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16. Abstract

Tests ~~were~~ conducted on CSX wood-tie track to determine the long-term stability of track in the context of rail neutral temperature. Two test sites were chosen by the FRA and CSX in Georgia: one a tangent section of high-tonnage (50 mgt/year) track north of Carterville, Georgia, and the second a 6-degree curve on grade just south of Manchester, Georgia. Each test section was instrumented over a 1600 ft section with 15 pairs of strain gage and thermocouple transducers, measuring rail longitudinal stress (load) and rail temperature. In addition, surveyor's benchmarks were set in beside the track to monitor the dimensional stability of the track. Tests were conducted over a 20-month period at the tangent section, and a 17-month period at the curved section.

Over the course of the program, the effects of rail destress, time and traffic, yearly seasons, maintenance (tie renewal and surfacing), and repair of a track misalignment were determined. The tangent track rail neutral temperature (RNT) was found to follow seasonal average temperatures, varying over roughly a 10-degree F temperature range, but returning to very nearly the original value. A minor loss in RNT was attributed to track surfacing. In the curved track section, a steady loss in RNT was seen over the 17-month period, with some minor variation with season. A remote monitoring system was installed under a separate SBIR contract. This system showed graphically the effects on RNT of localized sunshine and shade in producing large load variations with distance along the tangent track.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

PREFACE

The authors wish to acknowledge the support of CSX Transportation throughout the course of this program. Thanks are due to Messrs. Tom Larson, Dennis Witt, Tony Kozak, Mike Arther and others at CSX. Special thanks are due to Mr. I. Cornelius, roadmaster at Manchester, and the track and welding crews who made the experiment possible.

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Final Report

on

RAIL NEUTRAL TEMPERATURE TESTS ON CSX

by

Donald R. Ahlbeck and James M. Tuten

1.0 BACKGROUND

The widespread use of continuous welded rail (CWR) in North America has dramatically improved rail performance. Joint maintenance is no longer a major expense item for the railroads. Rail end and joint bar failures have been reduced significantly. At the same time, the use of CWR has led to an increase in track buckling incidents ("sun kinks") when compared with bolted joint rail (BJR). Consequently there is great interest on the part of the railroads and the FRA in preventing track buckling occurrences.

Track buckling is caused by high rail compressive loads in a track structure unable to prevent lateral shift. These compressive loads are the result of the stresses induced in a constrained rail by temperatures above its "stress-free" state. The temperature at this stress-free state is known as the rail neutral temperature (RNT). Expansion and contraction of the rail with changes in temperature can be accommodated to some extent by rail joints. With CWR, these changes are, for the most part, "locked in". Track maintenance practices address the CWR thermal load problem by anchoring the rail at an RNT that is near the middle of the ambient temperature range. This neutral temperature typically falls between 75 to 95 degrees F. A compromise between the problems of buckling and a rail break (pull-apart) is thus achieved. Since rail temperatures can reach 140 degrees F, however, compressive stress levels can exceed 12,000 psi, and compressive loads can exceed 150,000 lb per rail.

Recent studies by Kish, et al [1,2] have shown that RNT can decrease with time, reducing the margin of track buckling safety. The RNT is controlled by laying and anchoring the rail at the desired neutral temperature. This can require heating or cooling the rail if the ambient temperature is outside the desired range. Often the results are not what is expected. Decreases in RNT from the rail-laying temperature on the order of 15 to 30 degrees F are typical, and maximum decreases of 40 to 50 degrees F have been measured. These large reductions in RNT were measured on curved track rather than on tangent track, which indicates that the curve was adjusting to large compressive forces by moving laterally, (i.e., "breathing"). Track maintenance such as tie renewal and track surfacing also produces changes in the RNT, often decreasing the RNT sharply.

For the railroads to have an effective program to prevent track buckling, more data are needed on the changes in RNT due to track maintenance, rail installation or relay practices, and the seasonal influences of traffic and weather. Acquisition of these data require first, a method for measuring rail stress, longitudinal load, and rail neutral temperature, and second, an efficient means for monitoring and logging these measurements.

The primary objective of this study was to quantify the RNT changes in both tangent and curved track over a long time period. The test concept was to install new CWR in accordance with CSX rail laying practices and to monitor quarter-mile segments for rail installation effects, end effects and variations within the test zone (i.e., spatial effects), track maintenance, traffic (tonnage) and seasonal effects.

2.0 TECHNICAL DISCUSSION

2.1 Rail Longitudinal Stress and RNT Measurement

Since the early 1970s, the Federal Railroad Administration (DOT/FRA) and the Transportation Systems Center (DOT/TSC) have sponsored comprehensive research programs in the areas of track performance and strength. One of the many useful results produced from these programs was the rail longitudinal stress circuit, which has since become a standard tool in understanding rail behavior under mechanical and thermal loads. This strain gage circuit had been used by British Rail and in the 1981 TSC/FRA track buckling tests on the Southern Railway. It was suggested by Harrison [3] as a solution to measurement problems encountered at FAST. Since its effectiveness was verified by Battelle in a 1981 validation project, this circuit has been employed in a number of research projects by the FRA, TSC, the Association of American Railroads (AAR), Amtrak, Burlington Northern, and CSX railroads.

2.1.1 Longitudinal Stresses in Rail

Changes in rail temperature will cause dimensional changes as the rail expands or contracts, or (if the rail is restrained in any way) will cause changes in "locked-in" load and internal stress levels. The rail temperature follows the ambient temperature fairly rapidly, and can rise 30 to 40 degrees F (17 to 22 C) higher than the ambient air temperature in direct sunlight. If CWR is well-anchored on heavy-duty track structure such as the Northeast Corridor (NEC) concrete-tie track, the rail is essentially fixed in space, and the locked-in longitudinal stress and load can be calculated by:

$$\sigma_x = -E_r \alpha \Delta T \tag{1}$$

$$P_x = A_r \sigma_x \tag{2}$$

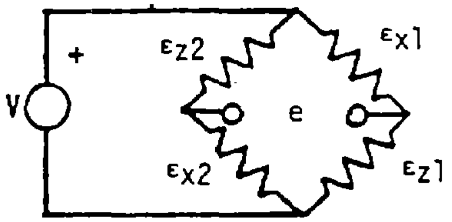
where A_r = rail cross-sectional area, in^2,
E_r = rail steel modulus of elasticity, lb/in^2,
α = coefficient of expansion, in/in-F,
ΔT = change in temperature from stress-free state, deg F,
P_x = longitudinal load, lb, positive tensile,
σ_x = longitudinal (x-axis) stress, lb/in^2, positive tensile.

If the rail is not fully constrained (for example, on a curve, or near an expansion joint), then the longitudinal strain is not zero and the stress becomes:

$$\sigma_x = -E_r[\alpha \Delta T - \epsilon_x] \tag{1a}$$

where ϵ_x = the longitudinal rail strain.

Rail longitudinal stress may be measured (in the absence of significant lateral restraint or vertical wheel loading) by strain gages applied to the rail web at the beam horizontal neutral axis. Consider the strain gage pairs sketched below, mounted longitudinally (x) and vertically (z) on opposite sides of the rail web:



The governing relationship for this circuit is:

$$\begin{aligned} e/V &= (K_g/4)(\epsilon_{x1} - \epsilon_{z1} + \epsilon_{x2} - \epsilon_{z2}) \\ &= (K_g/2)(\epsilon_x - \epsilon_z) \end{aligned} \tag{3}$$

where e = strain gage bridge output, volts,
V = bridge excitation, volts,
K_g = gage factor (usually "2"),
ϵ_{ij} = strain, indicated by change in resistance of gage "j" in direction "i".

Now, from Hooke's Law, the stress-strain relationships are given by:

$$\epsilon_x = (1/E_r)(\sigma_x - \nu\sigma_y - \nu\sigma_z) \tag{4a}$$

$$\epsilon_z = (1/E_r)(\sigma_z - \nu\sigma_x - \nu\sigma_y) \tag{4b}$$

where ν = Poisson's ratio for rail steel.

By substituting Equations 4a and 4b into Equation 3, we can describe the strain gage circuit output in terms of rail stress:

$$e/V = [K_g(1 + \nu)/2E_r][\sigma_x - \sigma_z] \tag{5}$$

The rail longitudinal stress can then be determined from the strain gage circuit output readings:

$$\sigma_x = [e/V][2E_r/K_g(1 + \nu)] \tag{6}$$

Using a typical strain indicator and applying an 0.1 mv/v reference calibration with a precision calibrator, Equation 6 will define the calibration equivalent stress for the nominal rail material parameters:

$$\begin{aligned} \sigma_x &= [0.1(10)^{-3}(2)(30)(10)^6]/[2.03(1 + 0.30)] \\ &= 2274 \text{ lb/in}^2 \end{aligned} \tag{6a}$$

For convenience, the strain indicator is set to 227.4 counts (10 psi per count) for the 0.1 mv/v reference calibration, using the gain (the gage factor setting) for adjustment. Note that the actual stress may range from 2122 to 2304 lb/in^2, depending on the chosen rail material properties.

2.1.2 Track Instrumentation

For the long-term RNT studies, strain gages were installed on both sides of the rail web at the rail neutral axis to measure thermally-induced strains. In addition to the strain gages, a chromel-alumel thermocouple was attached to the rail web within the protective cover to provide a quick, stable measurement of rail temperature. Heavy-gage steel protective covers were used to avoid damage to the gages and wiring. These covers, shown in Figure 2-1, also provided a stable thermal environment for the temperature measurements.

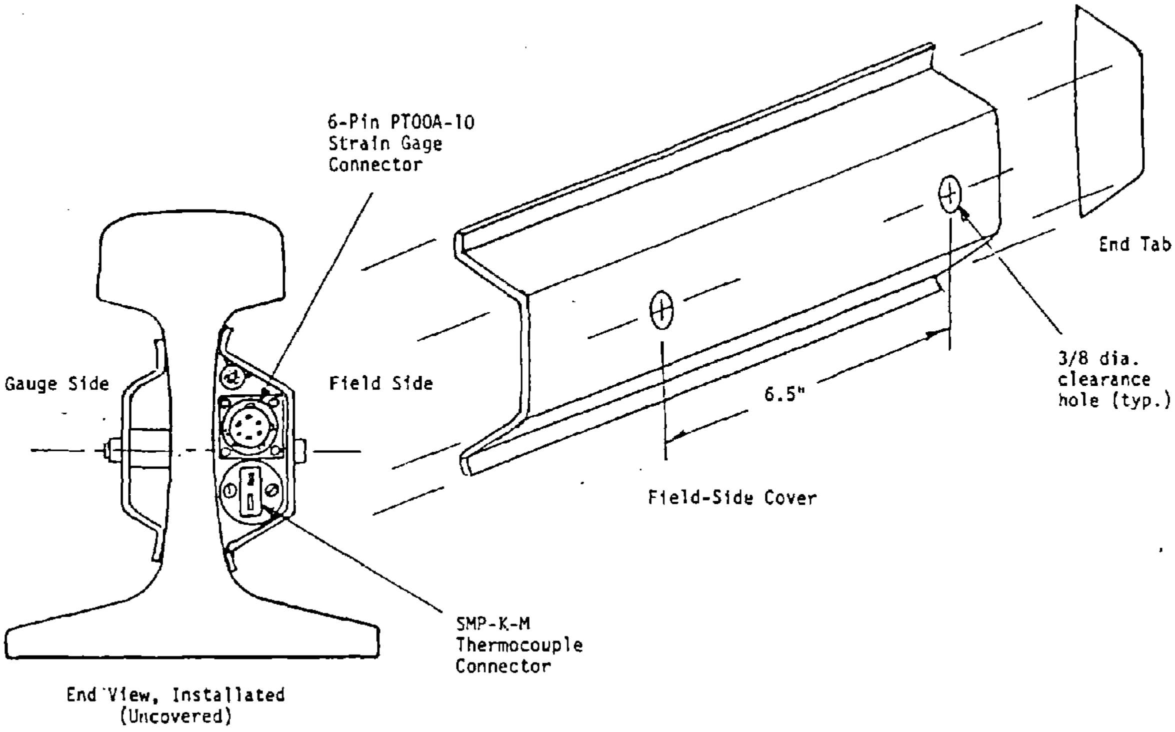


FIGURE 2-1. SKETCH OF RNT INSTALLATION PROTECTIVE COVERS

Instrumentation for the tests consisted of a strain indicator, precision calibrator, and digital thermometer. The strain indicator was calibrated using a precision reference signal of 0.1 millivolt/volt, as described above. Rail longitudinal load and apparent RNT were calculated:

$$P_r = 10\ A_r(N - N_o) \quad \text{lb}$$

$$= 0.129\ (N - N_o) \quad \text{kips} \qquad (7)$$

$$RNT = (N - N_o)/19.5 + T_{rail} \qquad (8)$$

where N = strain indicator "counts" (set to 10 psi per count),
N_o = counts at destress state (zero reference),
T_{rail} = measured rail temperature, F,
P_r = rail longitudinal (tensile) load, lb (or kips).

Note that stress is a direct transduced measurement from the calibrated rail circuit (analogous to load, rather than strain, as the transduced measurement from a load cell). The reading may range from 1.3 percent lower to 7.2 percent higher than actual stress due to the nominal rail parameters chosen. Rail load, P_r, may be lower than calculated if the actual rail cross-sectional area is smaller than the nominal ("catalog") area.

2.2 RNT Test Sections

Track sites for the long-term RNT tests were chosen by CSX, FRA and Battelle personnel to meet the various criteria of the test program. Two test sections were chosen: one on tangent track near Cartersville, Georgia on the former L&N Railroad, and the other on a six-degree curve on grade near Manchester, Georgia on the former Seaboard Coast Line railroad. A total of thirty RNT strain gage and temperature transducer sites, 15 on each rail, were installed on 100 or 150-ft intervals in each 1600 ft section. In addition, surveyor's benchmarks were set in adjacent to each site to allow long-term monitoring of rail longitudinal and lateral movements.

2.2.1 Tangent Track Test Site

The tangent section, called "Bolivar" (the name of the siding), is located about 22 miles north of Cartersville, Georgia, just west of U.S. Hwy 411 on Mt. Pleasant Road. It starts at the spiral-tangent (ST) point at Milepost 406.8 and runs for 1600 ft north. There is a passing siding on the east side at this location. If trains meet at Bolivar, southbound trains are usually held in the siding. These include loaded coal unit trains. About 50 million gross tons (MGT) of traffic per year are handled by this line.

The test section is of well-ballasted wood tie track construction. New 132 lb/yd CWR was laid first on the main (instrumented) track, then later on the passing siding. Ties are box-anchored, every other tie, with Unit rail anchors. From tests by Unit, the anchors provided 1520 ±460 lb of restraint after reinstallation.

The layout of instrumented sites within the test section is shown in Figure 2-2. The test section starts directly under the Mt. Pleasant Road overpass, rising out of a cut on an 0.45 percent grade (northbound). Toward the north end of the section (Sites 10 to 12), the track changes to a -0.65 percent downgrade. Site 1 is usually within the shade cast by the overpass during the day. Sites 2 through 8 are shaded during morning and late afternoon hours by a mixture of pine and deciduous trees to the east, and brush to the west. Beyond Site 8, the track is almost level with surrounding fields, shaded only by low brush. Occasional trains waiting on the siding can shade instrumented sites during morning hours.

Instrumentation was applied to the tangent track section during the week of October 31, 1988. Surveying benchmarks were set in beside each site on the west side of the track. Because of traffic density, the strain gage circuit calibration (destress) operation was postponed until a later date, when a track curfew could be imposed. The calibration was finally achieved nearly two months later, on December 20, 1988. A view of the test section and a typical site installation are shown in Figures 2-3 and 2-4, respectively.

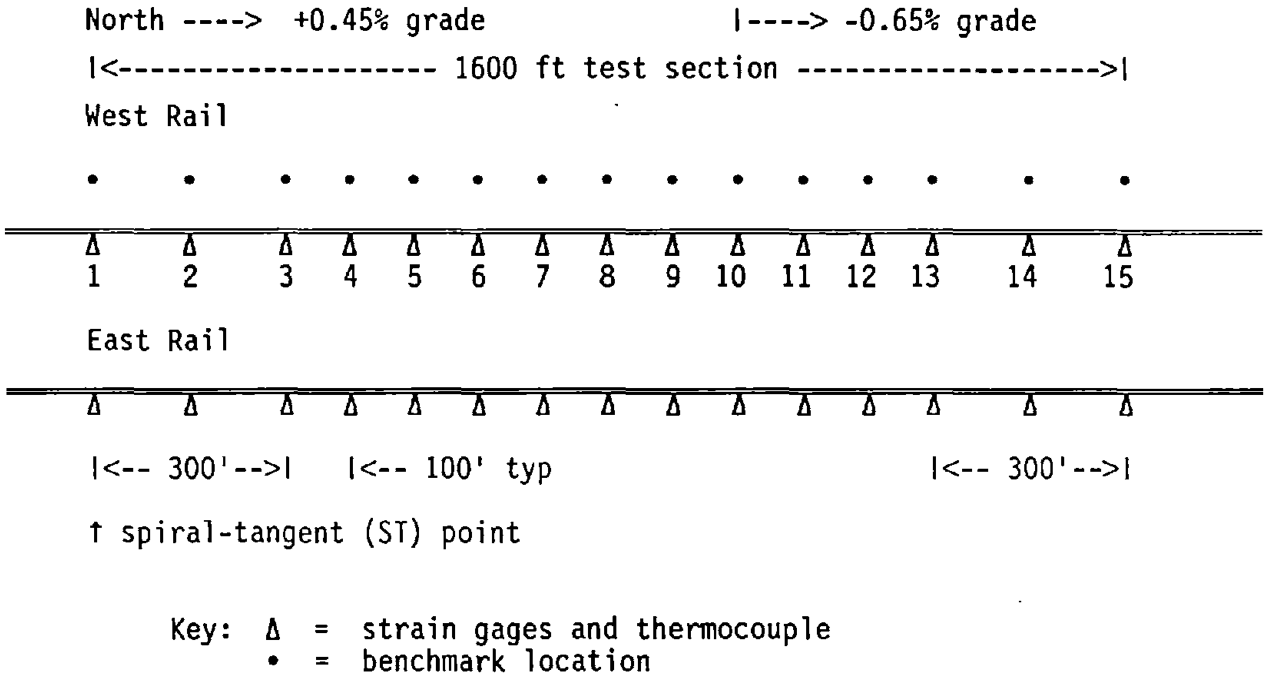


FIGURE 2-2. LAYOUT OF TANGENT TRACK TEST SECTION, BOLIVAR, GEORGIA

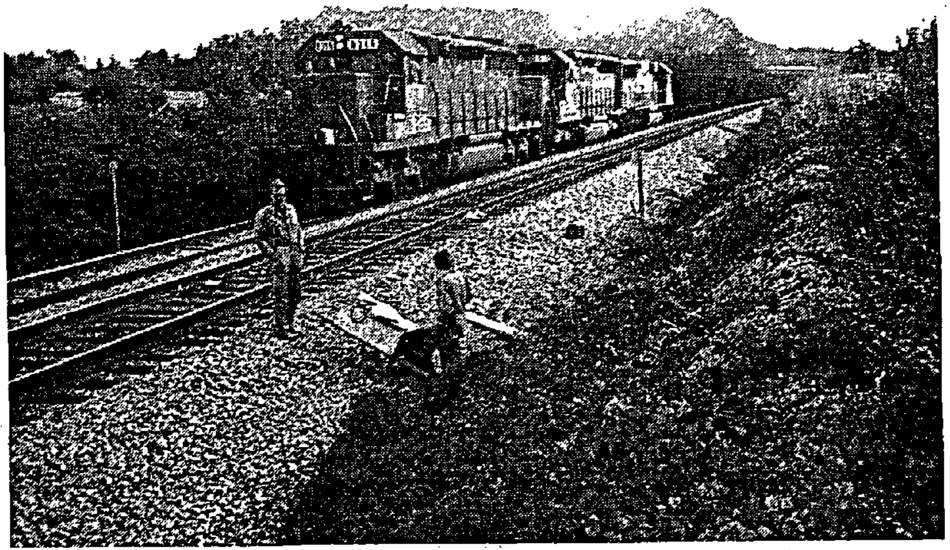


FIGURE 2-3. VIEW OF TANGENT TRACK TEST SECTION

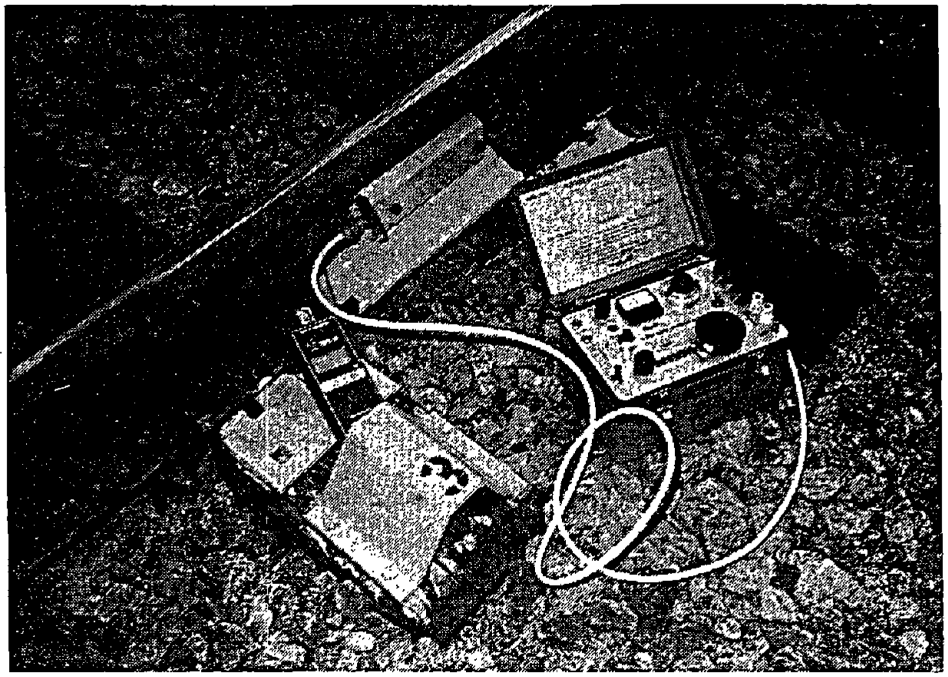


FIGURE 2-4. TYPICAL RNT INSTRUMENTATION SITE INSTALLATION

2.2.2 Curved Track Test Site

The curved track test section is located about two miles south of Manchester, Georgia. The section starts at Milepost NB 785.1, a six-degree right-hand curve with 2-1/2 inch super-elevation, on an 0.76 percent ascending grade (north, toward Manchester). The track speed limit is 30 mph. Instrumented Site 1 is 126 ft into the curve from the spiral-curve (SC) point. The curve-spiral (CS) point is 70 ft beyond Site 13, so that Sites 14 and 15 are in the spiral, with Site 15 about 60 ft short of the spiral-tangent (ST) point.

