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THE WEAR BEHAVIOR OF HIGH RAIL IN THE FIRST METALLURGY EXPERIMENT, 0 TO 135 MGT

FAST Facility for Accelerated Service Testing

TRANSPORTATION TEST CENTER
PUEBLO, COLORADO 81001

INTERIM REPORT

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16. Abstract

In the first rail metallurgy experiment, covering the period from September 1976 to September 1977, 135 million gross tons (MGT) of traffic were accumulated on the Facility for Accelerated Service Testing (FAST) track under two widely different lubrication regimes. The first regime of poor lubrication existed for the first 40-45 MGT while a second regime of generous lubrication followed through to the end of the first experiment.

This report presents wear results for the high rail only in FAST Sections 03 and 13. In the poorly lubricated regime (a) chrome molybdenum (CrMo) and head-hardened (HH) rail exhibited the greatest resistance to gage face wear and head area loss, (b) high silicon (HiSi) and fully heat-treated (FHT) rail were significantly less resistant to gage face wear and head area loss although FHT rail exhibited somewhat better resistance to head height loss than did HH rail, (c) the gage face wear behavior was strongly dependent on equivalent carbon content, and (d) the 1:14 tie plate cant produced approximately 20% more gage face wear and head area loss, on the average, for all metallurgies than did either the 1:30 or 1:40 tie plate cants.

In the more generously lubricated regime, (a) a strong metallurgy:lubrication interaction occurred such that relative to standard rail all other metallurgies behaved more alike and (b) the strength of the tie plate cant effect diminished although the 1:40 cant still produced the lowest gage face wear and head area loss.

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PREFACE

Data analysis/preparation for this Interim Report was provided by Dr. M.B. Hargrove, Manager, Office of Engineering Economics, Association of American Railroads, Washington D.C.; Dr. R.K. Steele, Manager of Metallurgy, Federal Railroad Administration, Transportation Test Center, Pueblo, Colorado; Mr. F.S. Mitchell, Track Engineer/Analyst, Association of American Railroads, Transportation Test Center, Pueblo, Colorado; and Mr. R.E. Young, Research Analyst, H.H. Aerospace Co., Cambridge Massachusetts.

The authors wish to express their appreciation to Messrs. N. Parikh, W. Bagnuollo, S. Roberts, and Ms. B. Pearson of the AAR staff, and to Mr. J. Morris of the TSC staff, for their continued help in obtaining the data needed for analysis. In addition, a very enlightening review of the wear information by Mr. W. Pellini is gratefully acknowledged.

This Interim Report covers the period of the first rail metallurgy experiment, September 1976 through September 1977, which accumulated approximately 135 million gross tons of traffic.

Because software for the analysis of low rail profiles did not become available until early 1980, only the high rail behavior is presented in this report.

The report describes the test design, the materials tested, and the data analysis methods. Because of the high variability inherent in the profilometry measurement system and the vagaries of the automated data processing system used, the reliability of the conclusions is substantially reduced when the wear rates are low. The problems with measurement methodology are discussed extensively. Results are presented to show the influence of metallurgy, tie plate cant, curvature, position-in-curve, lubrication, and interactions thereof and how the statistical strength of conclusions is influenced by the variability of the measurement system.

This report has described the wear behavior of the high rail in the first rail metallurgy experiment in substantial depth. A preceding report, FAST/TTC/TN-80/04, has covered both the wear and defect behavior of the rail in the first and second rail metallurgy experiments in considerably less detail. In addition, a paper entitled "A Perspectival Review of Rail Behavior at the Facility for Accelerated Service Testing" has been presented at the 19th Annual Conference of Metallurgists, Halifax, Nova Scotia, 24-25 August 1980; this paper presents, in addition to information from the first and second experiments, preliminary results from the third experiment and compares rail behavior at FAST (both wear and fatigue behavior) with that elsewhere.

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ACRONYMS

AAR	Association of American Railroads
ANOVA	Analysis of Variance
AREA	American Railroad Engineering Association
BHN	Brinell Hardness Number
CCW	counterclockwise
CW	clockwise
CWR	continuous welded rail
FAST	Facility for Accelerated Service Testing
FM	Figure of Merit
IIT	Illinois Institute of Technology
MGT	million gross tons
OPGM	operator grand mean
TSC	Transportation Systems Center

ABBREVIATIONS AND METRIC CONVERSIONS

C	Carbon	Mo	Molybdenum
Cb	Columbium (Niobium)	P	Phosphorus
Cr	Chromium	S	Sulpher
CrMo	Chrome-Molybdenum rail	Si	Silicon
FHT	Fully Heat Treated rail	Std	Standard Carbon rail
HiSi	High Silicon rail	V	Vanadium
HH	Head Hardened rail	yr	year
Mn	Manganese	w/o	weight percent

°	degree	
%	percent	
cm	centimeter	
MGT	million gross tons	= 0.907 MGMg
1", in	inch	= 2.54 cm
1', ft	foot	= 0.305 m
1 yd	yard	= 0.914 m
1 mi	mile	= 1.609 km
1 mi/h	mile(s) per hour	= 1.609 km/h
1 lb	pound	= 0.454 kg
1 kip	kilopound	= 453.59 kg
1 ton		= 0.907 metric tons

EXECUTIVE SUMMARY

The first rail metallurgy experiment was conducted during the period between September 1976 and September 1977 in Sections 03 and 13 of the FAST loop. Approximately 135 million gross tons (MGT) of traffic were accumulated on the track. Five different metallurgies--standard (Std), high silicon (HiSi), fully heat-treated (FHT), chrome molybdenum (CrMo), and head hardened (HH)--in 132 or 136 lb/yd sections were tested in Section 03 (5° curve) on three different tie plate cants: 1:40, 1:30, and 1:14. Four different metallurgies--Std, HiSi, FHT, and HH--were tested in Sections 13 (4° curve) only on the 1:40 cant tie plate; all rail in Section 13 was 115 lb/yd. The FAST consist was made up of three to four 4-axle locomotives pulling an approximately 9,500-ton trailing load at speeds of 40-45 mi/h. Typically, 1 MGT per operating day was imposed on the track. Axle loads were near 33 tons. The wheel population changed gradually through this experiment, shifting from a predominance of class U wheels at the beginning of the experiment to a predominance of class C wheels at the end. In addition, the level of lubrication also changed throughout the test period from a condition of underlubrication to one of very generous lubrication at the end.

High rail wear behavior was determined from area, gage face width, and head height changes as measured by 1x tracing profilometers. Typically, the profilometers could repeat a given profile over extended periods of time no better than ± 0.02" on any dimension. This variability was sufficiently small, when the wear rates were high due to poor lubrication, to yield a rather robust assessment of metallurgy, tie plate cant, and position-in-curve effects. However, when the wear rate diminished in the generously lubricated regime, the strength of the analysis diminished substantially.

The results show that in the poorly lubricated regime:

- CrMo and HH rail exhibited the greatest resistance to gage face wear and head area loss.

- HiSi and FHT rail were significantly less resistant to gage face wear and head area loss, although FHT rail exhibited somewhat better resistance to head height loss than did HH rail.

- The gage face wear behavior was strongly dependent on equivalent carbon content such that in Std rail a 0.1 w/o (weight percent composition) reduction in equivalent carbon content could cause a 50% increase in wear rate.

- The 1:14 tie plate cant produced approximately 20% more gage face wear and head area loss, on the average, for all metallurgies than did either the 1:30 or 1:40 tie plate cants, although the 1:40 tie plate cant caused slightly more head height loss.

When lubrication improved, the wear behavior changed in a somewhat unexpected manner such that:

- A strong metallurgy:lubrication interaction was observed as manifest in a reduction in the wear resistance benefit of premium rails relative to Std rail; i.e., all metallurgies looked more alike.

- The strength of the tie plate cant effect diminished significantly, but the 1:40 cant still consistently produced the lowest gage face and head area loss.

- Position-in-curve effects altered their behavior from that observed in the more poorly lubricated regime.

Irrespective of the amount of lubrication, the rail wear in the 4° curve was less than that in the 5° curve--overall it was less by about 20%, which is consistent with a linear relationship between wear and curvature. However, this conclusion is somewhat confounded by the fact that the rail in the 4° curve was all of the 115 lb/yd rail section, while that in the 5° curve was of 132 lb/yd or 136 lb/yd rail sections.

The rail wear at FAST in the underlubricated regime has been observed to be substantially higher than that observed elsewhere in the US Railroad environment, including those operations where 100-ton cars are utilized. However, the FAST rail wear does appear to be consistent with that projected from Australian heavy unit train type operation. The FAST rail life projections for standard rail are in reasonable agreement with a modified AREA rail life prediction in the well-lubricated regime, but are in substantial disagreement with that prediction in the underlubricated regime.

Future wear tests, if they are to be accomplished with lubrication of the wheel rail interface, must utilize wear measurement methods which are substantially more accurate than the profilometry techniques utilized in this first rail metallurgy experiment. Explanations should be sought for the wide variation in the wear rates of Std rail and for the poorer-than-expected performance of FHT rail. The reason for variation in the effect of lubrication on different metallurgies also requires further study.

1.0 INTRODUCTION

Rail wear represents one of the major concerns of railroads in terms of material replacement costs. The introduction of heavy cars and in particular the operation of unit trains have increased the need for reduction in wear rates. The approaches which have gained general acceptance as means of reducing wear rate have been to (a) increase the hardness of rails either by heat-treating or alloying and (b) lubricate the wheel/rail interface either with in-track lubricators or with vehicle borne lubricators. There is some indication[1 2 3*] that harder more wear resistant wheels also improve rail wear behavior, although this has not been confirmed by the analysis and studies conducted at Illinois Institute of Technology (IIT)[4].

Considering only changes in the character of the rail itself, Marich[5] has noted that microstructure has a significant effect in that at the same hardness level, a fully pearlitic microstructure of the smallest possible interlamellar spacing has superior wear resistance over those of bainitic or tempered martensitic microstructure. Other analyses[6] have suggested that, at least for fatigue dominated wear processes, cyclic parameters such as the cyclic fracture strength and the cyclic work hardening behavior can have a significant influence on wear behavior.

Generally, the accepted philosophy has been to refine the pearlitic interlamellar spacing either by heat-treatment of the entire rail section or of the rail head alone by induction heating or flame hardening techniques. Refinements can also be obtained by the introduction of alloying additions such as chromium (Cr), manganese (Mn), vanadium (V), molybdenum (Mo), and/or columbium (Cb); these additions increase hardenability sufficiently to retard the pearlite nucleation and growth process upon cooling and permit the development of the desired refined structure. Heat treatment or alloying generally permits an increase in hardness to between 321 and 388 Brinell Hardness Number (BHN). However, some exploration is underway in the Soviet Union[7] into the development of a "super rail" that is expected to be a heat-treated alloy rail containing possibly Cr, silicon (Si), and Mn, reaching hardnesses as high as 450 BHN, most likely with a bainitic microstructure.

Improvements in wear resistance by alloying or heat treatment over that of standard rail (Std) have been appreciable but variable. Marich[5] reports an improvement in wear rate of 67% for high silicon (HiSi) rail and of 262% for chromium molybdenum (CrMo) over that of Std rail in a 5° curve under heavy unit-train type service. Yet a University of Illinois[8] study indicated that HiSi rail in a 5° curve (high rail) in one case exhibited an improvement in wear rate over that of Std rail of only 18% and in another case possibly as much as 43%. Kalousek and Bethune[9] reported a 100% improvement in wear rate (50% reduction) of Cr rail over Std rail located in a 10° curve.

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* Numbered references are listed following text (page 93).

Comparable improvements to those achieved by alloying are also achieved by heat treatment. In both cases (alloying and heat treatment), the degree of improvement over Std rail is a function of the degree of curvature. The University of Illinois study cites Great Northern and Northern Pacific data which show a maximum improvement for heat-treated rail of 300% at 1° curvature diminishing to only 55% at 10° curvature. Similarly, Schoeneberg[10] has summarized the results of Chessie System wear tests on Std, intermediate Mn, HH, and FHT 140 lb/yd rail for the one-year period 1973-1974, 16.3 MGT. The data show that the improvement (reduction) in wear rate for a given premium rail relative to Std rail (average of two rails) diminished as the degree of curvature increased. The most striking example of this was for HH rail relative to Std rail where the improvement was 550% on a 4° curve but dropped to 210% at 8° and only 14% at 8° 30'.

However, data presented in the University of Illinois study for a second stage of measurements from Burlington Northern test sections suggest a different behavior. Here, if the average curves of wear rate vs degrees of curvature are compared, the degree of improvement (a reduction in wear rate) tends to increase with degree of curvature. For HH rail, the improvement appears to be near 20% at 4° and 56% at 8°. The average curves for FHT rail fall virtually on top of the average Std rail curves, suggesting no improvement at all for FHT rail in the 132 lb/yd section. However, if FHT and Std rail are compared (average curves) in the 115 lb/yd section, the FHT rail provides substantially improved (reduced) wear rates, relative improvement being approximately 100% at both 4° and 8° curvature.

The wide variability in reported wear behaviors could be the result of differences in the type of traffic passing over the test sections, local variations in track alignment or track characteristics from one section to another (i.e., degree of lubrication), and/or insufficient sample size to truly reflect the average wear behaviors and distributions for the different metallurgies. In any event, the variability is enough to prevent a reliable quantitative assessment of rail wear behavior necessary to verify the various predictive representations of the wear phenomenon.

The most commonly recognized of the representations for rail life was that developed by the American Railroad Engineering Association (AREA); a modified version proposed by TOPS-on-line,[11] is:

$$T = KWD^{0.565} \qquad (1)$$

where:

T = the rail life expected in MGT (million gross tons),

W = the rail section in lb/yd,

K = constant which reflects the characteristics of the track rail and train operation, and

D = the annual tonnage.

A most significant feature of this representation was the contribution of annual tonnage rate which predicts that higher utilization of track tends to enhance rail life in terms of MGT. For instance, under the FAST Section 03 unit train operating conditions (new continuous welded rail (CWR), 45 mi/h, 0.5% grade (average), 5° curvature with oilers, wheel loads near 32 kips and 200 MGT/yr), Std rail would be expected to last 679 MGT or approximately 3-1/2 years. If the annual tonnage rate dropped to 50 MGT, rail (Std) life would be expected to drop to 310 MGT or just about 1.5 years. The reason why there should be a tonnage rate effect is not perfectly clear, but Deardon[12] had noted a similar behavior for rail in tangent track under British Rail operating conditions. He noted that specific wear rate (inches per 10^6 axles) diminished as the square root of the number of axles/yr; i.e., MGT/yr. This behavior was believed to have been related to the growth of oxides on the rail running and gage face surfaces such that lower usage encourages a greater corrosive contribution to the wear process.

A major drawback of this type of expression has been the necessity to determine empirically the contribution of such factors as metallurgy, curvature, grade, and lubrication without reference to the fundamental processes of wear fatigue, metal flow, and/or corrosion.

A more fundamental representation of the rail wear process has been proposed by Kalousek and Bethune:[9]

$$V = C\eta L/(\mathrm{Sin}\gamma)H^{\alpha} \qquad (2)$$

where:

V = volumetric wear

L = lateral force

η = mean value of lateral and vertical creep

γ = angle between the normal to the rail gage face and the lateral force vector; i.e., basically the angle of inclination of the gage face from the rail vertical

H = metal hardness

α, C = coefficients reflecting (a) the possibly nonlinear contribution of metal hardness and (b) the effect of wear surface condition; i.e., lubrication

Although this expression relates wear to more basic characteristics of the wearing system, several of the parameters such as lateral load and lateral and vertical creep are not readily defined for specific curves and train operating conditions. Furthermore, monotonic (though not necessarily linear) dependence on reciprocal hardness was predicted, without consideration of microstructural contributions, and lubrication effects would be expected to apply, in a relative sense, to all different types of metallurgy; i.e., no lubrication: metallurgy interaction.

In view of these limitations in the existing information on wheel:rail wear behavior and in the predictive wear models, the rail metallurgy experiment at FAST has been undertaken to provide a relatively controlled railroad operational test environment which will generate wear information, of adequately high reliability, to resolve some of the uncertainties cited in previous paragraphs. Planned, systematic variations in both metallurgy and tie plate cant have been provided in one of the metallurgy test sections while in another, metallurgy alone has been varied systematically. In both test sections, compensation has been provided for position-in-curve effects by replication of the basic arrangement through the curves. The experiment description and results presented in the following sections apply to the high rail of the metallurgy test sections only and cover the period of the first experiment from startup to 134.7 MGT.

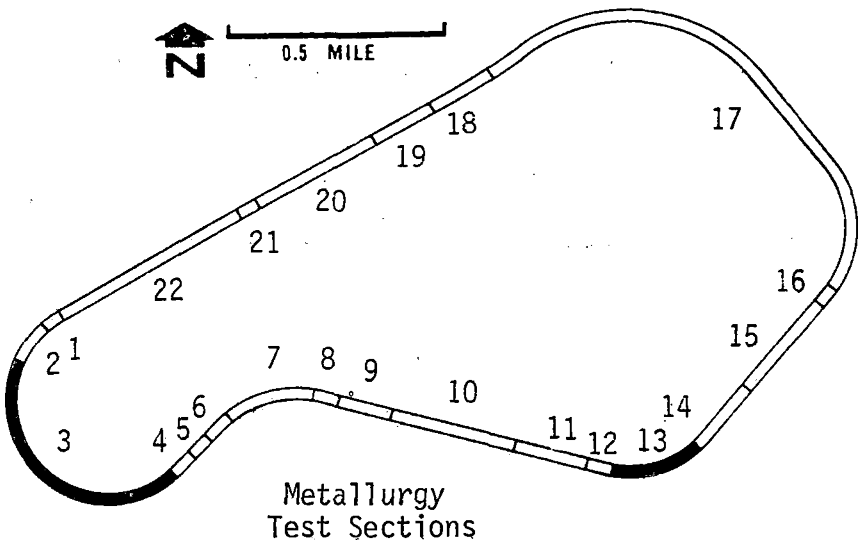
2.0 DESCRIPTION OF THE RAIL METALLURGY EXPERIMENT

The rail metallurgy experiment focused primarily on wear and metal flow behavior as reflected by the change in the shape of transverse rail head profiles and in the surface hardness of the ball of the rail. The experiment was contained in two Sections, 03 and 13, of the 22 test sections shown in figure 2-1.

Section 03 during the first experiment (0-135 MGT, September 1976 through September 1977) consisted of 3,673 ft of 4" superelevated, 5° curve with 300-ft long spirals at each end, and layed with five metallurgies: HH, HiSi, FHT, CrMo, and AREA Std. With the exception of the FHT rail, which was the 132 lb/yd AREA section, all other metallurgies in Section 03 were the 136 lb/yd AREA section. Ten, 374-ft long segments were plant-welded in 78-ft lengths (two 39-ft sticks plant-welded together) of HH, HiSi, FHT, and CrMo, together with 62-ft lengths of Std rail. These segments were then joined end to end by thermite field welds. Three tie plate cants, 1:14, 1:30, and 1:40, were used in a repeating pattern to support the high rail on creosoted softwood ties, 7"x9"x9' on 19-1/2" centers. The rail was box anchored every other tie. The arrangement of these metallurgies and tie plate cants throughout the curve is illustrated in figure 2-2. This pattern was selected to maximize the statistical discrimination of the experiment in its ability to assess the independent and interactive effects of metallurgy and tie plate cant. Position replication was incorporated to compensate for lubrication and consist performance variables along the curve. All segments except G utilized a five spike pattern--three cut spikes on the gage side and two cut spikes on the field side; segment G utilized a three spike pattern--two on the gage side and one on the field side. Although the original design called for three systematically varied different ballast shoulder widths (6", 12", and 18"), in actual fact, ballast shoulder width could not be varied systematically; the actual shoulder width varied somewhat randomly between 6" and 18". The ballast throughout the curve was crushed steel mill slag, exhibiting conchoidal fracture surfaces and meeting the AREA No. 4 size distribution. The measured nominal ballast depths averaged 15". The grade of the north half of the curve is 0.9% ascending to the north, while the more southerly half is approximately on level grade.

Section 13 is a 4° curve 1,248' in length with 300-ft spirals at each end and superelevated 3". All rail was of the 115 lb/yd AREA section. Four metallurgies--HH, HiSi, FHT, and AREA Std rail--all in 78-ft lengths, were plant welded into four 312-ft long segments which, in turn, were thermite welded end to end. The rail was set in standard 1:40 cant tie plates secured with 2 gage spikes and 2 plate spikes per rail on 7"x9"x9' creosoted softwood ties and box anchored every other tie. The ballast is AREA No. 4 crushed steel mill slag with a nominal depth of 12" and nominal shoulder width of 12". The grade of Section 13 is approximately level throughout.

Trains entering Section 13 from either end and entering Section 03 from the north end would have traversed extensive lengths (∿1100 ft) of tangent track, whereas trains entering Section 03 from the south end would have negotiated the nearby reverse curve at Section 07. Typical consist speeds through Section 03 were 43 mi/h clockwise (CW) and 45 mi/h counterclockwise (CCW);



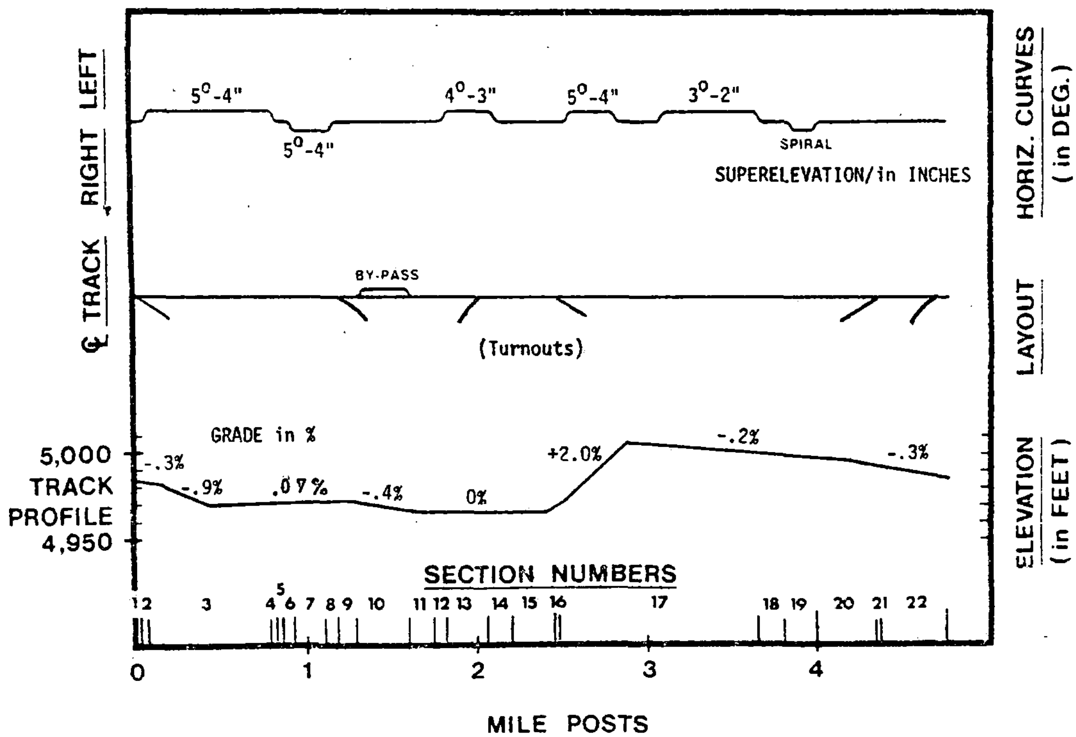


FIGURE 2-1. PROFILE AND CURVATURE OF FAST TRACK.

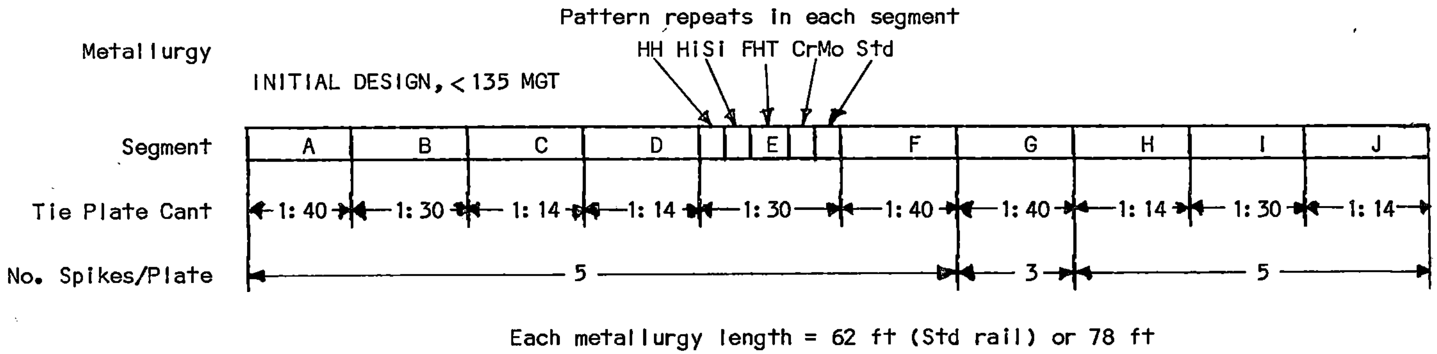


FIGURE 2-2. LAYOUT OF FAST SECTION 03.

though Section 13 speeds were 44 mi/h CW and 45 mi/h CCW. These speeds represented 3" average unbalance in Section 03 and 2.6" in Section 13.

The FAST consist is composed of three or four 4-axle diesel electric locomotives pulling an approximately 9,500-ton trailing load at speeds in the 40-45 mi/h range. The consist typically contained six to twelve 34,000 gallon 111A and 112A class tank cars, two or three 85-ft long flatcars with two trailers loaded to 70 tons, and 59 to 66 loaded 100-ton hopper cars. The direction of the consist was reversed every test day by moving the locomotives from one end of the consist to the other. In addition, the consist itself was reversed end for end on every second test day. A block of four cars was removed from the consist daily for inspection and measurements; concurrently, the block from the previous day was reinserted into the consist. The mixture of wheel types in the FAST consist varied throughout the period of the experiment. Although class B, C, and U wheels were used in the consist, the predominant wheel types were C and U. Their variation in number is shown in figure 2-3. Because of the relatively poor wheel/rail lubrication during the first part of the experiment (described later), the number of class U wheels diminished gradually from over 300, initially, to about 200 in July 1977 (95-106 MGT), after which their number continued to drop below 150. Correspondingly, the number of class C wheels rose from about 140 wheels, initially, to about 200 in May 1977 (62-77 MGT), followed by a slight drop to approximately 150 in July 1977 and then a sharp increase to approximately 260 wheels during August and September 1977.

The state of rail lubrication varied considerably throughout the period of the first metallurgy experiment; i.e., 134.7 MGT. Initially, a dual rail lubricator had been installed in Section 05 and a single rail lubricator in the segment between the 3° and 5° curves of Section 17. At approximately 38-50 MGT (February 1977), the single rail lubricator in Section 17 was rebuilt as a dual rail lubricator and was reinstalled in Section 14. At about the same time, a dual rail lubricator was installed at the east end of Section 18; this unit was converted to a single rail lubricator at approximately 94-106 MGT (July 1977). Thus, as traffic accumulated, the loop went from two lubricators to four lubricators, with the most significant increase in lubrication occurring near 40-45 MGT of traffic. In order to facilitate nondestructive rail inspection after four lubricators had come online, all lubricators were shut down twice a week for at least eight hours immediately before rail inspection.

There were 311 data measurement sites distributed uniformly along the high rail in Section 03; 91 sites were selected along the high rail in Section 13. Measurement sites generally were not closer than 8 ft to a weld. Profiles were taken approximately every 25 $\pm$5 MGT of traffic. The window for complete profile measurement of Section 03 was approximately 10 MGT, while that for Section 13 was approximately 2-1/2 MGT.

2.1 MATERIALS

The average chemical analyses (ladle) of all heats of rails tested in Sections 03 and 13 are tabulated in table 2-1. The ladle analyses of individual heats are given in appendix A, table A-1. With the exception of the FHT

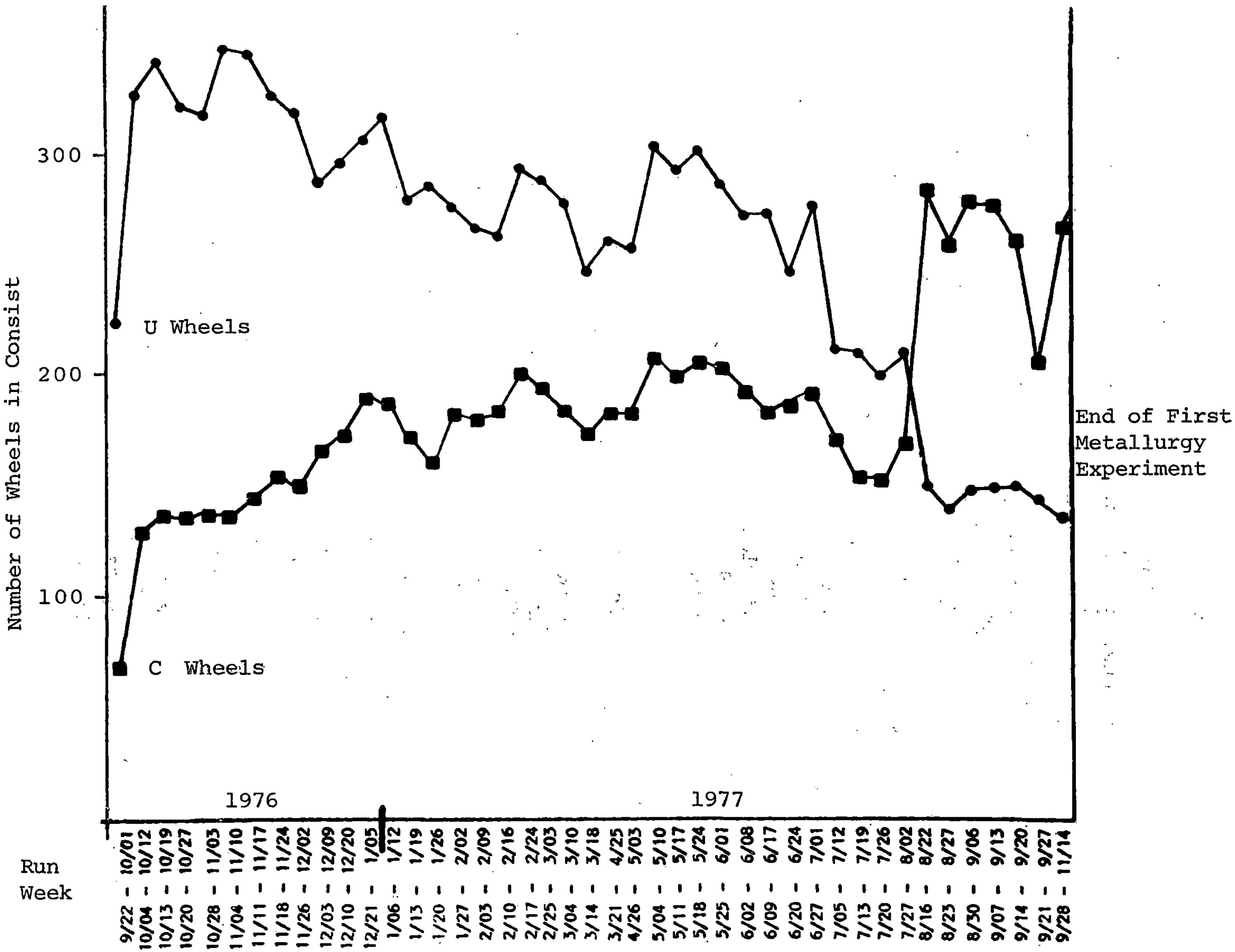


FIGURE 2-3. VARIATION OF WHEEL POPULATION DURING THE FIRST RAIL METALLURGY EXPERIMENT.

TABLE 2-1. AVERAGE LADLE ANALYSES OF RAIL HEATS.

Section	Rail Type	Weight Percent, w/o C	Mn	P	S	Si	Cr	Mo
Section 03								
	Std	0.78	0.86	0.027	0.025	0.15	--	--
	HiSi	0.76	0.86	0.028	0.027	0.63	--	--
	FHT	0.69	0.81	0.018	0.032	0.18	--	--
	CrMo	0.80	0.82	0.026	0.025	0.25	0.78	0.20
	HH	0.79	0.84	0.009	0.018	0.16	--	--
Section 13								
	Std	0.73	0.86	0.024	0.020	0.17	--	--
	HiSi	0.77	0.88	0.029	0.024	0.68	--	--
	FHT	0.77	0.81	0.020	0.041	0.15	--	--
	HH	0.77	0.88	0.015	0.025	0.18	--	--

rail tested in Section 03 which had an average carbon content just slightly less than 0.70 weight percent (w/o), and the Std rail tested in Section 13 which had a carbon content just under 0.75 w/o, all metallurgies had average carbon contents in the range of 0.76-0.80 w/o. The average manganese levels ranged from 0.81 w/o to 0.88 w/o. The carbon and manganese contents for all rails were within the specified AREA tolerance ranges.

For Std rail, the AREA carbon and manganese ranges would be expected to yield a minimum hardness of 248 BHN. Both the HH and FHT rails would be expected to have a hardness in the 321-388 BHN range.

2.2 INSTRUMENTATION

During this first metallurgy experiment, the only instrument utilized for wear measurements was the Yoshida Seiki type MR profilometer. Five units (45, 46, 47, 48, and 99) were available for use but the majority of measurements were taken with units 46, 99, and 47 in descending order. This profilometer produces a 1:1 tracing of the rail head from one fishing surface under one side of the rail head to that on the other side. Because, small variations in positioning and wear of the stylus (the pointer riding on the rail) and scribe (the marking pointer) could produce errors in the trace of the rail head profile, a calibration profile was made of a standard, virtually new, AREA 136 lb/yd rail section each measurement day. This standard profile, referred to as the section 80 profile, was not utilized to correct the test profiles but was used to independently check the variability of the profilometer. However, as used in this first metallurgy experiment, individual section 80 profiles and test rail profiles could not be compared in the field against a reference profile to permit the operator to determine if the instrument was correctly adjusted. Thus, a considerable variation in profile size was possible.

