface roughening and abrasive wear of both rollers, and the wear rate is seen to accelerate before reaching a steady state value.

Throughout each wear test, the specimens were regularly removed and weighed to generate graphs of weight lost versus number of revolutions. For most tests, after initial transient behavior (break-in), a linear relationship was found between weight lost and number of revolutions. Wear rates calculated from the slopes of these linear relationships are expressed in the units: µg/m/mm (micrograms per meter slid per mm contact width).

Measured wear rates for the J6 rail are shown in Exhibit A6 where they are compared with wear rates measured for the initial experimental cast of J6 steel and for premium rail steel. The specimens from the early experimental cast failed to achieve the transition to severe wear and gave very low wear rates. In contrast the J6 rail specimens did show the severe wear behavior expected from the test conditions and consequently gave much higher rates of wear. The highest wear rates were seen with the premium rail specimens, which also showed severe wear behavior. These laboratory results gave confidence that the production cast of J6 rail would have reasonable wear resistance.

Exhibit A6. As-rolled J6 Steel Wear Rates Compared with Wear Rates of Head-hardened Premium Steel

Steel	Wear rate, µg/m/mm	
	P_0 = 177 ksi	P_0 = 246.5 ksi
J6 – rail	2,420	4,240
J6 – experimental cast	78	136
Premium rail	5,966	8,149

4.0 FLASH-BUTT WELDING TRIALS

Trials to make welds between J6 rails were undertaken using a Model 400 mobile flash-welding machine supplied by the Holland Welding Company, and a fixed Schlatter machine made available by the Holland Welding Plant in Pueblo, Colorado USA.

Five welds were made using the mobile welder. The first weld was made at a forge pressure of 2,000 psi and a forge upset of 0.79 inch. Further welds were made at upset values between 0.51 and 0.67 inches, and at a reduced forge pressure of 1,600 psi. Metallographic examination of a prepared section of a weld made at the pressure of 1,600 psi and upset of 0.63 inch showed a good fusion line, with no obvious evidence of any brittle weld layer. This was confirmed by microhardness measurements. Tensile specimens were taken from the head and foot of two welds (S1 and S2) made at 1,600-psi pressure and 0.63-inch upset. The results are shown in Exhibit A7 where they are compared with results from the plain rail tensile tests reported in Exhibit A2. Welding has decreased strength, but the reduced yield and tensile strengths still match the Exhibits for as-rolled premium rail (refer to Exhibit A2).

Exhibit A7. Results of Tensile Tests on Flash-butt Welds made Between J6 rails

Specimen	Yield Strength (ksi)	Tensile strength (ksi)	Reduction in area (percent)	Elongation (percent)
S1-Head	131.1	176.4	17.2	4.0
S1-Head	128.1	176.8	18.0	5.0
S1-Foot	128.9	179.2	19.8	3.5
S2-Head	129.6	176.1	18.4	4.0
S2-Head	131.2	173.4	20.6	4.0
S2-Foot	134.7	175.2	18.5	4.0
Average	**130.6**	**176.2**	**18.7**	**4.1**
Plain rail head	147.1	203.2	6.2	4.5
Plain rail foot	153.0	204.6	4.3	4.5

Four further J6 welds were made using a fixed machine at the same pressure and forge parameters as used in the mobile welds. Three of these were bend-tested at Miner Enterprises, with the results shown in Exhibit A8 compared with the AREMA requirements for 341 HB (minimum) premium rail.[13] These results give confidence that the J6 rail can be used in service in the flash-welded condition, although further trials will be needed for service use since weld parameters need to be optimized for the particular plant to be used.

Exhibit A8. Bend Test Results of J6 Flash Welds

Weld	Weld parameters		Bend test results	
	Pressure (psi)	Upset (inch)	Deflection (inch)	Modulus of rupture (ksi)
1	1,800	0.79	1.42	238.2
2	1,600	0.67	0.92	225.5
3	1,600	0.63	0.82	213.5
AREMA requirements			0.75 min.	125 min.

5.0 SUMMARY

Based on the results outlined in Sections A2 to A4, the decision was made to undertake a full-scale wear evaluation of the J6 rail in the High Tonnage Loop at the Transportation Technology Center. Results from this evaluation are described in the main body of this report.

References

1. W.H. Hodgson and R.R. Preston, "Rails for the 90's," International Symposium on Accelerated Cooling of Rolled Steel, Winnipeg, Manitoba, August 1987.

2. B.L. Bramfitt R.L. Cross and D.P. Wirick, "Advanced In-Line Head Hardening of Rail," ISS Rail Steels for the 21st Century Symposium, Baltimore, Maryland, October 1994.