The track is well-ballasted wood tie construction. New (1987) head-hardened 132 lb/yd CWR was laid, and a tie renewal completed, prior to the start of tests. Rails are box anchored every other tie with Woodings rail anchors (and a few Unit anchors). A curve lubricator is located in the short tangent section just south of Site 1.

The layout of instrumented sites within the test section is shown in Figure 2-5. A view of the site is shown in Figure 2-6. The sites can be shaded during portions of the day by tall pine trees located on both sides of the track. Instrumentation was applied to the curved track section during the week of January 23, 1989. Surveying bench-marks were set in beside each site, about 10 ft from the low-rail side of the track. At this time, a number of bolted rail joints existed within the test section.

2.3 Test Section Calibrations

2.3.1 Tangent Section Calibration.

After removing (or knocking back) all rail anchors at the tangent section, the rails were cut at roughly the one-third and two-thirds points of the section. These cuts were made first between Sites 12 and 13 at 50 degrees F, so that the rail moved in release of tensile load. Gaps of 3-5/8 inches, west rail, and 4-1/2 inches, east rail, were developed. The west rail broke with 1.77 in^2 of uncut metal remaining. The strain gage circuits at Site 12

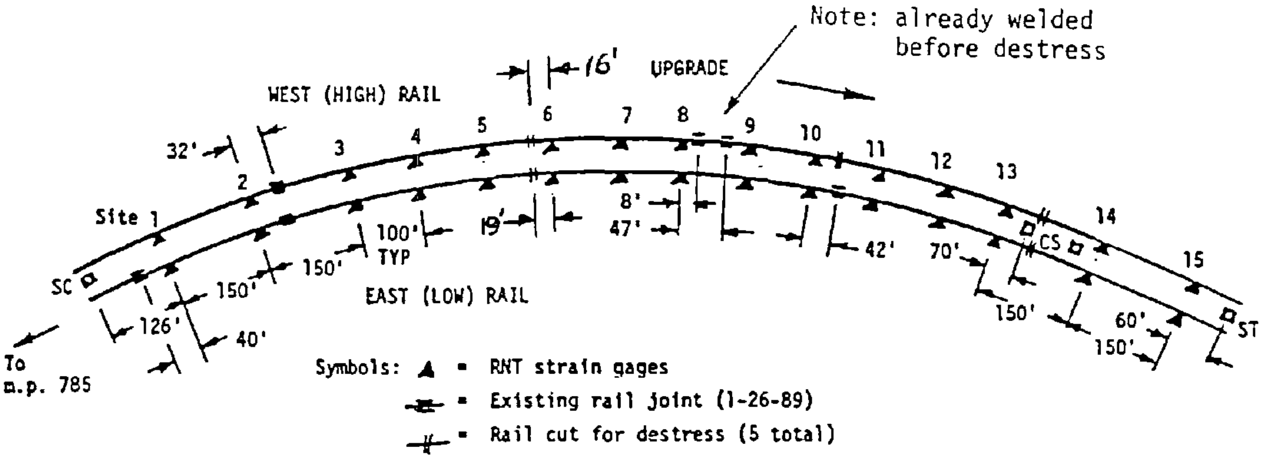


FIGURE 2-5. INSTRUMENTATION SITE LAYOUT IN CURVED TRACK SECTION

FIGURE 2-6. VIEW OF CURVED TRACK TEST SITE

were read before and after the cuts, and showed an 72,000 lb change in tensile load at this location, and an estimated neutral temperature T_N of 85 F.

Both rails were then cut between Sites 3 and 4 at temperatures of 47 to 50 F. About 1/2 inch pull at the east rail was noted prior to this cut, due to cutting the rail between Sites 12 and 13. The rail cuts developed gaps of 1-1/4 inches, breaking at remaining metal areas of approximately 0.39 in^2 at the west rail, 0.25 in^2 at the east rail. The strain gage circuits at Sites 3 and 4 were read before and after cuts, and showed average tensile load changes of 43,000 lb, both rails.

Following this, a CSX tamper was run the length of the test section to further vibrate and loosen the track, and two sets of strain and temperature readings were made as the rail warmed to about 75 F in the sun. This allowed changes in stress due to rail-tie plate friction to be estimated. Complete friction-force hysteresis loops (by continuing the measurements into the rail cooling cycle) were not obtained, however. Since the track curfew was running out, the rails were welded at Sites 3/4 as soon as the rail expanded to within the desired gap. The rails from the Site 12/13 gap almost to Site 15 were heated (by kerosene-soaked felt ropes) and welded to establish the desired RNT near 95 deg F. This resulted in actual RNT values ranging from 65 F at the south end of the test section to 88 F at the north end.

In our test plan, estimates of the rail stress-free strain indicator readings were to be based on measuring the complete thermal hysteresis loop during warming and cooling of the rail. Since time constraints made this impossible, stress-free (zero reading) estimates were based on the rail warming-cycle readings taken on December 20, 1988. These readings, however, would include some compressive frictional loads, depending primarily on site distance from the nearest rail cut.

Recent tests [4] on CWR strings lying free in the ballast have provided a basis for revising these estimates. These tests measured free-rail longitudinal load hysteresis loops of 12 to 29 kips, with effective longitudinal load increases of 36 to 57 lb per foot of rail. These values would correspond to effective friction coefficients ranging from 0.82 to 1.30.

For sites adjacent to a rail cut, the stress-free strain indicator reading can be estimated two ways: first, by using a reading halfway between the first (right after the cut) and the last readings. This assumes that the cutting process will leave the rail loaded in tension due to rail-tie friction forces, and that thermal expansion will then put the rail into an equal and opposite compressive force. In the second method, an estimated compressive friction force equivalent is subtracted from the last reading, which is assumed to be stable in the thermal expansion cycle. This force is based on an average friction coefficient and the distance of the site from the rail cut. As shown in Table 2-1, these two methods compare quite well, falling within 22 counts (220 psi, or 2.8 kips) of one another for the five sites. This comparison gives us confidence in estimating the other site zeros based on the second method.

Since the rail was cut in only four places, there is the possibility that a stable rail expansion (compression) cycle was not reached before the rail was rewelded. Most sites showed changes between the last two sets of readings within 7 counts (70 psi) of increased compression per degree F. Sites 1 and 2 exceeded this value, and stress zeros at these sites have the lowest confidence level.

2.3.2 Curved Section Calibration.

The curved-track section presented the additional complication of single-track operation. Calibration (destress) operations were therefore postponed until March 14, 1989, when two CSX welding crews would be available. Starting at about 8:30 a.m., all rail anchors were removed, the rails were cut at five locations, and the four existing rail joints were loosened. Strain and rail temperature measurements were made at nearby sites after each cut. With rail temperatures near 70 F, little rail movement was noted, and the resulting gaps were less than 7/16 inch. As the rail temperature rose slowly, some saw binding was experienced. Three heavy freight trains moved slowly over the track (using joint clamps) during this process, which provided some vibration to loosen the rail. Rail strain and temperature measurements were then made as the rail warmed, until the strain readings had stabilized. Since the track curfew was running out, the rail saw cuts and existing bolted joints were welded, finishing this work at about 4 p.m. A 25-car gravel train ran

TABLE 2-1. REVISED STRAIN INDICATOR ZERO READINGS, TANGENT TRACK SECTION

Test Site	Method 1 - Hysteresis Loop Zero Strain Readings West Rail	Method 1 - Hysteresis Loop Zero Strain Readings East Rail	Method 2 - Friction Force Zero Strain Readings West Rail	Method 2 - Friction Force Zero Strain Readings East Rail
1	+521	+2034	+509	+2026
2	+487	-487	+493	-487
3	+444	+829	+430	+820
4	+481	-377	+459	-396
12	-1304	+318	-1320	+323

Note: Friction force calculated from average $\mu = 1.0$

Strain differential readings = 7.75 counts/kip

TABLE 2-2. REVISED STRAIN INDICATOR ZERO READINGS, CURVED TRACK SECTION

Test Site	Method 1 - Hysteresis Loop Zero Strain Readings West Rail	Method 1 - Hysteresis Loop Zero Strain Readings East Rail	Method 2 - Friction Force Zero Strain Readings West Rail	Method 2 - Friction Force Zero Strain Readings East Rail
5	-883	-198	-900	-210
6	-54	-986	-47	-980
10	-796		-795	
11	-686		-692	
13	-1204	-639	-1197	-634
14	+28	-651	+47	-648

Note: Friction force calculated from average $\mu = 1.0$

Strain differential readings = 7.75 counts/kip over the section shortly afterward. Final RNT values ranged from 86 F near Site 1 (near the spiral) to 103 F in the body of the curve.

Again, initial estimates of the rail stress-free strain indicator readings were made based on the rail warming-cycle readings taken on March 14, 1989. Better estimates were possible based on the recent experiments [4]. A comparison of the two methods for estimating zeros at sites adjacent to rail cuts is shown in Table 2-2. Once again, the second (friction) method was used to estimate the actual zeros at the other sites. Because the rail could be freed at nine locations (versus four at the tangent section), a much higher level of confidence in zero values was achieved in the curved section. The change between the last two sets of readings (before the rail was rewelded) was within 3 counts (30 psi) of increased compression per degree F for all but four sites, indicating that a stable rail expansion cycle had been reached at most sites. The four sites (2E, 4W, 15W and 15E) exceeded this number, with values ranging up to 6 counts per degree F (at 2E), so that stable compression may not have been achieved at these sites.

2.4 Strain Gage Circuit Gain

From Section 2.1, it was shown that the nominal "gain" of the RNT strain gage circuit was 19.5 counts/deg F (195 psi/deg F) of increased compression, based on nominal rail material parameters. This is predicated on an ideal "locked in" longitudinal load due to increased rail temperature. From RNT experiments on the Northeast Corridor (NEC) concrete tie track, the circuit gain was found to range from 183 to 203 psi/deg F (191 ±8.0) on tangent track, and from 162 to 185 psi/deg F (173 ±8.5) on the high and low rails of a one-degree curve. Circuit gain may range from 182 to 198 psi/deg F based on expected variations in material properties. Lower values of gain result from actual movement of the rail: a nearby joint, slack in rail anchors, or lateral movement of the track in a curve.

Circuit gains were estimated for the two test sections based on the sets high and low temperature readings, either the heating cycle through one day, or the overnight cooling cycle. Gains for the tangent track section are given in Table 2-3 for three such cycles, the first cycle just prior to the

TABLE 2-3. RAIL CIRCUIT GAIN IN TANGENT TRACK SECTION

Test Site	Before Destress (12-19/20-88)		Heating Cycle (3-13-89)		Overnight Cool. (4-24/25-89)	
	West	East	West	East	West	East
1	175	154	b	b	b	b
2	167	160	155	165	152	167
3	179	147	179	169	178	165
4	154	166	159	168	189[c]	187[c]
5	169	a	164	144	172	153
6	158	166	161	164	181	178
7	156	137	168	141	170	145
8	160	156	163	150	198	174
9	157	148	173	151	154	134
10	153	144	161	159	180[d]	164[d]
11	150	163	201	226	183	199
12	165	161	174	161	168	156
13	165	152	162	153	174	150
14	188	174	171	158	194	159
15	168	170	159	170	159	179
ΔT	-28 to -43 F		-28 to -33 F		-35 to -60 F	
Mean	164	157	168	163	175	166
Std Dev	10.5	10.6	11.7	20.4	7.8	17.5

Numbers in psi/deg F (compression)

Note: On curved section, west = high rail, east = low rail.

a -- anomalous reading. b -- in shade of overpass.

c -- partially shaded, p.m., rail temp. about 7 deg F lower.

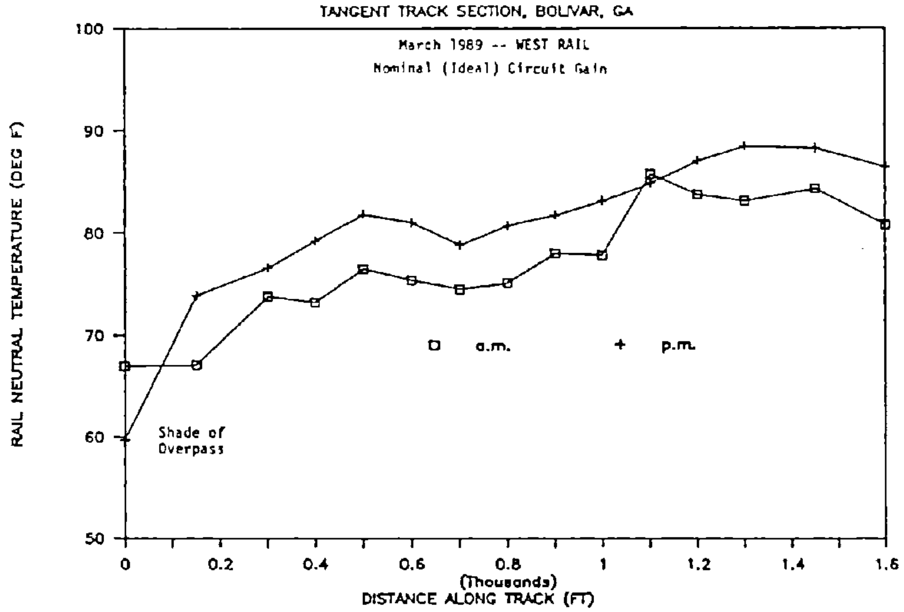
d -- for a.m. readings: dappled shade, Sites 5-9, full sun, Sites 10-15.

destress exercise. From this table, the west rail gains are seen to range from 164 ±10.5 (before destress) to 175 ±7.8 psi/deg F, with some sites approaching the nominal gain value. There appears to be some increase in circuit gain with increased temperature change, or perhaps with increased mean temperature. The east rail gains are seen to range from 157 ±10.6 (before destress) to 166 ±17.5 psi/deg F, exhibiting lower gains and greater scatter. Site 11 -- both 11W and 11E -- appears to be prone to anomalously high gains, for whatever physical reason. For the March 1989 cycle, these gains represent statistical three-sigma (0.3 percent) values on a normal distribution.

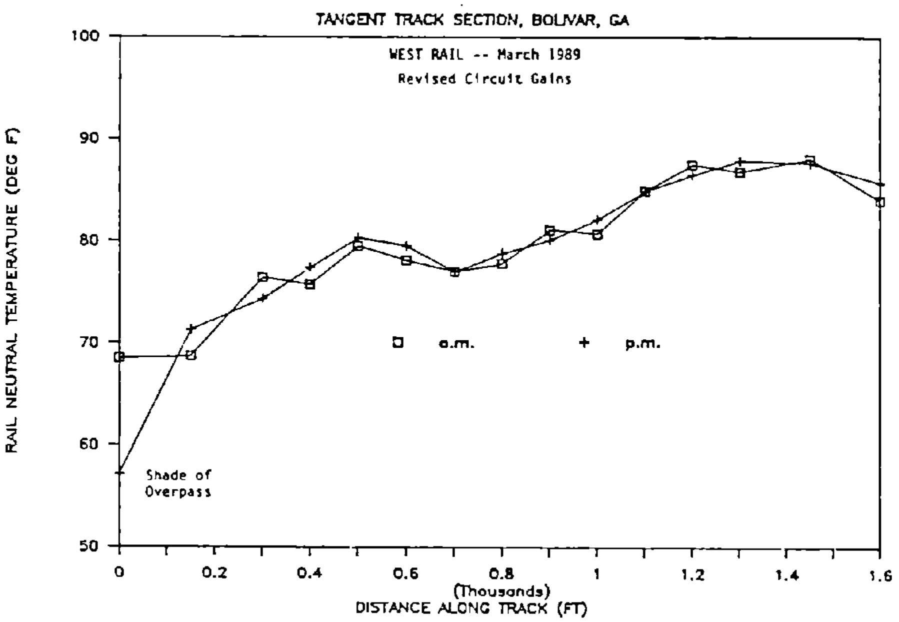
The effects of circuit gains are illustrated in Figure 2-7, showing the west rail calculated neutral temperatures for lower temperature (a.m.) and higher temperature (p.m.) readings. In the top figure, the nominal gain of 19.5 counts/deg F results in a substantial difference between morning and afternoon RNT values. In the bottom figure, an average gain of 16.4 counts per deg F is used for all but Site 11W (which uses 20.1 counts/deg F). Close agreement between sets of readings is then achieved, independent of the actual rail temperature.

No "gains" were calculated for Site 1, which remains for most of the day in the shadow of the overpass. This shadow results in rail temperatures well below that of the nearby rail. The compressive load is transferred through the rail and is reflected in the gage readings, but the measured temperature is unnaturally low and produces false calculated RNT and "gain" numbers. Some of the scatter in both calculated RNT and "gain" numbers occurs because of localized shading of other sections of the track, particularly during morning and late afternoon hours. If discrete tree shade falls on the site in the morning, an incorrect (lower) RNT and lower gain will be calculated. (Completely shaded track will be unaffected, except at the transition to sunlit track.) If discrete tree shade falls on the track in the afternoon, an incorrect (lower) RNT and higher gain will be calculated. Note, however, that the measured rail stress and calculated load will be accurate, except for minor temperature effects on the gages themselves.