The profiles produced each day, identified by tie number and rail identification (inside or outside), and with instrument number and operator initials recorded, were digitized to permit automated data processing. The digitizing operation is illustrated in figure 2-4. The target circle utilized to position the digitizing head on the profile during tracing was 0.125" diameter with approximately 0.005" diameter 'dot' at the center. An x, y data pair representing a position on the profile was generated each 0.01" along the profile. Thus, there are, typically, 975 discrete x, y data pairs for each profile. Each digitized profile was then analyzed to yield and produce the dimensions shown in figure 2-5, along with gross area and total area. D1, D2, and D5 were determined by a vector at 0°, 180°, and 90°, respectively, from the horizontal rotated about the r, θ origin. The cross sectional areas were also determined by rotation of this vector about the r, θ origin from one fishing surface projection to the other intersecting projection. The r, θ origin was established at the intersection of the linear portions of the fishing surfaces of the initial (zero MGT) profile at each measurement site and was maintained at the same location for all subsequent profiles taken at that measurement site. D7 was measured horizontally from the gage face to the y axis (which passed vertically through the x, y origin) 5/8" down from the current running surface. The x, y origin did not necessarily coincide with the r, θ origin. The x, y origin was located 0.25" vertically below that point which is 1" horizontally from each head/web fillet surface. The gross

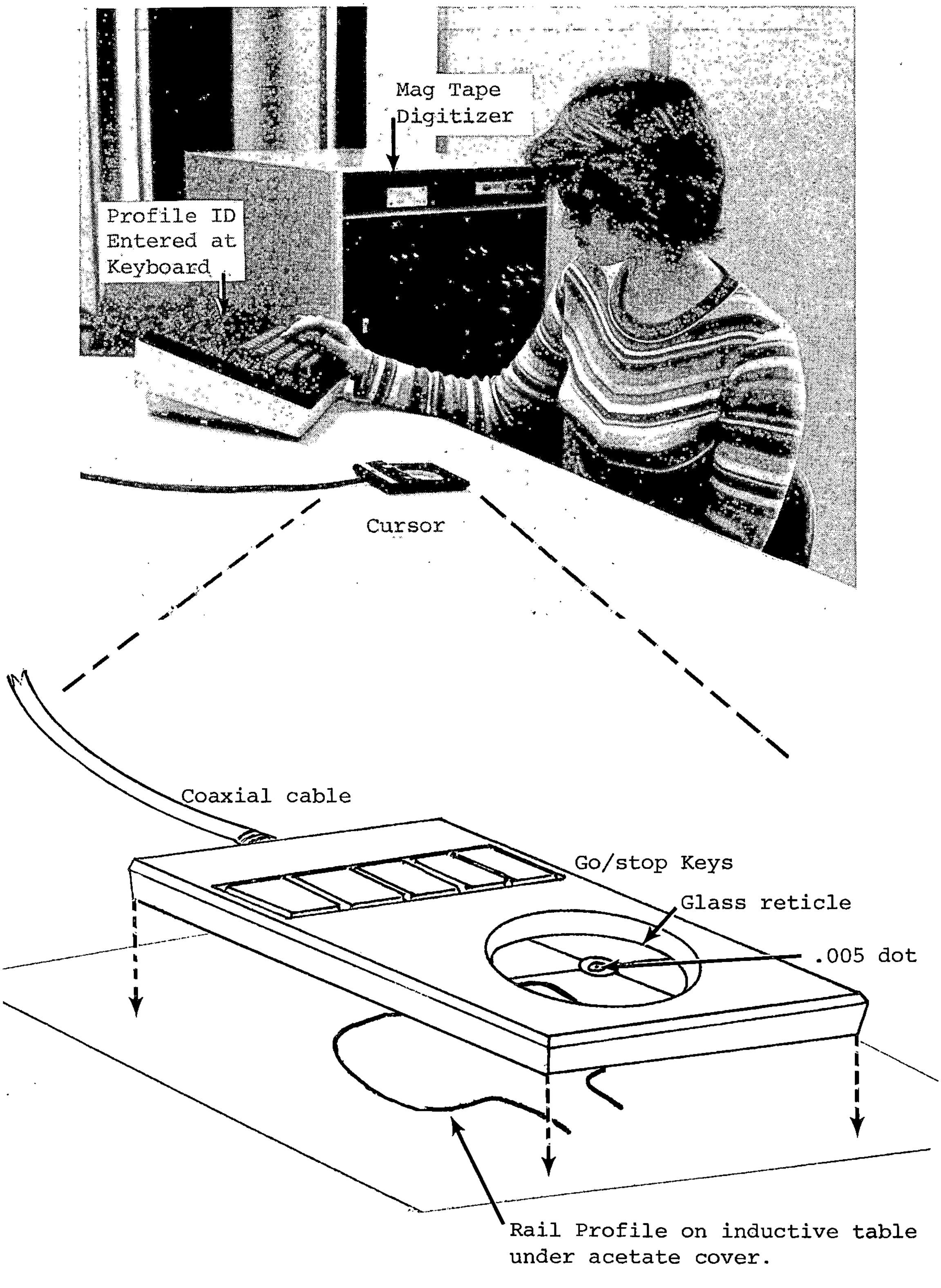


FIGURE 2-4. DIGITIZING OPERATION WITH CURSOR DETAIL.

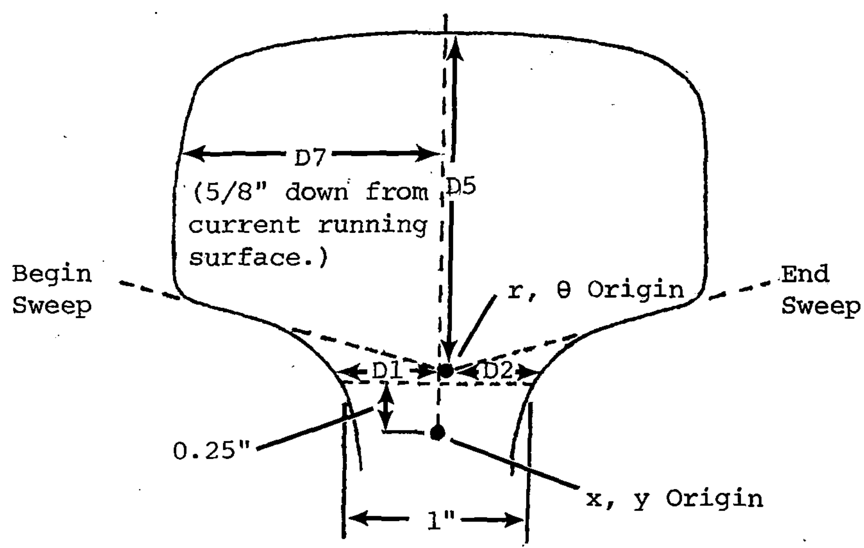


FIGURE 2-5. PROFILE DIMENSIONS.

area is the complete area of the rail head above the projected lines of the fishing surfaces. The total area, on the other hand, is that area of the rail head above the projected lines from the fishing surfaces but within the initial profile of the rail at the measurement site in question. Thus, the gross area will reflect the combined effect of the loss of metal due to gage face wear and head height loss, as well as the redistribution of metal due to plastic flow. In contrast, the total area reflects only rail head area loss due to wear. The difference between the gross and total area defines the metal moved outside the original profile by metal flow. The details by which the dimensions and areas were calculated are described in appendix B.

Two different correction procedures were employed in this first metallurgy experiment. The first procedure of these was utilized until 80 MGT, whereafter a second procedure was introduced. Neither correction procedure (appendix B) employed the section 80 profiles. The first procedure relied upon expansion or contraction of each succeeding profile at a given measurement site to make the lower corners of the rail head coincide with those of the original (initial) profile. Obviously, in as much as no comparisons were made against a standard profile, even for the initial measurements, this procedure provided only an indication of change from the initial condition. Furthermore, it presumed that instrument errors (percentages) were the same in both the horizontal and vertical directions, and that the lower corners of the rail head did not change their relative positions during the progression of the test.

Unfortunately, the underlubricated state which existed during the first 40 to 45 MGT of the first experiment eventually led to plastic flow down the gage face, which caused a change in relative position of these lower corners. Therefore, at 80 MGT, an arbitrary correction factor was applied to the digitized profile data. This correction factor was taken as the average of the corrections applied before 80 MGT. Thus, the discontinuity which occurred at 80 MGT was most noticeable for metallurgy/cant combinations which produced the greatest wear.

Appendix C presents information showing that over long periods of time, profilometry variation could be as much as ± 1/8" on a fixed unchanging reference dimension (width of a section 80 rail head).

3.0 ANALYSIS OF EXPERIMENTAL RESULTS

Because of the substantial inherent variability in measurement, correction, and data processing techniques as well as the occurrence of an uncertain number of phantom profiles, the use of powerful statistical analysis techniques has been necessary in order to draw conclusions with any degree of certainty. Basically, two types of analysis have been undertaken independently by the Association of American Railroads (AAR) and the Transportation Systems Center (TSC), to determine how sensitive the conclusions to be drawn from the experiment are to the details of the methods of analysis. High sensitivity to the analysis method would imply the impact (interaction) of many factors, some of which at least were beyond definition in this experiment. Substantial agreement between the different methods of analysis would suggest that the conclusions drawn are reliable, although the explanations for the noted occurrences might still be subject to substantial controversy and need further clarification.

Both analyses treat wear as a linear function of tonnage and have the general form:

$$W = W_O + \alpha x MGT_I + \beta x MGT_{II} + W_{80} + \quad \cdots \qquad (3)$$

where:

W = The measure of wear such as gage face loss, head height loss, or head cross sectional area loss,

W_O = Indicated wear at zero MGT,

α = The wear rate in the first wear regime (underlubricated at less than 40-45 MGT),

MGT_I = Tonnage in the first wear regime,

β = The wear rate in the second wear regime (generously lubricated after 40-45 MGT),

MGT_{II} = Tonnage in the second wear regime, and

W_{80} = An incremental change in the measure of wear due to the change in profile correction procedure introduced at 80 MGT.

In each analysis, the wear rate, β, above and below 80 MGT has been presumed to be unchanged by the change in profile correction procedure. However, the more comprehensive analysis integrated terms for each metallurgy, tie plate cant, and profilometer identifcation into a single linear functional relationship. The linear wear model was applied to head cross section area loss, gage face loss (ΔD7), and head height loss (ΔD5) to estimate the rates of wear (change as functions of traffic). The wear values represent the differences of individual measurement wear from the intercept of the best-fit straight line at 0 MGT. For data taken before the lubrication transition only, the best-fit line was not constrained to go through the mean zero wear at 0 MGT, but it did, in fact, come very close to doing so. In addition, the ratios of wear rate of Std rail to that of comparison rails were calculated to reveal whether a significant interaction existed between metallurgy and lubrication. This ratio was termed the Figure of Merit (FM) and reflected how many times, on the average, a given metallurgy was better than Std rail under essentially the same testing conditions.*

Using the revised data bases, four different types of linear statistical models were estimated and compared to establish the level of complexity needed to determine reliably the effects different factors have on wear behavior. Analysis of covariance was performed to establish the statistical significance of separate and combined effects of the two experimental factors, tie plate cant and metallurgy, originally intended for evaluation in this experiment. Subsequently, additional tests were taken to determine whether (a) there were position-in-curve effects in Section 03 and (b) the change in lubrication level which occurred near 40-45 MGT influenced the conclusions to be drawn from the experiment. The wear rates for each metallurgy were determined by regressing on the entire data population for all metallurgies.

In calculating the F ratio to test the significance of main factors and interactions, the deviations of each individual wear data point from the best fit regression estimate of the wear data (really a surface in multi-dimensional space) were utilized to determine the overall mean square term. Thus, the tests for statistical significance reflected the variability of the entire data set for each wear measure.

The four models developed and compared, listed in order of increasing complexity, are as follows:

Model A: Estimated a single common wear rate for all combinations of metallurgy and tie plate cant.

Model B: Estimated separate wear rates for each level of a single factor, either metallurgy or tie plate cant.

Model C: Estimated separate wear rates for each metallurgy/tie plate combination by adding the separate effects of each metallurgy and each tie plate cant.

Model D: Estimated separate wear rates independently for each combination of metallurgy and tie plate cant.

The relative predictive powers (as measured by the increase in variation explained by the model or decrease in unexplained error variation) of each model were compared. The relevant comparisons are as follows:

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* However, the reader is cautioned to remember that the Figures of Merit represent average wear rates of each metallurgy and are derived from a widely scattered data base with unbalanced numbers of heats among the different metallurgies. Thus, the Figures of Merit must be considered the best average ranking of the different metallurgies obtainable within the limitations imposed by testing.

a. Comparison of the two type B models to the type A model to ascertain whether the factor (metallurgy or tie plate cant) had a significant effect on the wear rate.

b. Comparison of the type C model to the type A model to ascertain whether the two factors have a significant additive joint effect on the wear rates.

c. Comparison of the type C model to the two type B models to determine the significance of adding a second factor to estimate the wear rates after the first.

d. Comparison of the type D model to the type C model to determine if the two experimental factors interact causing their joint effect to be different from that predicted by adding together the wear rates estimated separately.

In addition, the partial coefficient of determination (correlation coefficient) of the factors was computed for wear before and after 45 MGT, after MGT was considered. The coefficient measures the portion of variations in wear that is explained by the factors after the effect of traffic is taken into account.

The somewhat simpler analysis was applied to only the gage face wear dimension (D7). Although the same basic linear wear model (equation 3) was utilized as that applied in the more detailed analysis, the terms for profilometer contribution to wear were omitted. Best fit regression lines were determined for each combination of metallurgy and tie plate cant at each segment in each test curve (Sections 03 and 13). However, regression was performed upon the data for each metallurgy alone.

In this simpler analysis, the tests for statistical significance (analysis of variance) were applied only to the wear rates above and below the transition to the generously lubricated condition and to the FM. Thus, the mean square term which appears in the denominator of the F ratio reflected the variability of the wear rates and of the FM, but not of the entire wear data set from which the rates were derived. This analysis represents a weaker test for statistical significance than obtained when the entire wear data set was utilized in testing for statistical significance.

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4.0 EXPERIMENTAL RESULTS

The variation of gage face wear (dimension D7), head height wear (dimension D5), and head cross sectional area loss for each combination of metallurgy and tie plate cant (Section 03) are presented in figures 4-1 through 4-15. In general, the gage face and head area loss measures of wear exhibited the transition at 40-45 MGT, attributed to an appreciable change in the lubrication. The effect of change in the profile correction procedure at 80 MGT was less distinct; it was frequently discernible in the gage face wear data plots, but somewhat less so in the head area loss data plots, and least of all in the head height wear data plots.

A visual impression of the data plots suggests that the scatter of the data was greatest for the Std and HiSi metallurgies and least, in general, for the CrMo and HH. The scatter of the data for FHT rail, falling between the two extremes, appeared somewhat more variable. The larger scatters of the Std and HiSi rail data most likely can be attributed to the fact that, in Section 03, there were 10 different heats each of Std and HiSi rail distributed throughout the test sections. There was one heat each of HH and FHT rails and two heats of CrMo rail in Section 03.

The more detailed analysis yielded the average wear rates for gage face wear, total head area loss and head height loss given in table 4-1 for each of the 1:40, 1:30, and 1:14 tie plate cants above and below the approximate point (45 MGT) at which changes in lubrication are believed to have become effective. Again, these wear rates result from a single regression upon all the data for all five metallurgies in one functional expression.

From table 4-1, several interesting patterns in the wear rates can be observed. First, the wear rates above 45 MGT are substantially lower than the wear rates below 45 MGT for each combination of metallurgy and tie plate by factors of 4 to 8. Second, the 1:14 tie plate cant has, on the average, higher wear rates for gage face wear and head area loss (by about 20%), while the 1:40 cant produced higher rates of head height loss (27% average). However, the effect of the tie plate cant on gage face wear and head area loss was noticeably less marked for Std rail than it was for the less rapidly wearing premium rails. Third, the wear rates for HH and CrMo rails are typically lower than wear rates for Std rail or the other premium metallurgies, HiSi and FHT. HH had the lowest wear rates in gage face wear and head area loss, but CrMo had less head height loss. Fourth, above 45 MGT there was no significant loss in head height. Fifth, the degree of differential in wear rates among the premium metallurgies tended to be less in the above 45 MGT environment than in the below 45 MGT environment.

Table 4-2 shows a relative wear rate, or Figure of Merit (FM), for each metallurgy, computed by dividing the wear rate of Std rail on a given tie plate cant by the wear rate of a specified metallurgy on the same tie plate cant. Thus, a ratio greater than one indicates the degree to which the specified metallurgy wears at a lower rate than Std metallurgy on the same tie plate. From these tables, the diminished importance of premium metallurgy in the over 45 MGT environment is clear. In all premium metallurgy tie plate combinations, the FM for gage face wear was higher under 45 MGT than it was

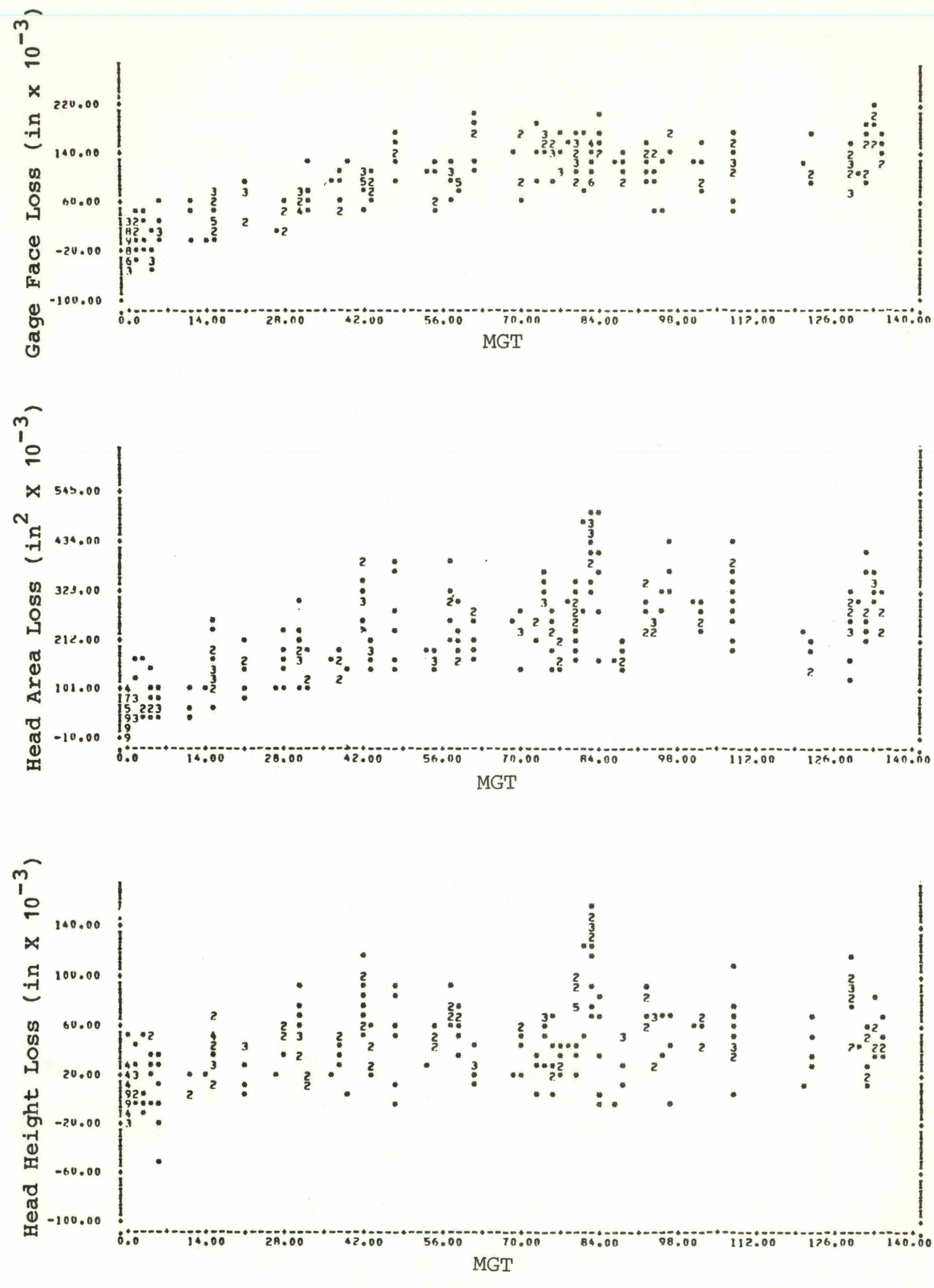


FIGURE 4-1. SCATTERGRAM OF HH RAIL REGRESSION,
5° CURVE - OUTER - 1:40 CANT.

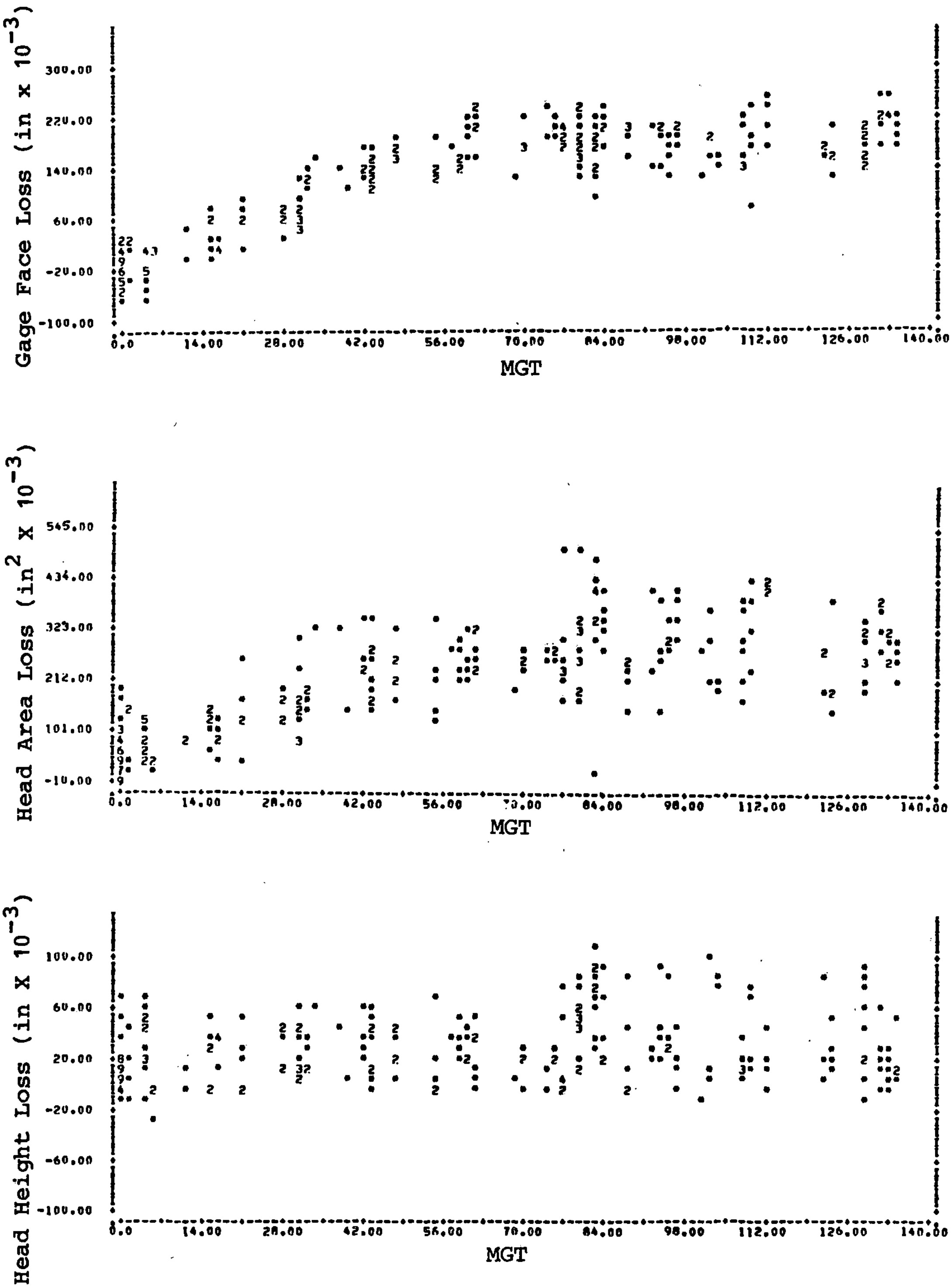


FIGURE 4-2. SCATTERGRAM OF CRMO RAIL REGRESSION,
5° CURVE - OUTER - 1:40 CANT.

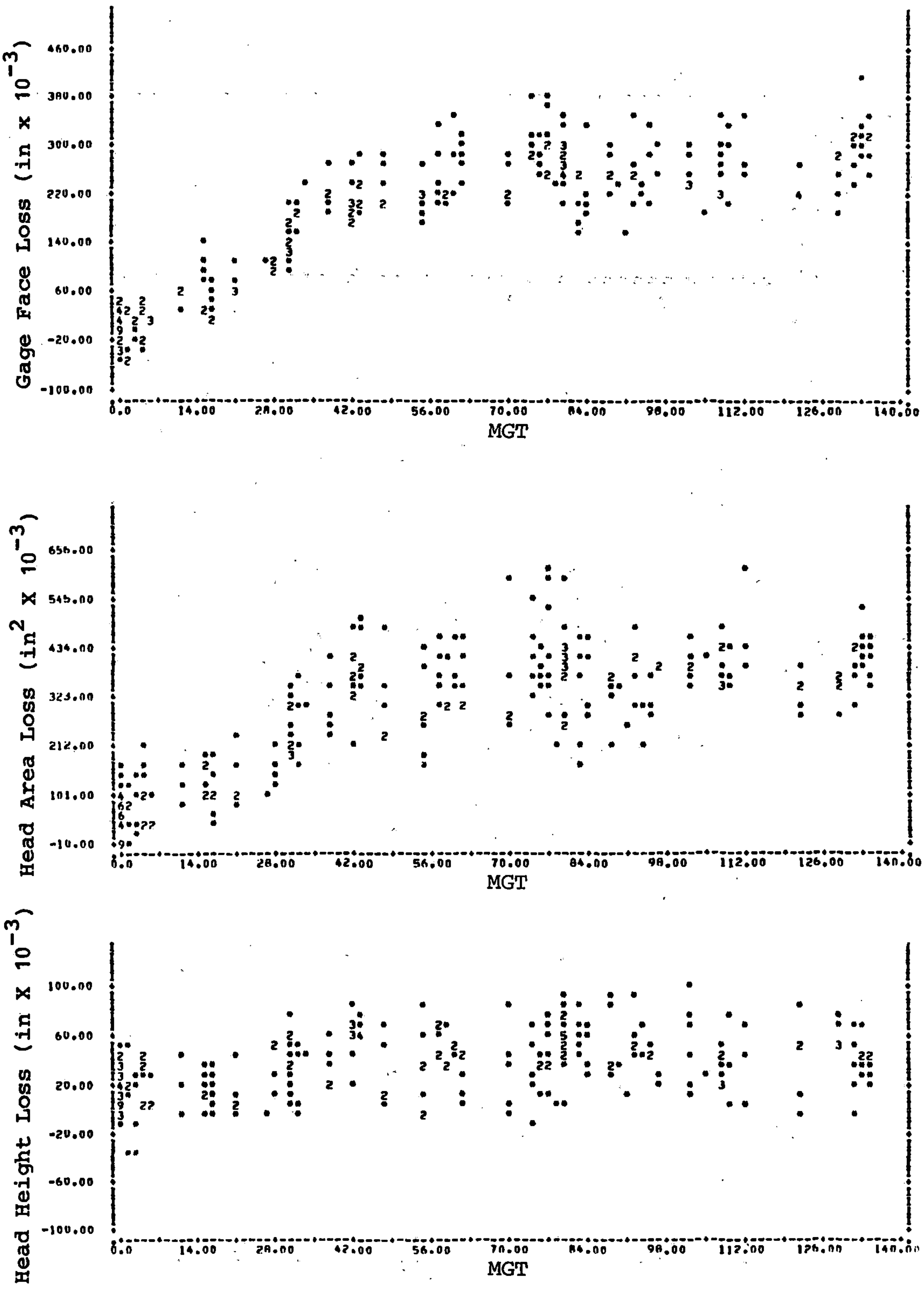


FIGURE 4-3. SCATTERGRAM OF FHT RAIL REGRESSION, 5° CURVE - OUTER - 1:40 CANT.

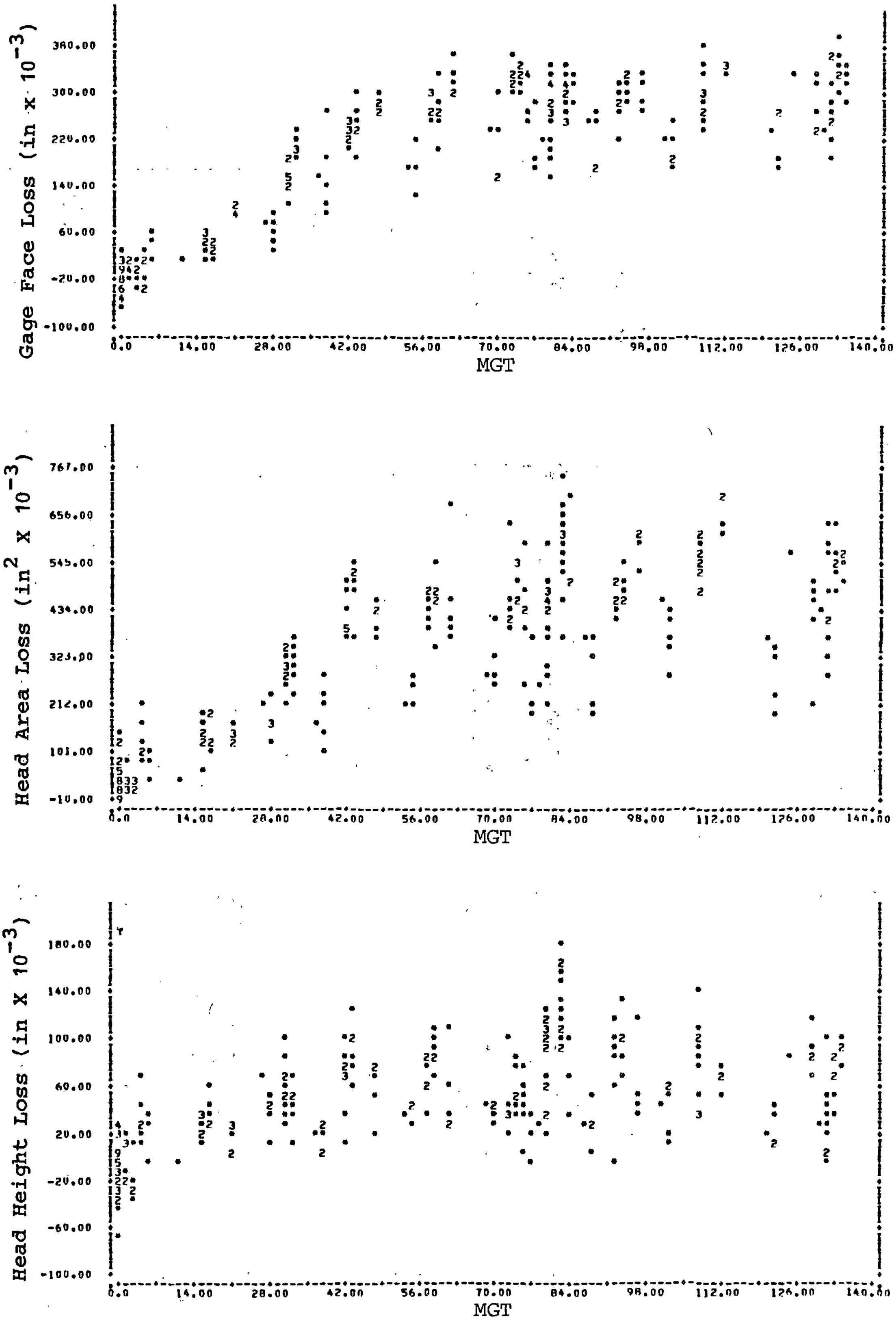


FIGURE 4-4. SCATTERGRAM OF HISI RAIL REGRESSION, 5° CURVE - OUTER - 1:40 CANT.