3. K. Sugino et al., "Development of In-Line Heat Treated DHH Rails, 4th. International Heavy Haul Railway Conference, Brisbane, Australia, 1989, pp. 41-45.

4. K. Uchino, M. Ueda, K. Kutaragi, and K. Babazono, "Development of Hypereutectoid Steel Rail for Heavy Haul Railways," 39th. MWSP Conf. Proc., ISS, Vol. XXXV, 1998, pp. 1047-1055.

5. P. Clayton, R. Devanathan, N. Jin, and R. K. Steele, "A Review of Bainitic Steels for Wheel/Rail Contact," *Rail Quality and Maintenance for Modern Railway Operation,* Kluwer Academic Publishers, Dordrecht, The Netherlands, 1993, pp. 41-51.

6. H.K.D.H. Bhadeshia, "Bainitic Ferrite," *Bainite in Steels*, The Institute of Materials, London, England, 1992, pp. 20-60.

7. B.L. Bramfitt and J.G. Speer, "A Perspective on the Morphology of Bainite," Met. Trans., Vol. 21A, April 1990, pp. 817-829.

8. W. Heller and R. Schweitzer, "Hardness, Microstructure and Wear Behavior of Steel Rails," 2nd. International Heavy Haul Railway Conference, Colorado Springs, Colorado, 1982, pp. 282-286.

9. H. de Boer et al., "Naturally Hard Bainitic Rails with High Tensile Strength," *Stahl und Eisen*, Vol. 115, No. 2, 1995, pp. 93-98.

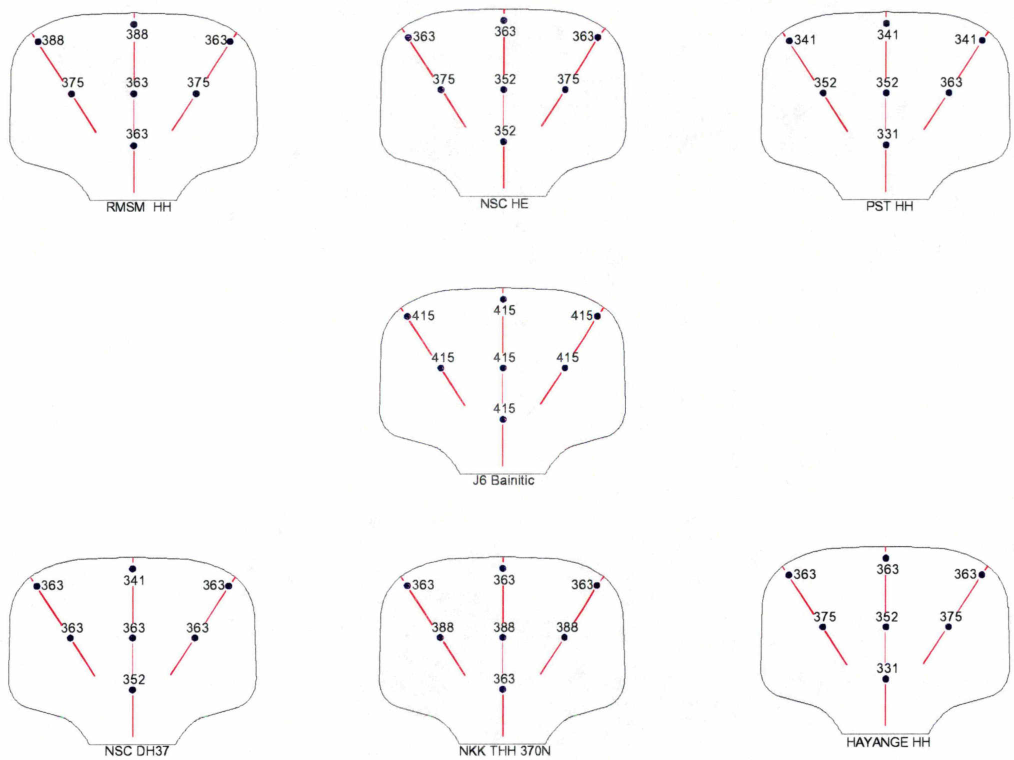
10. N. Jin, "Mechanical Properties and Wear Performance of Bainitic Steels," Ph.D. Thesis, Oregon Graduate Institute, Portland, OR, 1995.

11. N. Jin and P. Clayton, "Effect of Microstructure on Rolling/Sliding Wear of Low Carbon Bainitic Steels," *Wear*, Vol. 202, 1997, pp. 202-207.