Similar cycles for the curved track section are given in Table 2-4, the first prior to the destress exercise. Values of gain at some sites in the first cycle show the effects of existing rail joints in the curve. From this



a. Nominal (Ideal) Rail Circuit Gains



b. Revised Rail Circuit Gains

FIGURE 2-7. COMPARISON OF CALCULATED RNT WITH NOMINAL AND REVISED GAINS

TABLE 2-4. RAIL CIRCUIT GAIN IN CURVED TRACK SECTION

Test	Before Destress (1-25/26-89)		Overnight Cool. (4-25/26-89)		Overnight Cool. (7-31/8-01-89)	
Site	West	East	West	East	West	East
1	100	64	145[c]	164[c]	112[a]	139[d]
2	128	113	167	158	144	147
3	127	118	156	161	143	168
4	143	120	167	b	170	b
5	106	143	152	160	148	166
6	115	124	173	144	157	141
7	80	129	180	184	168	148
8	50	111	147	163	152	167
9	84	132	151	160	167	171
10	100	100	147	151	171	167
11	120	113	143	152	174	170
12	131	109	140	154	180	183
13	142	124	155	162	194	195
14	144	154	152	166	176	202
15	140	148	160	169	172	208
ΔT	-30 to -51 F		-34 to -59 F		-37 to -43 F	
Mean	114	120	156	161	165	169
Std Dev	27.4	21.7	11.6	9.4	14.8	21.3

Numbers in psi/deg F (compression)

Note: On curved section, west = high rail, east = low rail.

a -- anomalous reading. b -- inoperative circuit.

c -- shade, Sites 1-10; sun, Sites 11-15, but temp. stable.

d -- for p.m. readings: sun ⊥ at Site 2, sun ∥ at Site 15; for a.m. readings: shady Sites 1-8, dappled sun Sites 9-10, sun at oblique angle Sites 11-15.

table, the west rail gains are seen to range from 156 ±11.6 to 165 ±14.8 psi/deg F, while the east rail gains range from 161 ±9.4 to 169 ±21.3 psi/deg F. Again, the effects of tree shadows and angle of sun on the track must be considered.

2.5 Test Section Monitoring

One of the major technical problems faced in this program was the inconvenience of making measurements over relatively widely-spaced circuit locations at a relatively isolated test section. The time required to take strain and temperature readings at the 30 sites over the 1600-ft test section averaged about 40 minutes, with no interference from train traffic. During this long a time span, significant changes in rail temperature could (and often did) occur. In our Test Plan, we had anticipated that sets of readings were to be taken on one-month intervals, in early-morning and mid-afternoon temperatures, by CSX personnel. Due to unforeseen circumstances, sets of readings were obtained at longer intervals, primarily by Battelle personnel when the rail displacement surveys were conducted.

To address this type of problem, the FRA funded Salient Systems, Inc. of Dublin, Ohio (under a separate SBIR contract) to develop a prototype rail longitudinal load and temperature remote monitoring system [4]. This system was designed to be hard-wired into the existing RNT measurement transducers with minimum disruption of the on-going experiments. The system consists of 15 dual-circuit modules, mounted on the west rail, but servicing strain-gage bridges on both rails. The previously established zero stress readings were programmed into each module, and the module gains were set to convert the readings to load in kips.

A dedicated site controller (central computer) was developed to manage the array of modules. This controller acquires complete sets of load and temperature data, and stores the data in memory along with the time and date. The controller has an integral modem that can be accessed by telephone, allowing requests for current or stored data, as well as some reprogramming of the individual modules. Power and communications lines are tied into a nearby CSX signal/communications shed.

Installation of the remote monitoring system was completed by FRA's subcontractor at the Bolivar, Georgia (tangent) test section on May 3, 1990. Because power and communications lines were not available at the Manchester (curved) test section, a similar system was not considered for this second test location.

3.0 RESULTS OF RNT STUDY

3.1 Effects of Destress on Rail Neutral Temperature

The site calibrations were carried out at the tangent and curved test sections during unusually warm, pleasant winter weather in December 1988 and March 1989, respectively. At the tangent section, the "before" readings were taken on the morning of November 4, 1988 with rail temperatures between 56 and 64 degrees F, gradually warming as readings progressed from Site 1 to Site 12. The "after" readings were taken on the morning of December 21, with the rail temperatures stable between 53 and 55 F. Traffic had passed over the section all night.

The effects of the calibration ("destress") exercise, followed by rewelding the rails, are given in Figure 3-1, which shows the "before" and "after" rail neutral temperatures. The calculated rail neutral temperatures increased from Site 1, the spiral-tangent point, to a maximum between Sites 13 and 14. This increase ranged up to 27 degrees F over roughly 1400 ft. Before destress, the east rail RNT was as much as 12 degrees higher than the west rail RNT over most of the section. After rewelding, this difference between rails was reduced substantially, but the differences in RNT from one end of the section to the other were still present.

Since the rails were heated from the rail gaps between Sites 12 and 13 to almost Site 15 (about 350 ft) before welding, a higher RNT was again achieved at this end of the section. Rails at the gaps between Sites 2 and 3 were welded without heating. As a result of heating over such a limited section of rail, up to 20 degrees in RNT were lost over portions of the section.

The effects of destress at the curved track section are shown in Figure 3-2. At this test section, the "before" readings were taken on the afternoon of February 27, 1989 with rail temperatures between 67 and 69 degrees F. The "after" readings were taken on the morning of March 15, with rail temperatures between 69 and 79 F, and after traffic had passed over the section all night. A fairly uniform (but somewhat low) RNT existed throughout the body of the curve prior to destress, both in distance along the rail, and

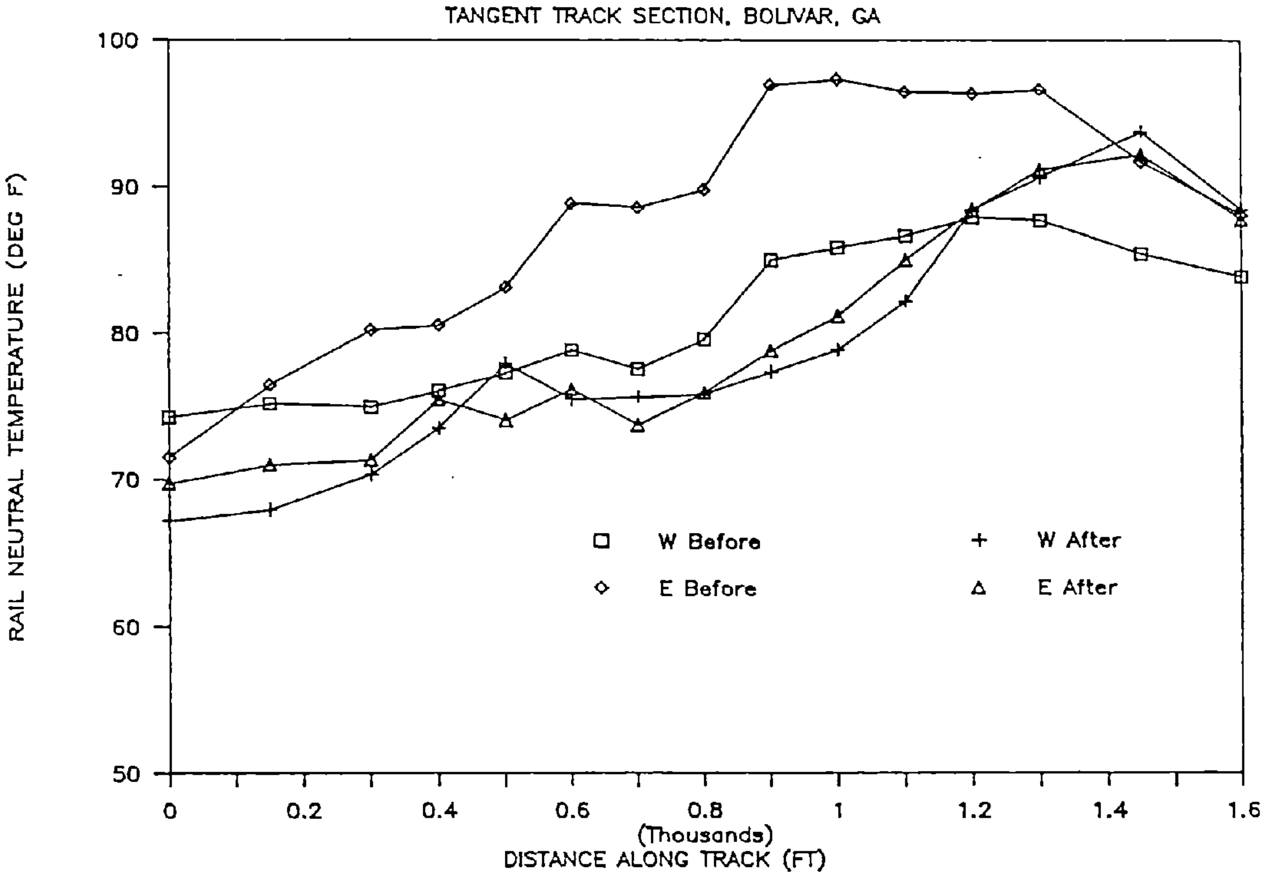


FIGURE 3-1. EFFECTS OF RAIL DESTRESS ON CALCULATED RAIL NEUTRAL TEMPERATURE AT THE TANGENT TRACK TEST SECTION

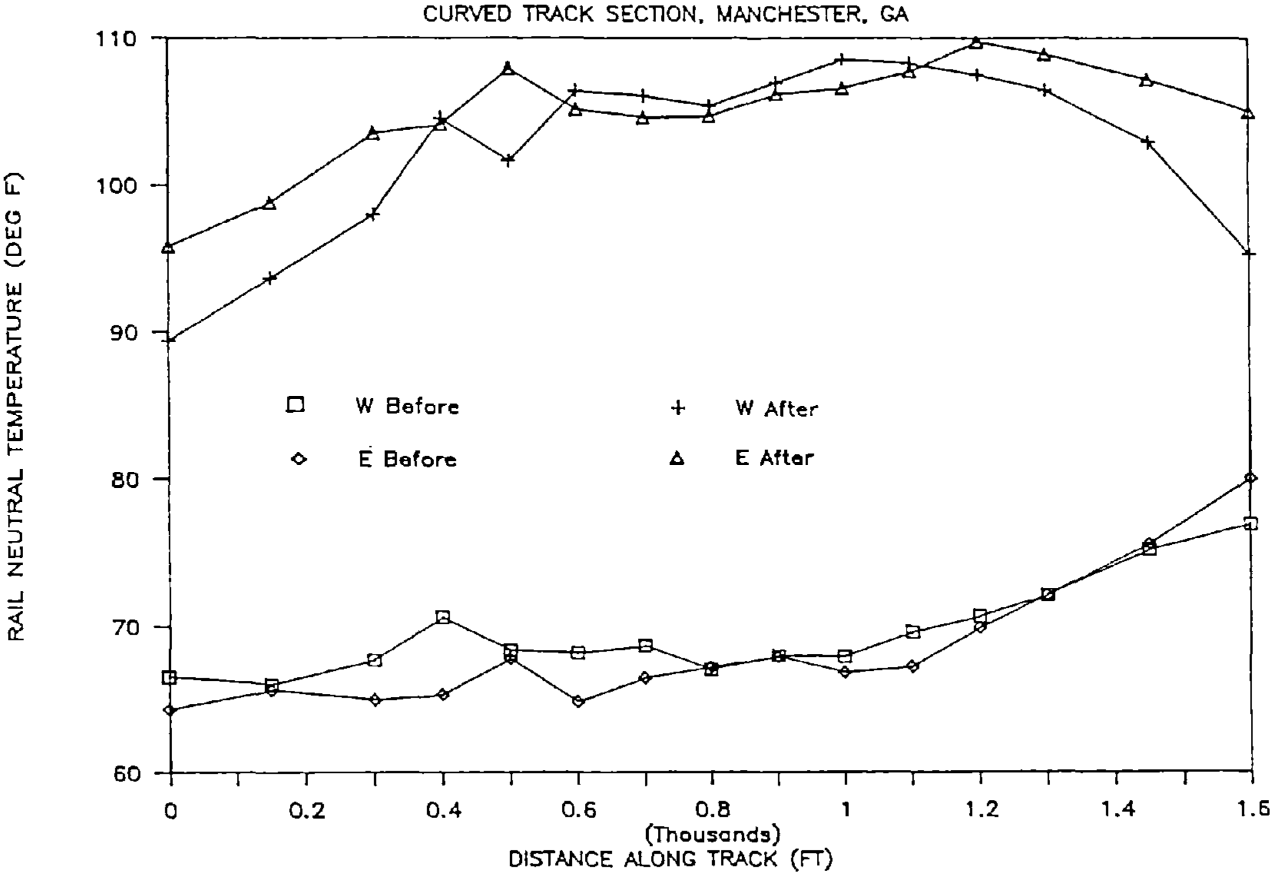


FIGURE 3-2. EFFECTS OF RAIL DESTRESS ON CALCULATED RAIL NEUTRAL TEMPERATURE AT THE CURVED TRACK TEST SECTION

from high to low rail values. Since rail temperatures rose to over 100 F by the time the rails were rewelded, an increase in RNT of 20-30 F was achieved throughout the curve. The lowest RNT values were noted at Site 1 (just past the spiral-curve point). Destress was conducted at nearly the original curve RNT, so that "rail break" pull effects were minimal due to the first rail cuts.

Variations in longitudinal load with distance along the rail before and after the destress exercise are shown in Figures 3-3 and 3-4. Since longitudinal load is calculated directly from measured stress, it provides a more accurate assessment of the actual state of the rail than RNT. It is, however, sensitive to rail temperature variations, which produce changes in load up to -2.5 kips/deg F. Before destress at the tangent track section, substantial load differences existed between west and east rails. These differences were greatly reduced by cutting and rewelding the rails. Variations in longitudinal load through the curved track section were much less pronounced than at the tangent section.

3.2 Effects of Time and Season on RNT

3.2.1 Tangent Track

From the discussion in Section 2.4, we have established that the calculated RNT value is subject to two sources of error:

1) Variations from site to site in "local" rail temperature due to isolated shade at the site, or a patch of sun through the trees, and,
2) Variations in circuit "gain" due to local constraints (rail anchor restraint, tie movement in ballast, the rail "running"). This "gain" can apparently change with time, traffic, season and/or track condition.

The effects of time, accumulated tonnage, and seasonal variations on RNT are shown in Figures 3-5 and 3-6 for the first seven months after destress. For these plots, circuit gains were adjusted to the average values