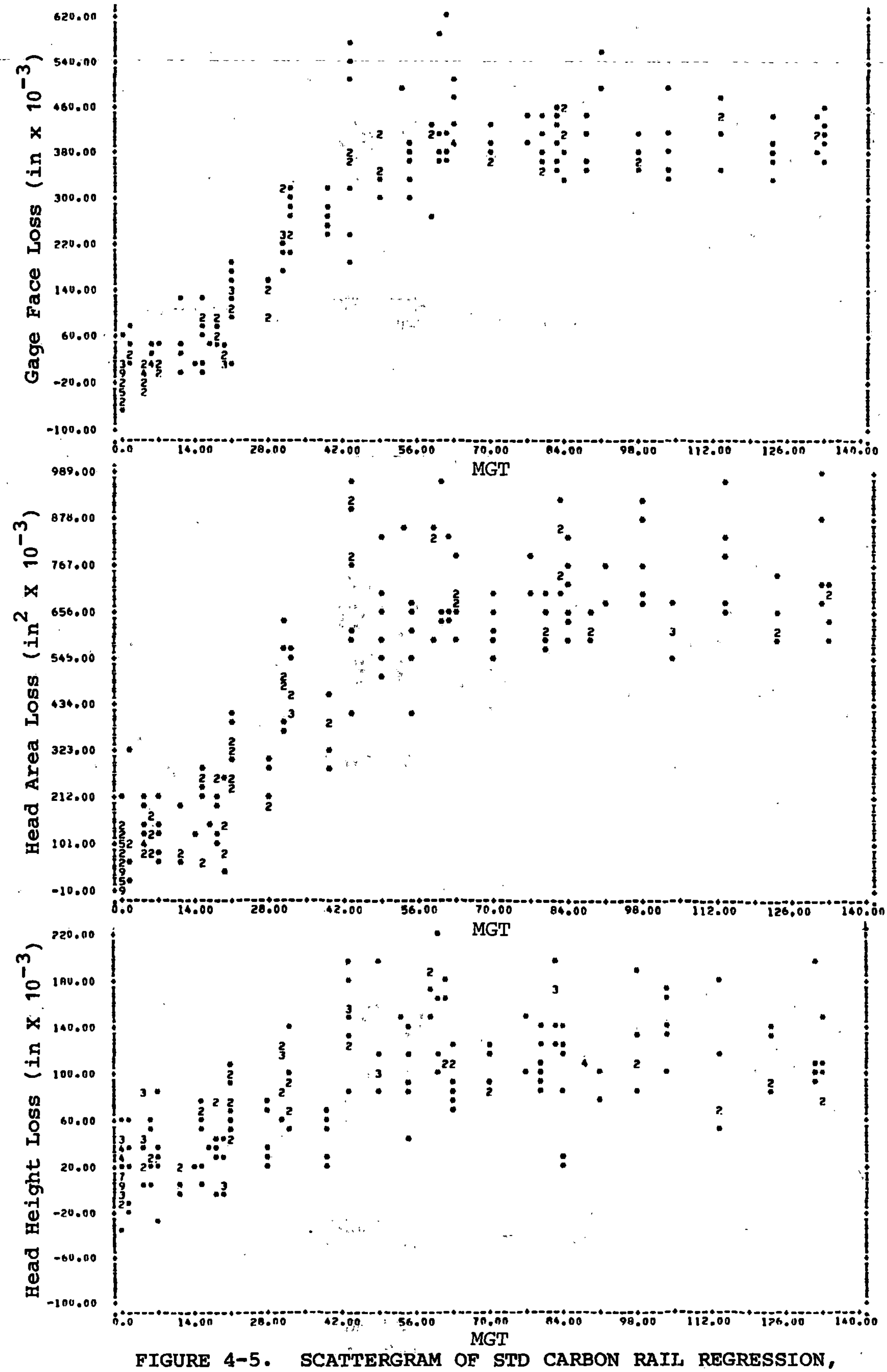


FIGURE 4-5. SCATTERGRAM OF STD CARBON RAIL REGRESSION, 5° CURVE - OUTER - 1:40 CANT.

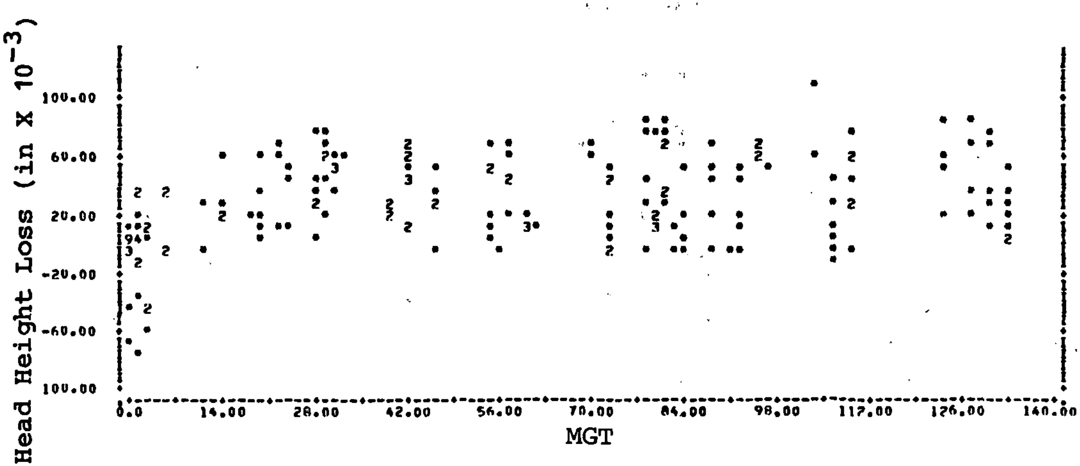
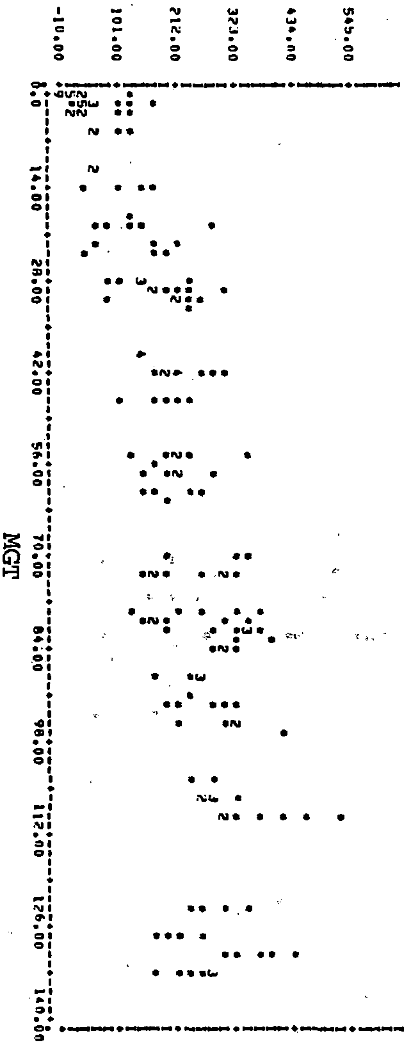
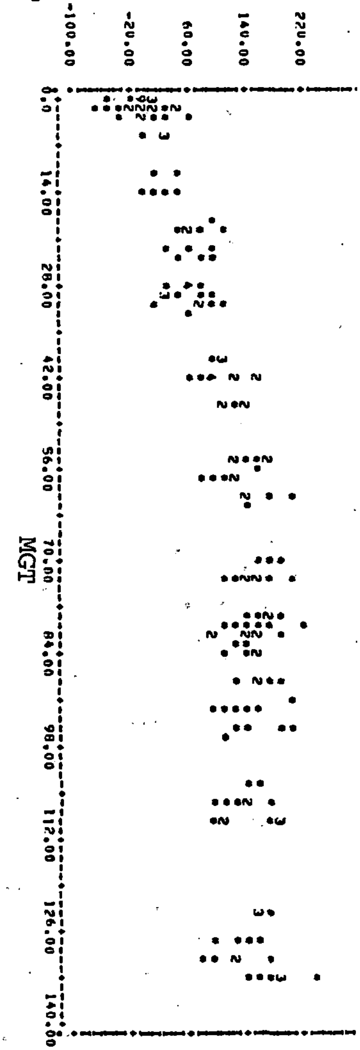


FIGURE 4-6. SCATTERGRAM OF HH RAIL REGRESSION, 5° CURVE-OUTER-1:30 CANT.

Head Area Loss (in^2 X 10^{-3})



Gage Face Loss (in x 10^{-3})



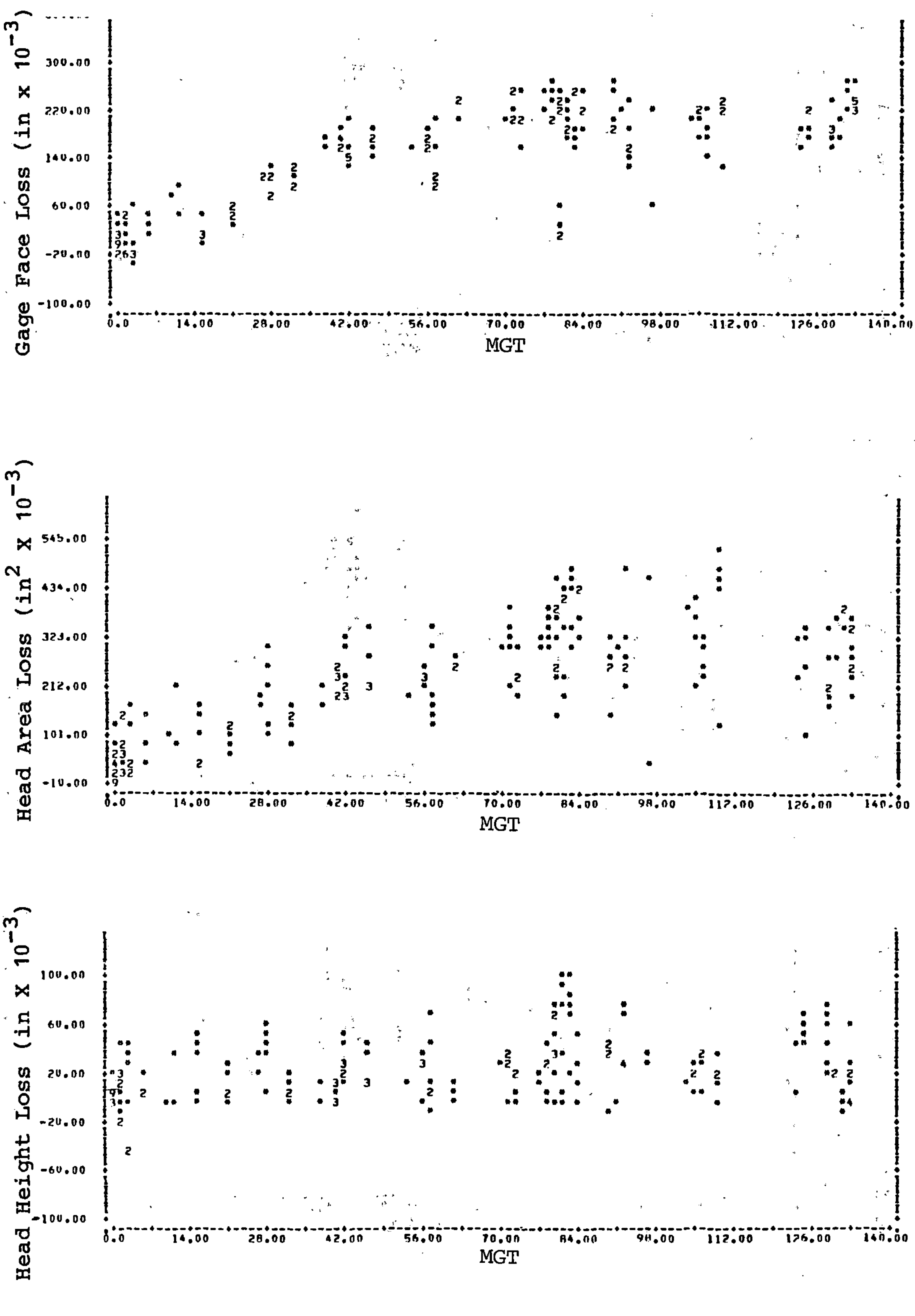


FIGURE 4-7. SCATTERGRAM OF CRMO RAIL REGRESSION,
5° CURVE - OUTER - 1:30 CANT.

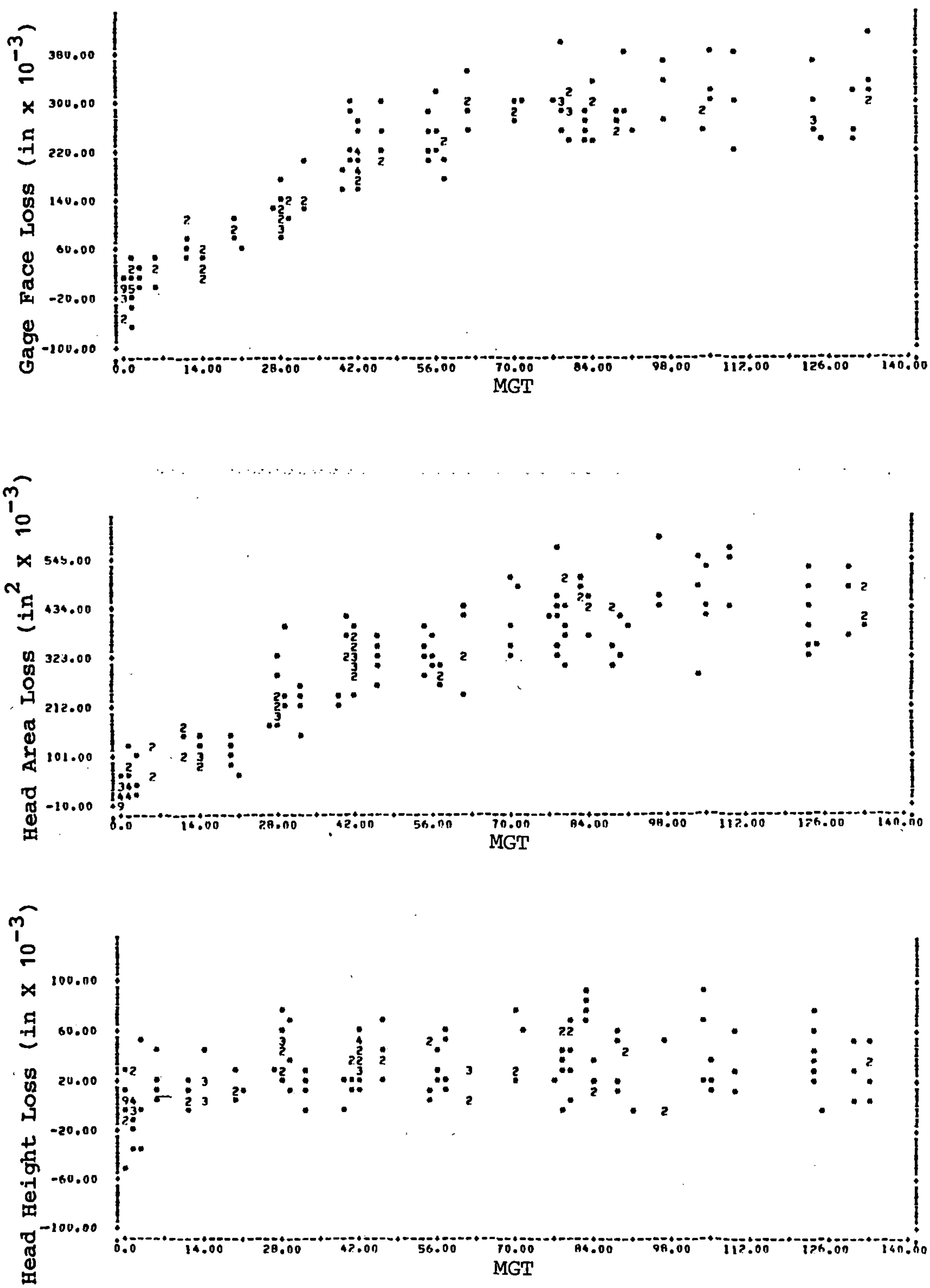


FIGURE 4-8. SCATTERGRAM OF FHT RAIL REGRESSION,
5° CURVE - OUTER - 1:30 CANT.

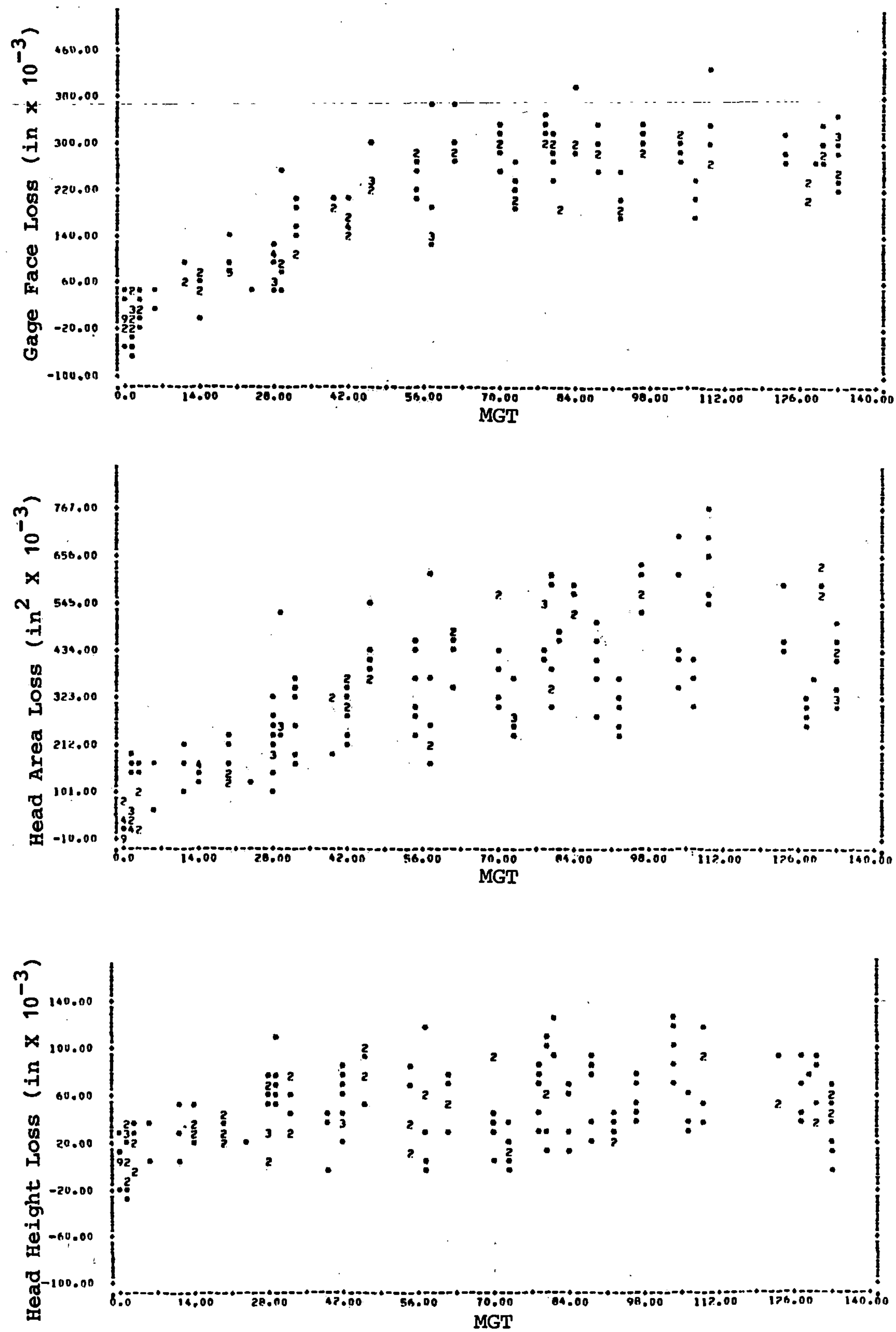


FIGURE 4-9. SCATTERGRAM OF HISI RAIL REGRESSION
5° CURVE - OUTER - 1:30 CANT.

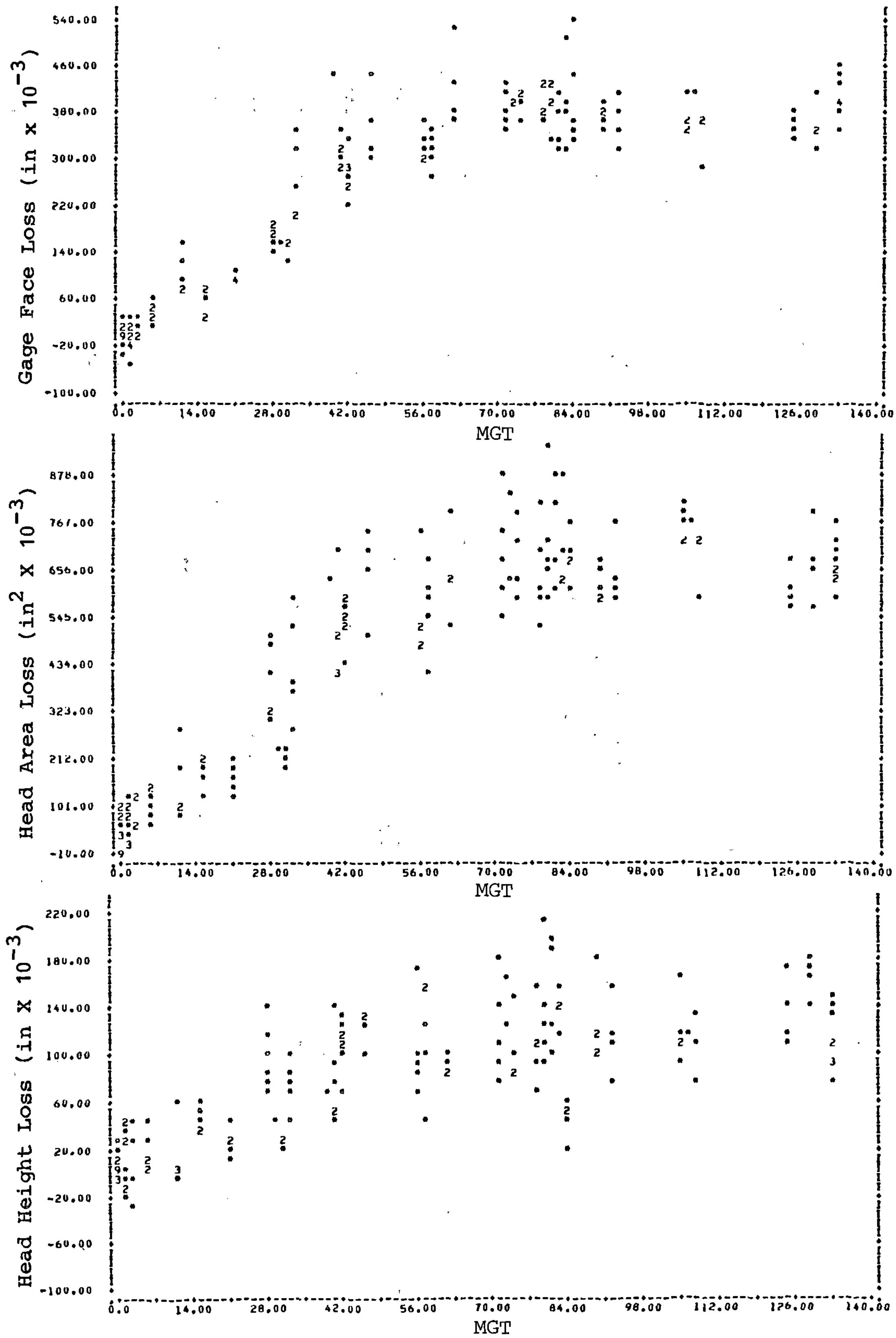


FIGURE 4-10. SCATTERGRAM OF STD CARBON RAIL REGRESSION 5° CURVE - OUTER - 1:30 CANT.

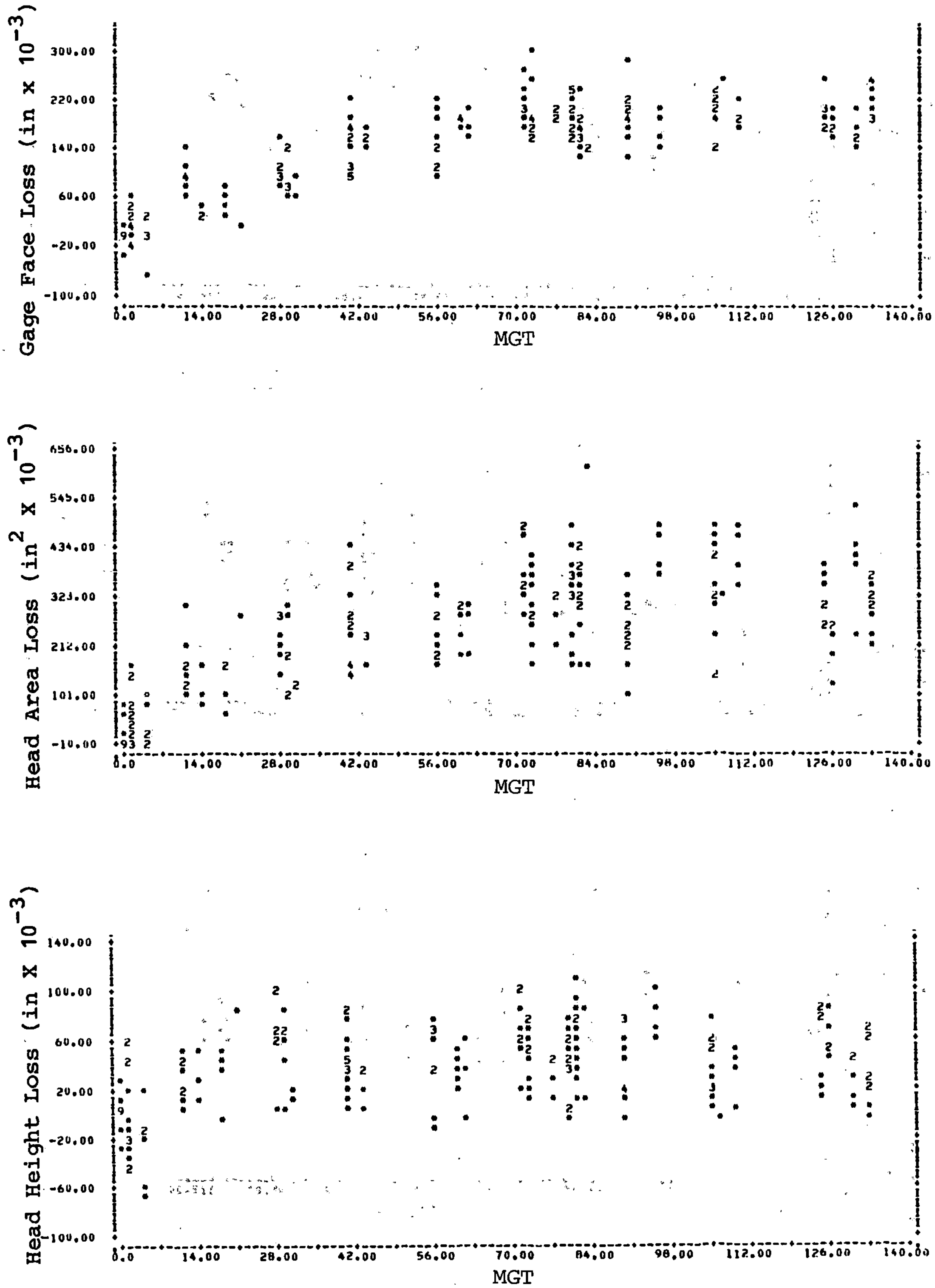


FIGURE 4-11. SCATTERGRAM OF HH RAIL REGRESSION, 5° CURVE - OUTER - 1:14 CANT.

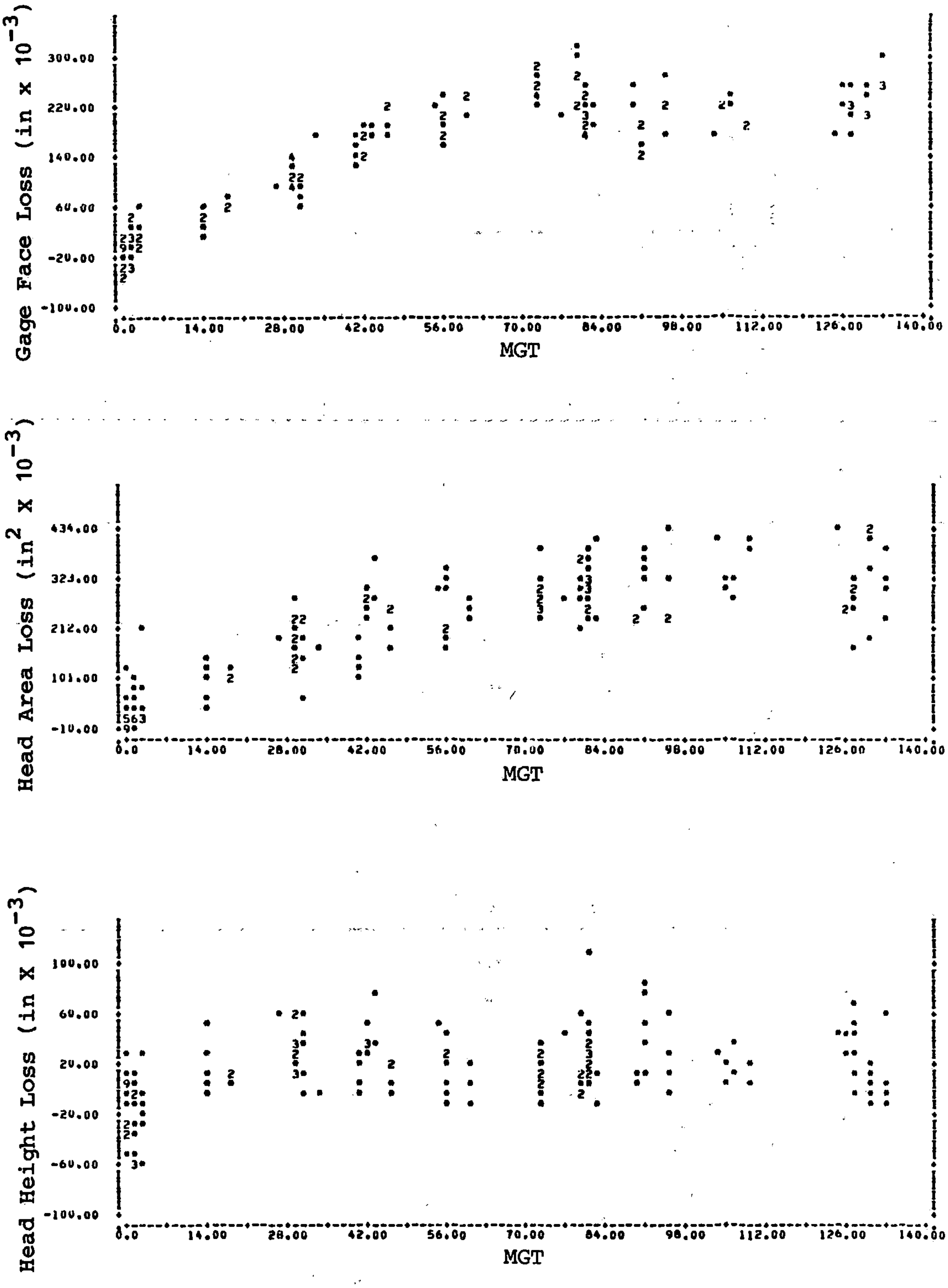


FIGURE 4-12. SCATTERGRAM OF CRMO RAIL REGRESSION, 5° CURVE - OUTER - 1:14 CANT.

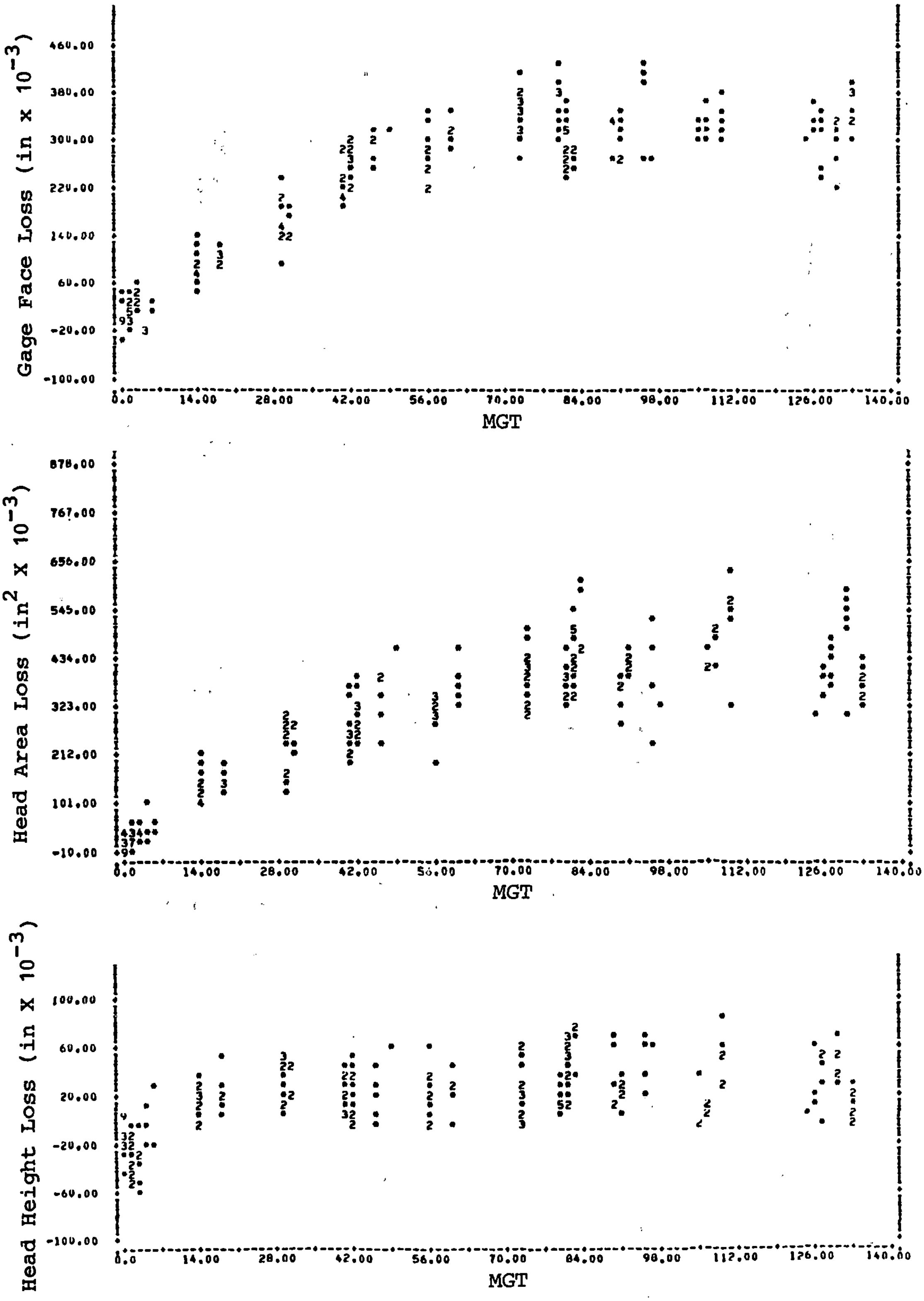


FIGURE 4-13. SCATTERGRAM OF FHT RAIL REGRESSION, 5° CURVE - OUTER - 1:14 CANT.