APPENDIX B:
HARDNESS MAPS ON TEST RAILS

Brinell Hardness

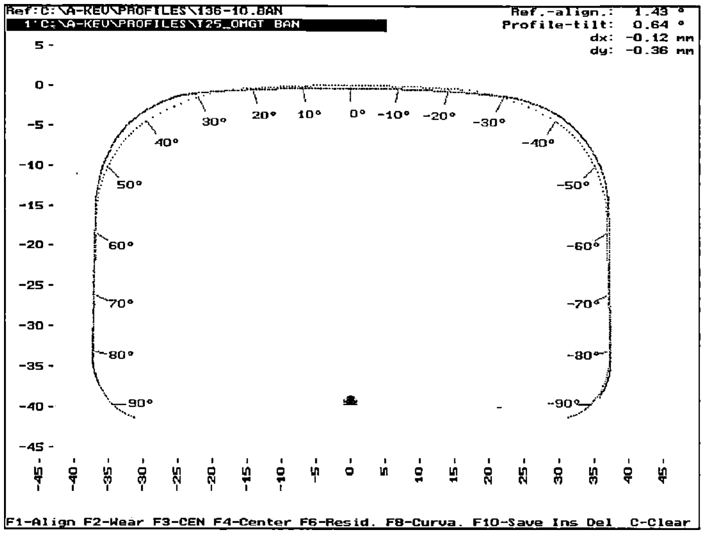
Manual Measurements taken at TTCI Metallurgy Lab



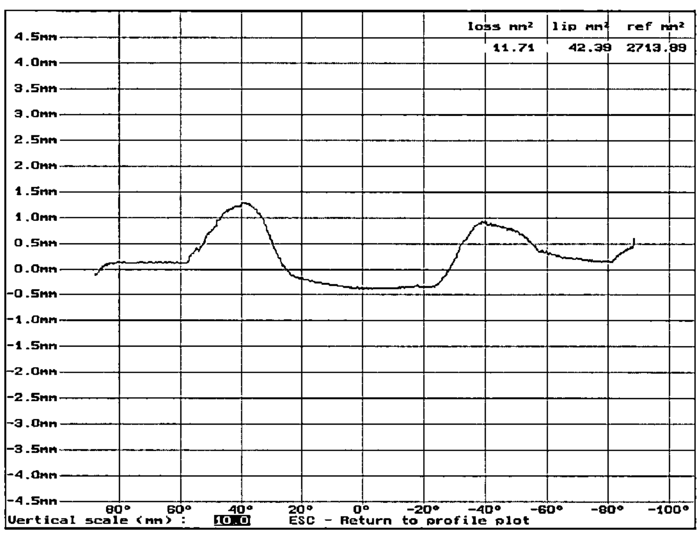
APPENDIX C:

COMPARISON OF AS-ROLLED RAIL PROFILES WITH DESIGN 136-10 RAIL SECTION

C1. HAYANGE (HAYHH) RAIL

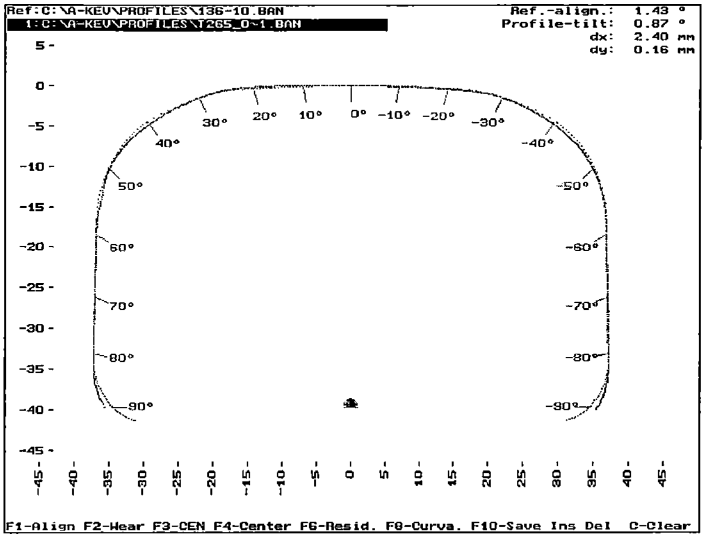


Comparison of manufactured and design profiles

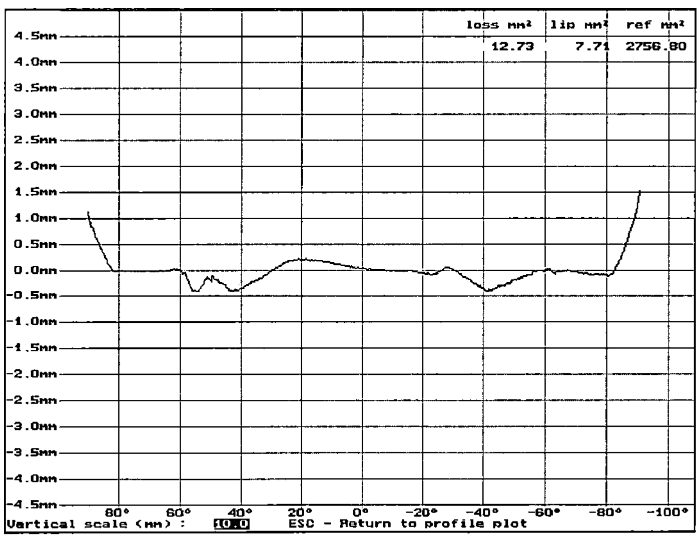


Residual plot

C2. NIPPON KOKAN (NKKTH37N) RAIL

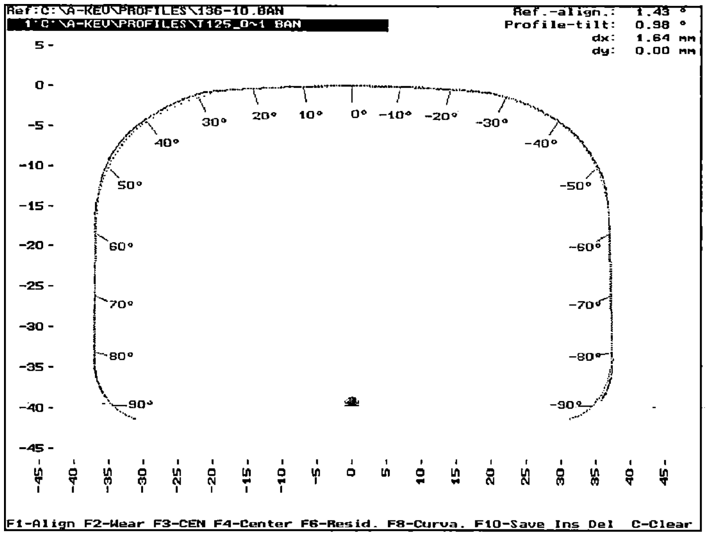


Comparison of manufactured and design profiles

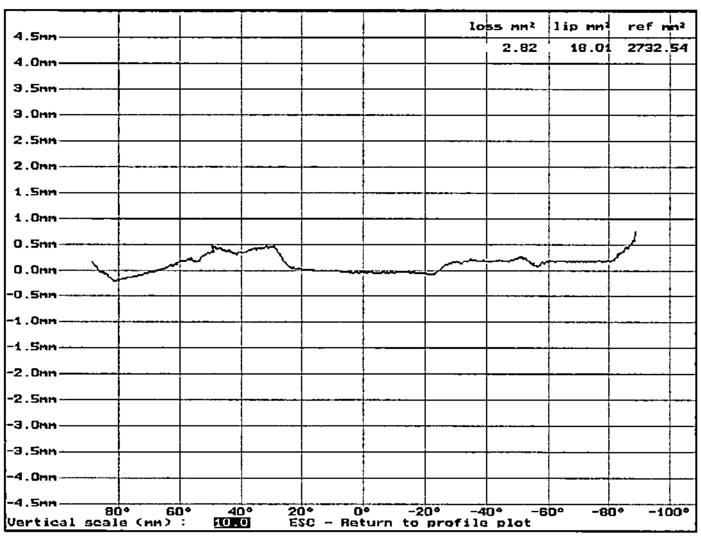


Residual plot