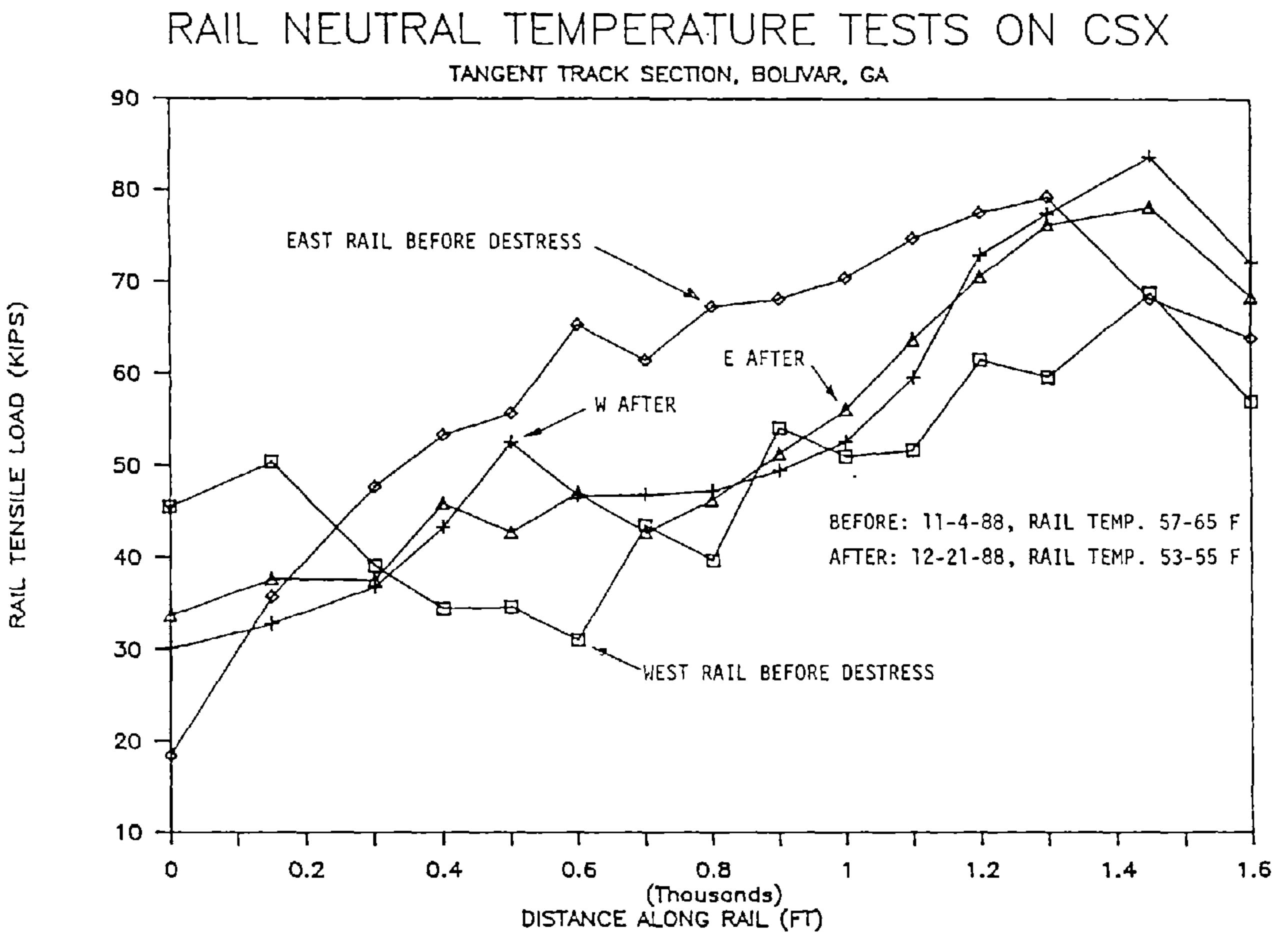


FIGURE 3-3. EFFECTS OF RAIL DESTRESS ON RAIL LONGITUDINAL LOAD AT THE TANGENT TRACK TEST SECTION

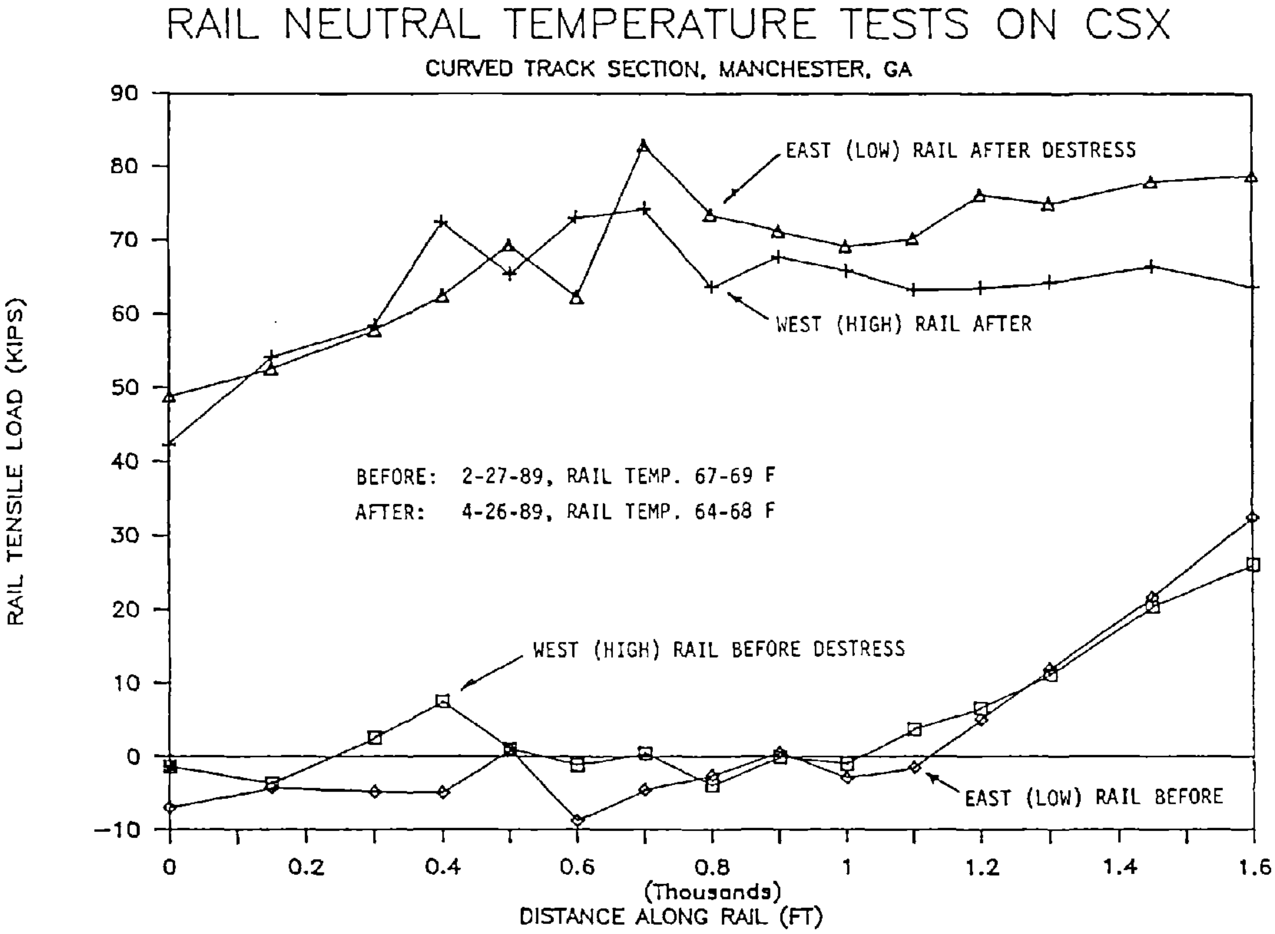


FIGURE 3-4. EFFECTS OF RAIL DESTRESS ON RAIL LONGITUDINAL LOAD AT THE CURVED TRACK TEST SECTION

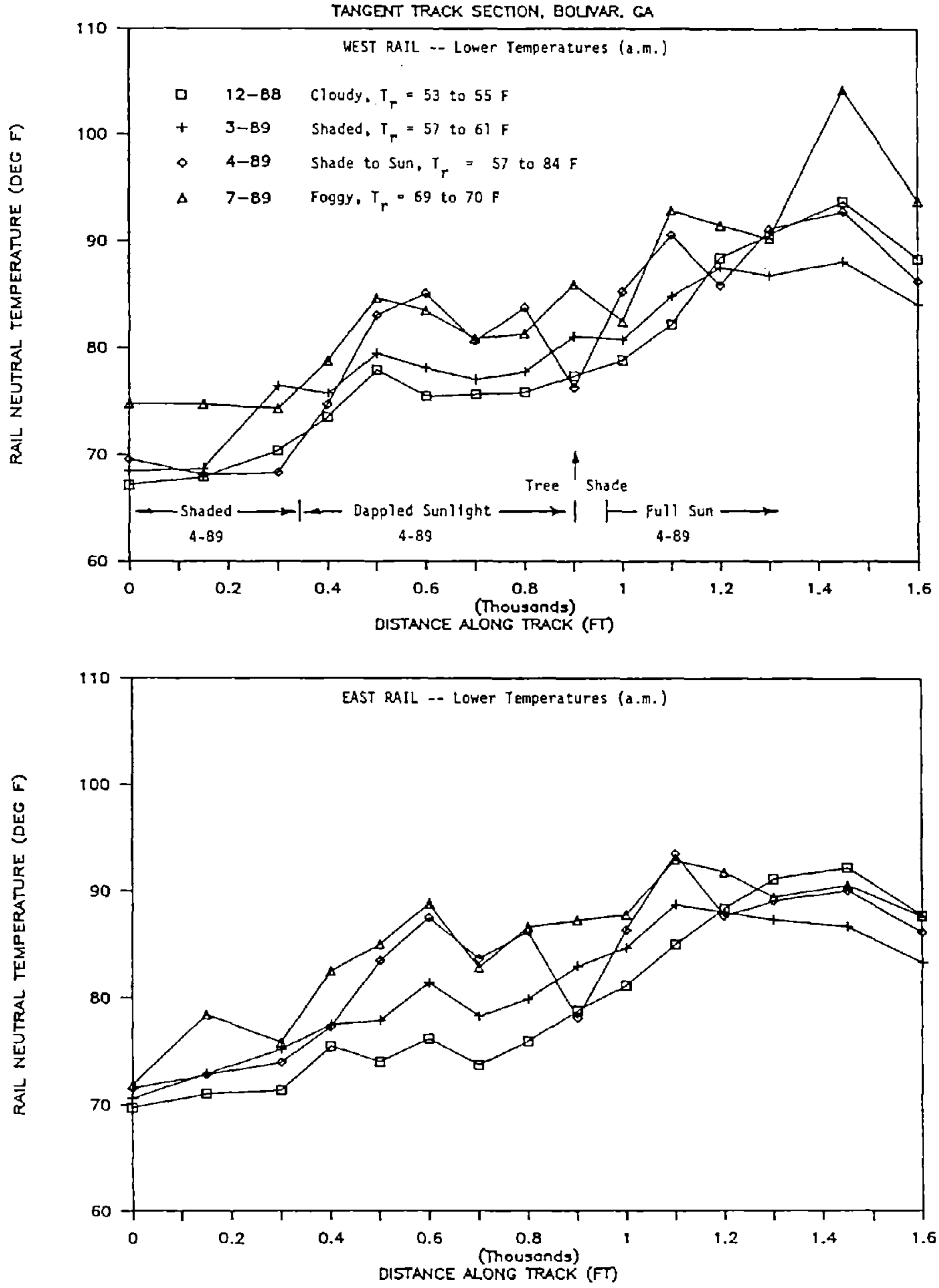


FIGURE 3-5. EFFECTS OF TIME (TONNAGE) AND SEASON ON CALCULATED RNT TANGENT TRACK TEST SECTION, LOWER TEMPERATURE READINGS

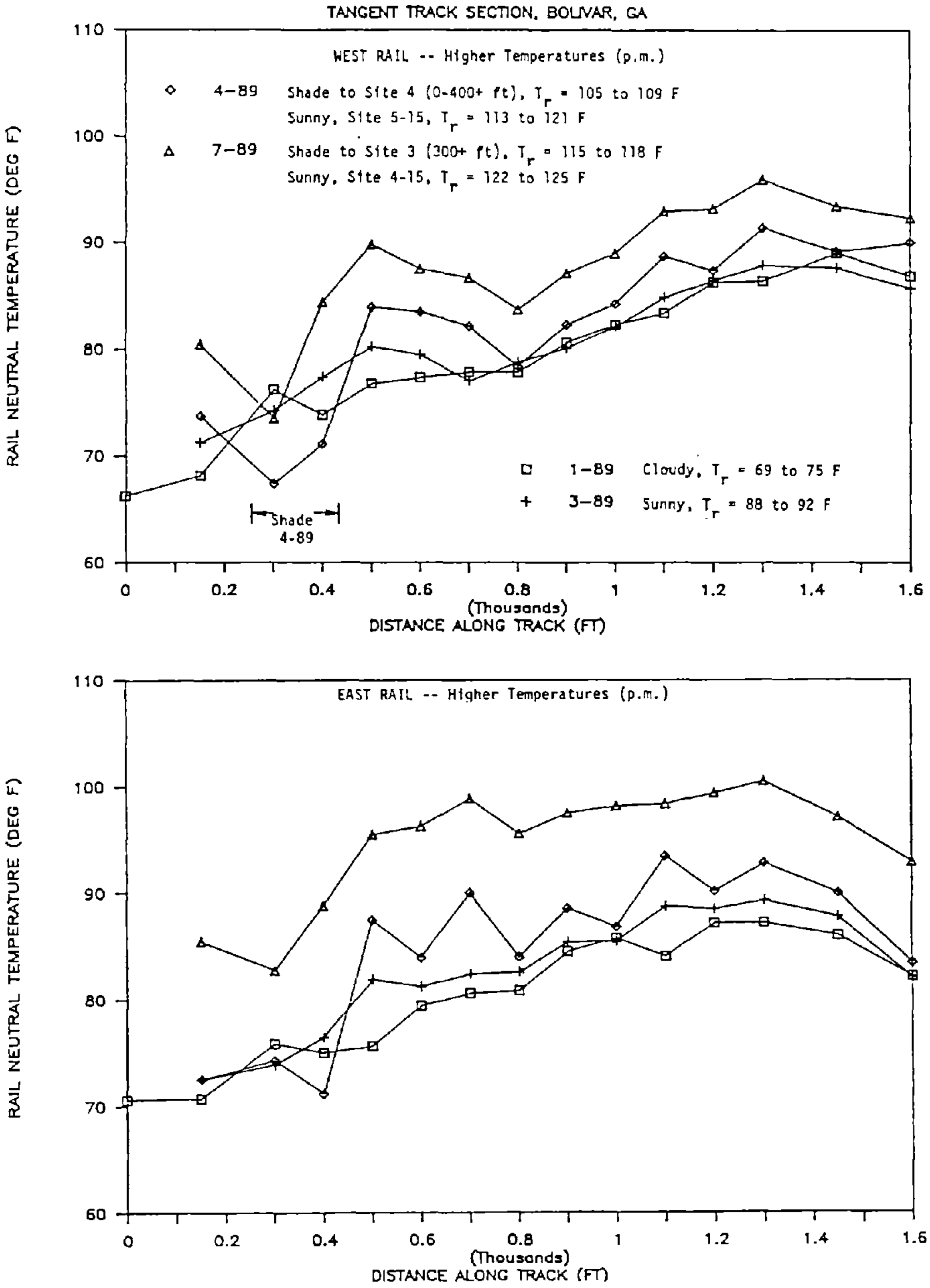


FIGURE 3-6. EFFECTS OF TIME (TONNAGE) AND SEASON ON CALCULATED RNT TANGENT TRACK TEST SECTION, HIGHER TEMPERATURE READINGS

given in Table 2-3. In Figure 3-5, RNT values for the lower temperature (morning) readings are plotted. The effects of local solar heating are readily seen: for example, the morning readings of March 1989 at Site 9 (900 ft) were fully shaded, giving rail temperatures of 67 F, while the nearby Sites 8 and 10 had temperatures of 76 and 81 F, respectively.

In plots of the higher temperature (afternoon) readings, almost all of the Site 1 (0 ft) values were left out. This site remains in the shadow of the road overpass; and on sunny days the rail temperatures may read 30 to 40 F lower than the Site 2 temperatures, resulting in calculated RNT values much lower than the actual. Again, differences between lower temperature readings, Figure 3-5, and higher temperature readings, Figure 3-6, can also result from differences in the individual circuit gains from the average gain value used in the calculations. Afternoon readings in mid-summer (7-89) were generally higher than the morning readings, particularly for the east rail. This suggests reductions in circuit gains throughout the test section as the track loosened itself under traffic and summer heat.

In spite of these local variations, we can see a general increase in tangent track RNT as the season progressed into mid-summer and peak rail temperatures approached 125 F. Test section average RNT rose from 79 F in late December to 88 F by August. This effect is confirmed in Figures 3-7 and 3-8, where a one-year cycle is plotted. After the mid-summer 1989 readings, there was a general reduction in RNT to the lower readings, again to a test section average of 79 F in October. This was followed by an increase in RNT to a test section average of 88 F by late May 1990.

3.2.2 Curved Track

While tangent track exhibits a seasonal variation in RNT, curved track shows a progressive decrease in RNT with time and tonnage, with the exception of a few anomalous sites. Test section average RNT dropped from 104 degrees F just after destress (March 1989) to 99 F in April and to 95 F by early August. Lower temperature (morning) readings are plotted in Figure 3-9 for a 13-month cycle. Some of the variation from site to site is again

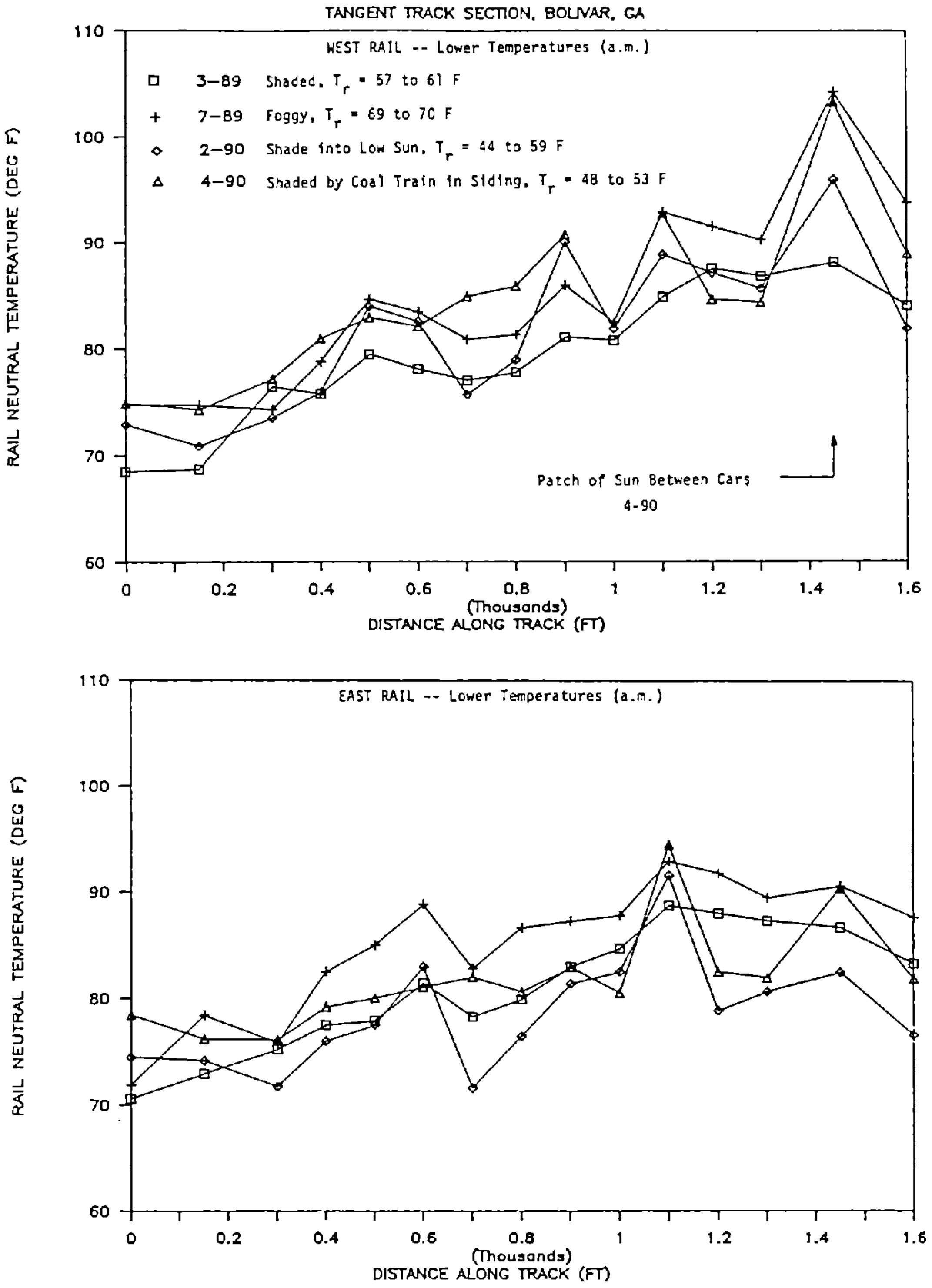


FIGURE 3-7. EFFECTS OF TIME (TONNAGE) AND SEASON ON CALCULATED RNT TANGENT TRACK TEST SECTION, LOWER TEMPERATURE READINGS

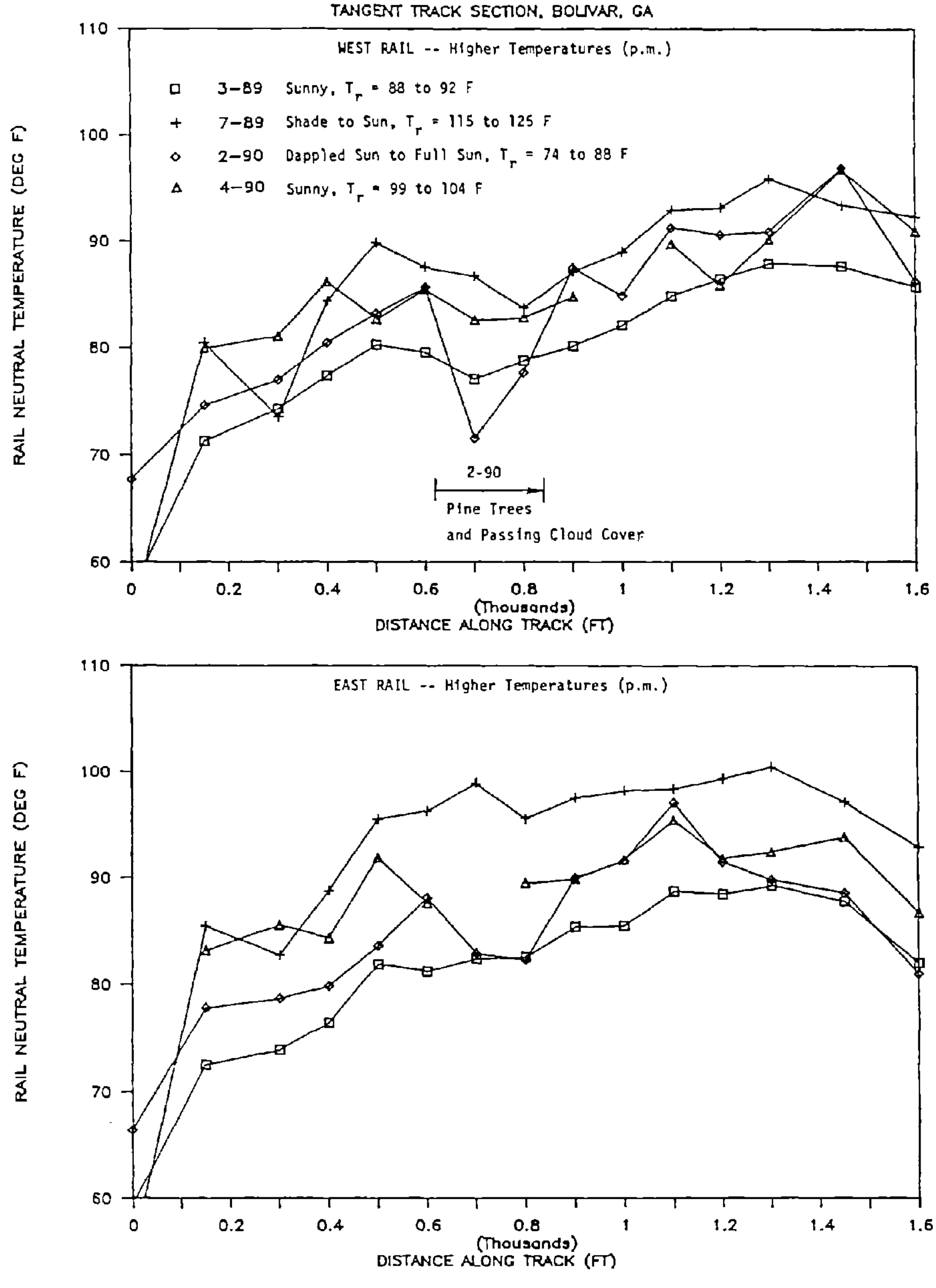


FIGURE 3-8. EFFECTS OF TIME (TONNAGE) AND SEASON ON CALCULATED RNT TANGENT TRACK TEST SECTION, HIGHER TEMPERATURE READINGS