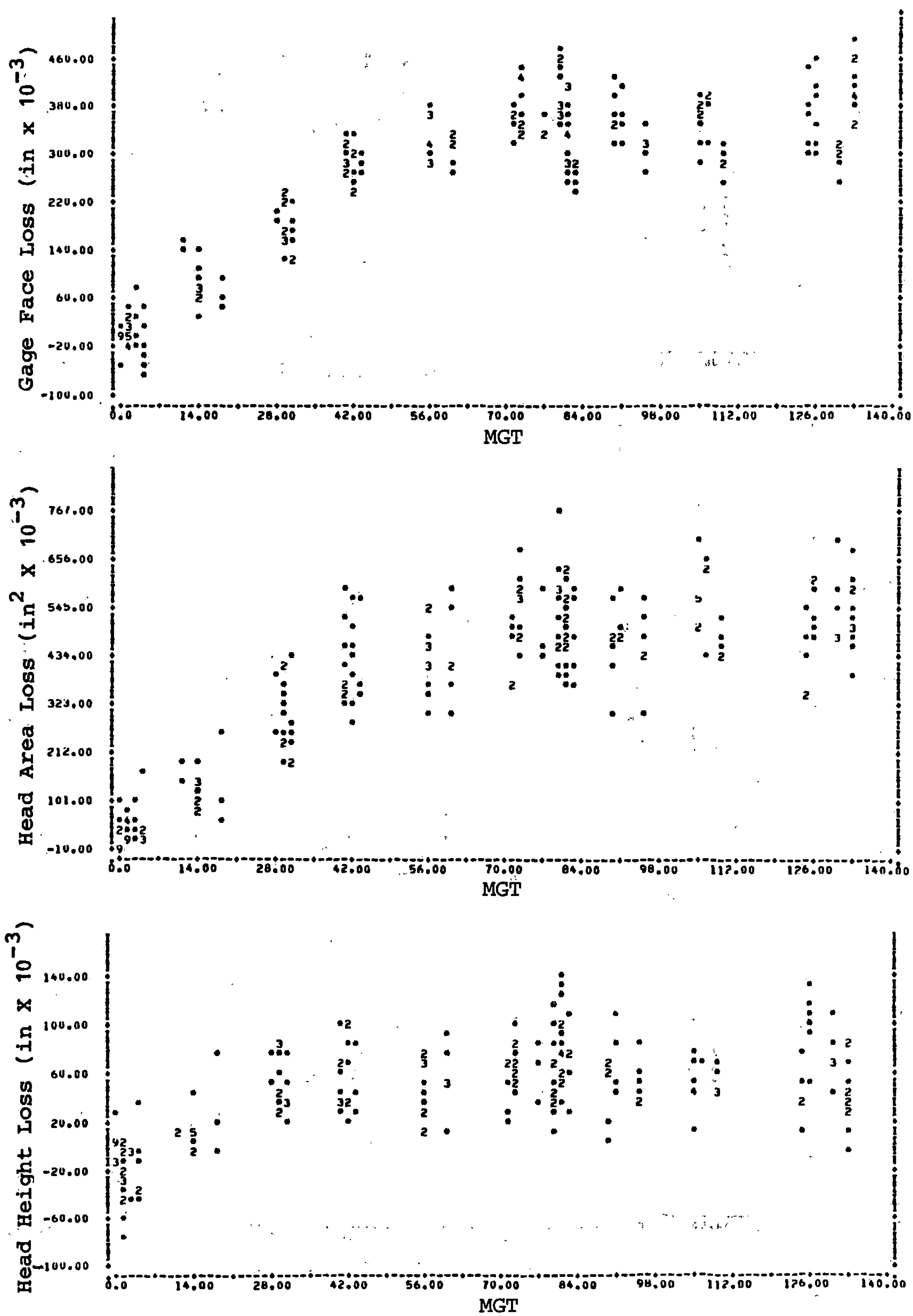


FIGURE 4-14. SCATTERGRAM OF HISI RAIL REGRESSION, 5° CURVE - OUTER - 1:14 CANT.

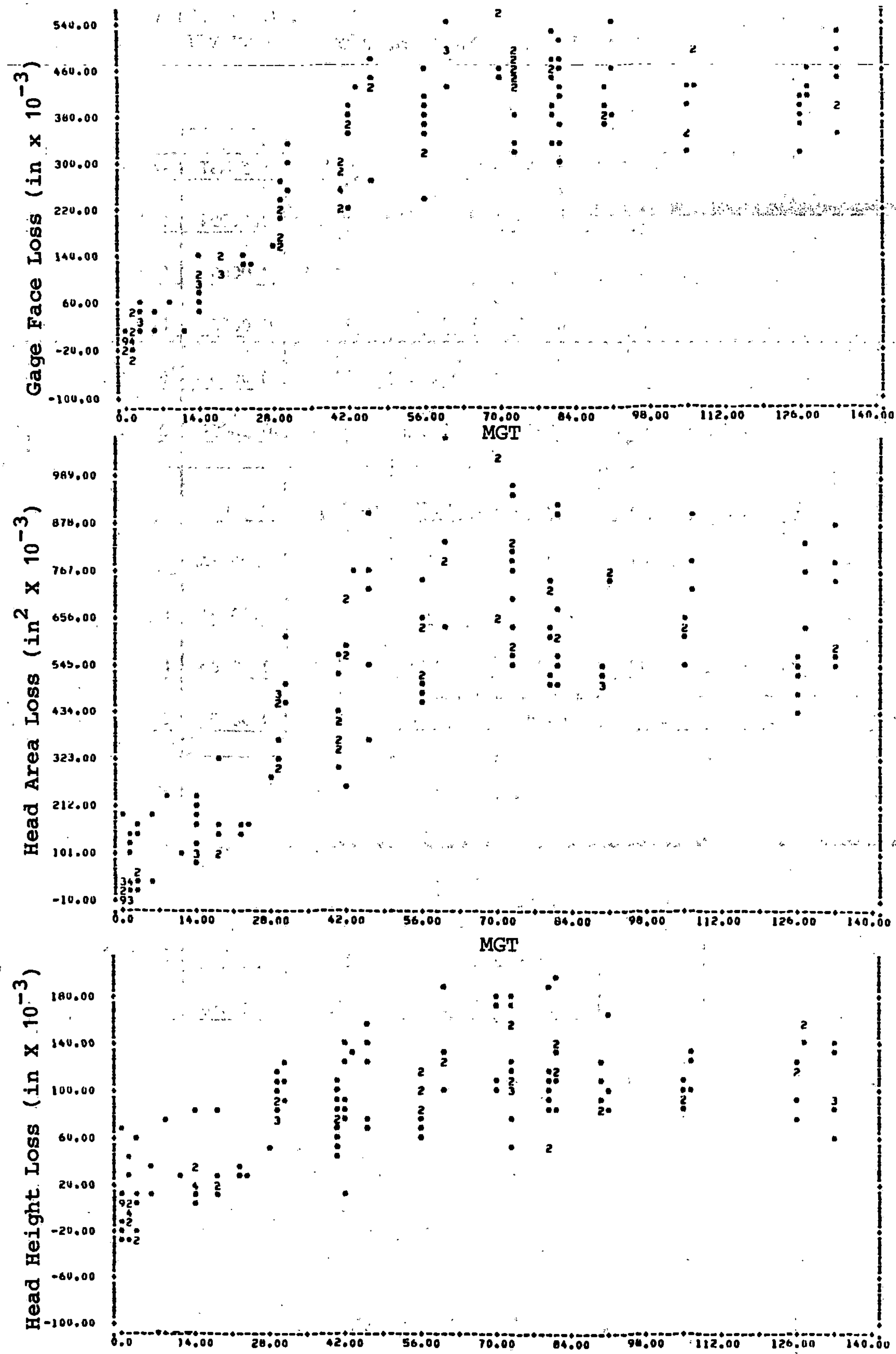


FIGURE 4-15. SCATTERGRAM OF STD CARBON RAIL REGRESSION, 5° CURVE - OUTER - 1:14 CANT.

TABLE 4-1. WEAR RATES ABOVE AND BELOW THE LUBRICATION TRANSITION FOR THE DIFFERENT TIE PLATE CANTS.

	Metallurgy	Tie Plate Cant 1:40 <45 MGT	Tie Plate Cant 1:40 >45 MGT	Tie Plate Cant 1:14 <45 MGT	Tie Plate Cant 1:14 >45 MGT	Tie Plate Cant 1:30 <45 MGT	Tie Plate Cant 1:30 >45 MGT	Avg <45 MGT	Avg >45 MGT
Gage Face Loss (In/MGT)	HH	0.00271	0.00030	0.00384	0.00090	0.00298	0.00054	0.00318	0.00058
	HiSi	0.00579	0.00031	0.00707	0.00149	0.00513	0.00097	0.00600	0.00092
	FHT	0.00550	0.00082	0.00658	0.00111	0.00548	0.00102	0.00585	0.00098
	CrMo	0.00355	0.00059	0.00444	0.00111	0.00401	0.00097	0.00400	0.00089
	Std	0.00809	0.00072	0.00835	0.00135	0.00778	0.00099	0.00807	0.00102
Head Area Loss (In^2/MGT)	HH	0.00496	0.00046	0.00514	0.00092	0.00424	0.00097	0.00478	0.00078
	HiSi	0.00812	0.00110	0.00907	0.00119	0.00708	0.00154	0.00809	0.00128
	FHT	0.00704	0.00046	0.00667	0.00149	0.00627	0.00183	0.00666	0.00126
	CrMo	0.00449	0.00092	0.00423	0.00107	0.00482	0.00085	0.00451	0.00095
	Std	0.01287	0.00167	0.01245	0.00127	0.01229	0.00156	0.01254	0.00150
Head Height Loss (In/MGT)	HH	0.00127	*	0.00109	*	0.00090	*	0.00109	*
	HiSi	0.00144	*	0.00134	*	0.00122	*	0.00133	*
	FHT	0.00097	*	0.00056	*	0.00079	*	0.00077	*
	CrMo	0.00073	*	0.00053	*	0.00052	*	0.00059	*
	Std	0.00256	0.00001	0.00233	0.00011	0.00223	0.00030	0.00237	0.00019

* Indicates no significant wear.

TABLE 4-2. FIGURES OF MERIT ABOVE AND BELOW THE LUBRICATION TRANSITION FOR THE DIFFERENT TIE PLATE CANTS.

	Metallurgy	Tie Plate Cant 1:40		1:14		1:30		Avg	
		<45 MGT	>45 MGT	<45 MGT	>45 MGT	<45 MGT	>45 MGT	<45 MGT	>45 MGT
Gage Face Loss	HH	3.0	2.4	2.2	1.5	1.8	1.8	2.6	1.9
	HiSi	1.4	1.3	1.2	0.9	1.0	1.0	1.4	1.1
	FHT	1.5	0.9	1.3	1.2	1.0	1.0	1.4	1.0
	CrMo	2.3	1.2	1.9	1.2	1.0	1.0	2.0	1.2
	Std	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Head Area Loss	HH	2.6	3.6	2.4	1.4	2.9	1.6	2.6	2.2
	HiSi	1.6	1.5	1.4	1.1	1.7	1.0	1.6	1.2
	FHT	1.8	3.6	1.9	0.8	2.0	0.8	1.9	1.8
	CrMo	2.9	1.8	2.9	1.2	2.5	1.8	2.9	1.6
	Std	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Head Height Loss	HH	2.0	*	2.1	*	2.5	*	2.2	*
	HiSi	1.8	*	1.7	*	1.8	*	1.8	*
	FHT	2.6	*	4.2	*	2.8	*	3.2	*
	CrMo	3.5	*	4.9	*	4.3	*	4.2	*
	Std	1.0	*	1.0	*	1.0	*	1.0	*

* Not calculated due to low wear rate.

NOTE: FM = Standard Carbon wear rate/specified metallurgy wear rate on specific tie plate cant.

over 45 MGT. The same relationship occurs in 10 of the 12 comparisions of head area wear ratios. In all cases, no meaningful comparisons were made for head height wear because of the lack of significant wear in the over 45 MGT environment.

The partial coefficient of determination for the experiment factors after MGT was computed for both wear below and above 45 MGT as an additional measure of how metallurgy and tie plate cant contributions influenced wear rate. This coefficient measured the proportion of variation in wear that was explained by the factors after the effect of traffic was taken into account. The coefficients below 45 MGT were 0.55 and 0.44 for gage face and rail head area wear, respectively, while the comparable coefficients above 45 MGT were 0.26 and 0.24. Thus, the variations in wear caused by metallurgy and tie plate cant combinations were far more important in explaining the wear variations of individual rails below 45 MGT than they were above 45 MGT. Because of the lack of wear above 45 MGT, no computations were calculated for head height loss.

Tables 4-3, 4-4, and 4-5 show that both tie plate cant and metallurgy have a significant effect on all three wear dimensions. The component of variation explained by metallurgy was greater than that attributed to tie plate cant for all three wear measures. The interaction between tie plate cant and metallurgy was significant in two of the three wear dimensions. Thus, the wear rate of a metallurgy and tie plate cant combination cannot be predicted by combining metallurgy wear rates with tie plate cant wear rates, except in the case of head height wear.

The simpler analysis, which was restricted to gage face wear, tested the effect on wear rates* of the varying division points (40 vs 45 MGT) between the two lubrication regimes. In addition, the effects of position-in-curve (Section 03) were separated by grouping segments A through C together to represent the start of the Section 03 curve; segments D through G represented the middle, and segments H through J were for the south end. The average gage face wear rates in inches per MGT for each segment are tabulated in tables 4-6 thru 4-9. When the data for the underlubricated regime are grouped by metallurgy for each tie plate cant averaged over the three positions-in-curve, an apparent metallurgy:tie plate cant interaction can be observed. This interaction was manifest by the 1:14 cant plate producing somewhat less gage face wear for Std rail while producing substantially more wear for all other metallurgies. Also, the 1:30 cant plate yielded slightly less wear, on the average, for Std and HiSi rail than did the 1:40 cant plate.

The wear rate data and FM when averaged over the beginning, middle, and end of Section 03, were in close agreement with the values determined by the more detailed analysis as shown in table 4-10. These results confirm the occurrence of a major reduction in wear rate after 40 or 45 MGT. The wear advantage of premium rail was reduced under conditions of generous lubrication as was attested by the results of a grouping of metallurgies into three groups (Std, HiSi; FHT, CrMo; HH) in the regime prior to 40-45 MGT and only two groups (Std, HiSi, FHT, CrMo; HH) above the transition. Table 4-11 illustrates the good agreement between the results of two different analyses

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* The wear rates were found by regression on that data for each metallurgy alone.

TABLE 4-3. ANALYSIS OF EFFECTS OF TIE PLATE CANT AND RAIL METALLURGY ON GAGE FACE WEAR.

VARIATION EXPLAINED BY LINEAR MODELS

MODEL TYPE	FACTORS EFFECTS IN MODELS	SUM OF SQUARED DEVIATIONS EXPLAINED	DEGREES OF FREEDOM
a	None	43.617	7
b (A)	Tie Plate Cant	51.839	25
b (B)	Metallurgy	58.064	29
c	Additive - Tie Plate Cant - Metallurgy	58.778	33
d	Interactive - Tie Plate Cant - Metallurgy	58.940	49
d	Unexplained by Factors	5.573	3541

ANALYSIS OF VARIANCE

COMPARISON TYPE	TEST FOR EFFECT	INCREMENTAL FACTOR EFFECT SUM OF SQUARE DEVIATION	DEGREES OF FREEDOM	MEAN SQUARE	F RATIO
a (A)	Tie Plate Cant	8.221	18	0.4567	290.2*
a (B)	Metallurgy	14.441	22	0.6667	417.2*
b	Additive - Tie Plate Cant - Metallurgy	15.160	25	0.6024	385.3*
c (A)	Tie Plate Cant (After Metallurgy)	0.714	4	0.1785	113.4*
a (B)	Metallurgy (After Tie Plate Cant)	6.225	8	0.7782	494.4*
d	Interactive - Metallurgy - Tie Plate Cant	0.162	16	0.0101	6.4*
	Unexplained	5.573	41	0.00157	

*Indicates 0.01 level of significance (significance at 99% confidence level).

TABLE 4-4. ANALYSIS OF EFFECTS OF TIE PLATE CANT AND RAIL METALLURGY ON RAIL HEAD AREA.

VARIATION EXPLAINED BY LINEAR MODELS

MODEL TYPE	FACTORS EFFECTS IN MODELS	SUM OF SQUARED DEVIATIONS EXPLAINED	DEGREES OF FREEDOM
a	None	88.972	7
b (A)	Tie Plate Cant	106.976	25
b (B)	Metallurgy	128.223	29
c	Additive - Tie Plate Cant - Metallurgy	128.551	33
d	Interactive - Tie Plate Cant - Metallurgy	129.054	49
d	Unexplained by Factors	25.649	3617

ANALYSIS OF VARIANCE

COMPARISON TYPE	TEST FOR EFFECT	INCREMENTAL FACTOR EFFECT			
		SUM OF SQUARE DEVIATION	DEGREES OF FREEDOM	MEAN SQUARE	F RATIO
a (A)	Tie Plate Cant	18.004	18	1.0002	141.0*
a (B)	Metallurgy	39.291	22	1.7841	251.6*
b	Additive - Tie Plate Cant - Metallurgy	39.579	25	1.5835	223.2*
c (A)	Tie Plate Cant (After Metallurgy)	0.328	4	0.0820	11.5*
c (B)	Metallurgy (After Tie Plate Cant)	21.575	8	2.6969	380.3*
d	Interactive - Metallurgy - Tie Plate Cant	0.503	16	0.0314	4.4*
	Unexplained	25.649	17	0.0071	

*Indicates 0.01 level of significance (significance at 99% confidence level).

TABLE 4-5. ANALYSIS OF EFFECTS OF TIE PLATE CANT AND RAIL METALLURGY ON HEAD HEIGHT.

VARIATION EXPLAINED BY LINEAR MODELS

MODEL TYPE		FACTORS EFFECTS IN MODELS	SUM OF SQUARED DEVIATIONS EXPLAINED	DEGREES OF FREEDOM
a		None	1.8729	7
b	(A)	Tie Plate Cant	2.6356	25
b	(B)	Metallurgy	3.5492	29
c		Additive - Tie Plate Cant - Metallurgy	3.5758	33
d		Interactive - Tie Plate Cant - Metallurgy	3.5963	49
d		Unexplained by Factors	2.2398	3449

ANALYSIS OF VARIANCE

COMPARISON TYPE		TEST FOR EFFECT	INCREMENTAL FACTOR EFFECT			
			SUM OF SQUARE DEVIATION	DEGREES OF FREEDOM	MEAN SQUARE	F RATIO
a	(A)	Tie Plate Cant	0.7627	18	0.0423	62.7*
a	(B)	Metallurgy	1.6763	22	0.0762	112.8*
b		Additive - Tie Plate Cant - Metallurgy	1.7029	25	0.0681	100.8*
c	(A)	Tie Plate Cant (After Metallurgy)	0.0266	4	0.0066	9.8*
c	(B)	Metallurgy (After Tie Plate Cant)	0.9402	8	0.1175	173.9*
d		Interactive - Metallurgy - Tie Plate Cant	0.0205	16	0.00128	1.896*
		Unexplained	2.3298	3449	0.00067	

*Indicates 0.01 level of significance (significance at 99% confidence level).

TABLE 4-6. GAGE FACE WEAR RATES (IN/MGT).

<40 MGT MILLION GROSS TONS

Cant	Section		Std	HiSi	FHT	CrMo	HH	Average
1:40	Start	(A)	0.0085	0.0041	0.0052	0.0033	0.0019	0.0046
	Middle	(F)	0.0101	0.0067	0.0060	0.0036	0.0025	0.0058
		(G)	0.0108	0.0068	0.0061	0.0039	0.0027	
	End	(J)	0.0095	0.0075	0.0066	0.0050	0.0033	0.0064
	Average		0.0094	0.0061	0.0059	0.0040	0.0026	
1:30	Start	(B)	0.0079	0.0059	0.0062	0.0042	0.0029	0.0056
	Middle	(E)	0.0073	0.0040	0.0053	0.0033	0.0030	0.0046
	End	(I)	0.0104	0.0071	0.0065	0.0048	0.0035	0.0065
	Average		0.0085	0.0057	0.0060	0.0041	0.0031	
1:14	Start	(C)	0.0074	0.0076	0.0059	0.0044	0.0039	0.0058
	Middle	(D)	0.0094	0.0075	0.0068	0.0043	0.0033	0.0063
	End	(H)	0.0114	0.0075	0.0067	0.0054	0.0045	0.0071
	Average		0.0094	0.0075	0.0065	0.0047	0.0039	

Note: Section 03 data.

TABLE 4-7. GAGE FACE WEAR RATES (IN/MGT).

<45 MGT MILLION GROSS TONS

Cant	Section		Std	HiSi	FHT	CrMo	HH	Average
1:40	Start	(A)	0.0083	0.0040	0.0049	0.0033	0.0019	0.0045
	Middle	(F)	0.0094	0.0063	0.0057	0.0035	0.0025	0.0056
		(G)	0.0102	0.0064	0.0058	0.0038	0.0025	
	End	(J)	0.0089	0.0059	0.0060	0.0047	0.0031	0.0057
	Average		0.0092	0.0056	0.0056	0.0038	0.0025	
1:30	Start	(B)	0.0076	0.0058	0.0059	0.0041	0.0029	0.0053
	Middle	(E)	0.0070	0.0039		0.0033	0.0029	0.0043
	End	(I)	0.0096	0.0065	0.0060	0.0044	0.0033	0.0060
	Average		0.0081	0.0054	0.0054	0.0039	0.0030	
1:14	Start	(C)	0.0073	0.0073	0.0058	0.0044	0.0037	0.0057
	Middle	(D)	0.0090	0.0073	0.0065	0.0042	0.0033	0.0061
	End	(H)	0.0107	0.0073	0.0062	0.0050	0.0041	0.0067
	Average		0.0090	0.0073	0.0062	0.0045	0.0037	

Note: Section 03 data.

TABLE 4-8. GAGE FACE WEAR RATES (IN/MGT).

>40 MGT MILLION GROSS TONS

Cant	Section		Std	HiSi	FHT	CrMo	HH	Average
1:40	Start	(A)	0.0003	0.0016	0.0013	0.0012	0.0011	0.0011
	Middle	(F)	0.0010	0.0014	0.0014	0.0017	0.0012	0.0014
		(G)	0.0024	0.0014	0.0015	0.0015	0.0009	
	End	(J)	0.0011	0.0012	0.0004	0.0010	0.0010	0.0009
	Average		0.0012	0.0014	0.0012	0.0014	0.0010	
1:30	Start	(B)	0.0019	0.0017	0.0016	0.0012	0.0012	0.0015
	Middle	(E)	0.0023	0.0019	0.0053	0.0020	0.0014	0.0026
	End	(I)	0.0004	0.0008	0.0007	0.0006	0.0002	0.0005
	Average		0.0015	0.0015	0.0025	0.0013	0.0009	
1:14	Start	(C)	0.0023	0.0015	0.0018	0.0016	0.0006	0.0016
	Middle	(D)	0.0028	0.0025	0.0018	0.0020	0.0014	0.0021
	End	(H)	0.0021	0.0011	0.0005	0.0006	0.0005	0.0010
	Average		0.0024	0.0017	0.0014	0.0014	0.0008	

Note: Section 03 data.

TABLE 4-9. GAGE FACE WEAR RATES (IN/MGT).

>45 MGT MILLION GROSS TONS

Cant	Section	Std	HiSi	FHT	CrMo	HH	Average
1:40	Start (A)	-0.0006	0.0014	0.0010	0.0009	0.0010	0.00074
	Middle (F)	0.0008	0.0011	0.0012	0.0016	0.0011	0.0012
	(G)	0.0020	0.0010	0.0012	0.0014	0.0009	
	End (J)	0.0007	0.0004	0.0002	0.0009	0.0009	0.0062
	Average	0.0003	0.0010	0.0009	0.0012	0.0010	
1:30	Start (B)	0.0014	0.0013	0.0012	0.0010	0.0009	0.0012
	Middle (E)	0.0019	0.0017	0.0091	0.0019	0.0012	0.0017
	End (I)	0.0000	0.0006	0.0005	0.0004	0.0000	0.0003
	Average	0.0011	0.0012	0.0006	0.0011	0.0007	
1:14	Start (C)	0.0018	0.0010	0.0013	0.0013	0.0004	0.0012
	Middle (D)	0.0023	0.0021	0.0014	0.0019	0.0012	0.0018
	End (H)	0.0015	0.0007	0.0003	0.0003	0.0004	0.0006
	Average	0.0019	0.0013	0.0010	0.0012	0.0007	

Note: Section 03 data.

TABLE 4-10. AVERAGE GAGE FACE LOSS (SECTION 03) COMPARISON OF RESULTS OF ANALYSIS FROM DIFFERENT SOURCES.

in/MGT / FM	Below Lubrication Transition			Above Lubrication Transition		
	AAR	T S C		AAR	T S C	
	<45 MGT	<45 MGT	<40 MGT	>45 MGT	>45 MGT	>40 MGT
Std	0.0081 1.0	0.0087 1.0	0.0091 1.0	0.0010 1.0	0.0011 1.0	0.0016 1.0
HiSi	0.0060 1.4	0.0060 1.4	0.0064 1.4	0.0009 1.1	0.0012 0.9	0.0015 1.1
FHT	0.0058 1.4	0.0057 1.5	0.0061 1.5	0.0010 1.0	0.0009 1.2	0.0013 1.3
CrMo	0.0040 2.0	0.0041 2.1	0.0042 2.2	0.0009 1.1	0.0011 1.0	0.0013 1.3
HH	0.0032 2.5	0.0031 2.8	0.0032 2.8	0.0006 1.7	0.0008 1.4	0.0009 1.8

Note: The Figure of Merit numbers in this table were calculated from ratios of average wear rates reported here; therefore, they may disagree slightly with those cited in other tables.

TABLE 4-11. TIE PLATE CANT EFFECT (SECTION 03). (AVERAGE OF ALL METALLURGIES AND POSITIONS-IN-CURVE).

(in/MGT)

	<40 or 45 MGT			>40 or 45 MGT		
Cant	AAR (45)	TSC (45)	TSC (40)	AAR (45)	TSC (45)	TSC (40)
1:40	0.0051	0.0052	0.0056	0.00055	0.0008	0.0011
1:30	0.0051	0.0052	0.0056	0.00090	0.0011	0.0013
1:14	0.0061	0.0062	0.0064	0.00119	0.0012	0.0016

for the average of all metallurgies on different tie plate cants. In the earlier regime (poorer lubrication) the 1:40 and 1:30 cants yielded similar, overall average wear rates, while the 1:14 cant produced approximately 20% higher wear rates. However, in the more generously lubricated regime above 40-45 MGT, the picture is less clear; although the 1:14 cant still produced the highest wear rate, the 1:40 cant appeared to produce noticeably lower wear rates than did the 1:30 cant.

Table 4-12 summarizes the overall averages of all metallurgies and tie plate cants for each position-in-curve. The earlier regime, at the beginning (Section 02 end) and middle portions of the Section 03 curve, exhibited about the same overall average wear rates, while the end portion (Section 04 end) exhibited about a 15% higher wear rate on the average. In the more generously lubricated regime, the end portions of the curve appear to have the lower overall average wear rate while the middle of the curve appears to have the higher wear rate--approximately two to three times as high as the Section 04 end portion.

The results from each metallurgy, tie plate cant, and position-in-curve analysis did not seem to be strongly influenced by whether or not the transition between the poorer and the more generous lubrication regimes was selected at 40 or 45 MGT.

Table 4-13 summarizes the results of the analysis of variance test for statistical significance of the wear rate observations described above. The results for wear rate show that the main effects of metallurgy, tie plate cant, and position-in-curve had very strong statistical significance (99% confidence level) in the early regime of wear but, in the more generously lubricated regime, the statistical significance of the tie plate cant effect was reduced; i.e., cant was statistically significant only at the 95% confidence level rather than the 99% confidence level. Both above and below the lubrication transition (40 MGT), a little weaker (95% confidence level) tie plate cant:position-in-curve interaction appeared to occur. This is to say that the combined effect of tie plate cant and position-in-curve could be different from the sum of the individual tie plate cant and position-in-curve contributions. The apparent tie plate cant:metallurgy interaction cited previously does not show up as statistically significant with the "F" test applied to the entire body of gage face wear rate data. However, if all wear rates are normalized against those of Std rail for each tie plate cant and position-in-curve, the "F" test, or analysis of variance (ANOVA), does reveal a weak (95% confidence) cant:metallurgy interaction along with a cant:position interaction. This is shown in table 4-14.

The simplifed analysis was also applied to the gage face loss data of rail in Section 13. The wear rates above and below 40 MGT for each metallurgy and position-in-curve along with the average FM for metallurgy are given in table 4-15. As was the case for Section 03, the results show that, overall, HH rail was substantially better (nearly four times) than Std rail in the first (poorer) lubrication regime, and that FHT and HiSi rail fell into the intermediate category. Above 40 MGT (in the regime of more generous lubrication), all premium metallurgies behaved only slightly better than did Std rail. Some exceptionally low wear rates (perhaps not really that low) which occurred in segment B with HiSi and FHT caused their behavior to appear marginally better than HH rail. No consistent position-in-curve effect could be observed for

TABLE 4-12. POSITION-IN-CURVE EFFECT (SECTION 03). (AVERAGE OF ALL METALLURGIES AND TIE PLATE CANTS).

(in/MGT)

	<40 or 45 MGT		>40 or 45 MGT	
Location	45	40	45	40
Section 02 End	0.0052	0.0053	0.0010	0.0014
Middle	0.0053	0.0056	0.0016	0.0018
Section 04 End	0.0061	0.0067	0.0005	0.0008

TABLE 4-13. RESULTS OF STATISTICAL TESTS FOR SIGNIFICANCE OF THE SECTION 03 GAGE FACE WEAR RATES FOR DIFFERENT TIE PLATE CANTS AND POSITION-IN-CURVE.

Effect or Interaction	Observed 'F'	Significance at 99% 'F' Req'd	Significance at 99% Yes/No	Significance at 95% 'F' Req'd	Significance at 95% Yes/No
<u><40 MGT:</u>					
Cant	7.98	6.23	Yes	3.63	Yes
Pos-in-Curve	16.79	6.23	Yes	3.63	Yes
Metallurgy	90.96	4.77	Yes	3.01	Yes
Cant:Pos	3.73	4.77	No	3.01	Yes
Pos:Met	1.27	3.89	No	2.59	No
Met:Cant	0.75	3.89	No	2.59	No
<u>>40 MGT</u>:					
Cant	3.86	6.23	No	3.63	Yes
Pos-in-Curve	57.97	6.23	Yes	3.63	Yes
Metallurgy	14.85	4.77	Yes	3.01	Yes
Cant:Pos	4.57	4.77	No	3.01	Yes
Pos:Met	0.96	3.89	No	2.59	No
Met:Cant	2.19	3.89	No	2.59	No

Note: 'F' from analysis of variance.

TABLE 4-14. RESULTS OF STATISTICAL TESTS FOR SIGNIFICANCE OF FIGURE MERIT FOR SECTION 03 GAGE FACE WEAR RATE BELOW 40 MGT.

Effect or Interaction	Observed 'F'	Significance at 99% 'F' Req'd	99% Yes/No	95% 'F' Req'd	95% Yes/No
Cant	8.92	6.23	Yes	3.63	Yes
Pos-in-Curve	2.93	6.23	Yes	3.63	Yes
Metallurgy	84.84	4.77	Yes	3.01	Yes
Cant:Pos	3.94	4.77	No	3.01	Yes
Post:Met	0.62	3.84	No	2.59	No
Met:Cant	3.21	3.89	No	2.59	Yes

Note: 'F' from analysis of variance

TABLE 4-15. GAGE FACE WEAR RESULTS FROM SECTION 13 (IN/MGT).

Metallurgy	Position-in-Curve A	B	C	D	Avg	Average Figure of Merit
<u><40 MGT</u>						
HH	0.0021	0.0017	0.0025	0.0021	0.0022	3.5
HiSi	0.0052	0.0049	0.0045	0.0043	0.0047	1.6
FHT	0.0038	0.0038	0.0034	0.0037	0.0037	2.1
Std	0.0063	0.0092	0.0094	0.0060	0.0077	1.0
Avg	0.0044	0.0049	0.0050	0.0046		
<u>>40 MGT</u>						
HH	0.0014	0.0012	0.0003	0.0010	0.0010	1.3
HiSi	0.0025	0.0001	0.0006	0.0014	0.0012	1.1
FHT	0.0020	-0.0001	0.0010	0.0012	0.0010	1.3
Std	0.0016	0.0010	0.0010	0.0016	0.0013	1.0
Avg	0.0019	0.0006	0.0007	0.0013		

A = Section 02 End
B,C = Middle
D = Section 04 End

all four metallurgies. Typically, more effective lubrication reduced the wear rate of Std rail by factors of 4 to 10 while the improvement for the premium rails was substantially less.

The statistical tests for significance (table 4-16) confirmed the presence of strong metallurgy and lubrication main effects. Also, the occurrence of a strong lubrication:metallurgy interaction suggests that the Section 03 observation (that not all metallurgies were influenced in an equivalent way by improved lubrication) is valid. However, unlike Section 03, the presence of a position-in-curve effect could not be confirmed statistically.

The average gage face wear rates and FM's for each metallurgy common to Sections 03 and 13 (1:40 cant only), as determined by the simplified analysis, are given in table 4-17 along with the ratio of Section 13 to Section 03 wear rates. Overall, the gage face wear rate of Section 13 was approximately 80% of that in Section 03, which was consistent with a linear relationship of gage face wear to the degree of curvature. But individual metallurgies behaved substantially differently.

Statistical tests for significance of the average gage face wear rates and FM's (table 4-18) revealed that the main effects of metallurgy and lubrication were strongly significant in both test sections, that there was a real lubrication:metallurgy interaction in both test sections, and that the FM's for a given metallurgy in both sections were statistically the same. This last observation means that insofar as the metallurgy main effect was concerned, the relative wear behavior of the different metallurgies tested in Section 13 matched that in Section 03.