C3. NIPPON STEEL CORPORATION (NSCDH37) RAIL

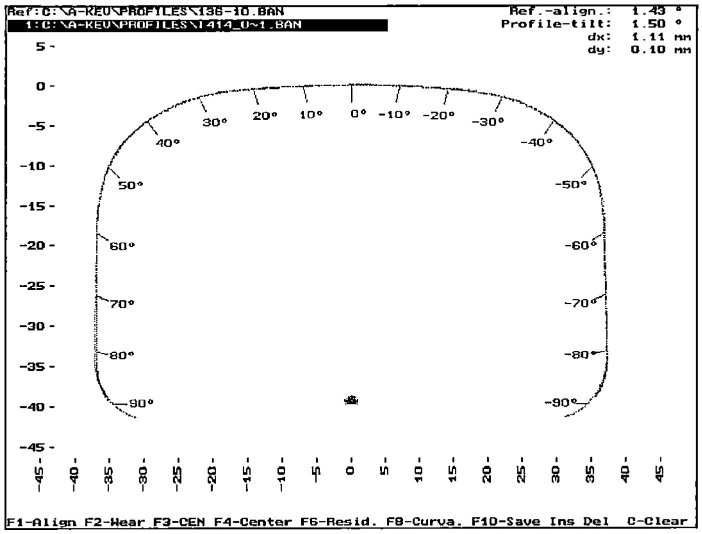


Comparison of manufactured and design profiles

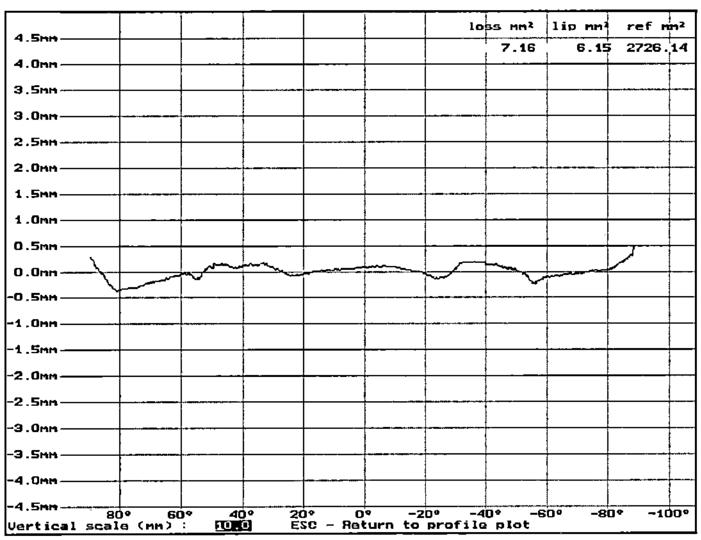


Residual plot

C4. NIPPON STEEL CORPORATION (NSCHE) RAIL

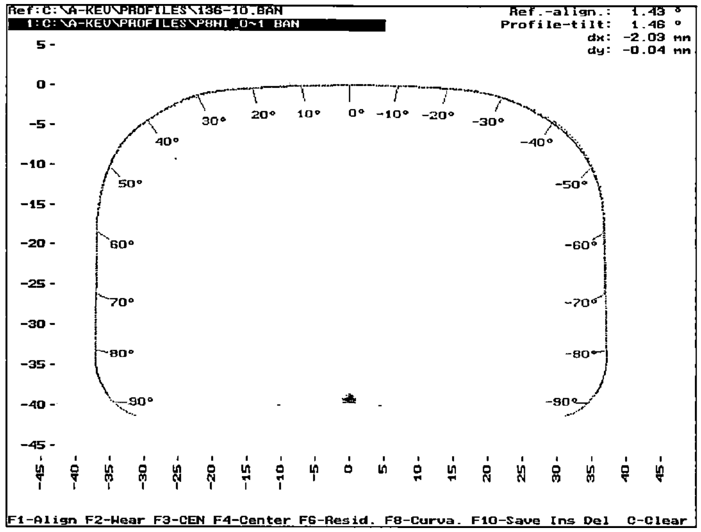


Comparison of manufactured and design profiles

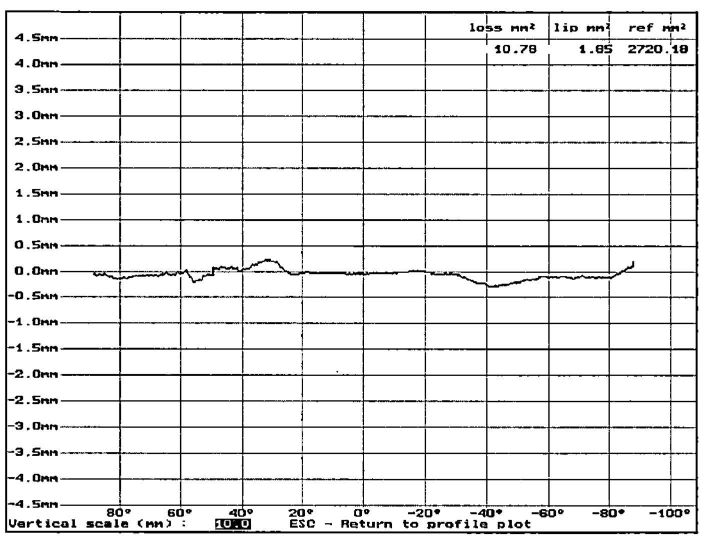


Residual plot

C5. PENNSYLVANIA STEEL TECHNOLOGIES (PSTHH) RAIL