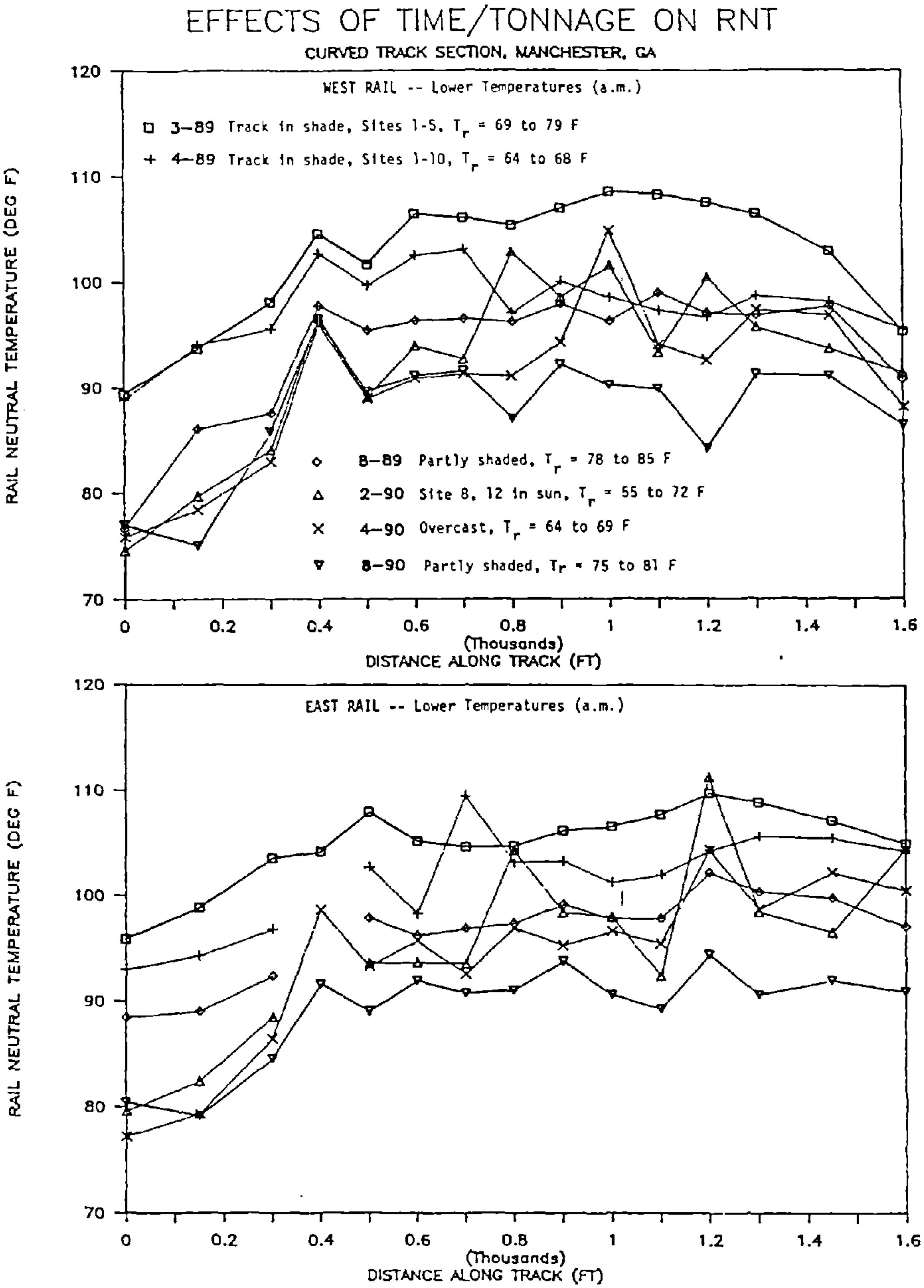


FIGURE 3-9. EFFECTS OF TIME (TONNAGE) AND SEASON ON CALCULATED RNT CURVED TRACK TEST SECTION, LOWER TEMPERATURE READINGS

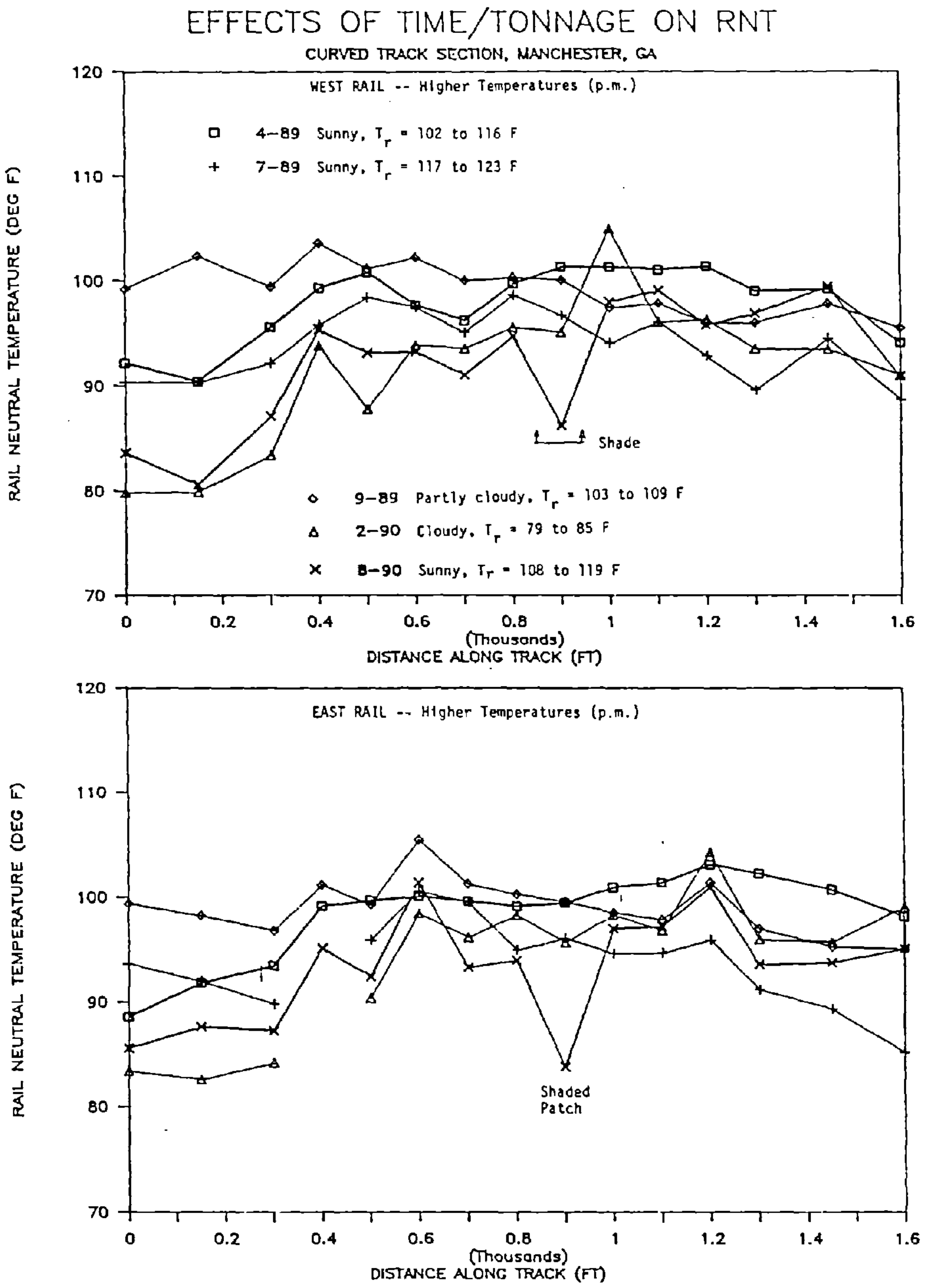


FIGURE 3-10. EFFECTS OF TIME (TONNAGE) AND SEASON ON CALCULATED RNT CURVED TRACK TEST SECTION, HIGHER TEMPERATURE READINGS

attributed to local solar heating between shady spots. The angle of the sun also changes by more than 90 degrees through the test section.

The decrease in RNT is confirmed in higher temperature (afternoon) readings plotted in Figure 3-10. Higher temperature readings were not available during the April 1990 visit due to stable temperatures and threatened rain. Note the increase in RNT in the first 400 ft of the curve over the original (destress) RNT. In mid-September, a southbound (downgrade) freight train broke a coupler knuckle and went into emergency braking. Slack action forces pushed the track out of alignment by several inches near Site 4. About one inch of each rail was cut out, the track realigned, and the rails heated and rewelded. This resulted in the newly-established, higher RNTs seen in Figure 3-11 and a test section average RNT of 99 F. The effect was relatively short-lived, however, and RNT thereafter continued to decrease. Test section average RNT dropped to 94 F by February 1990, to 93 F by April, and to 91 F by August.

3.3 Effects of Track Maintenance

Tie renewal and surfacing operations were scheduled for mid-summer through the tangent track test section. A set of RNT readings was made on the afternoon of July 30 and the morning of July 31, 1989, just prior to maintenance operations through the test section. Surfacing had progressed southward to just north of Site 15 before the readings, and tie renewal was scheduled for the following day. RNT readings were repeated on the morning of August 2 after tie renewal was completed (about 1/3rd of the ties were replaced). The ballast regulator had been through most of the section, but surfacing had not begun. In the process of tie renewal, Site 15W was badly damaged. Surfacing was completed through the test section sometime well after the tie renewal. A set of "after" RNT readings was not obtained until late October.

The effects of these maintenance operations on RNT are shown in Figure 3-12. Tie renewal (TR) is seen to have a negligible effect, with the "before" and "after" RNT values within normal temperature-related variance.

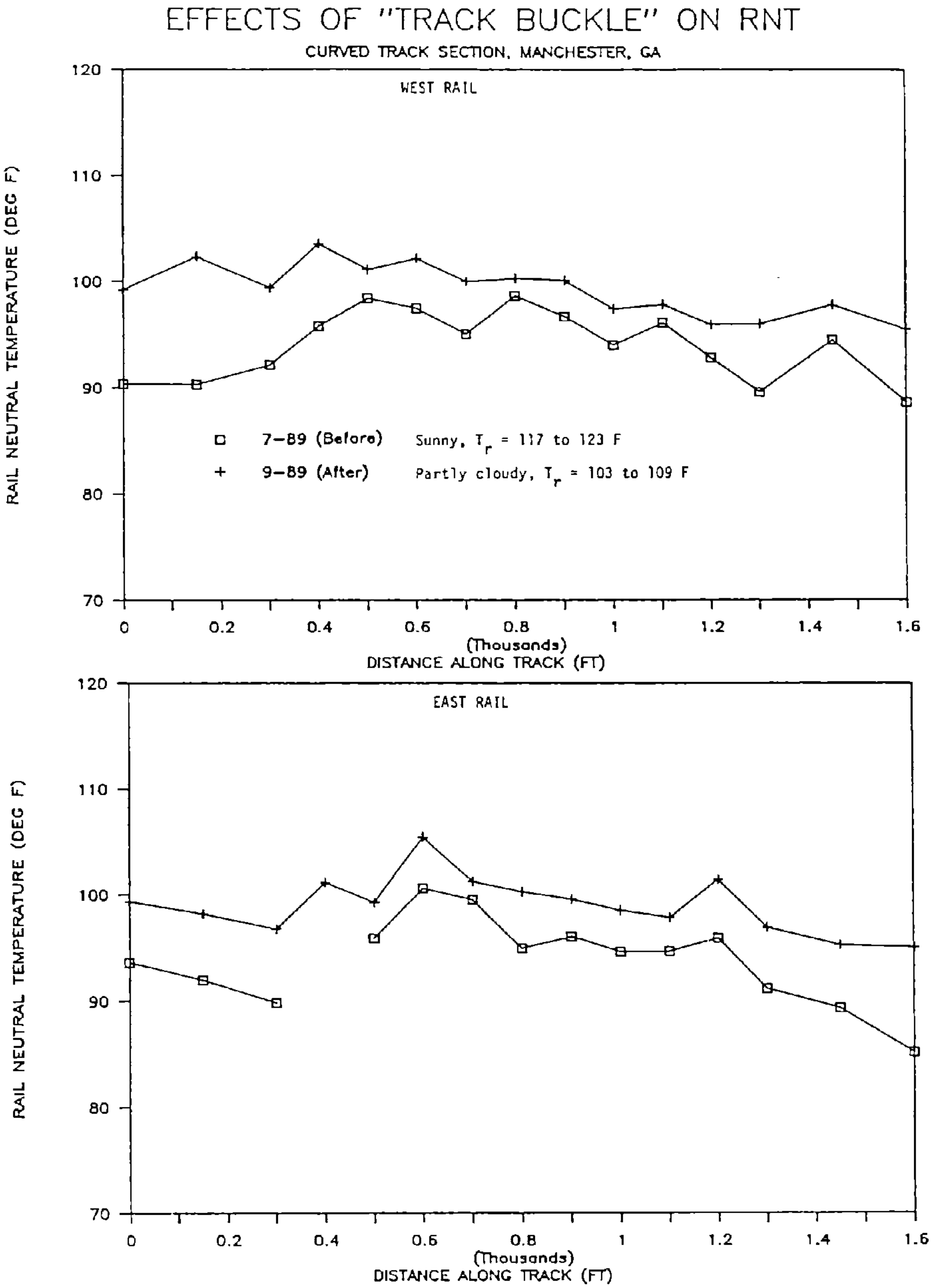


FIGURE 3-11. EFFECTS OF REPAIR OF TRACK MISALIGNMENT ON CALCULATED RNT, CURVED TRACK TEST SECTION

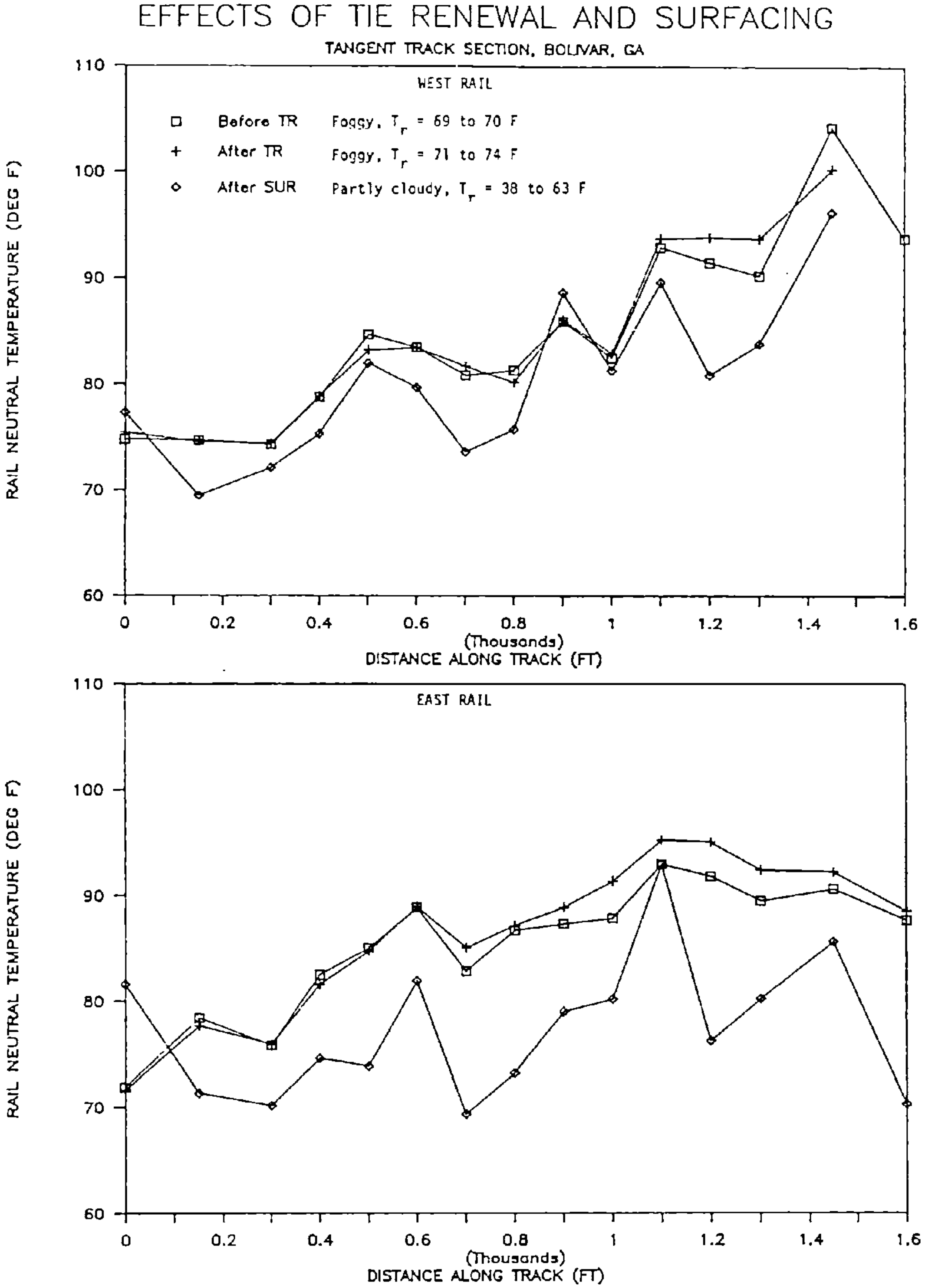


FIGURE 3-12. EFFECTS OF NORMAL TRACK MAINTENANCE OPERATIONS ON CALCULATED RNT, TANGENT TRACK TEST SECTION

The plot of "after surfacing" (SUR) shows some loss in RNT and accentuation of existing variations with distance along the section. Some of this change, however, may be related to the seasonal reduction in RNT as the track settled into cooler average temperatures of the autumn season. The variations are due, in part, to the 25-degree variation in rail temperature over the time period necessary to make these "after" readings.

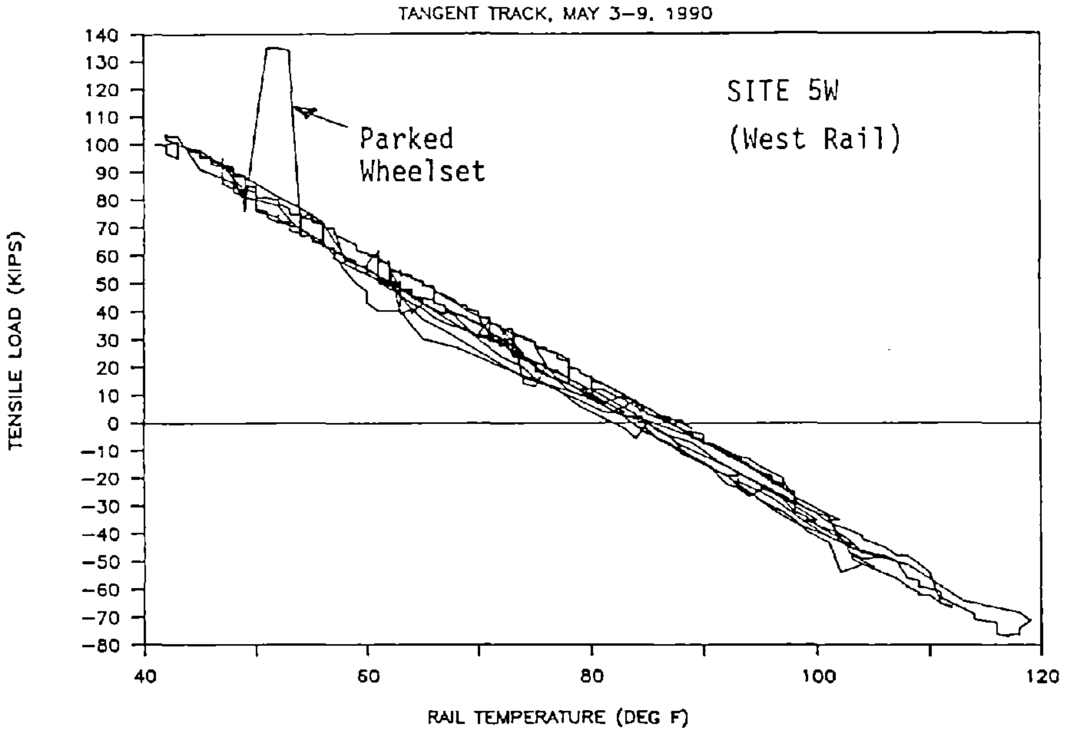
3.4 Effects of Daily Temperature Cycles

The installation of a remote monitoring system at the tangent track test section provided not only a day-to-day collection of rail load and temperature data, but an almost-instantaneous collection of data on roughly ten minute intervals. This provided "snapshots" of the track as it worked under solar heating and cooling cycles. Blocks of data stored by the monitor were accessed on 4 to 7-day intervals. These data were then imported into spread sheet files for analysis and plotting.

An example of rail longitudinal load versus rail temperature from Site 5, west and east rails, is given in Figure 3-13. Here data points for a 7-day period, 10-minute intervals, are plotted. Load versus temperature follows (more or less) the expected inverse linear relationship (increasing tensile load with decreasing temperature) with some minor deviations. The one major trapezoidal-shaped anomaly was caused by a train axle parked for about 30 minutes over the site.