The comparisons between different metallurgies previously cited represent a somewhat unbalanced assessment; i.e., many more heats of Std and HiSi rails were tested than those of the other three rail metallurgies. Thus, the wider range of wear rates observed for Std and HiSi rails compared to the somewhat less variable rates of the CrMo, FHT, and HH rails could lead to an over estimation of improvement in wear rates achievable through the use of premium rails (by comparison with the performance of Std rail). Indeed, as shown in Figures 4-16 through 4-18, some of the Std rail heats (29776, 29780, 29782, and 29792) on various tie plate cants seemed to yield noticeably higher wear rates in the first wear regime than did the remaining heats. This behavior also was reflected in the one sigma (σ) maximum and minimum bounds on gage face wear rate determined in the simplified analysis; figure 4-19 shows the maximum and minimum values of gage face wear for those Section 03 test segments containing even one rail of the high wear heats, as distinguished from segments with one or more rail from those heats with lower wear rates. Where high-wear-rate heat/tie plate cant combinations occurred in a segment with a low-wear-rate heat, the maximum value of wear rate was assigned to the high-wear-rate heat, and the low-wear-rate was assigned to the other heats. Most of the heats (6) produced gage face wear rates within the range from 0.0049 to 0.0108 in/MGT while only four heat/tie plate cant combinations yielded noticeably higher wear rate extremes. If the high-wear-rate heat/tie plate cant combinations were to be removed, the mean gage face wear rate of the Std rails would be reduced by approximately 8% below 45 MGT; this in turn would reduce the overall FM for each premium metallurgy roughly by an equivalent amount. Reduction in the overall wear rate for head area loss and head height loss would be comparable below 45 MGT, approximately 8 and 4%, respect-

TABLE 4-16. RESULTS OF STATISTICAL TESTS FOR SIGNIFICANCE OF SECTION 13 GAGE FACE WEAR RATES ABOVE AND BELOW 40 MGT.

Effect or Interaction	Observed 'F'	Significance at 99% 'F' Req'd	Significance at 99% Yes/No	Significance at 95% 'F' Req'd	Significance at 95% Yes/No
Pos-in-Curve	0.61	6.99	No	3.86	No
Lubrication	180.40	10.60	Yes	5.12	Yes
Metallurgy	23.91	6.99	Yes	3.86	Yes
Pos:Lub	3.61	6.99	No	3.86	No
Lub:Met	19.01	6.99	Yes	3.86	Yes
Met:Pos	1.26	5.35	No	3.19	No

Note: 'F' from analysis of variance

TABLE 4-17. COMPARISON OF GAGE FACE WEAR IN TEST SECTIONS 03 AND 13 ALL ON 1:40 TIE PLATE CANT.

METALLURGY	Section 03				Section 13			
	<40 MGT		>40 MGT		<40 MGT		>40 MGT	
	WEAR RATE (in/MGT)	FM	WEAR RATE (in/MGT)	FM	WEAR RATE (in/MGT)	FM	WEAR RATE (in/MGT)	FM
Std	0.0097	1.0	0.0016	1.0	0.0078	1.0	0.0014	1.0
HiSi	0.0063	1.5	0.0013	1.2	0.0046	1.7	0.0009	1.6
FHT	0.0060	1.6	0.0012	1.3	0.0037	2.1	0.0009	1.5
HH	0.0026	3.7	0.0010	1.6	0.0022	3.6	0.0010	1.5

RELATIVE GAGE FACE WEAR IN SECTION 03 AND 13.

Ratio: Wear Rate Section 13/Wear Rate Section 03

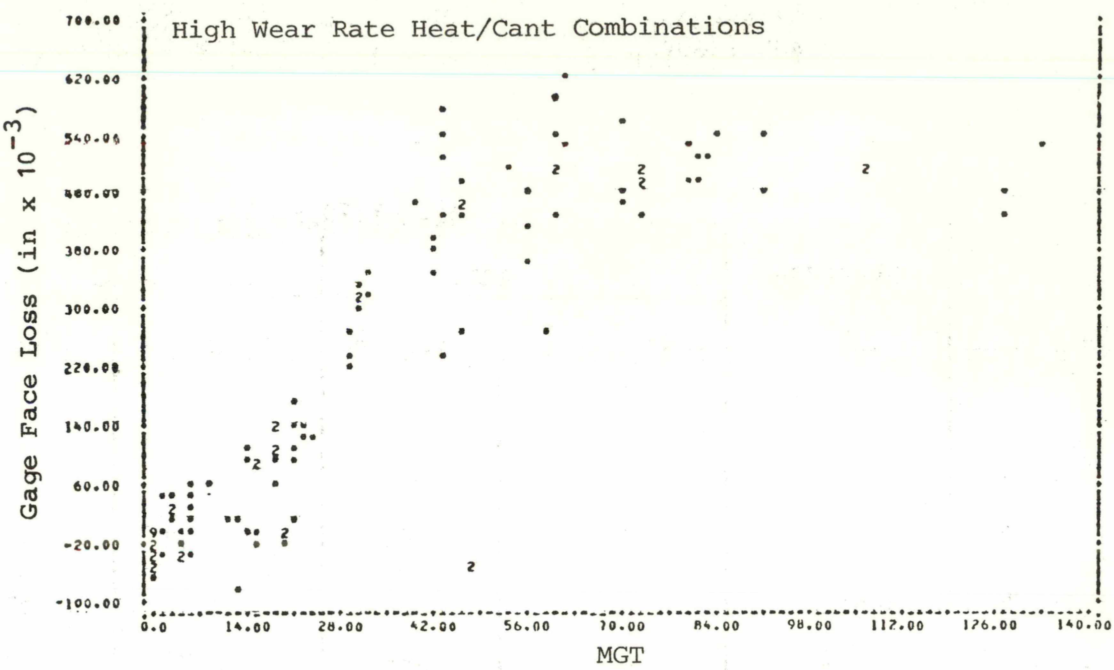
Metallurgy	<40 MGT	>40 MGT
Std	0.804	0.906
HiSi	0.746	0.671
FHT	0.617	0.809
HH	0.846	0.993
Avg	0.753	0.845

Overall Average = 0.799

TABLE 4-18. RESULTS OF STATISTICAL TESTS FOR SIGNIFICANCE OF AVERAGE GAGE FACE WEAR RATES (1:40 CANT ONLY) AND FIGURES OF MERIT FROM TEST SECTION 03 AND 13.

Effect or Interaction	Observed 'F'	Significance at 99% 'F' Req'd	99% Yes/No	95% 'F' Req'd	95% Yes/No
Gage Face Wear Rate:					
Section	22.23	34.1	No	10.10	Yes
Lubrication	500.56	34.1	Yes	10.10	Yes
Metallurgy	56.74	29.5	Yes	9.28	Yes
Sec:Lub	13.14	34.1	No	10.10	Yes
Lub:Met	40.70	29.5	Yes	9.28	Yes
Met:Sec	1.57	29.5	No	9.28	No
Figure Of Merit:					
Section	3.25	3.1	No	1.10	No
Lubrication	109.72	34.1	Yes	10.10	Yes
Metallurgy	97.56	29.5	Yes	9.28	Yes
Sec:Lub	0.03	34.1	No	10.10	No
Lub:Met	52.44	29.5	Yes	9.28	Yes
Met:Sec	3.01	29.5	No	9.28	No

Note: 'F' from analysis of variance



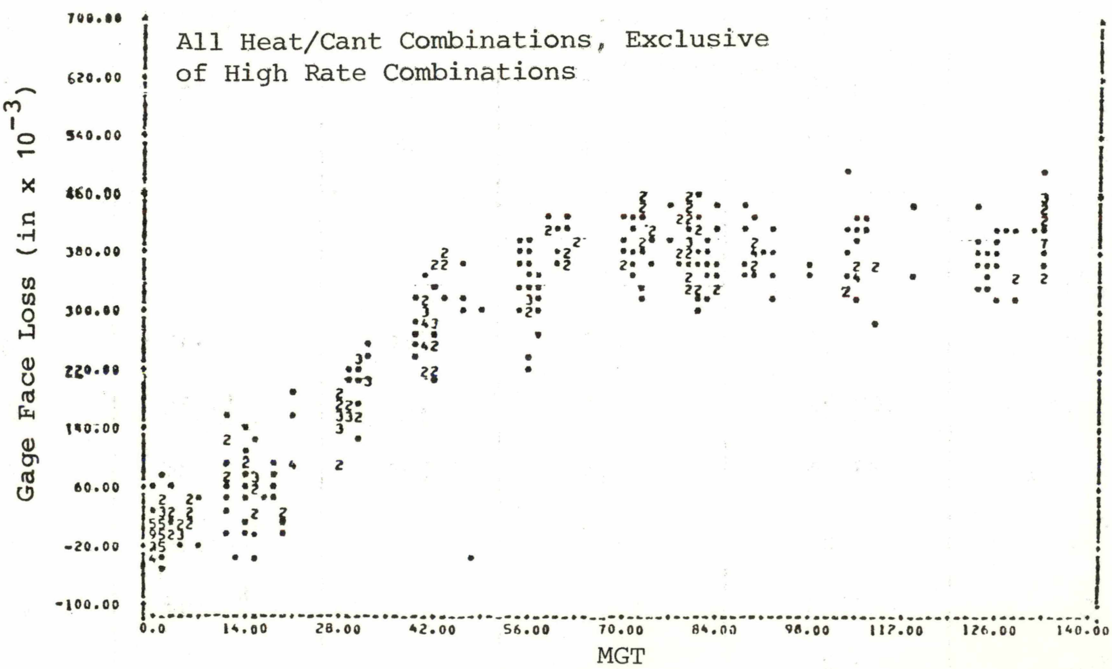
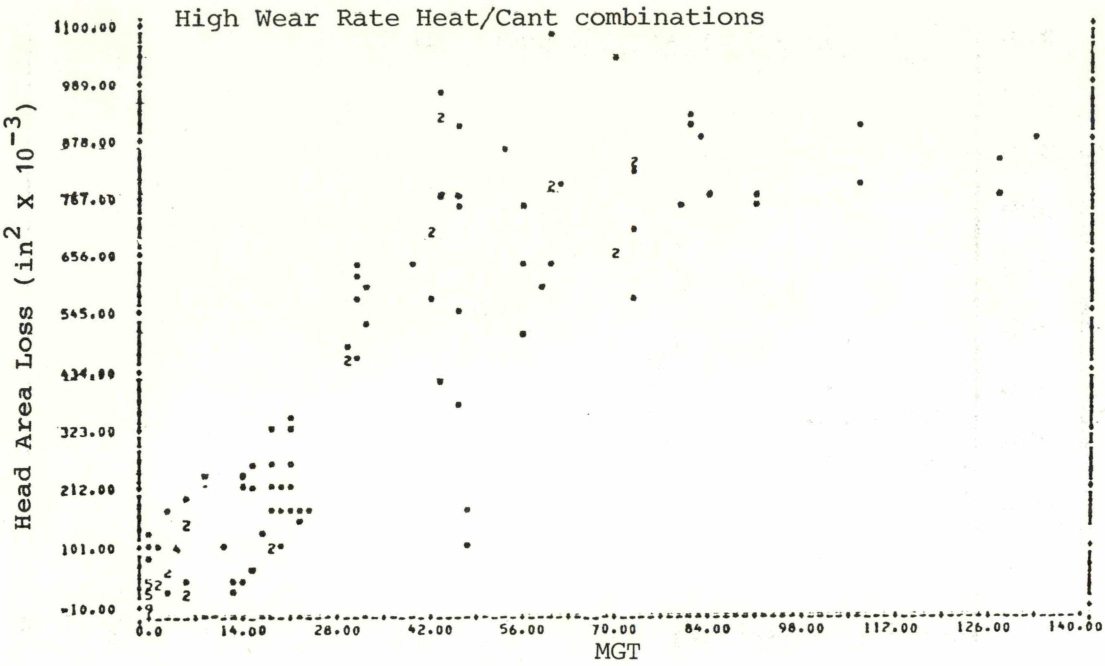


FIGURE 4-16. GAGE FACE WEAR SCATTERGRAM OF HEAT DATA PLOTS.



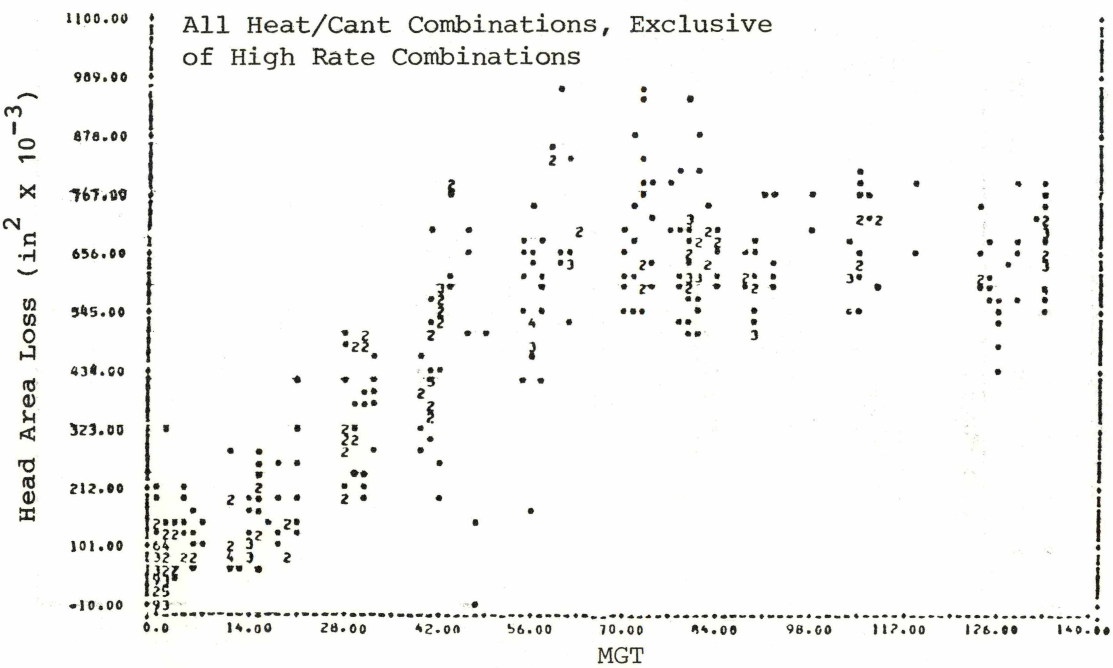
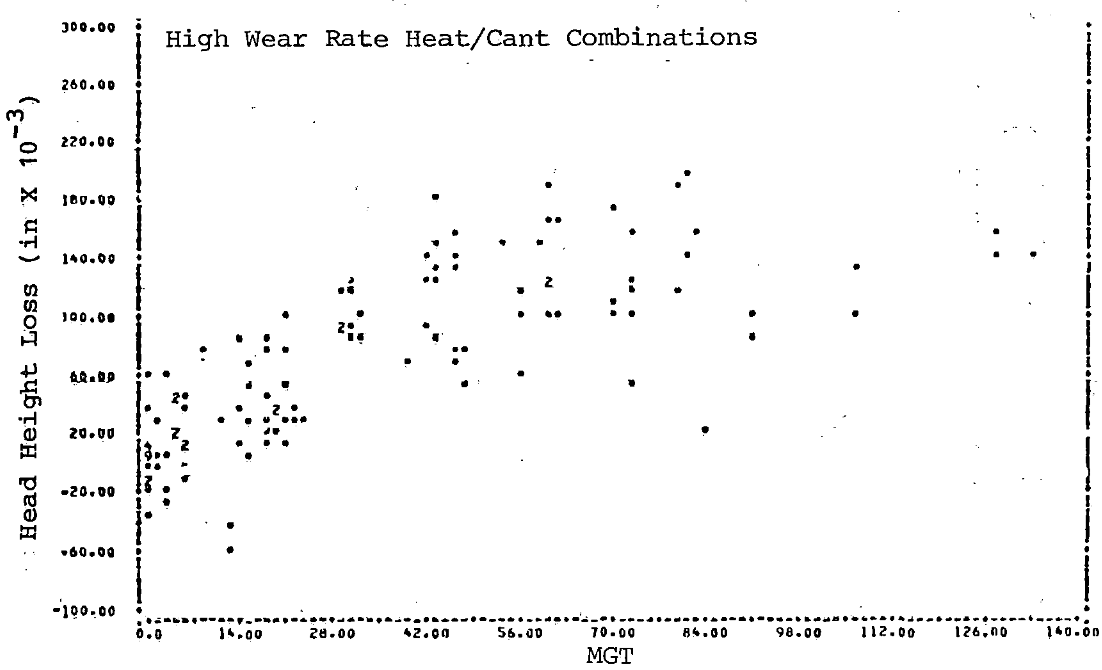


FIGURE 4-17. AREA LOSS SCATTERGRAM OF HEAT DATA PLOTS.



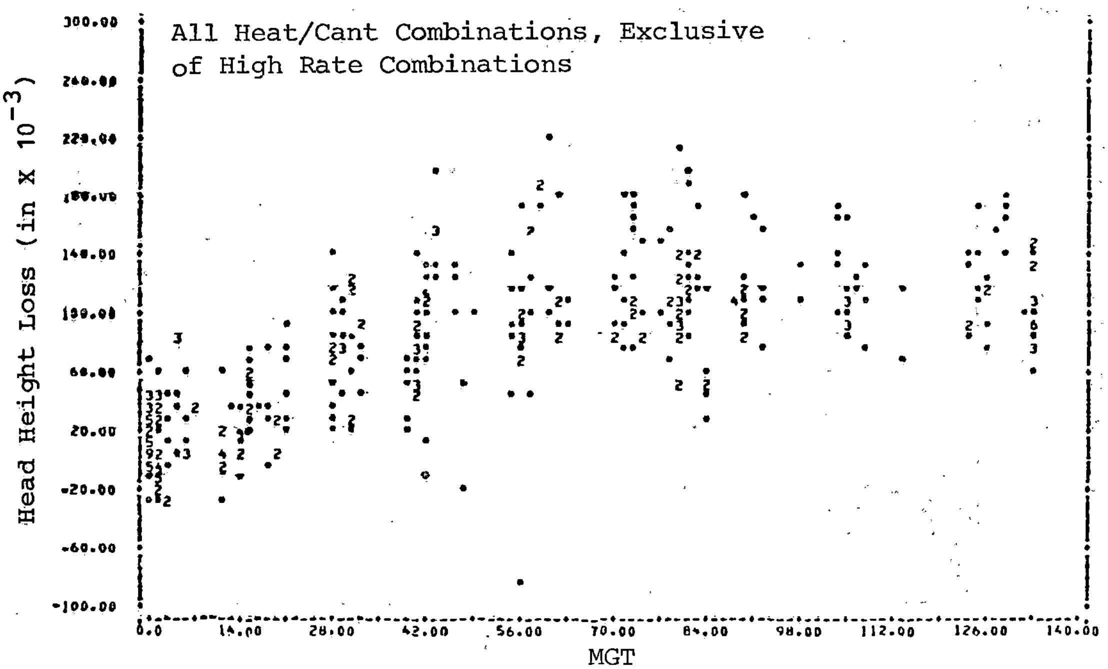


FIGURE 4-18. HEAD HEIGHT LOSS SCATTERGRAM OF HEAT DATA PLOTS.

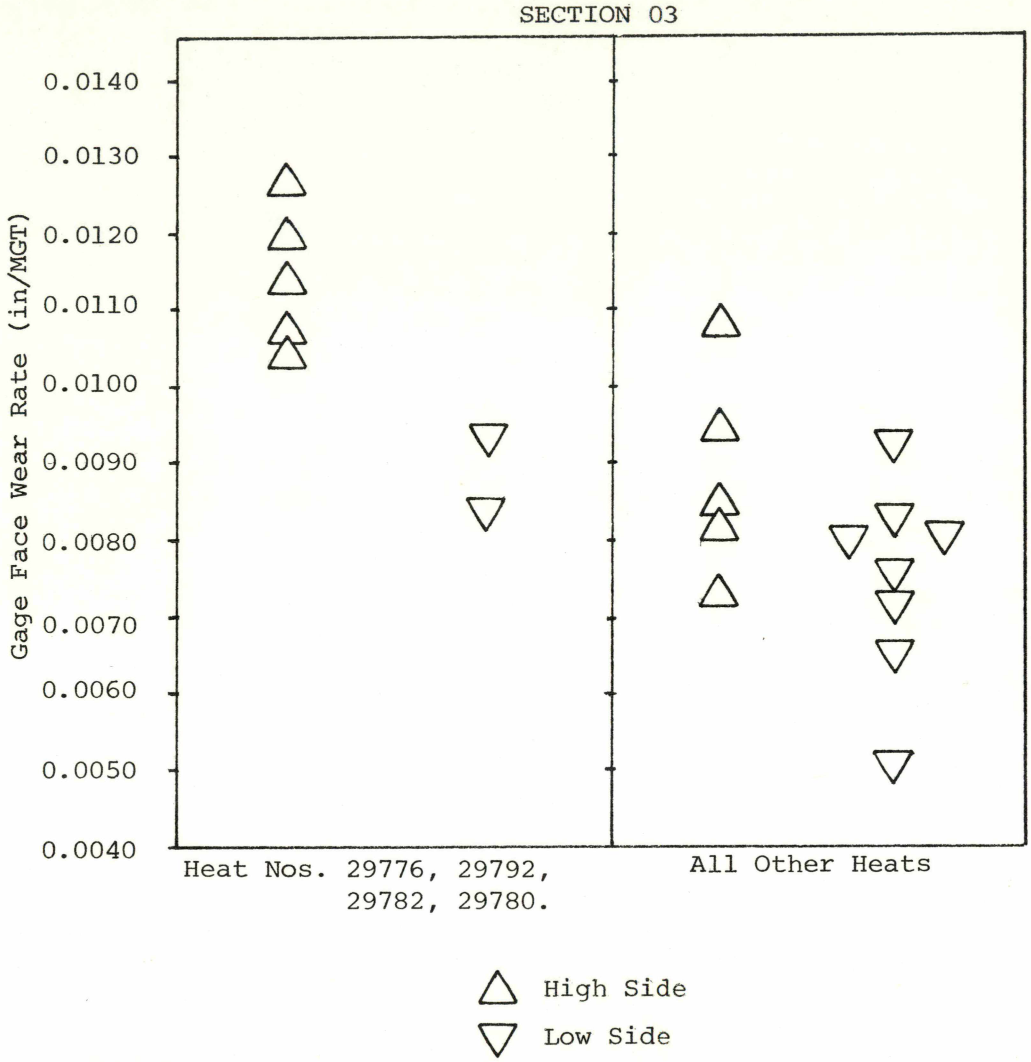


FIGURE 4-19. VARIATION OF ONE SIGMA MAXIMUM/MINIMUM VALUES FOR GAGE FACE WEAR OF DIFFERENT STANDARD RAIL HEATS.

ively, as cited in table 4-19. Above 45 MGT, the data are so scattered that the possible effect of heat is obscured. It should be noted that the numbers in table 4-19 are slightly different from the averages of the wear rates given in table 4-1 because they were created by regressing only on the Std rail data, and not upon the entire set of data for all metallurgies, as was the case for the data given in table 4-1. Furthermore, the results of table 4-1 are the averaged rates for each metallurgy:cant combination, based on the presumption that there was an identical amount of data for each cant; this presumption, however, is not quite true.

Because there is a scatter band around the wear rates, as well as around the wear data itself, the calculated FM's have a range of values as well. The standard deviations for the calculated wear rates are summarized in table 4-20. An estimate in the variability of the FM can be made by calculating maximum and minimum values based on the standard deviations of the wear rates of each metallurgy such that:

$$FM^{max} = \frac{\text{mean wear rate of Std rail + std dev (Std rail)}}{\text{mean wear rate of premium rail - std dev (premium rail)}} \qquad (4)$$

$$FM^{min} = \frac{\text{mean wear rate of Std rail - std dev (Std rail)}}{\text{mean wear rate of premium rail + std dev (premium rail)}} \qquad (5)$$

Results of these calculations are given in table 4-21 with the transition in lubrication taken at 45 MGT. Typical of the more poorly lubricated regime, less than 45 MGT, the tolerances on the FM's are between plus 10 to 25% and minus 10 to 15%. However, in the more generously lubricated regime where the standard deviations were 1/4 to 1/2 the values of the mean wear rates as opposed to 1/10 to 1/20 the values of the mean wear rates in the more poorly lubricated regime, the tolerance range on the FM is immensely larger; i.e., plus 90 to 160 percent and minus 60 to minus 90 percent. This is a variability, inherent in the profilometry equipment and techniques utilized, leading to a major loss of experimental resolution when the wear rates are very low.

The profiles shown in figure 4-20 were selected to illustrate the general appearance of the rail cross section at tie numbers which yielded wear behavior very close to the mean for the groups from which they were taken. Typically, they illustrate that:

- The profilometry equipment and techniques produce considerable variability, typically ± 0.02" in the profile sizes. (Observe the variations in the widths at the bottom of the rail heads, especially for HH and CrMo rail.)
- Virtually no head height loss occurred in the second wear regime and the gage face wear was substantially reduced in this regime.
- For Std rail, and in some cases for HiSi and FHT rail, a so-called "front porch" type of gage face wear was initiated during the first wear regime.
- This "front porch" type of gage face wear did not develop to anywhere near the same extent in HH and CrMo rail even late into the second regime.

TABLE 4-19. STANDARD RAIL WEAR RATES WITH AND WITHOUT HIGH-WEAR-RATE HEAT/TIE PLATE CANT COMBINATIONS INCLUDED, <45 MGT.

	Gage Face Wear Rate (in/MGT)	Head Area Loss Rate (in^2/MGT)	Head Height Loss Rate (in/MGT)
All Heats Together	0.00832	0.0131	0.002307
High-Wear-Rate Heat/Tie Plate Cant Combinations Alone	0.0102	0.0159	0.002619
All Heats Except High-Wear-Rate Heat/Tie Plate Cant Combinations	0.00762	0.0120	0.002211
% Change By Eliminating High-Wear-Rate Heat/ Tie Plate Cant Combinations	-8.4%	-8.4%	-4.2%

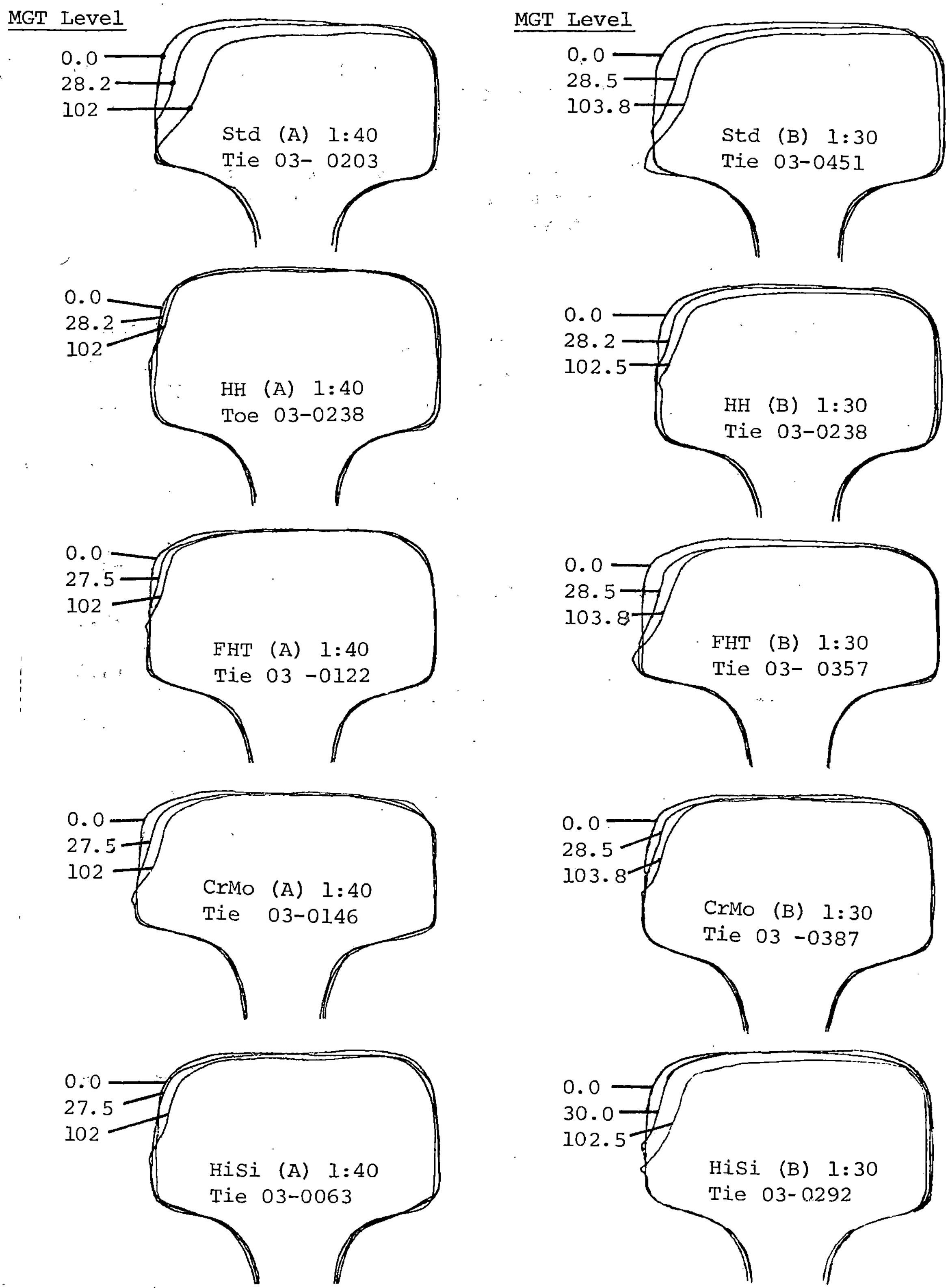
TABLE 4-20. AVERAGE STANDARD DEVIATIONS ON GAGE FACE WEAR RATES, SECTION 03 DATA ONLY.

Metallurgy	Average Standard Deviations (in/MGT)	
	<40 MGT	>40 MGT
HH	0.00024	0.00021
HiSi	0.00033	0.00029
FHT	0.00032	0.00028
CrMo	0.00025	0.00024
Std	0.00057	0.00058
	<45 MGT	>45 MGT
HH	0.00021	0.00023
HiSi	0.00037	0.00041
FHT	0.00027	0.00028
CrMo	0.00022	0.00023
Std	0.00048	0.00058

TABLE 4-21. TOLERANCES ON FIGURE OF MERIT WITH LUBRICATION TRANSITION TAKEN AT 45 MGT.

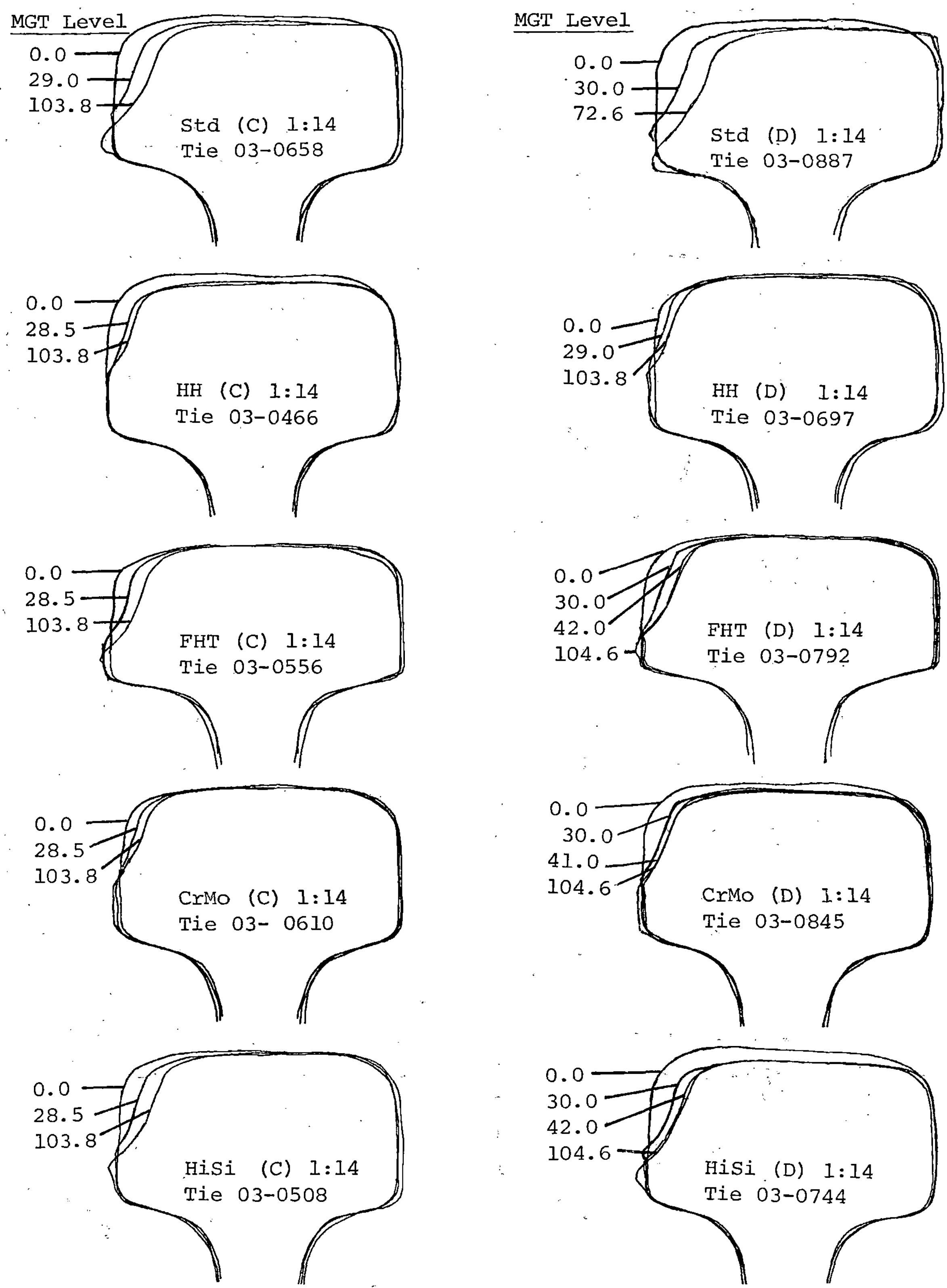
Gage Face Wear Figure Of Merit And Tolerance From 1σ Scatter Band On Wear Rates.