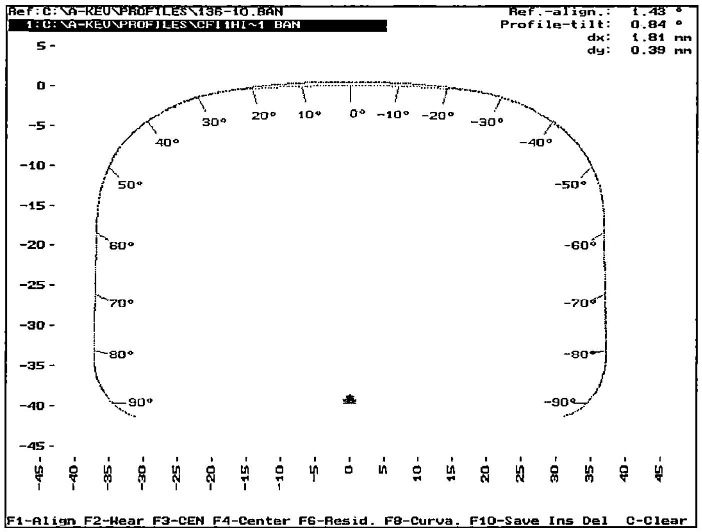


Comparison of manufactured and design profiles

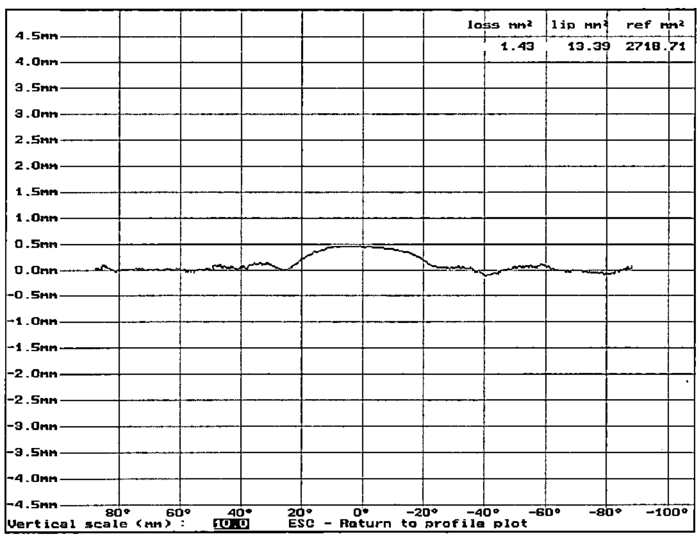


Residual plot

C6. ROCKY MOUNTAIN STEEL MILLS (RMSDHH) RAIL

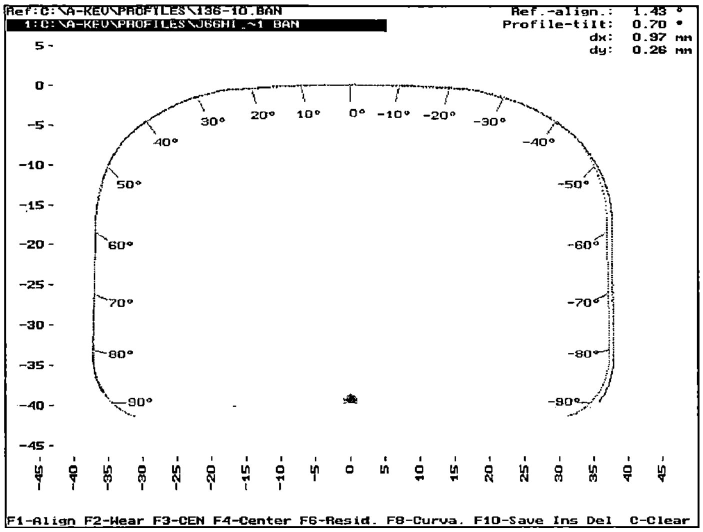


Comparison of manufactured and design profiles

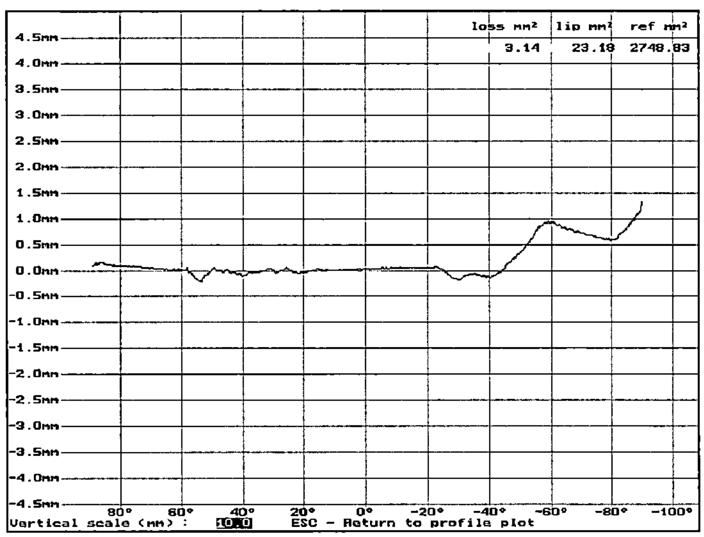


Residual plot

C7. J6 BAINITIC RAIL (MANUFACTURED BY PENNSYLVANIA STEEL TECHNOLOGIES)