Other sites in the test section were not as well-behaved in the sense of following the expected load/temperature curve. In Figure 3-14, plots of load versus temperature from Site 2 show a reasonably linear relationship for the first three days (May 3-5, 1990), followed by three decidedly non-linear morning heating cycles (May 6-8). It is instructive to look at the prevailing weather conditions (an average for Atlanta and Chattanooga) for this 7-day period, as shown in Table 3-1.

During the first three days of this period, the rails cycled through a temperature range (ΔT) of less than 40 degrees in partly cloudy, humid weather. A cold front then passed through the area, and rail temperatures dropped to as low as 38 degrees F overnight, followed by a sunny day with rail



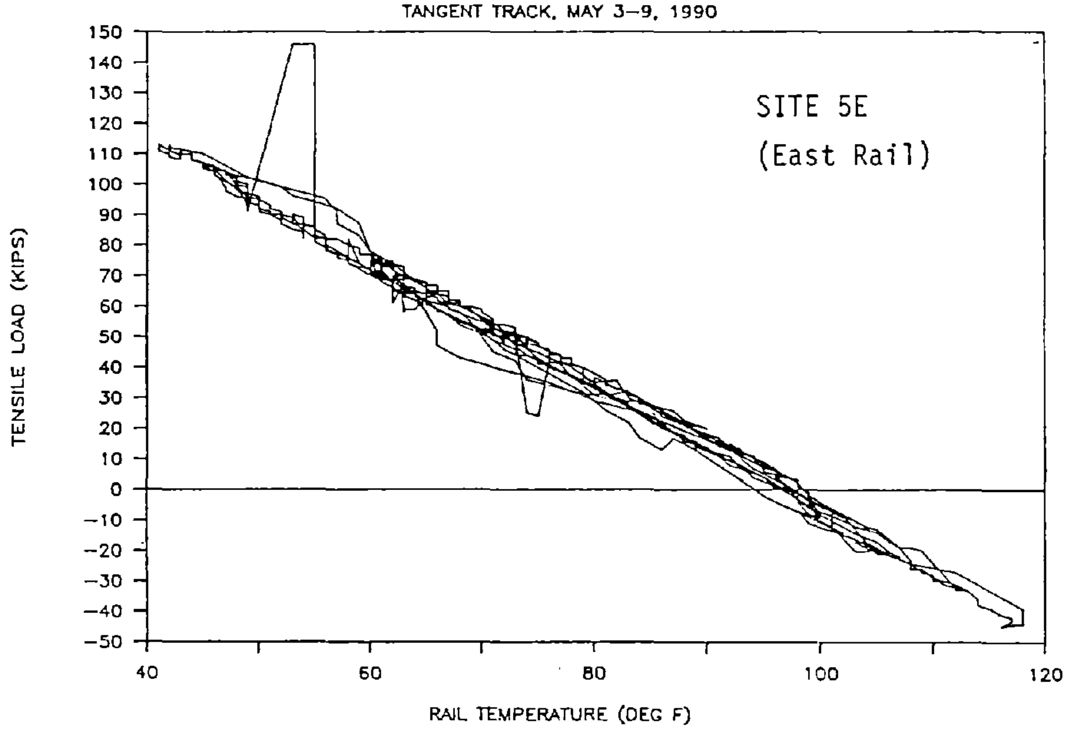


FIGURE 3-13. CYCLIC VARIATION OF RAIL LONGITUDINAL LOAD VERSUS RAIL TEMPERATURE OVER 7-DAY PERIOD, TANGENT TRACK SITE 5

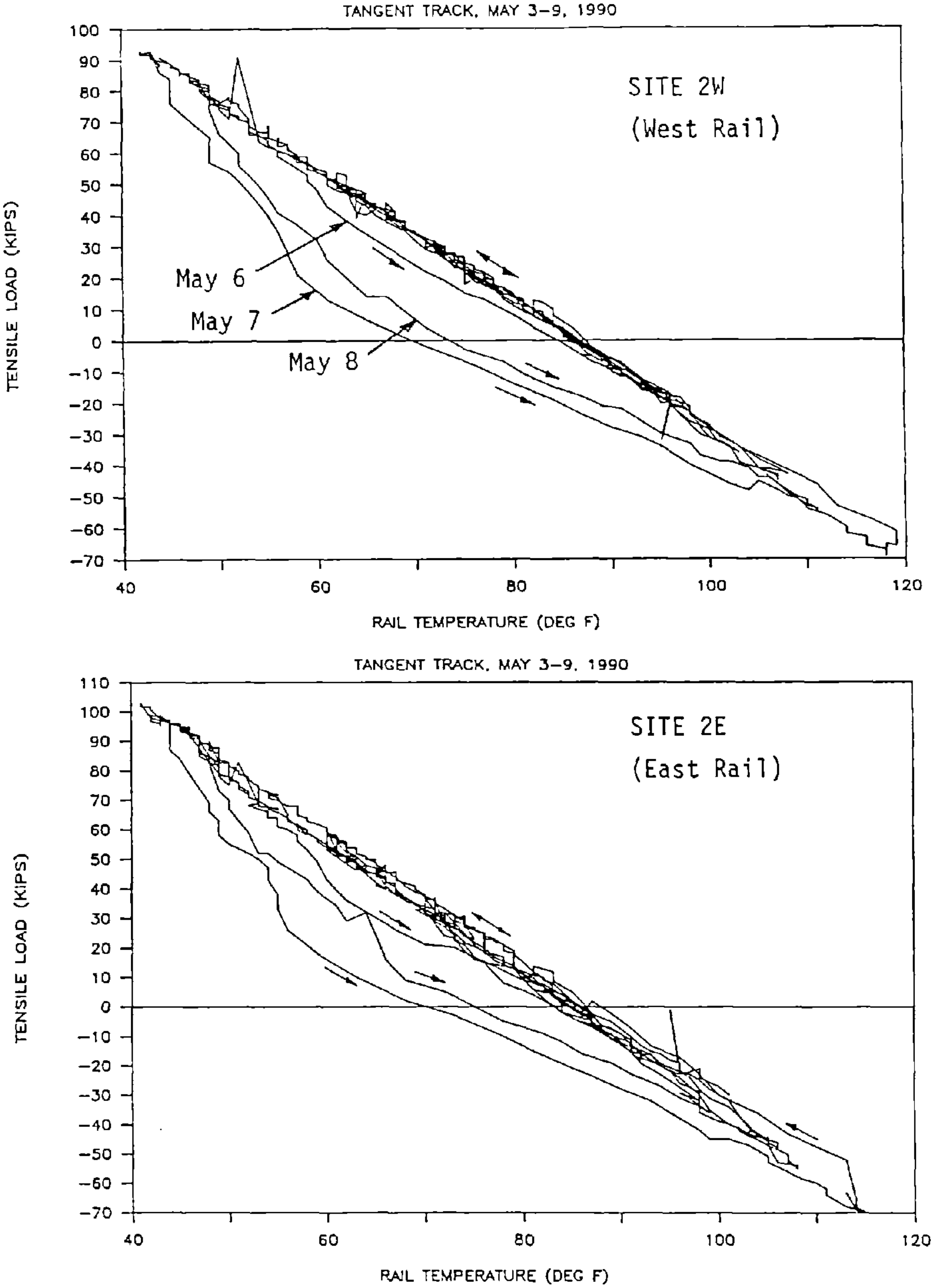


FIGURE 3-14. CYCLIC VARIATION OF RAIL LONGITUDINAL LOAD VERSUS RAIL TEMPERATURE OVER 7-DAY PERIOD, TANGENT TRACK SITE 2

TABLE 3-1. WEATHER CONDITIONS DURING SEVEN-DAY MEASUREMENT PERIOD

Date	Temperature	Condition	Rain (in)
May 3	86/67	Partly cloudy	0
4	81/67	Partly cloudy	0
5	72/65	Mostly cloudy	0.39
6	68/45	Partly cloudy	0
7	74/45	Sunny	0
8	77/50	Cloudy	0
9	66/60	Mostly cloudy	0.59

temperatures in the 110 to 120 F range. This gave a one-day rail temperature change of 70 degrees or greater. Temperature cycles this large may have some effect on localized track longitudinal restraint, but the effects of local sunlight and shade (even passing clouds) are probably of greater importance.

The load/temperature "hysteresis loops", as seen in Figure 3-14, are consistent to a particular location (site): a track location that produces a counter-clockwise loop one day will produce a similarly oriented loop on subsequent days when similar weather conditions exist. The loops are similar for both rails of the given site. However, moving from site to site, the loops appear to change direction (counter-clockwise to clockwise) on a cyclic basis. This is illustrated in Figures 3-15 through 3-17, moving north along the west rail. It can be seen from these curves that, for any given site and under "normal" weather conditions, the RNT may be calculated from the measured rail stress and temperature within an accuracy band of about five degrees F. Given the weather conditions that prevailed on May 7 and 8, 1990, however, calculation of RNT can be in error by 10 degrees F or more.

A look at rail longitudinal load versus temperature behavior through the test section during the heating and cooling cycles can be instructive. This behavior on May 7, 1990 is shown in Figures 3-18 and 3-19, in which both load and temperature variations are plotted versus distance along the track at the given clock time. These are instantaneous "time slices" of track load

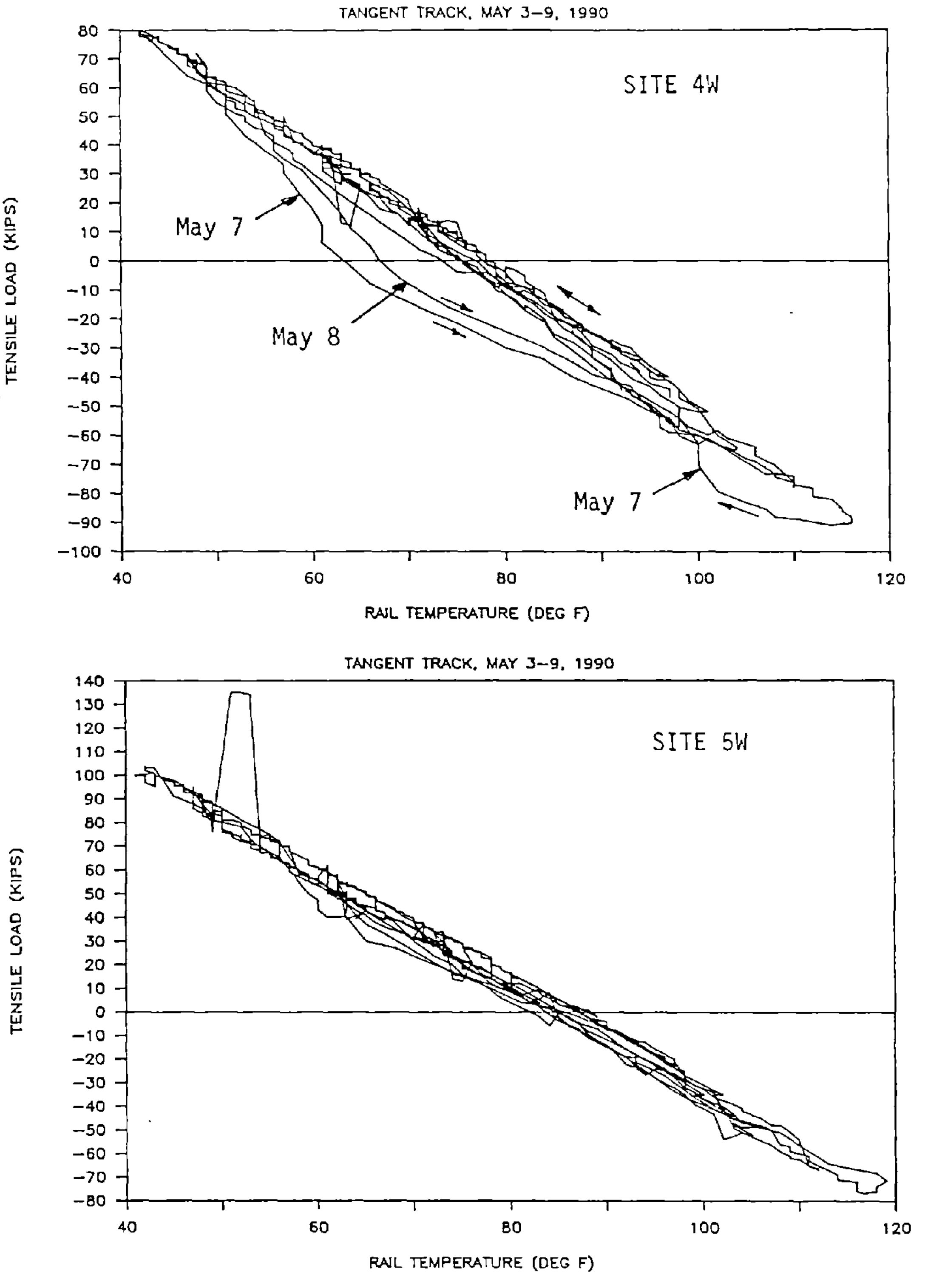


FIGURE 3-15. CYCLIC VARIATION OF RAIL LONGITUDINAL LOAD VERSUS RAIL TEMPERATURE OVER 7-DAY PERIOD, WEST RAIL SITES 4 & 5

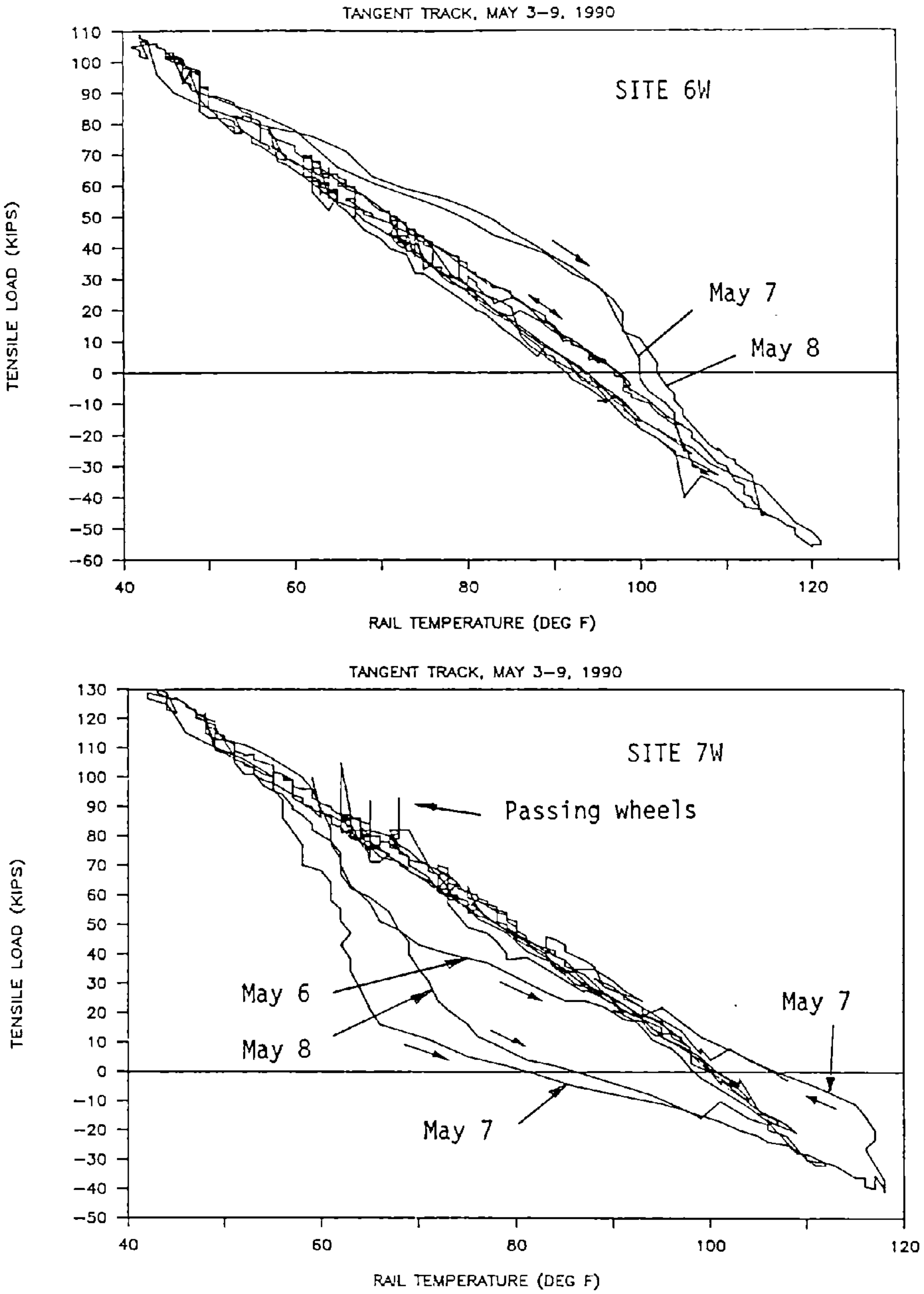


FIGURE 3-16. CYCLIC VARIATION OF RAIL LONGITUDINAL LOAD VERSUS RAIL TEMPERATURE OVER 7-DAY PERIOD, WEST RAIL SITES 6 & 7

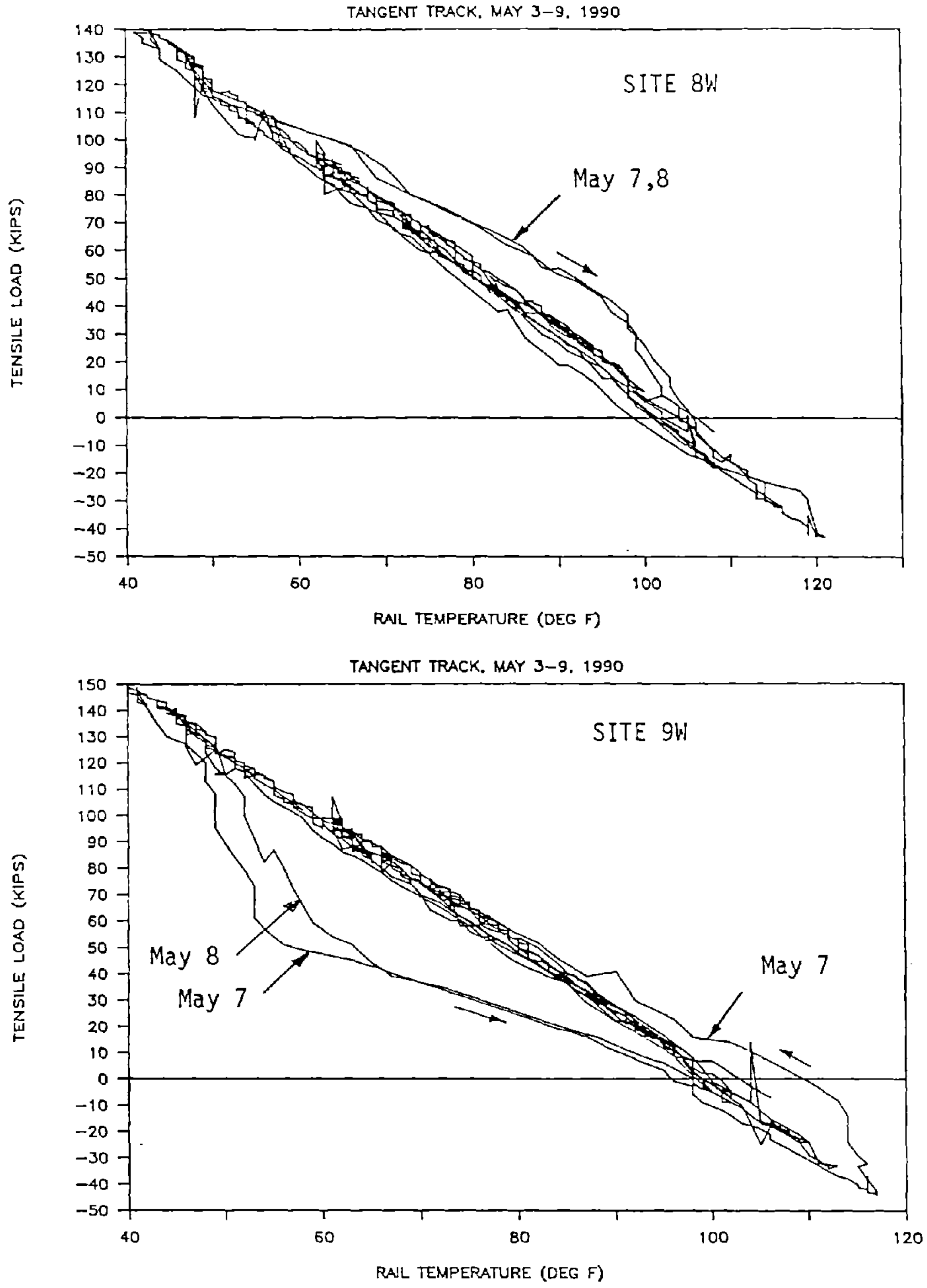
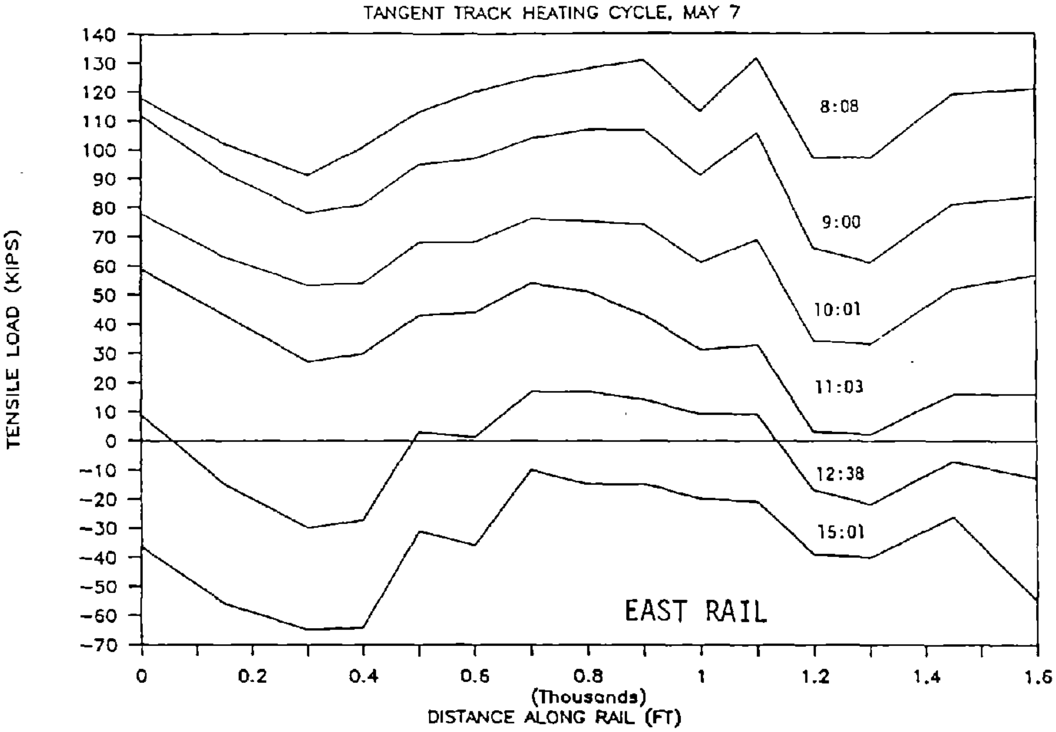