Metallurgy	<45 MGT	>45 MGT
HH	$2.8^{+0.7}_{-0.3}$	$1.4^{+1.4}_{-0.9}$
CrMo	2.2 ± 0.2	$1.0^{+0.9}_{-0.6}$
FHT	1.5 ± 0.2	$1.2^{+1.6}_{-0.8}$
HiSi	1.5 ± 0.2	$0.9^{+1.2}_{-0.6}$



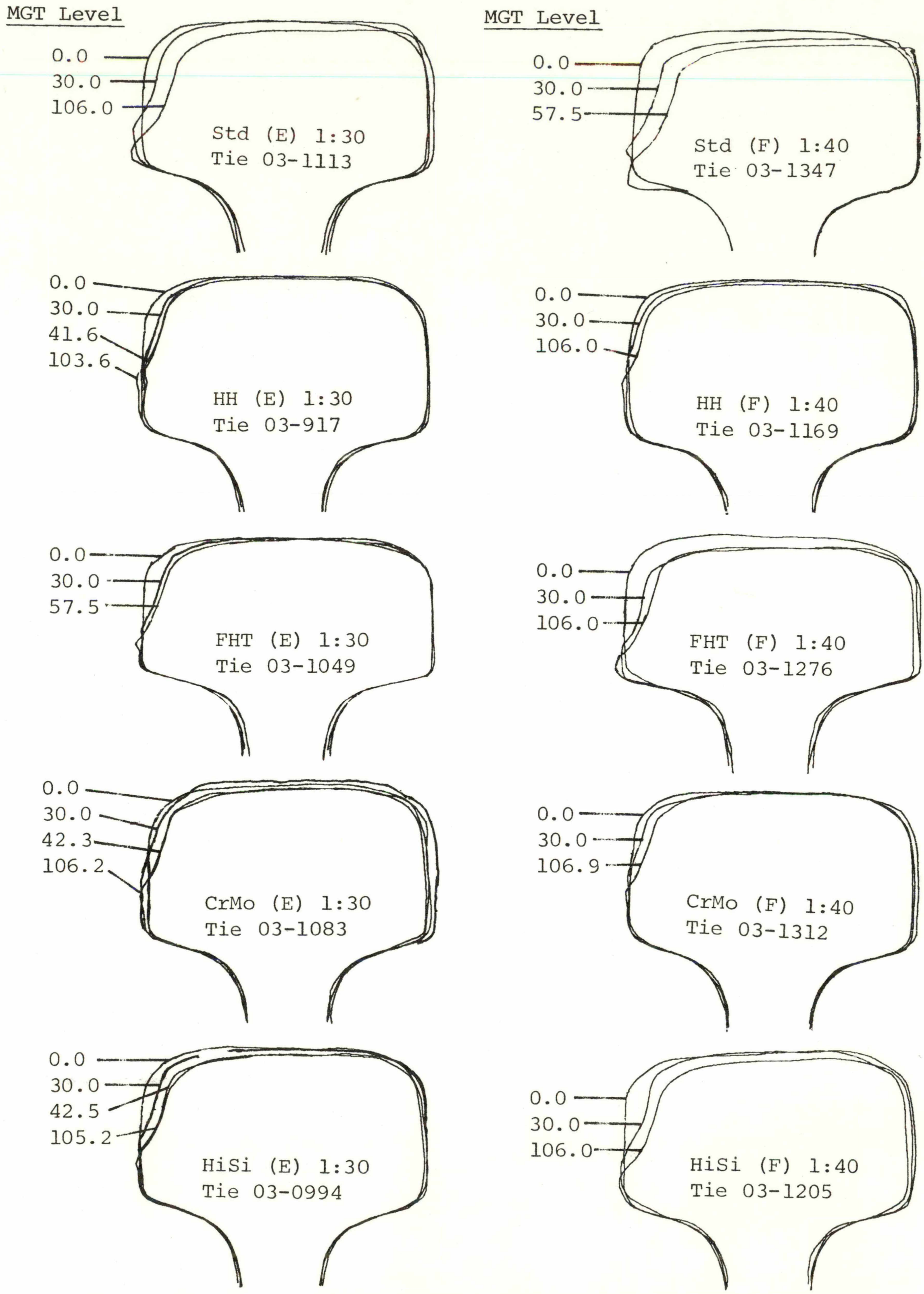
(One Group of Profiles for Each Metallurgy) A thru J segments.

FIGURE 4-20. RAIL PROFILES FOR THREE MGT LEVELS.



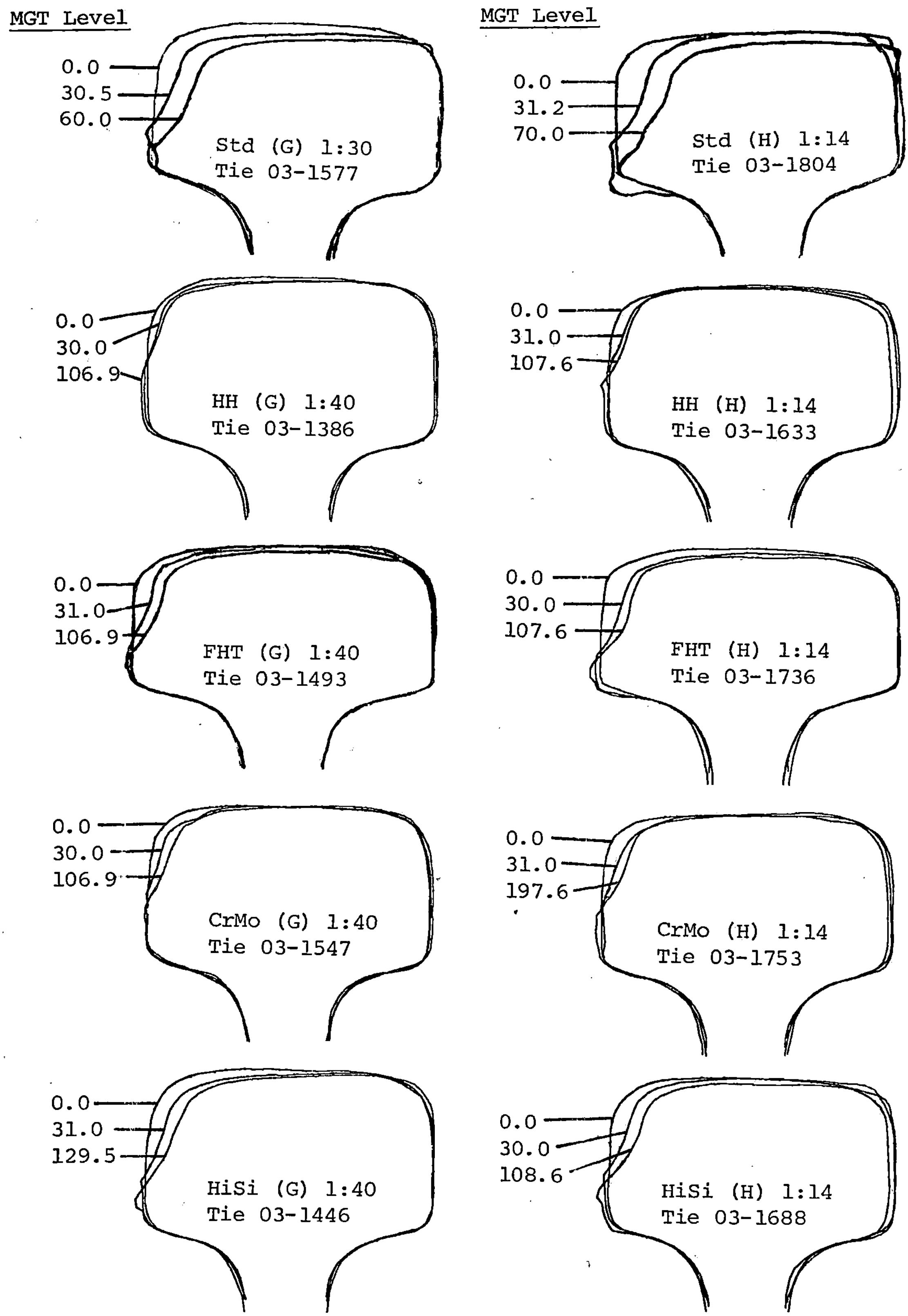
(One Group of Profiles for Each Metallurgy) A thru J segments.

FIGURE 4-20. RAIL PROFILES FOR THREE MGT LEVELS, CONTINUED.



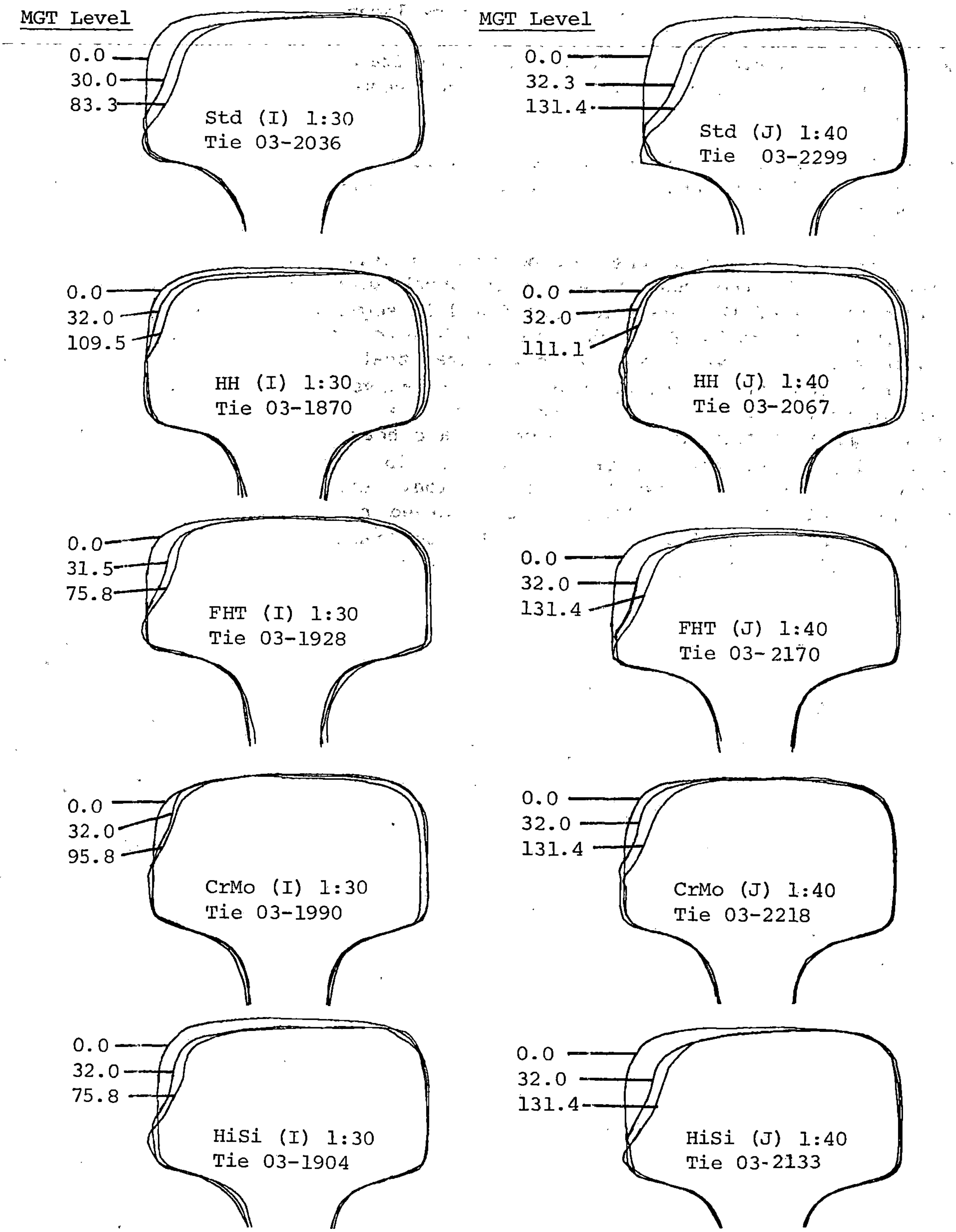
(One Group of Profiles for Each Metallurgy) A thru J segments.

FIGURE 4-20. RAIL PROFILES FOR THREE MGT LEVELS, CONTINUED.



(One Group of Profiles for Each Metallurgy) A thru J segments.

FIGURE 4-20. RAIL PROFILES FOR THREE MGT LEVELS, CONTINUED.



(One Group of Profiles for Each Metallurgy) A thru J segments.

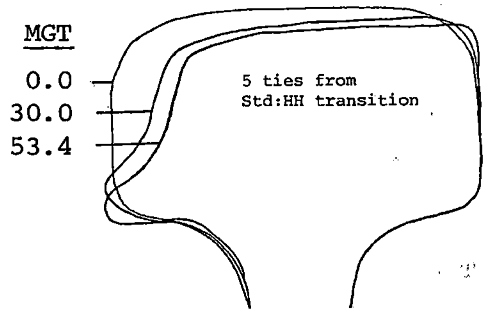
FIGURE 4-20. RAIL PROFILES FOR THREE MGT LEVELS, CONTINUED.

- By 60-80 MGT, noticeable distortion of the underside of the Std rail head, on the gage side, had developed in some locations in the curve.

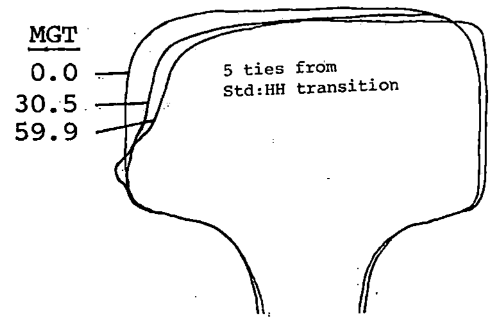
- This distortion occurred, in this time frame, in some rails on all three different tie plate cants and did not seem restricted to high-wear-rate heats.

- All other metallurgies were more resistant than Std rail to metal flow to the field side, and to distortion of the lower gage face side of the rail head.

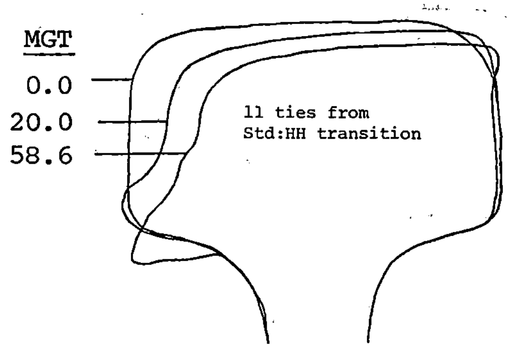
Some other observations can be made as well. There can be considerable variability in the wear behavior in short distances along a single rail. Illustrations of this behavior are found in segments F and G on the 1:40 cant tie plate, on rails from the same high-wear-rate heat. This is shown in figure 4-21. However, lest it be believed that there is an effect related to the position of a measurement site relative to a transition from one metallurgy to another, figure 4-22 illustrates the non-effect of position for both high-wear rate and non-high-wear rate heats of Std rail. It should be noted that substantial variation in wear along the Std rail tended to occur somewhat removed from the HH/Std transition. Little variation in the wear of the Std rail along its length was observed near the Std/CrMo transitions. Perhaps it is significant that all HH/Std transitions were thermite welds, whereas all Std/CrMo transitions were plant welds.



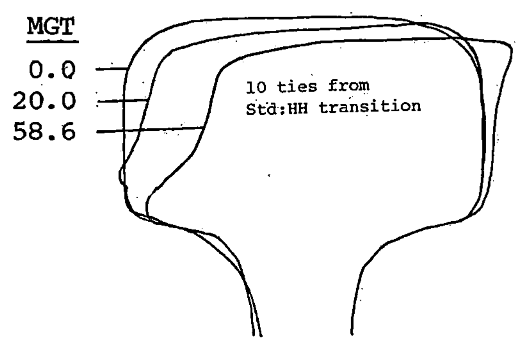
Tie 03-1586ϕ, 1:40 Cant (G)



Tie 03-1592ϕ, 1;40 Cant (G)



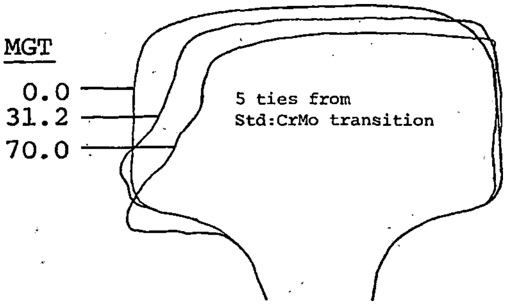
Tie 03-1363ϕ, 1:40 Cant (F)



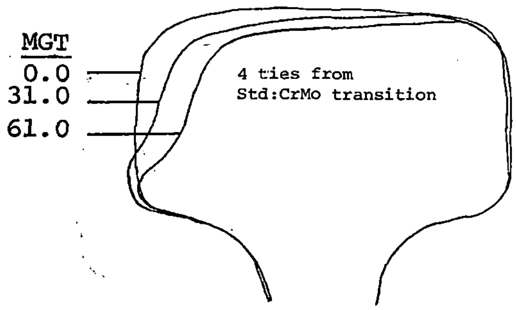
Tie 03-1358ϕ, 1:40 Cant (F)

Note: All samples from high-wear-rate heat #29792.

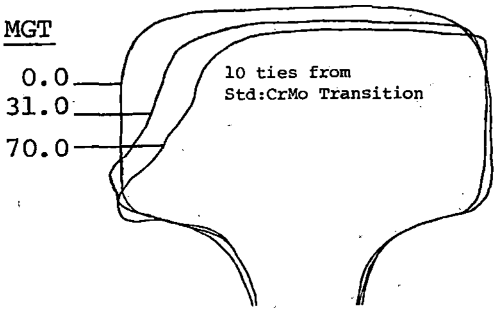
FIGURE 4-21. VARIATION IN GAGE FACE WEAR OVER A SHORT DISTANCE ALONG A STANDARD RAIL.



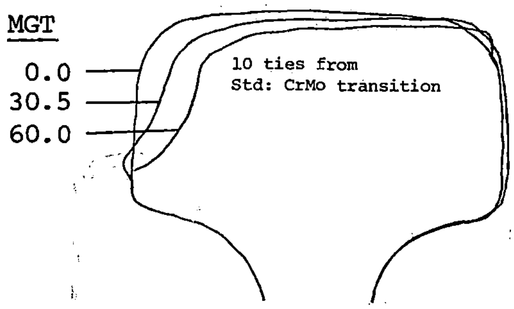
Tie 03-1794ϕ, 1:14 Cant (H)



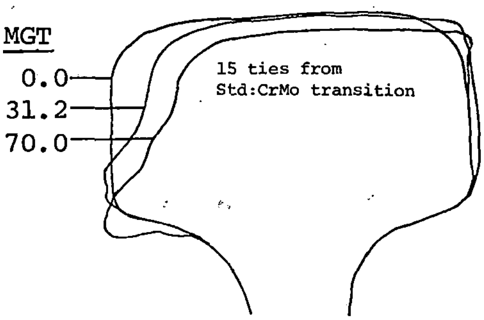
Tie 03-1564ϕ, 1:14 Cant (G)



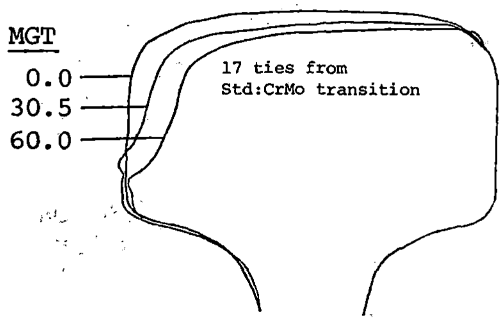
Tie 03-1799ϕ, 1:14 Cant (H)



Tie 03-1570ϕ, 1:14 Cant (G)



Tie 03-1804ϕ, 1:14 Cant (H)



Tie 03-1577ϕ, 1:14 Cant (G)

(a) High-wear-rate heat # 29776

(b) Non-high-wear-rate heat #29779

FIGURE 4-22. NON-EFFECT OF POSITION WITHIN A STANDARD RAIL SEGMENT.

5.0 DISCUSSION

The test environment at FAST, developed under 100-ton capacity cars, with typical vertical static wheel loads near 33 kips, operating on track having a high portion of 3° to 5° curves, is substantially more severe than that of the normal U.S. railroad operation whereon the average wheel load is 19.2 kips. Nevertheless some comparisons can be made to previously reported behavior. Figure 5-1 displays the average high rail head area loss behavior of four types of rail as a function of track curvature reported by the University of Illinois in its 1976 review[7] of Burlington Northern data.

In those cases where more than a minimal number of data points (two) were available, the scatter about the mean curves for Std and HiSi rail exceeded 50%, especially at higher curvatures. With few exceptions, the data for the FHT and HH rail were substantially more compact. However, no mention was made of the number of heats, the level of lubrication for each of the test curves, nor the degree of unbalance. The average FAST head area wear in both the first and second regimes bracketed the University of Illinois data, with the FAST data for Std rail from the first regime showing approximately twice that as reported by the University of Illinois. While the FAST tests show CrMo and HH rail performing the best, the University of Illinois data showed 115 lb/yd FHT rail having the lowest wear rate. However, the FHT rail in the 132 lb/yd section behaved very similarly to Std rail. Also, HiSi and HH rails in the 132 lb/yd section were observed to be much more similar in performance than was the case at FAST.

Shown on the same plot are Std AREA and CrMo data from a study by Curcio et al.[13] of the behavior of rail on the Mount Newman Mining Railroad where train weights of 17,500 tons are employed and static axle loads are 34 tons. In this respect, service is similar to the FAST loading environment. Lubrication was also provided by a single track lubricator at the entry to each test curve. The data reported for both Std and CrMo rail fall very close to a straight line projected from a low ($\sim$ zero) area loss rate at 0° curvature to the FAST data at 5° curvature. This behavior suggests that the Mount Newman experience is consistent with that observed at FAST, if it is presumed that the level of lubrication at Mount Newman was approximately equivalent to that obtained in the first regime at FAST.

Rougas[14] has reported rail wear (both Std and HH rail) on the Bessemer and Lake Erie Railroad. These data are also shown on figure 5-1 and, in general, tend to be slightly above the University of Illinois data for Std rail and substantially below these data for HH rail. On a 5° curve, HH rail appears to have an FM relative to Std rail of about 5 to 6. Again, however, as with the University of Illinois data, the level of lubrication and the degree of unbalance are uncertain.

Thus, it is difficult to draw quantitative comparisons between the wear performance of different metallurgies when translating from one railroad operation to another except to say that at 5° curvature, HH rail could wear (head area loss) anywhere up to 5 to 6 times better than Std rail. The influence of lubrication seems to be crucial in establishing the exact degree of improvement.

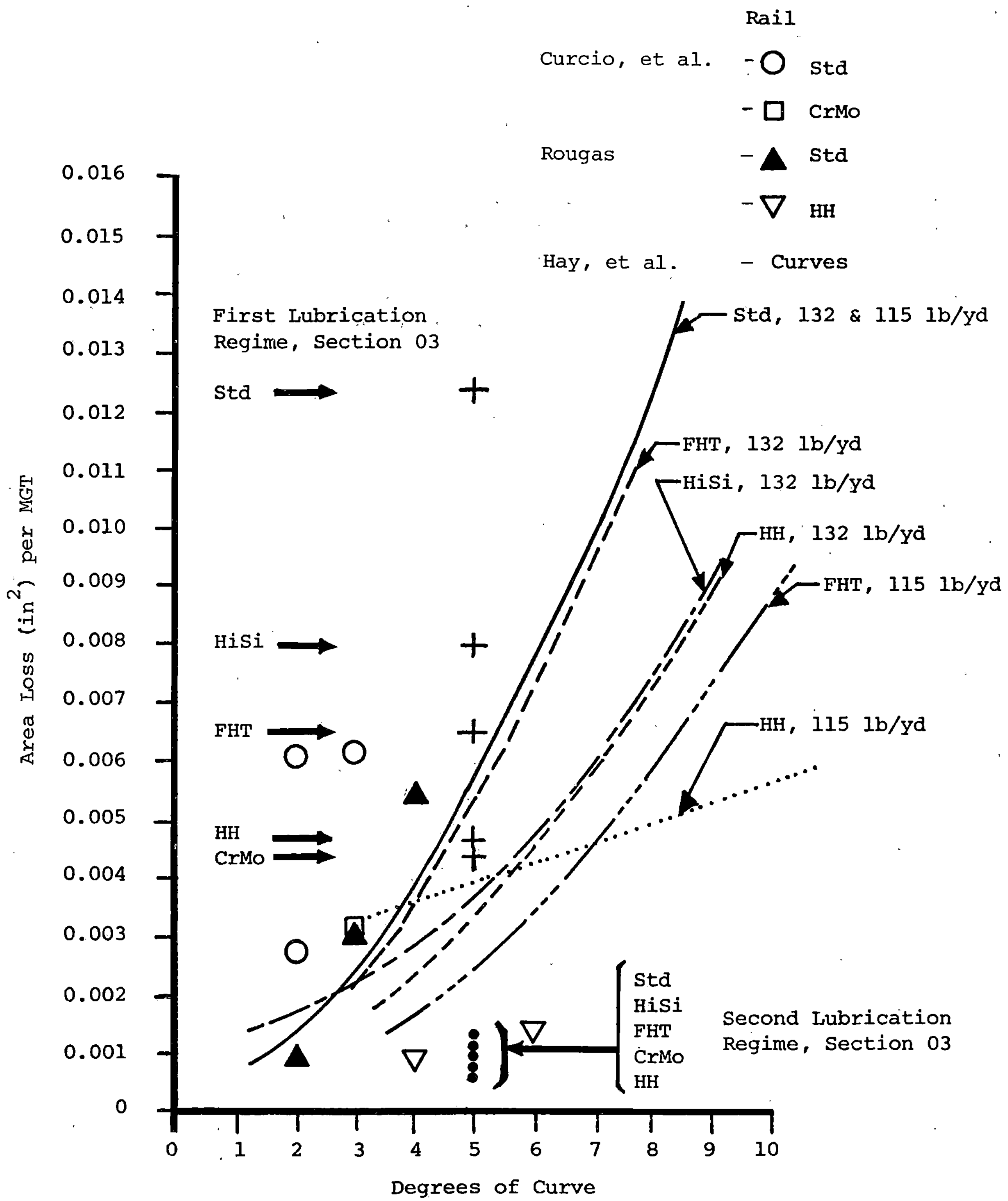


FIGURE 5-1. COMPARISON OF WEAR RATE DATA FROM DIFFERENT SOURCES WITH THAT FROM THE FIRST FAST EXPERIMENT.

Thus, it is difficult to draw quantitative comparisons between the wear performance of different metallurgies when translating from one railroad operation to another except to say that at 5° curvature, HH rail could wear (head area loss) anywhere up to 5 to 6 times better than Std rail. The influence of lubrication seems to be crucial in establishing the exact degree of improvement.

The TOPS-on-line study[11] based upon a review of Southern Pacific conditions suggests that the presence of lubrication enhances rail life by only 63% on a 5° curve and by 43% on a 4° curve. The presence of generous lubrication at FAST reduced gage face wear rate on the average by factors of 4 to 8 on a 5° curve and 2 to 10 on a 4° curve. Typically, the degree of improvement (by lubrication) of the premium rails was noticeably less than that observed for Std rail. This finding implies the existence of a metallurgy:lubrication interaction which was not factored into life or wear expressions such as those given by the AREA nor that proposed by Kalousek and Bethune[9]. However, the gradual change in the wheel population (from a predominance of class U wheels to predominance of class C wheels), which occurred during the same period of time that the character of lubrication changed, has somewhat confounded the determination of the true effect of lubrication. Based upon the work of Kumar and Margasahaya[4] one would expect that an increase in the "hard" wheel population (i.e., class C wheels) would increase the overall wear rate. Yet, preliminary gage face wear rate results from the second rail metallurgy experiments,[15] wherein the portion of class C wheels remained about constant at the same level as that at the end of the first experiment, revealed an even lower overall rail wear rate than that observed in this first experiment. Initial results from the third rail metallurgy experiment (see Preface) also suggest lower rail wear rates with hard wheels. These observations from the second and third rail metallurgy experiments are at variance with the conventional wisdom but do seem to support other observations[1 2 3]. If the effect of harder wheels is to reduce rail wear, the change in wheel population throughout the period of this first experiment may have exaggerated the contribution of lubrication.

Another factor, which in most circumstances should not be ignored when making wear rate comparisons, is the annual tonnage rate. If the AREA rail life formulation is truly appropriate, variations in annual tonnage rate could produce substantial variations in life. For instance, if all other factors were equal, a 2:1 variation in annual tonnage rate would produce a 40-50% change in rail life. The TOPS-On-Line Services, Inc., modified AREA formulations would predict a 679 MGT life for Std rail in the Section 03, 5° curve at 200 MGT/year but only 310 MGT at 50 MGT/year. If the average gage face wear rates of 0.006 to 0.0016 in/MGT in the well-lubricated regime were projected to a 3/4" condemning limit, wear life would be in the range 470 to 750 MGT, which is in reasonable agreement with the modified AREA life predictions. However, fatigue most likely would have become a worrisome failure mode long before reaching the 470 to 750 MGT life[8 9 15]. If the average gage face wear rate (0.0081 to 0.0091 in/MGT) of the first regime were projected to a 3/4" condemning limit, the life would be 82 to 92 MGT, far less than that (417 MGT) predicted by the modified AREA formulation. It cannot be determined from the FAST data of the first experiment whether annual tonnage rate is an important contribution to rail life.

The wear rate formulation of Kalousek and Bethune can be recast into the form:

$$\frac{V_1}{V_2} = \frac{C_1}{C_2} \cdot \frac{(H_2)^{\alpha_2}}{(H_1)^{\alpha_1}} \tag{6}$$

for different metallurgies on the presumption that the lateral force, lateral and vertical creep, and the angle of the gage face to the lateral force vector are not functions of the type of metallurgy. C and are empirical constants and H is the hardness. Thus, the ratio V_1/V_2 is really an FM for volumetric wear where V_1 is taken to represent the volumetric wear of Std rail. If volumetric wear is assumed to be more closely related to head area loss rather than gage face or head height loss, the FAST FM for both lubrication regimes may be plotted as shown in figure 5-2. Indeed, it appears there is a linear relationship (i.e. $\alpha_{1,2} = 1$) between wear rate as reflected in the FM and hardness as measured on the gage face of the rail with a portable full load (3,000 kg) Brinell tester after completion of testing in the second regime. However, the slope of the plot ($C_{1,2}$) appears to be different for premium metallurgies achieving the increase in hardness through heat treatment as opposed to alloying. In addition, lubrication has a different effect depending upon how the hardness improvement was achieved. Although alloying seems to achieve more head area loss wear improvement per increment of hardness increase, improved lubrication appears to have a greater effect (to reduce FM) on alloyed rail than it does on heat-treated rail.

The manner in which metal was lost from or redistributed on the rail head was not necessarily the same for all the different metallurgies, as shown in figures 5-3 and 5-4. The FHT rail did not seem to have as high a resistance to gage face wear as would be expected from its gage face hardness. On the other hand, HH rail, which exhibited the highest gage face wear resistance, exhibited poorer head height loss resistance than would have been expected. However, there appears to be a relationship between these three different measures of wear. If one plots a composite FM calculated as the square root of the product of the gage face loss FM and the head height loss FM as done in figure 5-5, virtually a one-on-one relationship obtains. Thus, although head area loss tells part of the story about wear resistance, it, in itself, is not sufficient enough to tell the entire story. On the basis of the results from this first experiment, it seems possible at least to calculate how well a particular rail metallurgy will do based upon its performance in resistance to gage face and head height loss.

The behavior of gage face and head height wear was not the same for each metallurgy. The ratio of gage face wear rate to head height loss rate is given in table 5-1. These data show that the ratio seems to be a function of metallurgy with HH and Std rail showing the lowest ratio and FHT and CrMo showing the highest ratios. The 1:14 cant produced the highest ratios for each metallurgy with the 1:40 cant yielding the lowest ratios. However the degree to which cant influenced the ratio seemed to be a function of metallurgy, with FHT and CrMo exhibiting the greatest effect of cant. This is shown in figure 5-6. The implication of these observations is that even under similar loading environments, the wear distribution will not be similar for

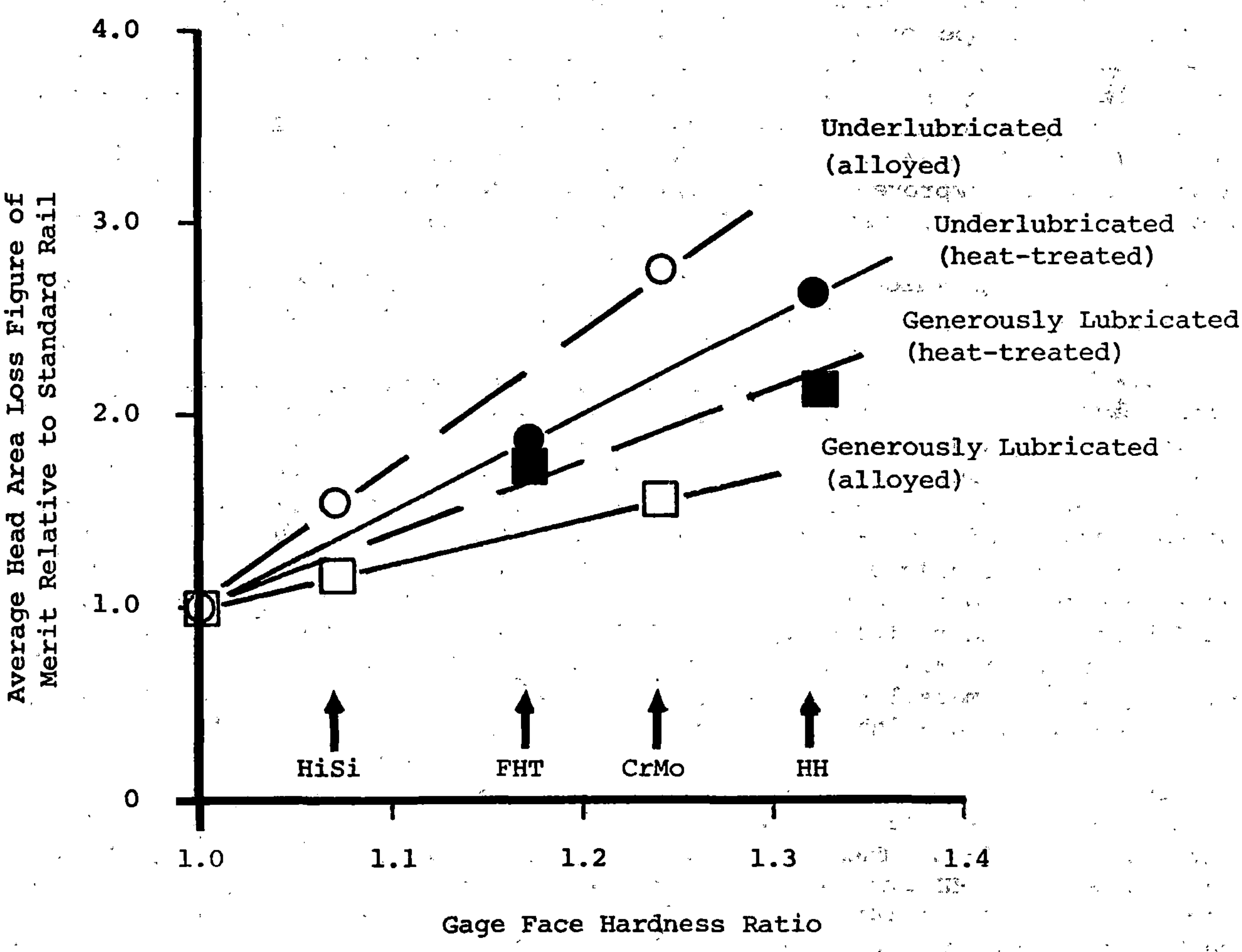


FIGURE 5-2. EFFECT OF RELATIVE GAGE FACE HARDNESS UPON HEAD AREA LOSS FIGURE OF MERIT.