Comparison of manufactured and design profiles

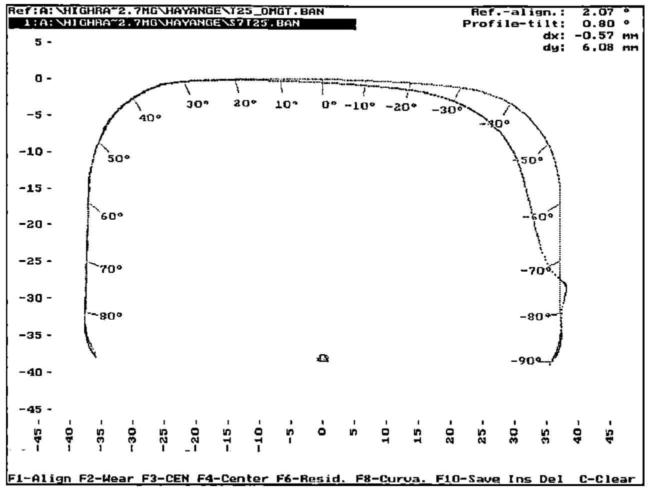


Residual plot

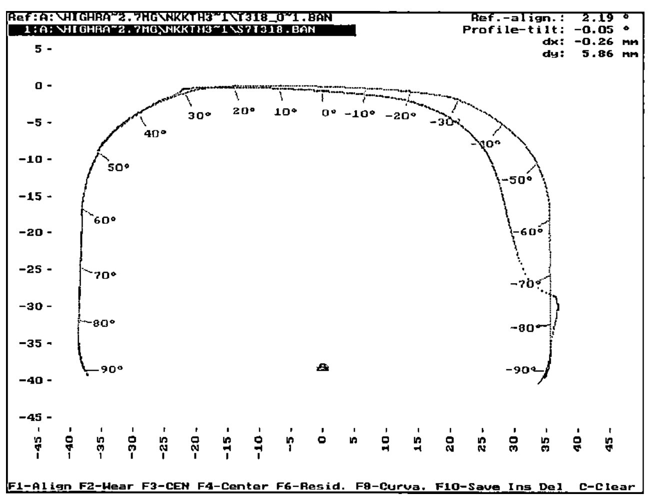
APPENDIX D

COMPARISON OF FINAL HIGH-RAIL WORN PROFILES TO INITIAL MEASURED PROFILES

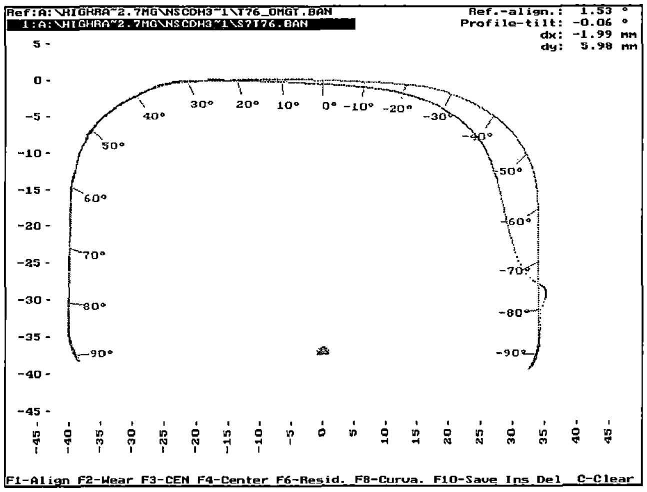
D1. HAYANGE (HAYHH) RAIL, 317 MGT



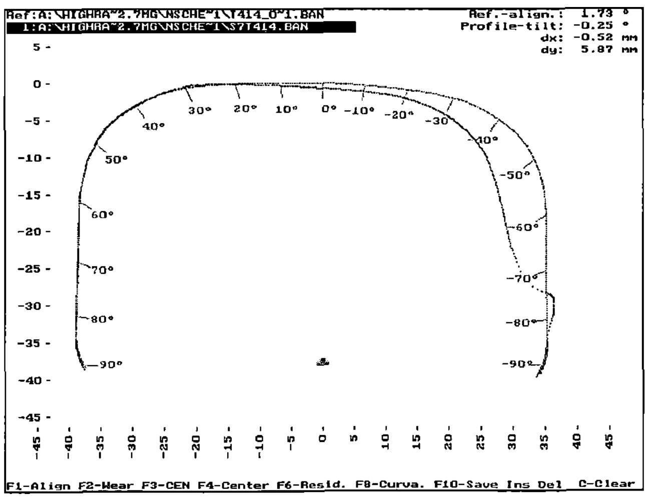
D2. NIPPON KOKAN (NKKTH37N) RAIL, 317 MGT