FIGURE 3-17. CYCLIC VARIATION OF RAIL LONGITUDINAL LOAD VERSUS RAIL TEMPERATURE OVER 7-DAY PERIOD, WEST RAIL SITES 8 & 9



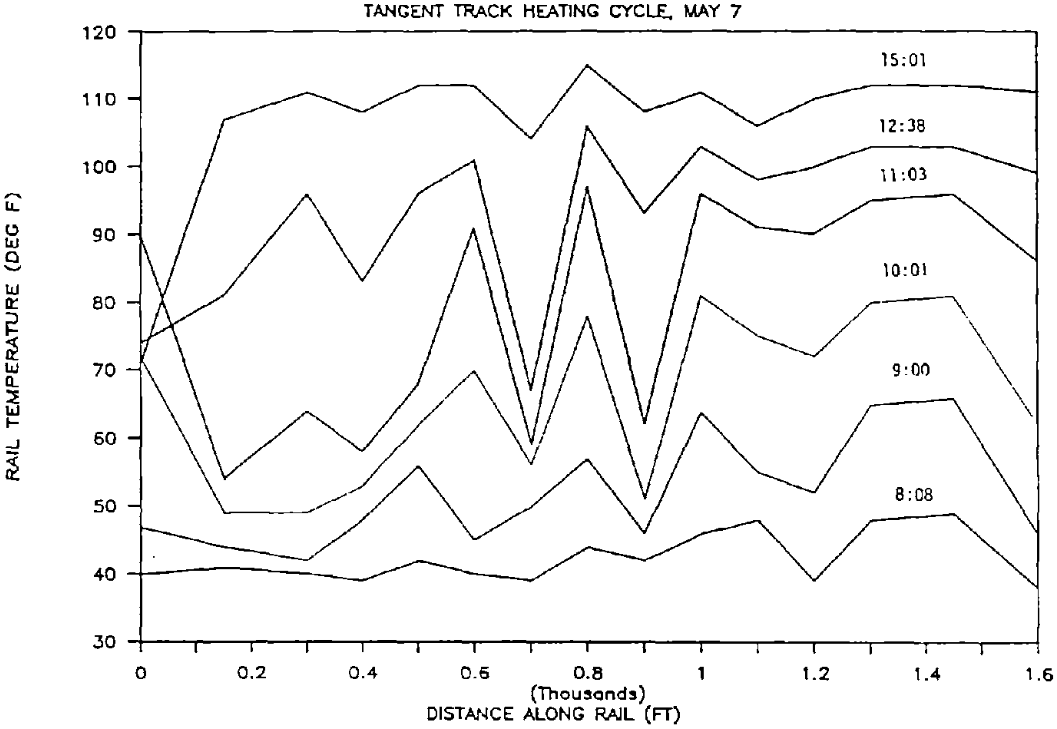
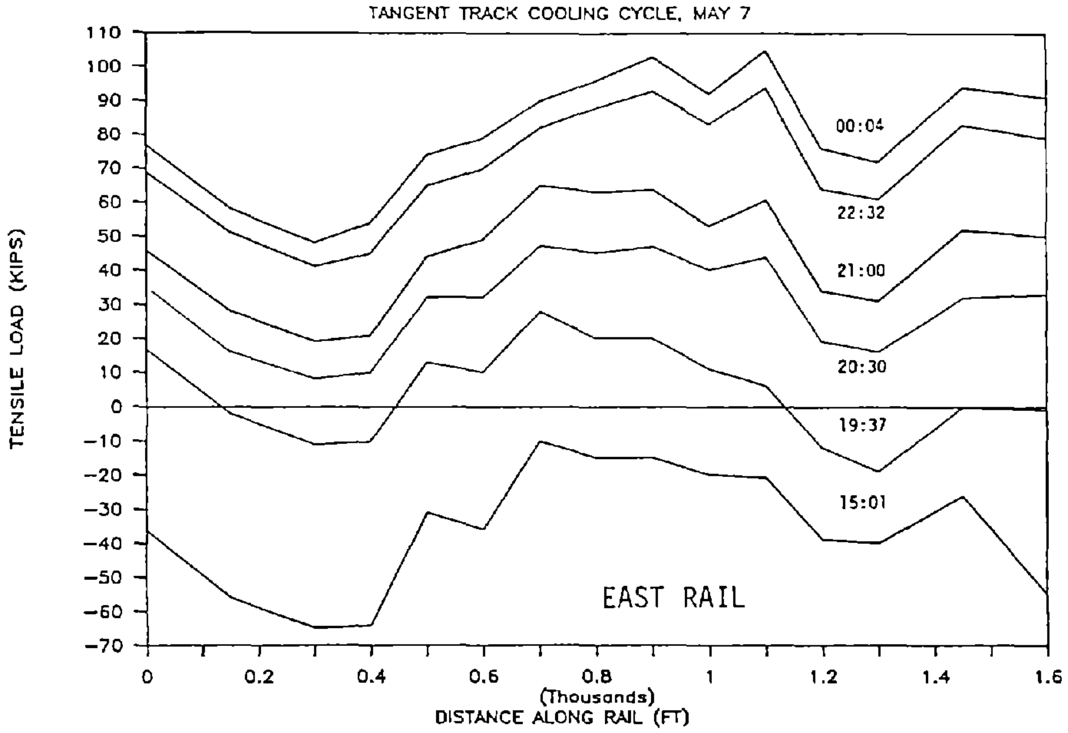


FIGURE 3-18. VARIATION OF RAIL LONGITUDINAL LOAD VERSUS DISTANCE DURING MORNING SOLAR HEATING CYCLE, MAY 7, 1990



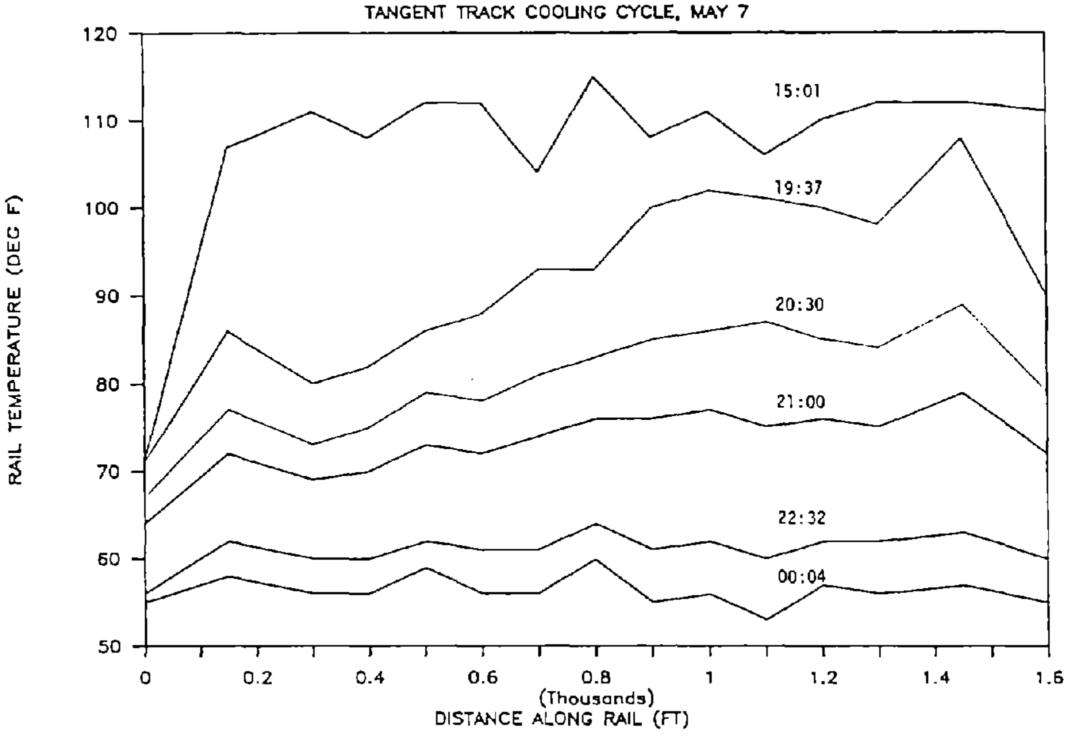


FIGURE 3-19. VARIATION OF RAIL LONGITUDINAL LOAD VERSUS DISTANCE DURING EVENING COOLING CYCLE, MAY 7, 1990

behavior. The heating cycle, Figure 3-18, started at 8 a.m. with stable rail temperatures in the low to mid-40s. Significant local temperature variations were then developed along the track as direct sunlight hit the rail at certain sites, while adjacent sites remained in shade. This is particularly evident at Sites 6 (600 ft) and 8 (800 ft), in direct sunlight from 10 a.m. on, compared with Sites 7 (700 ft) and 9 (900 ft), in shade until after noon. Note that Site 1 (0 ft) was in direct sunlight from before 10 a.m. until about noon, and then went into the shadow of the overpass. Shade conditions at the tangent section are described in Table 3-2.

In the subsequent cooling cycle, Figure 3-19, the lower half of the test section (Sites 1 through 8, 0 to 800 ft) fell into the shade of brush on the west side of the track and therefore cooled relatively quickly. The effects of shade can be seen in the temperature plots: tall brush on the west side near Site 13 (the 1300-ft point), for example, with direct sunlight on Site 14 (1450 ft), then a tree and tall brush near Site 15 (1600 ft). By midnight, stable temperatures in the mid-50s were measured, and the characteristic (stable) test section load curve was again established.

The plots in Figures 3-18 and 3-19, when compared with the load versus temperature plots of Figures 3-15 to 3-17, show that the counter-clockwise loops are associated with discretely shaded sites (such as Sites 7 and 9, for example), while the clockwise loops are associated with sunlit locations (such as Sites 6 and 8). In these cases where a site temperature is substantially different from the average rail temperature, the longitudinal load is transferred through the site, but the temperature either lags the average in the shade or leads the average in a patch of direct sunlight. In either case, an erroneous RNT value would be calculated from the two real measured variables.

3.5 Track Dimensional Stability

To monitor track position over the duration of the RNT test program, surveyor's benchmarks were set in beside each of the instrumented track sites. An auger was used to bore holes about three feet deep. A 4-inch diameter plastic pipe was then set in the hole, which was filled with concrete. A 1/2-inch diameter steel rod was embedded in concrete inside the pipe, and an "X"

TABLE 3-2. TANGENT TRACK SECTION SHADE DESCRIPTION

Site	West Side of Track	East Side of Track
1	Shade of overpass, high brush[a].	Overpass angles slightly south of east; site in sun in summer early a.m. hours.
2	Brush (sumac, etc.) high on bank.	Tall, dense pine trees[b].
3	Tall deciduous trees directly west, otherwise brush high on embankment.	Tall pines directly east, can be a bit of gap higher up ~5° S.
4	Pine and deciduous (~20 ft tall) on top of bank.	Pines, but sun can peek through lower branches and trunks[b].
5	Short (~15 ft) deciduous on top of bank.	Tall (~30 ft), thin deciduous trees with gaps sun can peek through.
6	Deciduous trees (~20 ft) and brush with plenty of gaps.	Mostly a gap, young tree and brush.
7	Low brush ~10 ft above rail.	Tall pine and deciduous trees clumped, with gap ~5° N.[c]
8	Thick brush 10-15 ft above rail.	Tall, full deciduous trees ~5° S, shades in mid-August sun to 10-10:30 a.m.
9	Low brush.	Fat, tall pine directly opposite, August sun climbs along south edge, where there is low brush.

Notes: a -- Track in deep cut at Site 1.
b -- Just coming out of shade at noon (8-14-90).
c -- Still in shade at noon (8-14-90).

TABLE 3-2. TANGENT TRACK SECTION SHADE DESCRIPTION

Site	West Side of Track	East Side of Track
10	Low brush, head high.	Brush, two small deciduous trees.
11	Low weeds (out of cut).	Low brush, small tree.
12	Tall brush 10-12 ft above rail.	Two small deciduous trees, ±5°, with gap between.
13	Scattered tall brush.	Brush.
14	Short brush and weeds.	Tall brush, short trees.
15	Bushy cherry trees ~15 ft tall.	Large deciduous tree ~5° N, 20-ft pine ~5° S, brush and small trees in gap.

cut in the top of the rod with a hacksaw. This provided a stable base, a target for sighting from the adjacent benchmark, and a vertical mark for setting up the theodolite. The benchmarks were set into the ditch on the west side of the tangent track at distances ranging from 113 to 163 inches from the west rail. Space constraints and vegetation in the cut made this test section difficult to survey.

The survey, after setup of the theodolite, consisted of first sighting the target on the next benchmark, then swinging the theodolite 90 degrees and sighting on the rail. A punch mark was made on the rail web as a reference. On subsequent surveys, movement of the punch marks, east and west rails, relative to the 90-degree position provided a measure of rail longitudinal movement. Horizontal distance was measured with a tape from the benchmark to the west rail base, and "gauge" was measured with the tape from outside west to inside east rail bases.

At the curved track, benchmarks were set evenly from 190 to 196 inches from the east (low) rail, and at an even height (about 3 ft) above the ground. The surveying procedure was the same, except a swing of 93 degrees was used in the 6-degree curve (and 91 degrees at Sites 14 and 15, in the spiral) to compensate for track curvature. This test section, with no significant obstructions, could be surveyed in half the time required at the tangent site. Just prior to the final survey in August 1990, CSX pulled the old rail strings close to the ballast section for future retrieval by the rail train. In the process, benchmarks at Sites 5 and 8 were knocked over, and benchmarks at Sites 6, 7, 9 and 10 were significantly scraped at the base in dragging the rail string. We do not know if these last four benchmarks were moved in the process.

Changes in rail position at the tangent section over an 18-month time period are given in Tables 3-3 through 3-5. One benchmark (Site 3) had been damaged during August 1989 by track maintenance equipment. The benchmark at Site 3 was again moved laterally during the trenching for the RNT remote monitor cable installation in April 1990. Measurements at Site 2 based on this benchmark were geometrically corrected according to the new position.

In general, the tangent track section has been stable over the 20-month period. Lateral track position at most of the sites, Table 3-3, has remained within 1/2 inch of its original position. The largest deviation is

TABLE 3-3. LONG-TERM STABILITY ASSESSMENT OF CSX WOOD-TIE TRACK, TANGENT TEST SECTION, MILEPOST 406.8, BOLIVAR, GA -- LATERAL TRACK POSITION (BENCHMARK TO WEST RAIL BASE)

Site	Start	Change in Position from Start (inch)			
No.	12-20-88	3-13-89	2-13-90	4-09-90	8-13-90
1	119-7/8	-1/8	+1/4	+1/8	+1/16
2	115-1/2	+1/8	0	0	-1/16
3	113-5/8	-1/16	+5-7/8[a]	+2-13/16[b]	+2-7/8
4	118-3/8	-1/4	-1/4	-5/8	-13/16
5	126-9/16	-5/16	-1/16	-1/8	-1/16
6	162-5/8	0	+1/8	+5/16	+3/8
7	151-9/16	-3/16	-1/8	+5/16	+3/8
8	148	+1/8	+1/16	0	+5/16
9	136-1/2	-3/8	-1/4	-1/4	-3/16
10	130-1/2	-3/8	-3/8	-1/2	-5/16
11	124	-3/4	0	-9/16	-1/2
12	126-9/16	+1/16	+5/16	+5/16	+7/16
13	138-1/8	-1/8	+1/4	+1/8	+3/8
14	138-3/16	0	+3/16	0	+1[c]
15	124	0	+3/8	+3/16	+5/16

Note a: Benchmark #3 pushed outward by track maintenance equipment.
b: Benchmark #3 moved again during cable trenching.
c: Doubled-checked -- no visual sign of line error.

ΔY = west rail lateral movement (+ is west rail moved east).

Rail Temps.: 12-20-88 -- 69-71 F, Sites 1-5; 53-55 F, Sites 6-15

3-13-89 -- from 61 F at Site 1 to 91 F at Site 15

2-13-90 -- 65 F at Site 15 to 91 F at Site 6 to 81 F at Site 1

4-09-90 -- 75-80 F, Sites 15-10); to 103 F, Sites 9-1)

8-13-90 -- 70 to 80 F

TABLE 3-4. LONG-TERM STABILITY ASSESSMENT OF CSX WOOD-TIE TRACK, TANGENT TEST SECTION, MILEPOST 406.8, BOLIVAR, GA -- TRACK GAUGE (WEST RAIL OUTER BASE TO EAST RAIL BASE)

Site	Start	Change in Gauge[a] from Start (inch)			
No.	12-20-88	3-13-89	2-13-90	4-09-90	8-13-90
1	59-7/8	+1/16	0	-1/16	-1/8
2	59-15/16	+1/16	+1/16	-1/16	-1/16
3	59-7/8	-1/16	0	-1/16	-1/16
4	59-7/8	-1/16	0	-1/16	0
5	59-13/16	0	+1/16	-1/16	0
6	59-7/8	0	0	0	0
7	59-3/4	0	0	0	+1/8
8	59-13/16	-1/16	+1/16	0	0
9	59-13/16	0	+1/16	0	0
10	59-13/16	0	+1/16	0	0
11	59-3/4	0	+1/8	+1/16	+1/8
12	59-7/8	+1/16	+1/8	+1/8	+1/16
13	59-7/8	+1/16	0	+1/16	+1/16
14	59-15/16	-1/16	+1/16	0	-1/16
15	59-13/16	0	+1/16	0	-1/16

Note a: Standard gauge defined as 56-1/2 + 3-5/16 = 59-13/16, assuming no gauge-face wear, 1:40 cant angle.