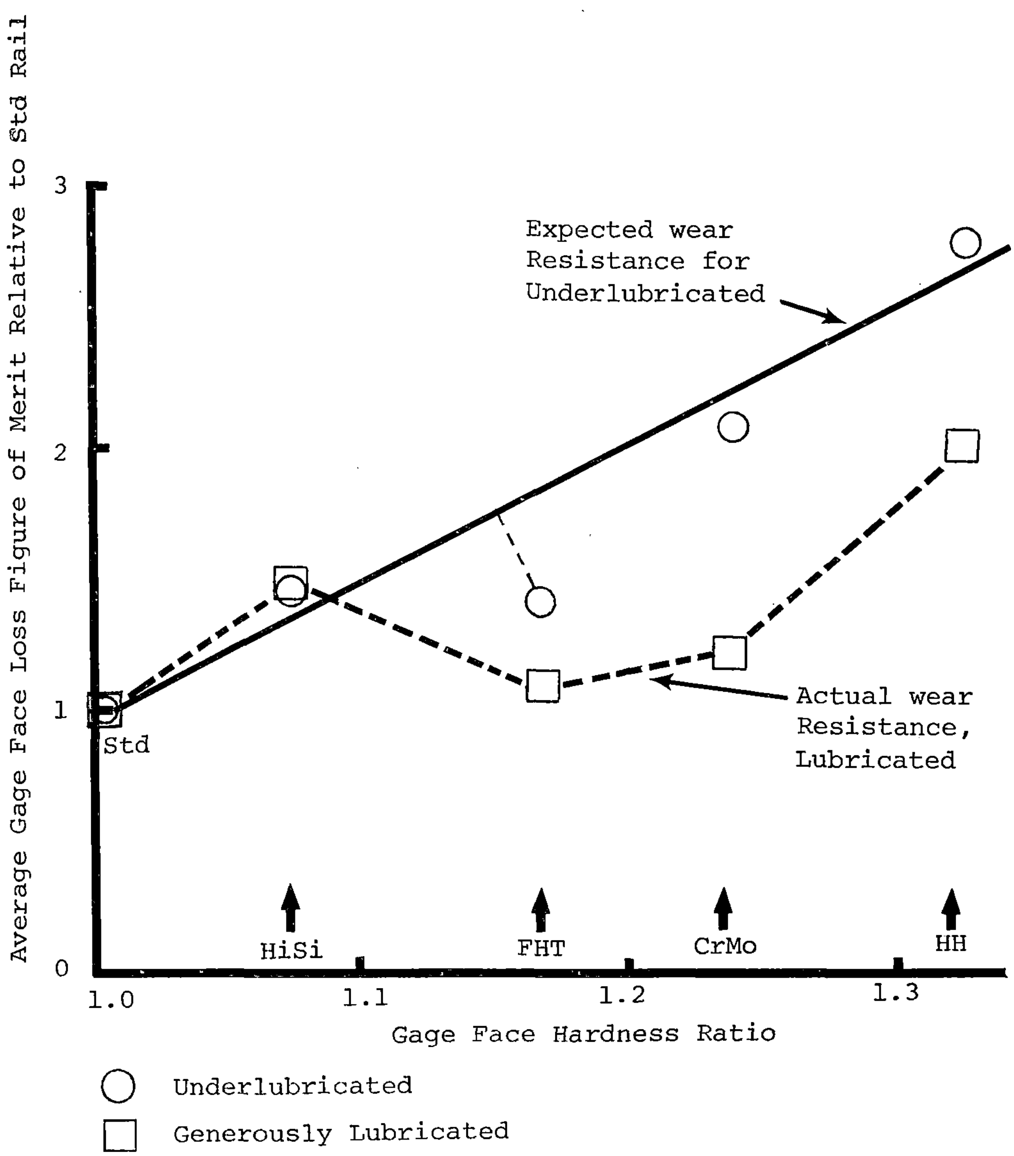


FIGURE 5-3. AVERAGE GAGE FACE LOSS FIGURE OF MERIT RELATIVE TO STANDARD RAIL.

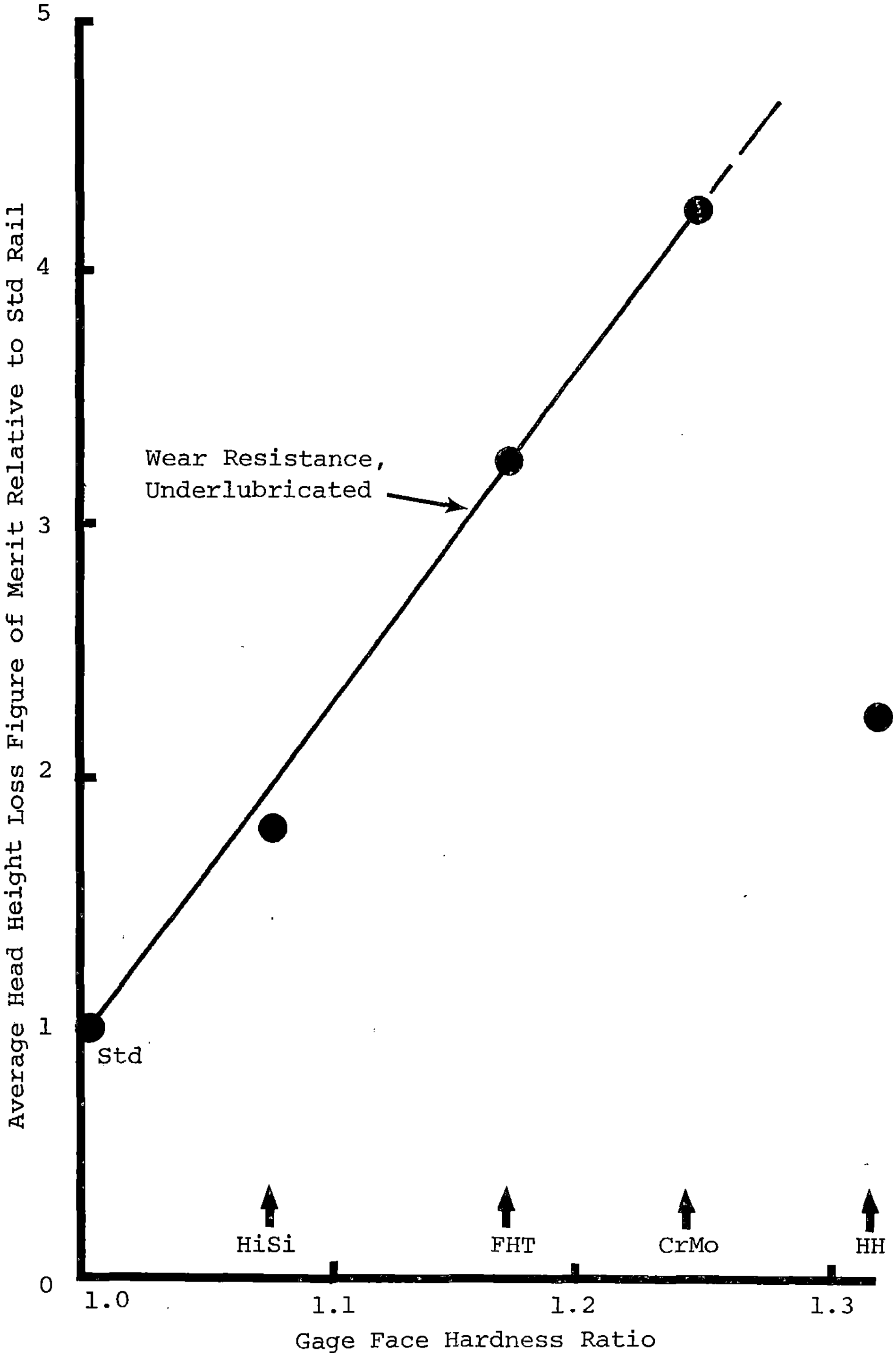


FIGURE 5-4. AVERAGE HEAD HEIGHT LOSS FIGURE OF MERIT RELATIVE TO STANDARD RAIL.

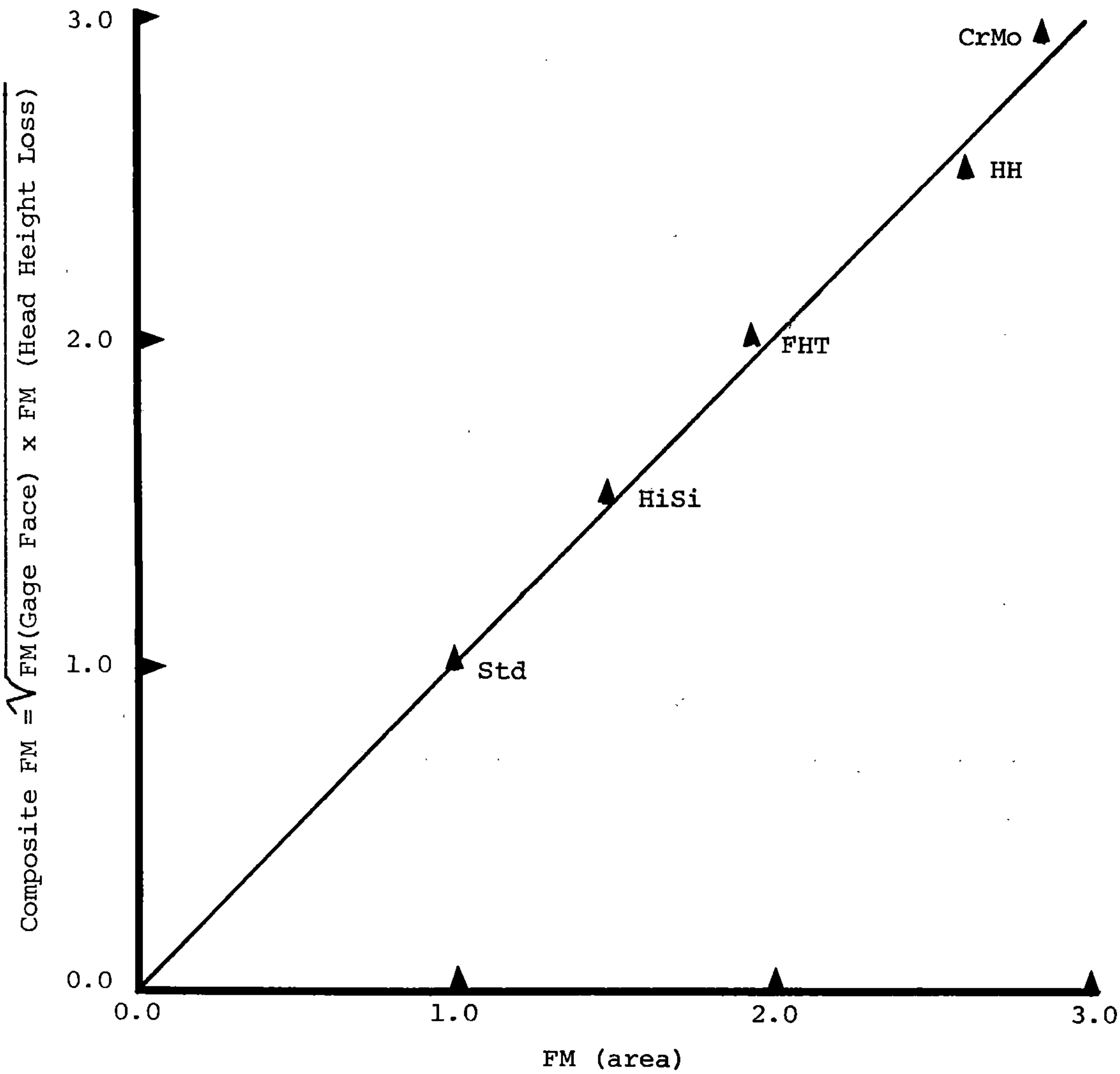


FIGURE 5-5. COMPOSITE FIGURE OF MERIT VS HEAD AREA FIGURE OF MERIT.

TABLE 5-1. RATIO OF GAGE FACE WEAR RATE TO HEAD HEIGHT LOSS RATE (<45 MGT).

Metallurgy	Tie Plate Cant		
	1:40	1:30	1:14
HH	271/127 = 2.13	298/90 = 3.31	384/109 = 3.52
HiSi	579/144 = 4.02	513/122 = 4.20	707/134 = 5.28
FHT	550/97 = 5.67	548/79 = 6.94	658/56 = 11.75
CrMo	355/73 = 4.86	401/52 = 7.71	444/53 = 8.38
Std	809/256 = 3.16	778/223 = 3.49	835/233 = 3.58

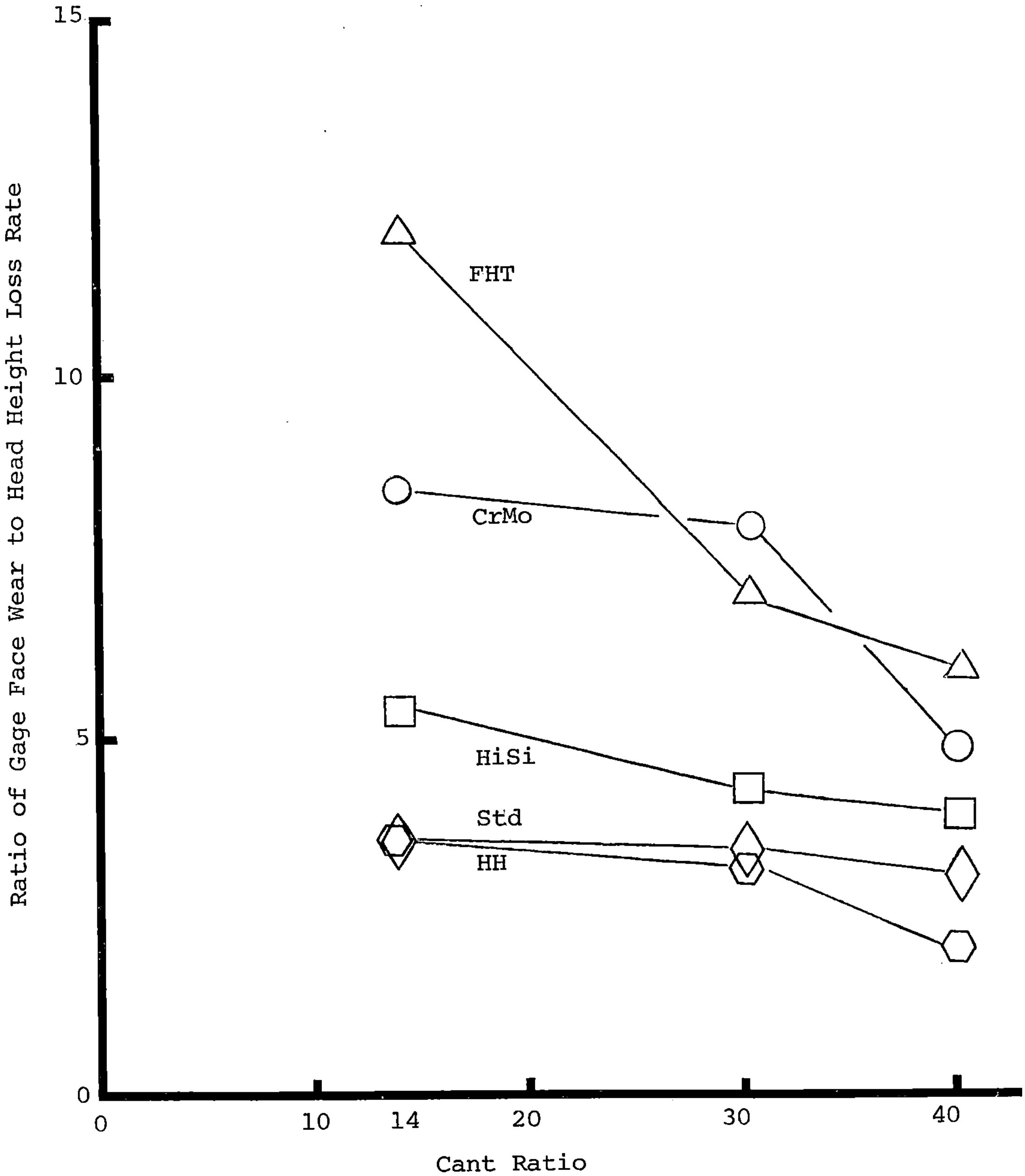


FIGURE 5-6. RATIO OF GAGE FACE WEAR TO HEAD HEIGHT LOSS RATIOS AS INFLUENCED BY THE PLATE CANT.

different metallurgies, and confirms that a single parameter measure of wear such as area loss will not provide an adequate representation of wear behavior.

In the underlubricated regime, the 1:14 cant tie plate has been associated with gage face and head area loss significantly increased over that observed for the 1:40 cant tie plate for all metallurgies tested except Std rail. The primary intent of using the 1:14 cant plate on the high rail of a curve is to redistribute the contact stresses away from the gage corner of the rail, thereby altering the metal flow behavior and reducing the tendency toward shell and detail formation. This very redistribution of contact stresses in the fashion shown in figure 5-7 may well have increased the contact stresses in the gage face region under the action of lateral flanging forces, resulting in an increased gage face wear rate. However, the relatively high overall wear rate of Std rail, in the underlubricated regime, caused full and identical wheel/rail contact irrespective of the tie plate cant early in rail service life. Figure 5-8 shows two profiles of the same heat of Std rail from nearby test segments having about the same average gage face wear rate (of two rails) in each segment. Even at 30 MGT the gage face/running surface contours were identical. Thus, it seems that the high-wear-rate in the underlubrication regime has destroyed the utility of using the 1:14 cant plate, at least for Std rail. The diminution of statistical strength of tie plate cant effect, observed in the generously lubricated regime, may have had more to do with the wearing of the rails into full wheel/rail contact in the underlubricated regime than with the presence of an actual tie plate cant:lubrication interaction which is implied from the results.

Considerable variability in wear behavior was observed in the test sections, particularly in Std rail. This variability can be related to chemical composition if corrections to wear rates are applied for tie plate cant and position-in-curve. Using the data in table 4-7 to obtain correction factors, adjusted wear rates for Std and HiSi rail have been computed for each segment of Section 03 during the period before 45 MGT. These values are tabulated in tables 5-2 and 5-3 along with the mean chemical composition and carbon equivalents* of the Std and HiSi rails in each of the segments. The adjusted mean gage face wear rates are plotted against the carbon equivalent in figure 5-9. All Std and HiSi data points fall around a single line having the equation:

$$\text{Wear rate (in/MGT)} = 3.79 \times 10^{-3} - 3.1 \times 10^{-3}\ C_{eq}\ (\text{w/o}) \qquad (7).$$

Segments D, F, G, H, and I contained at least one rail (of two) which exhibited a substantially higher wear rate (Std rail). Interestingly, segment A contained no rails of exceptionally high wear rate, yet it is grouped with those in D, F, G, and H. Also, segment I, which did contain a high wear rate rail, was grouped with the lower wear rate segments. High wear resistance in Std rail seems to be achieved when the carbon equivalent is near unity. The range of 0.1 w/o carbon equivalent inherent in the Std rail steel tested in the experiment yielded about a 50% increase in gage face wear rate calculated from the minimum wear rate observed for Std rail.

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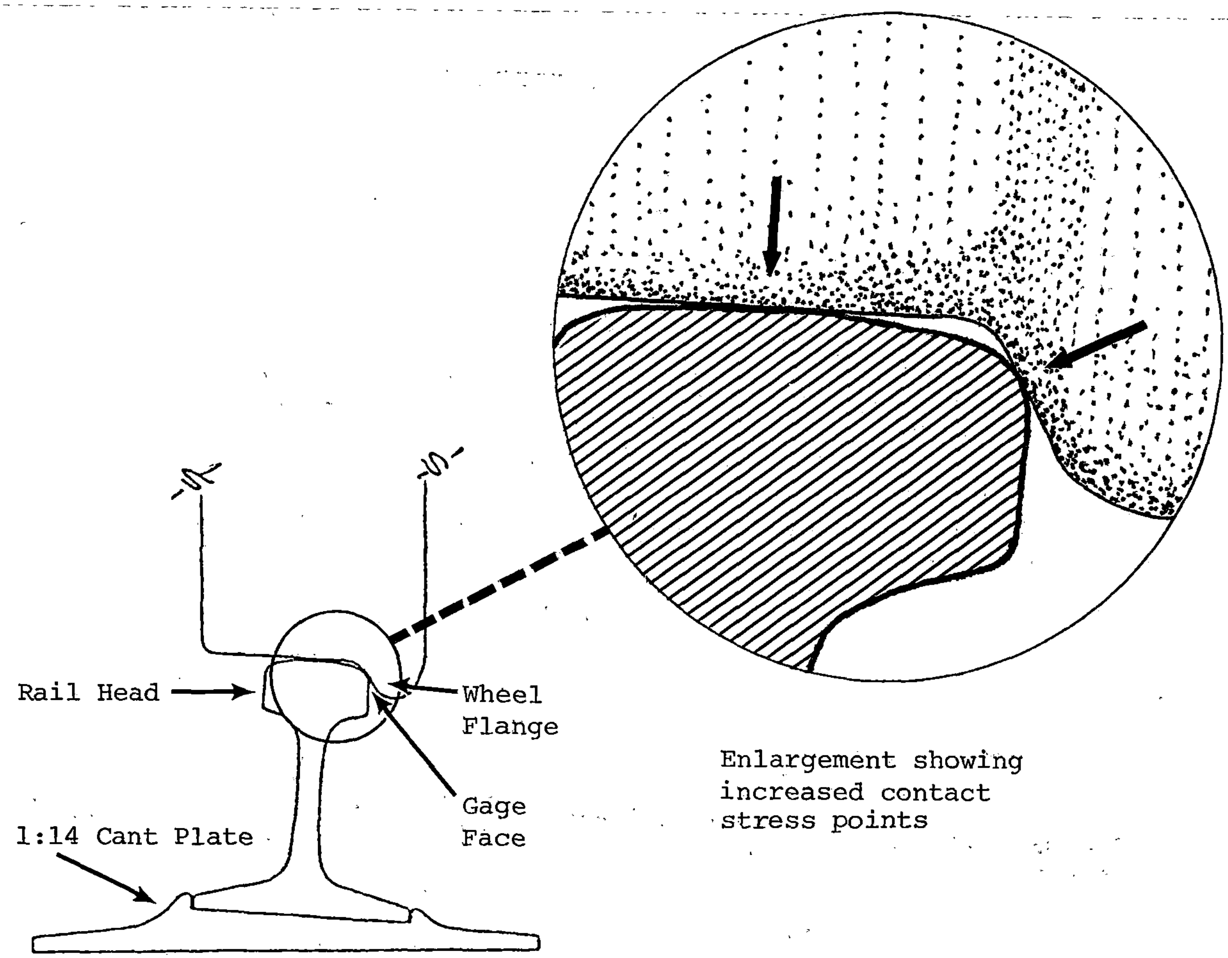
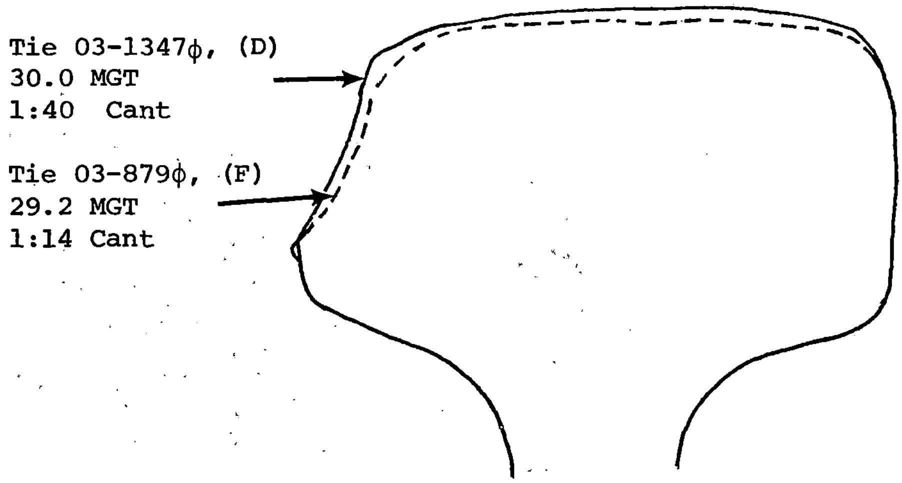
* Carbon Equivalent $= C_{eq} = \text{w/o C} + \dfrac{\text{w/o Mn}}{4.75} + \dfrac{\text{w/o Si}}{10}$ *(reference 16)*



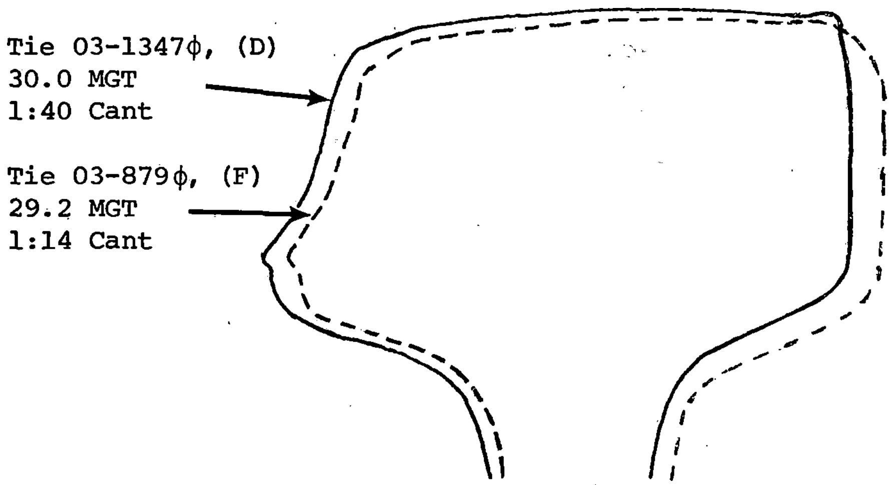
Hi-Cant Plate

(From "Concerning Hi-Cant Tie Plates," by J.E. Campbell and E. Thompson.)

FIGURE 5-7. CONFIGURATION OF WHEEL ON RAIL USING 1:14 CANT TIE PLATE.



(A) Fillets aligned



(B) Tilted and displaced slightly to show conformance of contours

FIGURE 5-8. PROFILES OF RAILS FROM SAME HEAT (#29776) AT APPROXIMATELY 30 MGT TRAFFIC ON 1:14 AND 1:40 CANT TIE PLATES.

TABLE 5-2. ADJUSTED GAGE FACE WEAR RATES OF STANDARD RAIL IN SECTION 03 WITH CHEMICAL COMPOSITIONS.

Segment	Cant	Avg Wear Rate (in/MGT)	Corrected for Cant	Corrected for Pos-in-Curve	Compositions, w/o C	Mn	C_{eq}	Si	C_{eq}	Total C_{eq}
A	1:40	0.0083	-	-	0.76	0.90	0.189	0.13	0.013	0.962
B	1:30	0.0076	0.0067	-	0.76	0.93	0.196	0.15	0.015	0.971
C	1:14	0.0073	-	-	0.80	0.94	0.198	0.15	0.015	1.013
D	1:14	0.0090	-	-	0.77	0.87	0.162	0.15	0.015	0.947
E	1:30	0.0070	0.0062	-	0.80	0.94	0.198	0.15	0.015	1.013
F	1:40	0.0094	-	-	0.74	0.81	0.171	0.15	0.015	0.926
G	1:40	0.0104	-	0.0084	0.76	0.89	0.188	0.15	0.015	0.952
H	1:14	0.0107	-	0.0088	0.76	0.85	0.179	0.16	0.016	0.955
I	1:30	0.0096	0.0084	0.0069	0.78	0.91	0.191	0.16	0.016	0.987
J	1:40	0.0089	-	0.0073	0.80	0.96	0.202	0.16	0.016	1.017

$$C_{eq} = \text{w/o C} + \frac{\text{w/o Mn}}{4.75} + \frac{\text{w/o Si}}{10}$$

TABLE 5-3. ADJUSTED GAGE FACE WEAR RATES OF HiSi RAIL IN SECTION 03 WITH CHEMICAL COMPOSITIONS.

Segment	Cant	Avg Wear Rate (in/MGT)	Corrected for		Compositions, w/o					Total C_{eq}
			Cant	Pos-in-Curve	C	Mn	C_{eq}	Si	C_{eq}	
A	1:40	0.0040	-	-	0.78	0.91	0.192	0.66	0.066	1.038
B	1:30	0.0058	-	-	0.78	0.95	0.200	0.70	0.070	1.050
C	1:14	0.0073	-	0.0056	0.76	0.92	0.194	0.70	0.070	1.024
D	1:14	0.0073	-	0.0056	0.76	0.88	0.185	0.65	0.065	1.010
E	1:30	0.0039	-	-	0.81	0.98	0.206	0.85	0.086	1.102
F	1:40	0.0063	-	-	0.80	0.92	0.194	0.66	0.066	1.050
G	1:40	0.0064	0.0057	-	0.76	0.83	0.175	0.61	0.061	0.996
H	1:14	0.0073	0.0065	0.0050	0.78	0.82	0.173	0.75	0.025	1.028
I	1:30	0.0065	0.0058	-	0.78	0.82	0.173	0.75	0.075	1.028
J	1:40	0.0059	0.0052	-	0.77	0.91	0.192	0.72	0.072	1.039

$$C_{eq} = \text{w/o C} + \frac{\text{w/o Mn}}{4.75} + \frac{\text{w/o Si}}{10}$$

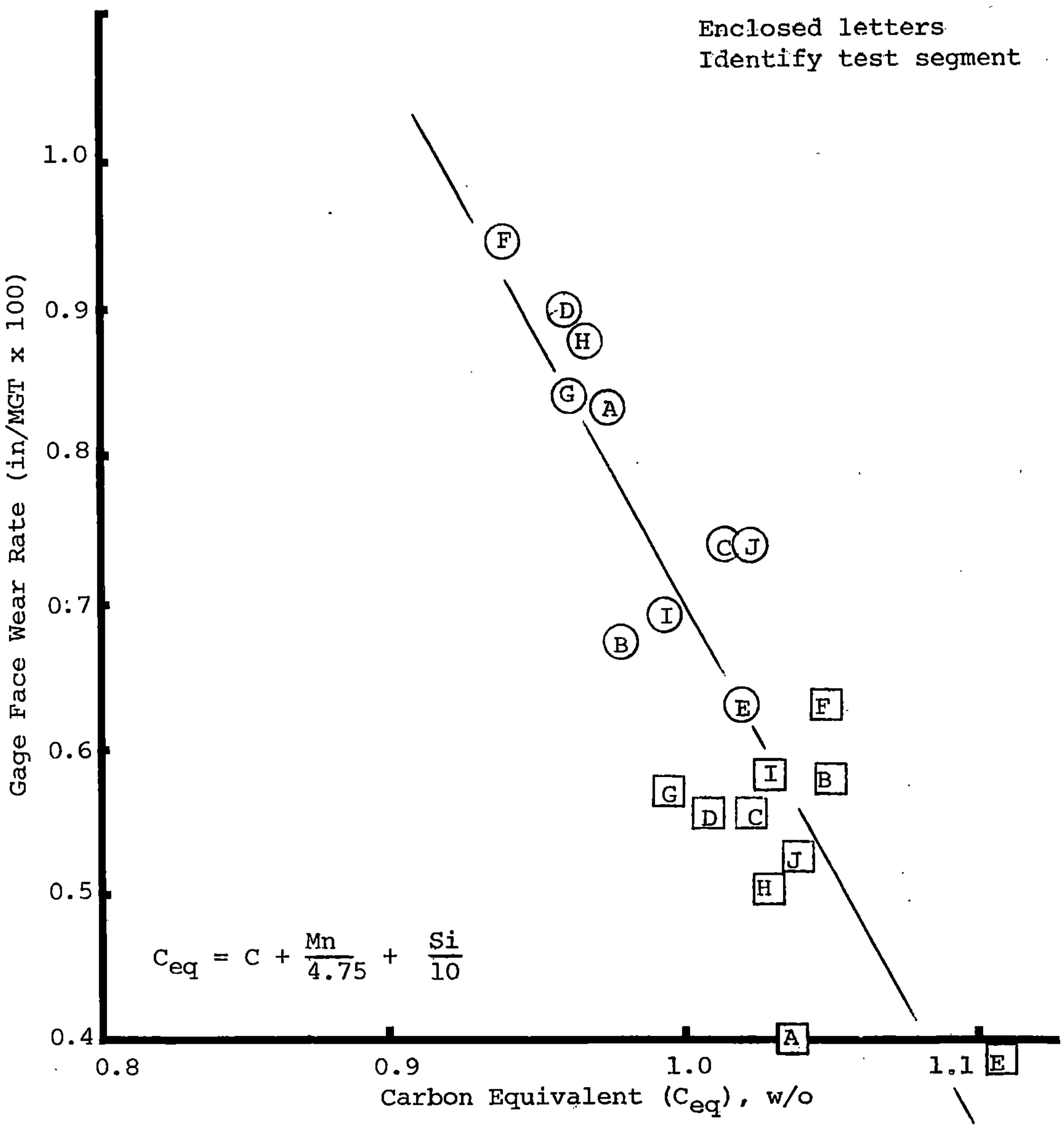


FIGURE 5-9. GAGE FACE WEAR RATE AS A FUNCTION OF EQUIVALENT CARBON CONTENT.