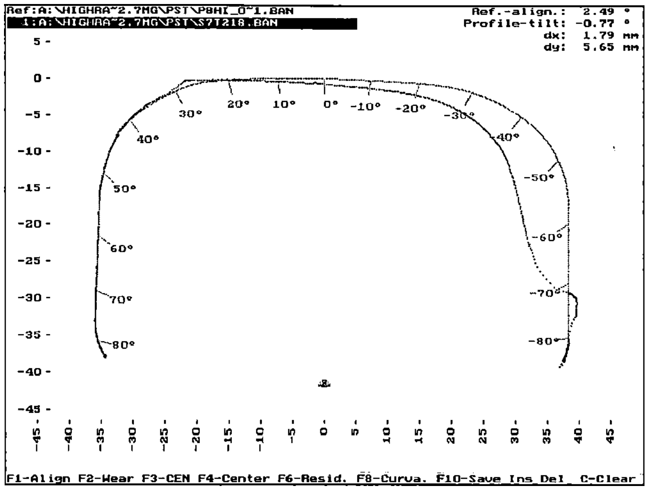
D3. NIPPON STEEL CORPORATION (NSCDH37) RAIL, 317 MGT



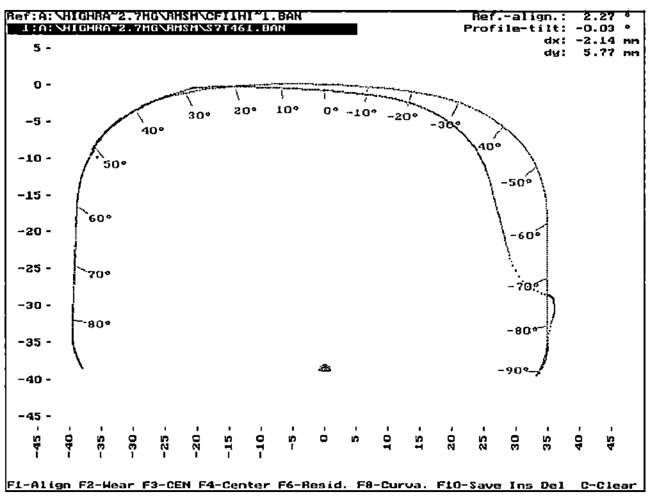
D4. NIPPON STEEL CORPORATION (NSCHE) RAIL, 317 MGT



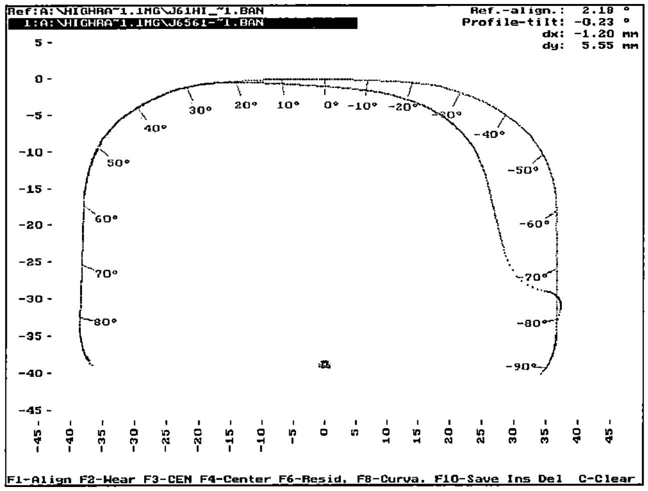
D5. PENNSYLVANIA STEEL TECHNOLOGIES (PSTHH) RAIL, 317 MGT



D6. ROCKY MOUNTAIN STEEL MILLS (RMSDHH) RAIL, 317 MGT



D7. J6 BAINITIC RAIL (MANUFACTURED BY ELLWOOD CITY FORGE AND PENNSYLVANIA STEEL TECHNOLOGIES), 252 MGT



TTCI
Transportation
Technology Center, Inc.
55500 DOT Road
P.O.Box 11130
Pueblo, Colorado 81001-0130 USA

A SUBSIDIARY OF THE ASSOCIATION OF AMERICAN RAILROADS