ΔG = change in "gauge" (rail outer base to opposite inner base).

TABLE 3-5. LONG-TERM STABILITY ASSESSMENT OF CSX WOOD-TIE TRACK, TANGENT TEST SECTION, MILEPOST 406.8, BOLIVAR, GA -- LONGITUDINAL RAIL POSITION (MOVEMENT OF PUNCH MARK)

Site	Change in Position from Start[a] (inch)					
	2-13-90		4-09-90		8-13-90	
No.	West	East	West	East	West	East
1	-1/8	+3/16	+1/8	+3/8	+5/16	+21/32
2	-15/32	-5/32	-9/32	-1/32	-1/4	+1/32
3	b	b	b	b	b	b
4	-3/16	+5/32	-1/2	-9/32	-17/32	-9/32
5	-11/16	-13/32	-7/32	+1/16	-1/8	+1/8
6	-3/8	-1/16	-13/32	-1/32	-1/8	+3/16
7	-17/32	-1/4	-3/8	-1/16	-3/16	0
8	-15/32	-1/4	-7/16	-5/32	-3/16	+1/32
9	-9/16	-1/4	-3/8	+3/16	-15/32	-1/8
10	-15/32	-5/32	-3/8	-1/16	-7/16	-1/8
11	-15/32	-3/16	-7/16	-3/32	-3/32	+3/16
12	-13/32	-3/32	-5/32	+1/8	-7/16	-1/16
13	+3/32	+21/32	-1/16	+3/16	-7/16	-1/8
14	-1/2	-3/16	-1/4	+1/32	-1/2	-1/8
15	-1/8	+5/32	-7/32	+1/16	-3/8	-1/16

Notes a: Use survey of 3-13-89 as start to avoid swing angle discrepancies in survey of 12-20-88.

b: Damaged benchmark (swing angle at Site 2 compensated).

ΔX = rail longitudinal movement (+ defined as rail moving north, upgrade-- crest near Site 12).

one inch at Site 14, but there is no visual evidence of a line error between Sites 13 and 15. Track "gauge" -- at the rail base, Table 3-4 -- has not increased by more than 1/8 inch during this period. Longitudinal position of the rail in Table 3-5 has changed by as much as 21/32 inch, mostly movement south (downgrade) between Sites 2 and 12, north (also downgrade) between Sites 13 and 15, and north near Site 1. Southbound is the direction of loaded unit trains. No rail repairs were reported for this period that would account for anomalous rail movement. Engine burns over Site 10W were welded and ground in February or March of 1990.

Changes in rail position at the curved section over a 17-month time period are given in Tables 3-6 through 3-8. Change in track lateral position over this period, Table 3-6, has remained within 1/2 inch. (Unfortunately, we did not survey the track during the coldest ambient temperatures in mid-December of 1989.) Track "gauge", Table 3-7, has changed by no more than 3/16 inch. Rail longitudinal movement in Table 3-8 is predominantly positive (upgrade) through Site 10. Beyond this point, negative (downgrade) movement is seen. In the most recent survey (August 13, 1990), a rather strange 1-3/8 inch movement downgrade was measured at Site 15, near the spiral-tangent point. Track maintenance people at Manchester said that no trackwork (rail welds, etc.) had been performed on this curve since last September. No damage to the benchmark was noted.

One of the problems with the survey method is the time required and the changes in rail temperature that occur. Temperature changes up to 30 F were noted at both tangent and curved track sections by the time the survey could be completed. Two of the surveys, in fact, were completed over a two-day period. In addition, revenue trains could pass in mid-survey. For example, during the tangent-track survey of August 13, 1990, Sites 1 through 10 were completed before loss of sunlight. One northbound empty unit train and two southbound loaded unit trains passed. The following morning, the survey of Sites 11 through 15 was completed, during which another southbound unit train passed. These factors have indeterminant effects on survey measurement accuracies.

TABLE 3-6. LONG-TERM STABILITY ASSESSMENT OF CSX WOOD-TIE TRACK, CURVED TEST SECTION, MILEPOST 785.1, MANCHESTER, GA -- LATERAL TRACK POSITION (BENCHMARK TO LOW RAIL BASE)

Site No.	Start 3-14 89	Change in Position from Start (inch)		
		2-14-90	4-10-90	8-13-90
1	189-7/8	-3/16	-3/16	-3/16
2	190-7/16	-3/16	-1/8	-3/16
3	190-7/8	-3/16	-1/4	-3/16
4	191-5/8	-3/16	-1/4	-3/16
5	193-7/8	-3/8	-3/8	[b]
6	192-3/16	+1/4	+1/8	+1/4[c]
7	195-3/8	-1/4	-5/16	+1/2[c]
8	191-9/16	-1/8	-3/8	[b]
9	195-11/16	-3/8	-7/16	0[c]
10	190-3/4	-5/16	-3/8	-1/16[c]
11	191-13/16[a]	-5/16	-1/4	-3/16
12	194	-3/16	-1/4	-1/8
13	191-7/16	-3/8	-7/16	-1/2
14	193-15/16	-1/8	-1/16	-1/8
15	196-1/2	+3/16	-7/16	+1/2

Note a: Original reading 192-13/16, assumed misread by 1 inch (no visual sign of 1-inch line error).

b: Benchmark damaged in retrieving old rail string.

c: Base of benchmark noticeably scraped by dragging rail string.

ΔY = east rail lateral movement (+ is low rail moved west).

High rail is west rail, low rail is east rail.

Rail Temps: 3-14-89 -- 95 to 100 F

2-14-90 -- 61 to 73 F, Sites 1-5; 85 to 90 F, Sites 6-15

4-10-90 -- 69 to 72 F

8-13-90 -- 80 to 100 F, Sites 1-15

TABLE 3-7. LONG-TERM STABILITY ASSESSMENT OF CSX WOOD-TIE TRACK, CURVED TEST SECTION, MILEPOST 785.1, MANCHESTER, GA -- TRACK GAUGE (LOW RAIL OUTER BASE TO HIGH RAIL BASE)

Site	Start	Change in Gauge[a] from Start (inch)		
No.	3-14-89	2-14-90	4-10-90	8-13-90
1	59-11/16	+1/16	+1/16	+1/16
2	59-7/8	0	0	0
3	59-11/16	+1/16	0	0
4	59-13/16	0	-1/16	0
5	59-5/8	+1/16	0	0
6	60	0	0	0
7	59-7/8	0	0	0
8	59-11/16	+1/16	0	+1/16
9	59-11/16	0	-1/16	-3/16
10	59-13/16	-1/16	-1/16	-1/16
11	59-3/4	0	-1/16	0
12	59-11/16	+1/16	+1/16	+1/16
13	59-13/16	+1/16	+1/16	0
14	59-13/16	-1/16	-1/16	0
15	59-15/16	-1/16	-1/16	-1/16

Note a: Standard gauge defined as 56-1/2 + 3-5/16 = 59-13/16, assuming no gauge-face wear, 1:40 cant angle.

ΔG = change in "gauge" (rail outer base to opposite inner base).

TABLE 3-8. LONG-TERM STABILITY ASSESSMENT OF CSX WOOD-TIE TRACK, CURVED TEST SECTION, MILEPOST 785.1, MANCHESTER, GA -- LONGITUDINAL RAIL POSITION (MOVEMENT OF PUNCH MARK)

Site	Change in Position from Start (inch)					
	2-14-90		4-10-90		8-13-90	
No.	High	Low	High	Low	High	Low
1	+9/16	+3/32	+13/16	+3/8	+11/16	+1/4
2	+11/32	-1/16	+5/8	+1/4	+17/32	+7/32
3	+1/8	-1/4	-7/32	-19/32	+13/32	+5/32
4	+1/8	-5/16	+7/16	+3/32	+1/2	+5/32
5	0	-11/32	+5/8	+5/16	a	a
6	-1/4	-1/2	+1/8	-1/8	-5/32	-1/4
7	-7/32	-13/32	+5/32	-3/32	+17/32	+11/32
8	-7/32	-3/8	+5/16	+1/16	a	a
9	-1/8	-5/16	+1/32	-3/16	+3/32	0
10	-5/32	-7/16	+5/32	-1/8	+9/32	+3/16
11	-7/32	-7/16	-1/16	-11/32	-3/16	-1/4
12	-3/8	-1/2	-11/32	-1/2	-11/32	-5/16
13	-1/4	-5/16	-7/32	-3/8	-17/32	-15/32
14	-1/4	-11/32	-1/4	-11/32	-1/4	-1/4
15	-1/2	-5/8	-1/2	-5/8	-1-3/8[b]	-1-3/8[b]

Note a: Benchmark damaged in retrieving old rail string.
b: Double-checked at 91-deg swing; no sign of benchmark damage.

ΔX = rail longitudinal movement (+ defined as rail moving north, upgrade).

High rail is west rail, low rail is east rail.

4.0 CONCLUSIONS

4.1 Measurement Methodology

In this report, the development of a method for measuring rail longitudinal load and temperature, and from these the calculation of rail neutral temperature (RNT), has been described. The method was first explored in laboratory tests, then used extensively in tests at the Transportation Test Center near Pueblo, Colorado. This was followed by a 27-month test to monitor the long-term stability of RNT in the Northeast Corridor concrete-tie track. The same basic measurement technique was used in this study of RNT on CSX wood-tie track.

Estimates of measurement accuracy have been made as part of this study. Bridge strain is measured using a Vishay strain indicator, set to an equivalent 10 psi per count, based on the rail sectional area. This setting utilizes nominal rail steel parameters. With the possible range of these parameters, the value per count can range from 9.3 to 10.1 psi. The strain indicator, calibrated in Battelle's instrument laboratory, has a resolution of ±1 count (±10 psi). When including the positioning tolerances and minor thermal effects on strain gages, the circuit readings have a probable tolerance band of about 10 percent.

While the measurement of rail longitudinal load and temperature is straightforward, the subsequent calculation of RNT is not. Since the rail is not fully constrained, the circuit stress "gain" (psi/deg F) is less than the nominal value. From our observations, this gain varies from site to site with variations in rail restraint, and may vary with time (traffic) and season as well. In addition to these gain variations, site thermal effects due to localized sunshine or shade can introduce serious errors in calculated RNT.

The measurement technique has proven itself to be robust in this CSX study. Over a 20-month period at the tangent track section, one site (out of 30) was badly damaged during tie renewal, but the gages themselves remained intact and strains could be measured using clip leads. A second site was destroyed when rail surface defects over the site were repaired by welding and grinding. A thermocouple at a third site was lost, but temperature was measured using the thermocouple leads of the digital thermometer on the rail head. Over a 17-month period at the curved track section, one site (out of 30) developed a partial short in the connector which was repaired, and two thermocouples were lost. Again, temperature was measured off the rail head using the digital thermometer.

One major problem with the measurement technique is the need to establish the rail stress-free state. This can be done most directly by cutting the rail fairly close to the circuit (within about 10 ft), with the rail free of anchors between the circuit and the cut. The bridge circuit zero reference reading is then established, and the rail rewelded. The further the distance between circuit and cut, the greater the uncertainty in this zero reference. This process requires extensive support by the railroad. As an alternative, the gages can be applied to the rail before the rail is put into the track. Strain measurements over a 24-hour temperature cycle can then be used (on a long rail string) to estimate the zero reading as the rail expands and contracts on the ballast shoulder. However, gages may then be damaged in the rail laying operations.

The passive measurement system used in this study has certain inherent advantages: for one, it is immune to electrical problems, such as lightning strikes, and will not short the track signal circuits. On the other hand, the technique is slow and labor-intensive. The effects of rapid change in rail temperature cannot be assessed, since a minimum of 30 minutes is needed to service a 30-site array. The advantage of a remote monitoring system is well demonstrated.

4.2 RNT Study Results

Effects of Rail Destress. As part of the site installation and calibration process, the rails were destressed by removing rail anchors and cutting at several places within the test section. Rails were then rewelded and the rail anchors refastened. Throughout most of the tangent section, the initial RNT of the east rail was found to be as much as 10 degrees higher than the west rail. New rail had been laid through this section in September 1988.

The destress process resulted in east and west-rail RNT within a few degrees of one another. The new RNT values increased from just under 70 F at Site 1 (at the spiral/tangent point) to over 90 F at Site 14. At rewelding, the rail was artificially heated between Sites 12 and 15, but not at the lower end of the section.

In the curved track section, a fairly uniform RNT between 65 and 70 degrees F existed through most of the curve, primarily due to a number of existing rail joints and the ambient temperature at that time. RNT rose beyond Site 12 to maxima between 75 and 80 F due to the welding of two rail joints a week earlier just beyond Site 15. After the rail destress, rewelding was done at naturally high rail temperatures, and a fairly uniform RNT between 100 and 110 F was achieved through the body of the curve. At either end of the curve, RNT values tapered off to somewhat lower values as a transition to the non-destressed track.

From these two examples of rail destress, we see that uniformity in RNT can be achieved if the rail is free in relatively short lengths, as was the case on the curved track section. With longer rail strings (900 ft at the tangent section), significant variations in RNT can exist from one end to the other (over 20 degrees F in this example), depending on rail temperature and change in temperature at the time of welding. The change in temperature induces frictional hysteresis loads on the rail which are then locked in at the time rail anchors are reset. If both of the rails are not destressed at the same time, substantial differences in RNT, one rail to the other, can result.

Effects of Time/Tonnage and Season. Each of the instrumented track sections in the RNT study was monitored over approximately 1-1/2 years. In the tangent track section, several interesting trends were noted in values of calculated RNT:

- RNT seems to "track" the average seasonal temperature, increasing in value by as much as 10 degrees F in the summer. This probably is the result of the track structure settling mechanically into stable conditions related to average ambient temperatures.

- The test section average RNT has remained stable within the range of seasonal variation cited above.
- The east rail has assumed an RNT a few degrees higher than the west rail, similar to its state before destress.
- Differences between lower and higher-temperature RNT values for the same day indicate that the rail circuit "gains" used in the RNT calculations have changed, possibly due to changing rail support and anchoring conditions under traffic.

These trends are somewhat masked by localized sun/shade conditions. Average RNT values over the site have standard deviation values of 5 to 8 degrees F, due both to sun/shade variations and the change over the length of the section. Since the RNT recording intervals were infrequent, the tendency of RNT to lag seasonal temperatures by a month or two (a trend that was seen in NEC concrete-tie data [5]) could not be verified.

Within the curved track section, a less-pronounced seasonal effect on RNT could be seen. However, the major trend appears to be a steady loss in RNT with time and traffic. Test section average RNT values have declined from an initial 104 degrees F to the current (August 1990) 91 degrees F. Accounting again for sun/shade effects, RNT appears fairly uniform from one rail to the other, and is reasonably uniform through the body of the curve.

Effects of Track Maintenance. Tie renewal and surfacing operations were conducted through the tangent section during August 1989. Readings before and after tie renewal showed essentially no change in RNT. Due to a delay in surfacing the track, readings after surfacing were not obtained until October, about two months later. The apparent loss in RNT of up to 13 degrees F could be attributed in part to surfacing, but also to seasonally lower average temperatures.

No scheduled maintenance was performed through the curved track section. In September 1989, severe slack action on a southbound train pushed the track out of alignment near Site 4. The rails were cut (about one inch removed), the track realigned, and the rails then rewelded. This produced a short-lived increase in RNT from Sites 1 through 5, and a longer-lasting RNT "high spot" at Site 4.

Track Dimensional Stability. Survey measurements of rail lateral and longitudinal movements showed both tangent and curved track sections to be quite stable over the 1-1/2 year period. In the tangent section, rail lateral position at most sites remained within 1/2 inch of the original measurement. The largest deviations were -13/16 inch at Site 4, +1 inch at Site 14 (which is a 5/8-inch line error over 300 ft). Rail longitudinal movement (rail run) was modest: a maximum of 21/32 inch at Site 1 (the spiral-tangent point), and much less at most other sites. Track gauge change (at the rail base) was at most 1/8 inch.

On the curved track section, rail lateral position remained within 1/2 inch of its initial position over the test period. These measurements did not, however, include any extreme low temperatures when greater movement might have occurred. Maximum longitudinal movement of 17/32 inch was measured in the body of the curve. In the last survey (August 1990), a 1-3/8 inch movement downgrade was measured on both rails at Site 15 (near the spiral-tangent point). No visual clues were found to explain these readings. Track gauge change (at the rail base) was generally 1/16 inch or less, with one reading of 3/16 inch at Site 9.

4.3 Remote Monitoring System

A remote monitoring system was installed in April 1990 at the tangent track section under a separate SBIR contract. The last passive-system readings were obtained by Battelle from this section on April 9, 1990. Ten of the 15 rail modules (servicing both west and east rails) were operational by the last week in April, so that preliminary data could be assessed. By May 3, all 15 modules (30 rail circuits) were operational and "production" rail load and temperature data could be gathered.

The remote monitoring system allowed us, for the first time, to track changes in rail load and temperature on a 24-hour basis. "Time slices" of almost-simultaneous measurements over the length of the test section showed graphically the effects of different weather conditions and different sun and shade characteristics at the 15 instrumented sites. The resulting "hysteresis loops" in force versus temperature showed that at some sites substantial changes in load could occur with relatively little change in temperature, while at adjacent sites relatively smaller changes in load would occur for a given change in temperature.

Data taken on 10-minute intervals were stored in memory, along with the associated date and time. Once a week these data could be transferred by telephone to a spread-sheet file at Battelle for analysis and plotting. The system in concept and initial execution proved itself to be an invaluable research tool and a potentially useful track monitoring tool.

The remote monitoring system programming provides that if a rail-mounted module does not "call in" (respond on the communications line), a value of -999 is inserted for its load and temperature values at that clock date and time. During the first two weeks of operation, all 15 sites were operational, but it was noted that blocks of "-999" values were seen from Sites 1, 13, 14 and 15. The latter three, the most distant sites, were subject to low supply voltage and this was thought to be the cause of this problem. Occasionally data from all 15 sites were received at one given time, so that test section load and temperature changes could be tracked.

By the fourth week of operation, a progressive system failure could be noted. More than 24 hours of data were lost (-999 values) from Sites 7 through 13, starting on May 27, although occasional legitimate values from Sites 14 and 15 were still recorded. Data accessed on June 13 showed no values for Sites 11 through 15, but portions of data for Sites 7 through 10 were salvaged. By June 16, only Sites 1 through 6 were recording values. On June 18, SBIR contractor personnel attempted to diagnose the problem on-site, but were unsuccessful when one of the main computer boards failed under a low-resistance power drain. This board was during the August 14 survey, but it was not possible to diagnose the system communications problems on-site. Currently, none of the rail-mounted modules can be accessed by the main computer. Without the benefit of a complete diagnosis or "post-mortem", we must assume that component-level degradation or failure has occurred at the encapsulated rail-mounted modules.

5.0 RECOMMENDATIONS

Long-term rail neutral temperature tests have been conducted on CSX for 20 months at the tangent-track site (Bolivar, Georgia), and for 17 months at the curved track site (Manchester, Georgia). Currently both test sections are "operational". All curved-track circuits are working, and only two out of 15 survey benchmarks have sustained damage. We assume no damage has occurred to tangent-track circuits, although the remote monitoring system precludes checking the strain gage circuits by hand, and is itself currently not operational. One tangent section benchmark has been damaged.

Battelle recommends that the FRA extend the time period of RNT experiments at these two sites to monitor track degradation effects over an additional year. As more tonnage is accumulated through these sections, both scheduled and unscheduled maintenance will occur. The effects of these events on RNT and track stability will be of much interest to both the railroad and research communities.

The remote monitoring system installed has proven itself in concept to be a remarkable research tool, and potentially to be a valuable track monitoring tool, provided the current system problems can be identified and corrected. For the first several weeks after installation, the system provided consistent rail load and temperature data on 10-minute intervals that allowed us a better understanding of rail response under ambient heating and cooling cycles. The system has undergone some type of progressive failure in its rail module to main computer communications link. Battelle recommends that the FRA sponsor additional work to determine the cause of these problems and to upgrade the existing system for continued RNT monitoring over the next year.

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