6.0 CONCLUSIONS

Under the FAST operating conditions and with the wear measurement constraints imposed by instrumentation and data processing techniques, the following conclusions are drawn:

- Overall, CrMo rail achieved the greatest improvement over Std rail in the more poorly lubricated environment. However, as lubrication improved, the advantage of CrMo rail in terms of wear resistance diminished relative to the heat-treated rails.

- Heat-treated rails ranked next with their overall FM being approximately proportional to their in-service gage face hardness. This advantage decreased less with increased lubrication than did that of the alloy rails. But the heat treated rails were not equivalent in their resistance to gage face wear; the HH rails exhibited substantially higher resistance.

- The gage face wear behavior of rail is strongly dependent on the equivalent carbon content, such that a 0.1 w/o reduction in equivalent carbon could cause a 50% increase in wear rate in standard rail.

- The FM's for gage face wear from the 4° curve, Section 13, are in close agreement with those from the 5° curve, Section 03. Gage face wear on the 4° curve is approximately 20% less overall than that on the 5° curve, which is consistent with a linear relationship between gage face wear and the degree of curvature.

- In the underlubricated regime, and averaging over all metallurgies, the 1:14 tie plate cant produced approximately 20% more gage face and head area wear than did either the 1:30 or 1:40 cants, while the 1:40 cant produced higher head height loss. However, if only standard rail alone were considered, the 1:14 and 1:40 cant plates produced comparable wear rates, while the 1:30 cant plate produced the lowest wear rates. In the more generously lubricated regime, the 1:40 cant consistently produced the lowest gage face and head area loss.

- Section 03 exhibited a position-in-curve effect for gage face wear, the character and magnitude of which varied with the level of lubrication. No position-in-curve effect was observed in Section 13.

- Wear measurement accuracy and sensitivity were not satisfactory under conditions of low wear rates (i.e., generous lubrication) to permit the assessment of the test variables on high rail wear behavior with the same reliability achieved in the higher wear rate, poor lubrication regime.

- In the underlubricated regime, the wear of rail at FAST was substantially greater than that observed elsewhere in U.S. railroad operation, even where 100 ton cars were utilized. However, the FAST rail wear behavior was consistent with that projected from Australian heavy unit train type operation.

- Rail life projections for Std rail in the 5° curve of Section 03 were in reasonable agreement with a prediction based upon a modified AREA rail life equation in the well lubricated regime, but were in substantial disagreement with prediction in the underlubricated regime.

7.0 RECOMMENDATIONS

- In future rail metallurgy experiments, determine whether alloy and heat-treated premium metallurgies truly respond differently to the effects of lubrication.
- Determine by separate testing why the gage face wear behavior for FHT rails is so markedly different from its overall total head area loss behavior.
- Determine whether the heats of Std rail which exhibited substantially higher wear rates are different in microstructural and mechanical strength character from those others being tested.
- Design and implement a proper in-track test to determine the true utility of increased tie plate cant to achieve its design intent--namely to reduce fatigue defect initiation in the rail head.
- Utilize more sensitive direct (dial gage) measurement techniques which will provide needed discrimination in low wear rate regimes.

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APPENDIX A

TABLE A-1. LADLE ANALYSIS OF RAIL HEATS.

Element		C	Mn	P	S	Si	Cr	Mo
				Section 03				
Std	029769	0.74	0.83	0.024	0.025	0.13	-	-
	029770	0.80	0.96	0.018	0.023	0.15	-	-
	029771	0.78	0.90	0.022	0.021	0.18	-	-
	029772	0.78	0.85	0.032	0.023	0.13	-	-
	029773	0.81	0.92	0.033	0.024	0.15	-	-
	*029776	0.76	0.84	0.030	0.025	0.15	-	-
	029779	0.79	0.90	0.031	0.026	0.15	-	-
	*029780	0.76	0.86	0.033	0.030	0.18	-	-
	*029782	0.77	0.85	0.037	0.030	0.17	-	-
	*029742	0.73	0.78	0.026	0.037	0.15	-	-
HiSi	016678	0.76	0.83	0.033	0.028	0.61	-	-
	016681	0.79	0.84	0.038	0.026	0.64	-	-
	016700	0.75	0.93	0.024	0.025	0.67	-	-
	016706	0.74	0.92	0.028	0.025	0.66	-	-
	016712	0.80	0.99	0.025	0.022	0.68	-	-
	016713	0.78	0.82	0.013	0.023	0.75	-	-
	018697			Analysis not available				
	032872	0.77	0.91	0.035	0.027	0.72	-	-
	032878	0.81	0.98	0.028	0.021	0.86	-	-
	032879	0.78	0.98	0.036	0.018	0.68	-	-
FHT	CT08767	0.69	0.81	0.018	0.032	0.18	-	-
CrMo	011978	0.80	0.76	0.026	0.025	0.25	0.81	0.20
	011980	0.80	0.88	0.027	0.025	0.25	0.75	0.19
HH	E28625	0.79	0.84	0.009	0.018	0.16	-	-
				Section 13				
Std	H35882	0.75	0.85	0.024	0.035	0.15	0.01	0.01
	H27417	0.73	0.86	0.025	0.020	0.17	0.01	0.01
HiSi	035533	0.80	0.84	0.020	0.025	0.67	--	--
	035883	0.75	0.90	0.031	0.021	0.68	--	--
FHT	007571	0.77	0.78	0.021	0.039	0.15	--	--
	008493	0.75	0.84	0.021	0.043	0.15	--	--
	008495	0.78	0.82	0.019	0.041	0.14	--	--
HH	CT026465	0.77	0.88	0.015	0.025	0.18	--	--

* High-wear-rate heats.

APPENDIX B

DATA REDUCTION PROCEDURE

The procedures followed by the data reduction programs are described below (figure B-1 flow chart). First, the relevant data for the profile were read from a magnetic tape record. These data consisted of the date the profile was taken and the location of the section and tie numbers. The profilometer number, the initials of the profilometer and digitizer operators, and whether the profile was taken on an inner or outer rail were also recorded. The 975 data points obtained through the digitizing process were read and then placed in x and y coordinates. The data were then examined to see if the profile was the first measurement at a given tie, or whether it was a subsequent measurement.

The profile was aligned on a coördinate grid by means of an iterative procedure shown in figures B-2 and B-3. This procedure positioned point "A" at the midpoint of a horizontal line joining two points on the sloping surfaces on the underside of the railhead. The iterative procedure also assured that point "A" was 0.60" above the midpoint of a horizontal line joining two points on the web. The origin of the coordinate system was located 0.25" below point "A".

The reduction procedure continued with the subsequent profiles being corrected for distortion as described below and shown in figure B-4.

<u>Rail head area computation</u>. In this step, the profile areas, rail head wear, and gage face wear were computed. The sloping lines on the underside of the head were determined and the result was stored, if the profile was the first in the series. Total area, or the area of subsequent profiles inside the first profile and its sloping lines, was determined.

A gross area was also computed. This was the total area of the subsequent profile, above its sloping lines. The gross area minus the total area defined metal flow.

After the areas were computed, the information was stored and the program proceeded to the next profile in the set. When all the profiles in a set were completed, the program superimposed the first and last profiles.

<u>Rail Profile Correction Procedure, <80 MGT</u>. Profile correction procedures were used to compensate for profilometer and operator errors. The correction program operated to find the lower corners of a profile (figure B-4) and compared the distances between the corners of the profile and the corresponding distances of the first profile of the set at a specific tie number location. If the profile was the first one of a set, the corner distances were stored and no correction was required. The subsequent profiles were then expanded or contracted according to whether or not the corner distances were greater or less than those of the first profile.

The corners were defined as those points along the profile where the absolute value of the slope equalled 1.00 (figure B-3). These points were

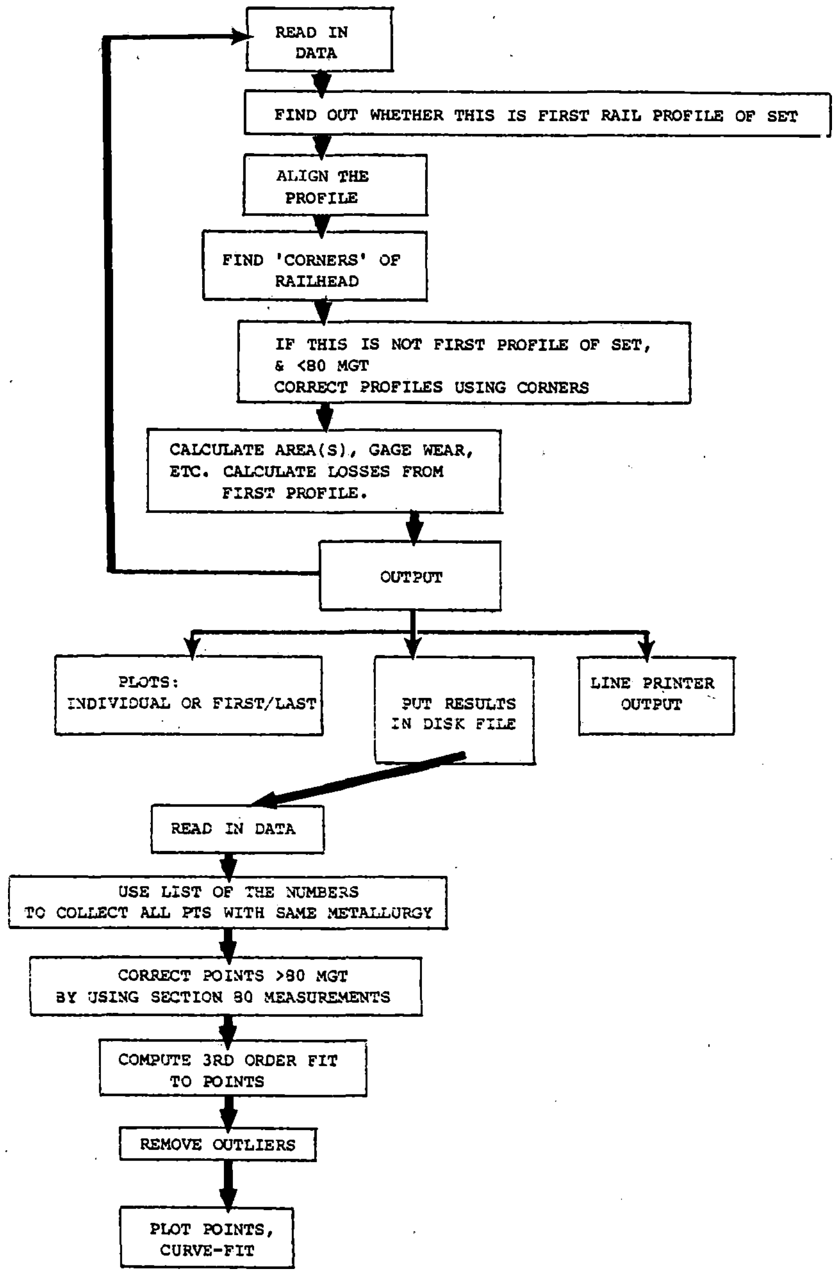


FIGURE B-1. BASIC REDUCTION PROGRAM.

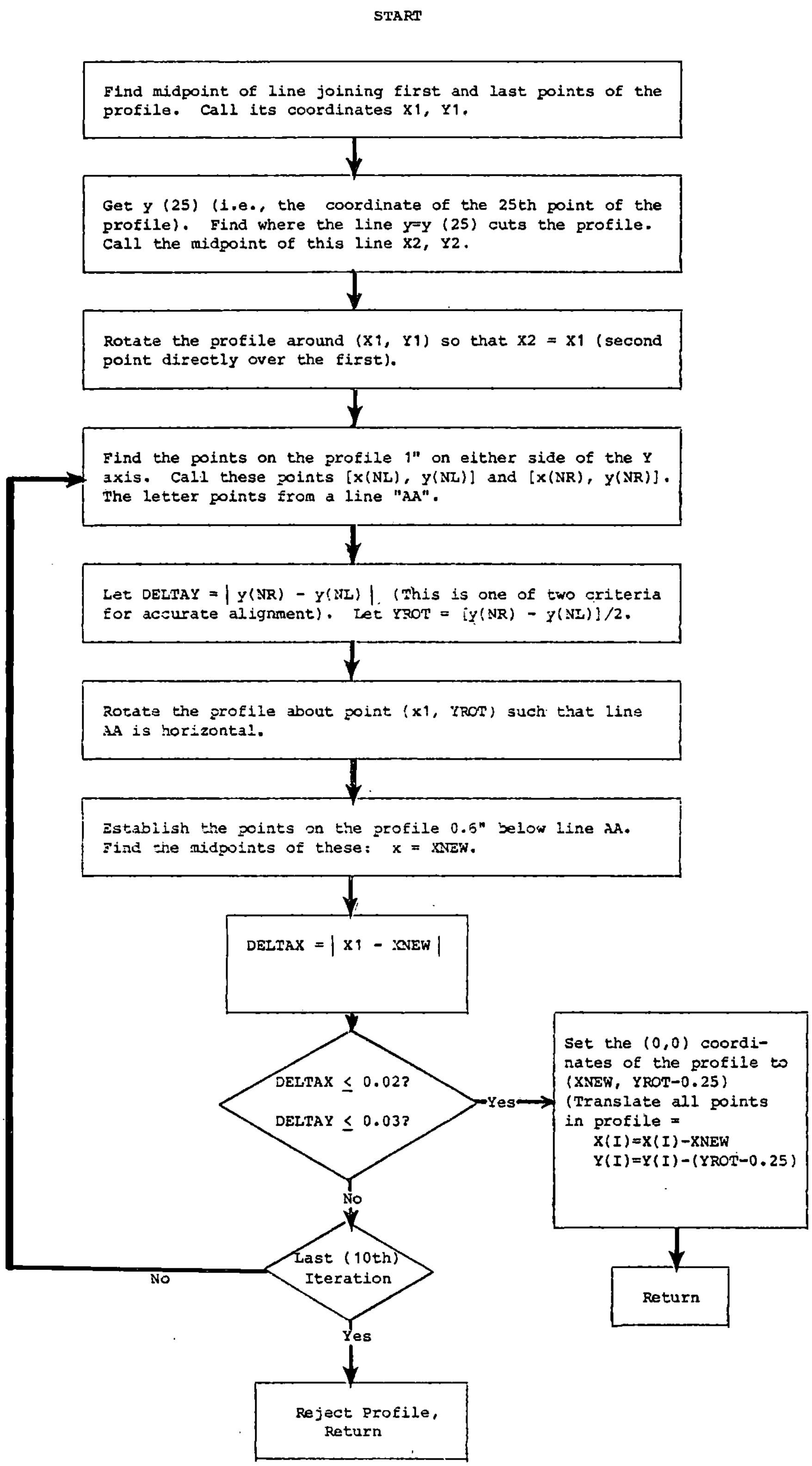
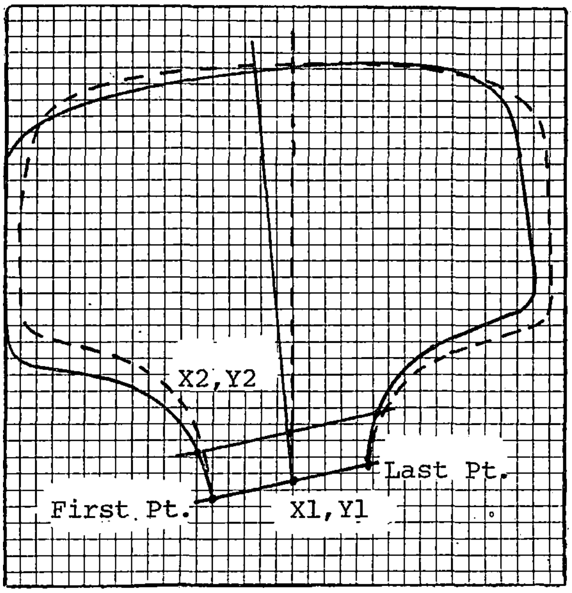
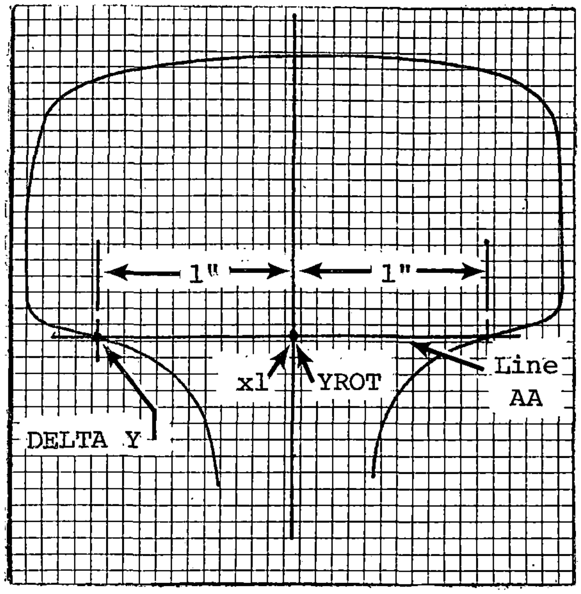


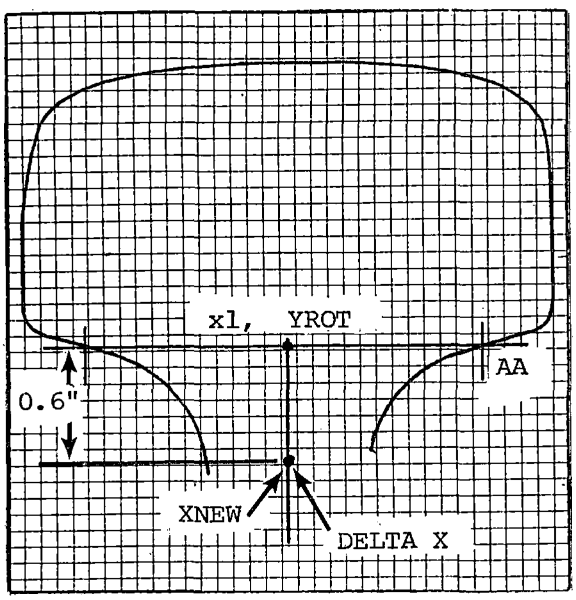
FIGURE B-2. FLOW CHART OF PROFILE ALIGNMENT PROCEDURE (ALINE).



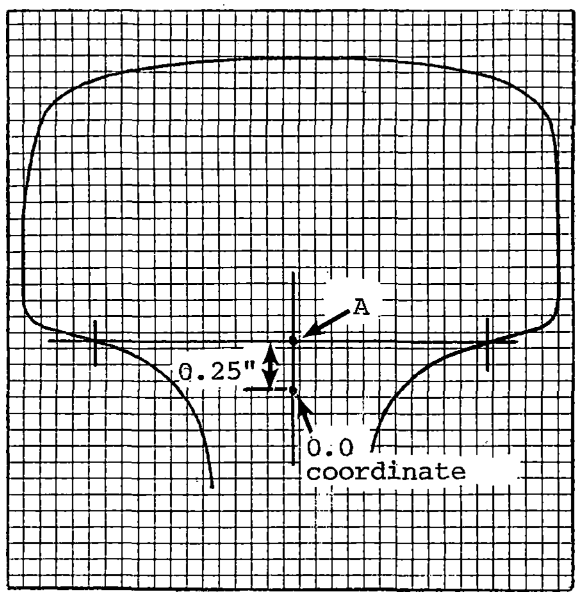
(a) Software pivots profile to align Y-axis on grid; establishes initial x,y origin.



(b) Line AA, DELTA Y, and x1 (YROT) are established. Profile is aligned by pivoting on YROT to align AA with grid.



(c) XNEW (DELTA X) is located on Y-axis. Software reiterates rotations until DELTA X and DELTA Y fall within tolerance. Profile is now aligned.



(d) From point A, new X,Y origin is established for grid. All data points translate to new (0,0) origin.

FIGURE B-3. METHOD OF CENTERLINE AND ORIGIN DETERMINATE.

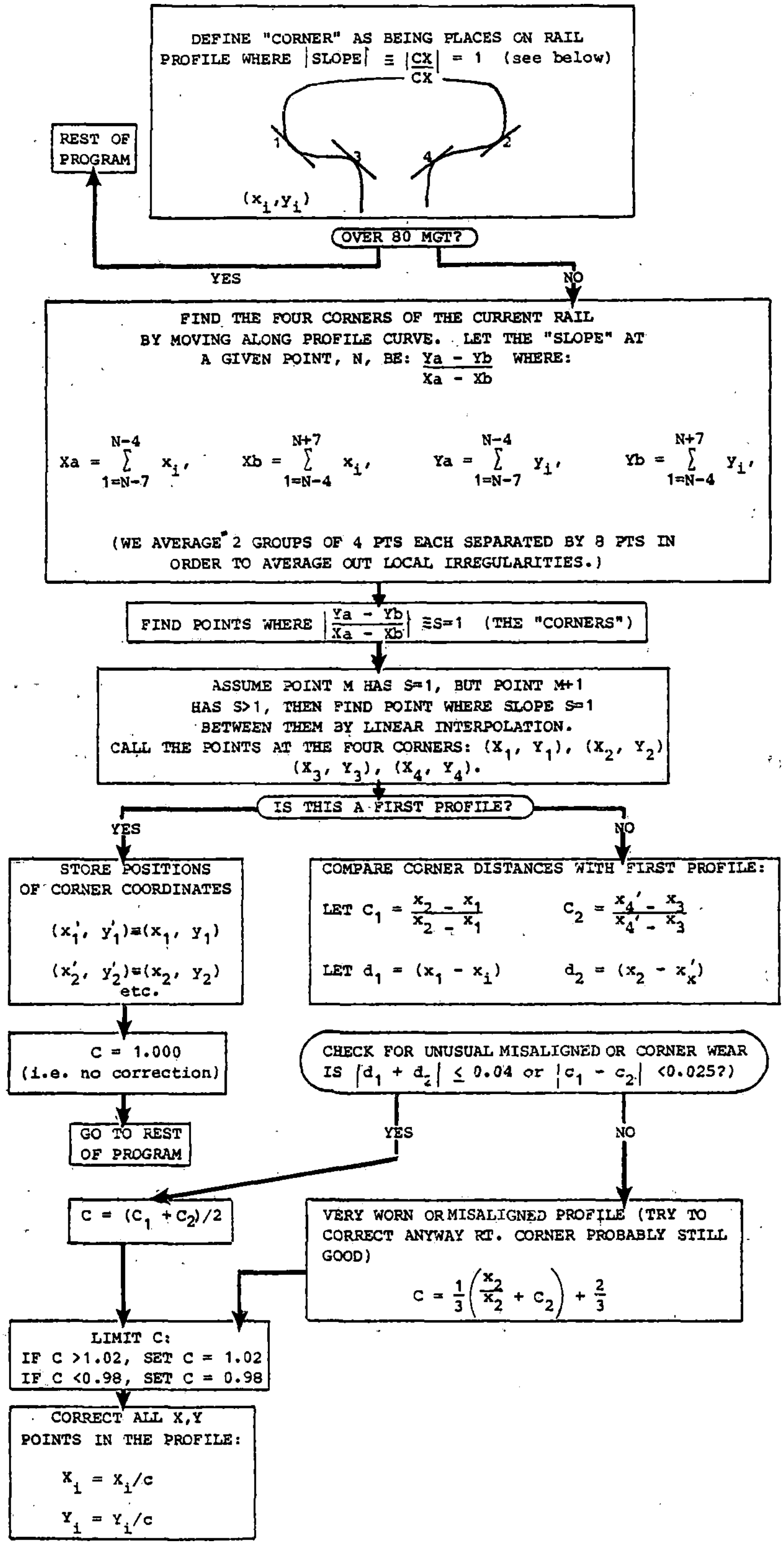


FIGURE B-4. OUTLINE OF PROCEDURE FOR AREA CORRECTION BY CORNERS FOR MGT <80.

found by estimating the slope, s, using the average positions of two groups of four points each, with a gap of eight points between them. When the absolute value of s equalled 1.00, the corner point had been found. If the profile was the first in a set, these corner positions were stored for comparison with successive profiles in the set. If it was not the first profile, the program calculated a correction factor based on the corner distances. Because the corners should not have been altered, it was assumed that the difference in corner distances between the first and subsequent profiles was due to profilometer and/or digitizing error.

The ratio of the width of the outer corners of the subsequent profile to that of the first profile was given as C_1. The ratio of inner corner widths was defined by C_2. The program checked for unusual misalignment or a large difference between C_1 and C_2. In over 90% of the cases, the program proceeded normally and found an average correction factor, C. For the minority of the profiles that failed the above test, the right corner distances (that were presumably undistorted) and the inner corner widths were used to estimate a correction factor. The value of C was limited to between 1.02 and 0.98 to preclude any large over corrections. Finally, as a first approximation, the x and y coordinates of all profile points were corrected by a factor of C, because experience has shown that profilometer errors tend to affect both x and y distances of the profiles.

APPENDIX C

PROFILOMETRY VARIATIONS

Before judging the experimental results obtained from the profilometer measurement, the reader will be well advised to review the behavior of the profilometers over the period of the first metallurgy experiment to provide an insight into the reliability of the measurement. The section 80 calibration profile data (gross areas) were reviewed for the period from startup to December 8, 1977, which was somewhat beyond the end of the first metallurgy test (September 30, 1977). Attention was focused upon instruments 46, 99, and 47 which accounted for nearly 80% of all section 80 profile measurements (32%, 27%, and 19%, respectively). Figures C-1, C-2, and C-3 show the trend in profilometer behavior for these three instruments over the specified period. The solid horizontal line on each plot represents the mean gross area determined for that particular instrument; the dashed horizontal line represents the mean gross area of the calibration standard (section 80) rail determined from all readings taken on all five instruments. Although there are some extreme, apparently noncyclic, variations for all three instruments illustrated here, as they were utilized until December 1977, instrument 46 appeared to be closest to the overall mean (the great grand mean, GGM), which probably was a reasonable representation of the actual Std rail gross area. Instrument 47 tended, on the average, to be somewhat low (1.9%), although during the period from June 8 through November 28, 1977, its gross area profiles were very close to the GGM. Instrument 99, for the entire interval between September 1976 through September 1977, averaged somewhat above (+1.6%) the GGM, although the period of most extensive high reading occurred after June 21, 1977.

The noneffect of instrument calibration, which was accomplished periodically during this period, generally at increasing frequencies, is illustrated in figures C-2 and C-3 for instruments 47 and 99. Note that following each calibration no noticeable change in instrument behavior was observed. A further check on instrument behavior was applied to instruments 47 and 99 by randomly selecting profile cards made by each and comparing these cards with Lucite templates to match the calibration standard (section 80) rail cross section within ± 0.005". The comparison of the width of the rail head as indicated on the section 80 profile card with the Lucite templates was indicated periodically in figures C-2 and C-3. Generally, the greater the departure of profile width from the template width, the greater would be the departure in area from the GGM. However, note that when instrument 47 was producing a profile approximately 1/16" too narrow, the average gross area for the instrument fell very close to the GGM. On the other hand, when instrument 99 produced a standard profile in good (ok) agreement with the templates, the gross area was frequently close to the GGM, but not always, suggesting that there existed some nonsystematic error in area calculation from the profiles. Numerous errors of at least 1/8" on each side of the mean ($\sim$4%) indicated that the 2% limit on the correction factor was too restrictive and that in many cases, not enough correction was applied.

Nothing has been said about operator induced variability. During the interval between September 1976 and December 1977, nine different operators produced section 80 standard profiles. Of these nine, four operators produced

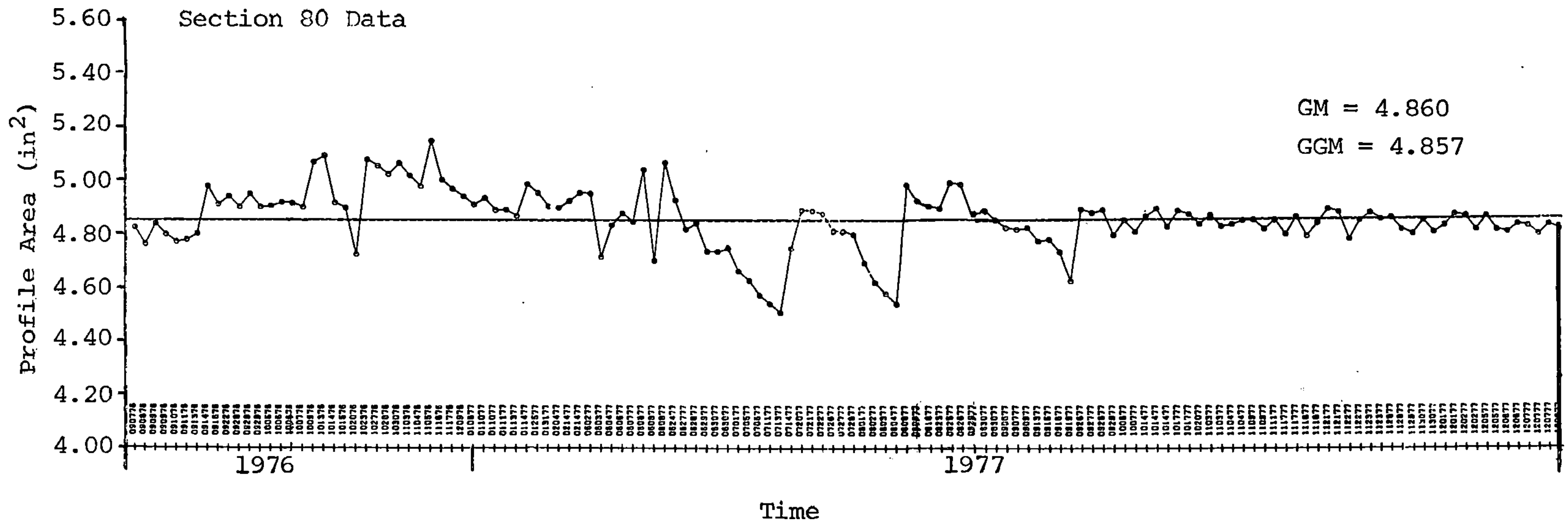


FIGURE C-1. PROFILOMETER 46 BEHAVIOR TREND.

Narrow Profile - N
Wide Profile - W

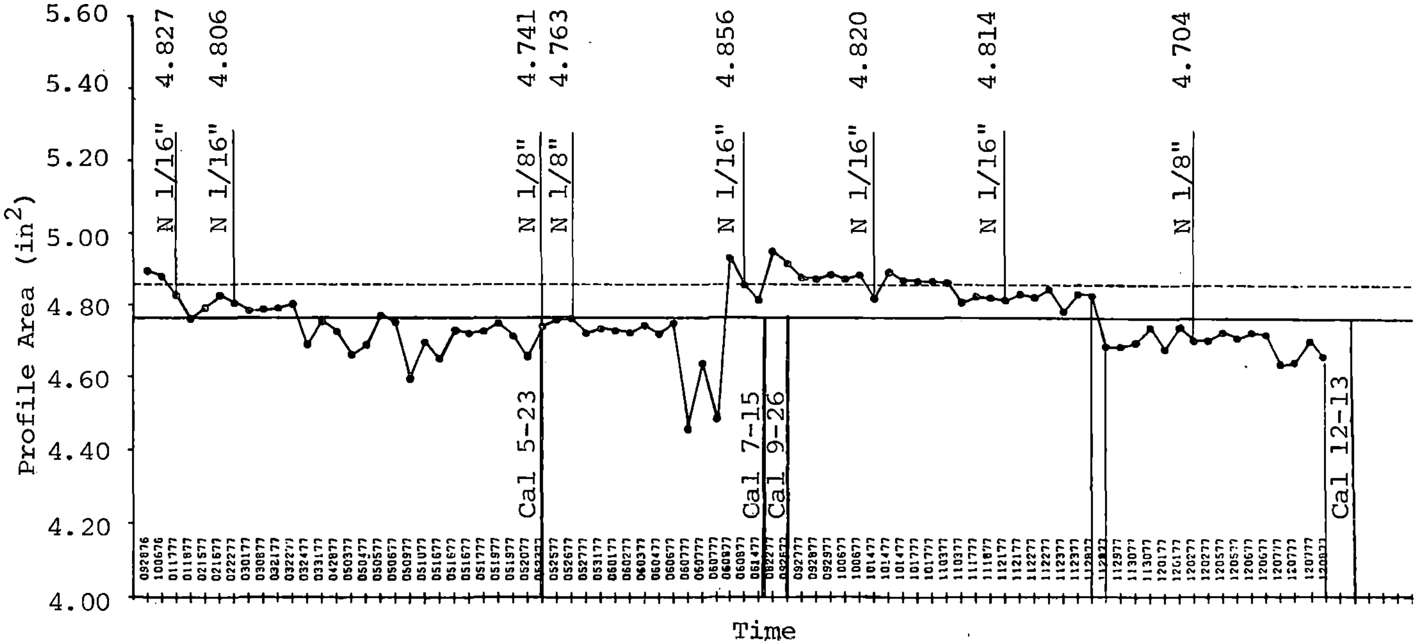


FIGURE C-2. PROFILOMETER 47 BEHAVIOR TREND.

Standard Profile - OK
Narrow Profile - N
Wide Profile - W

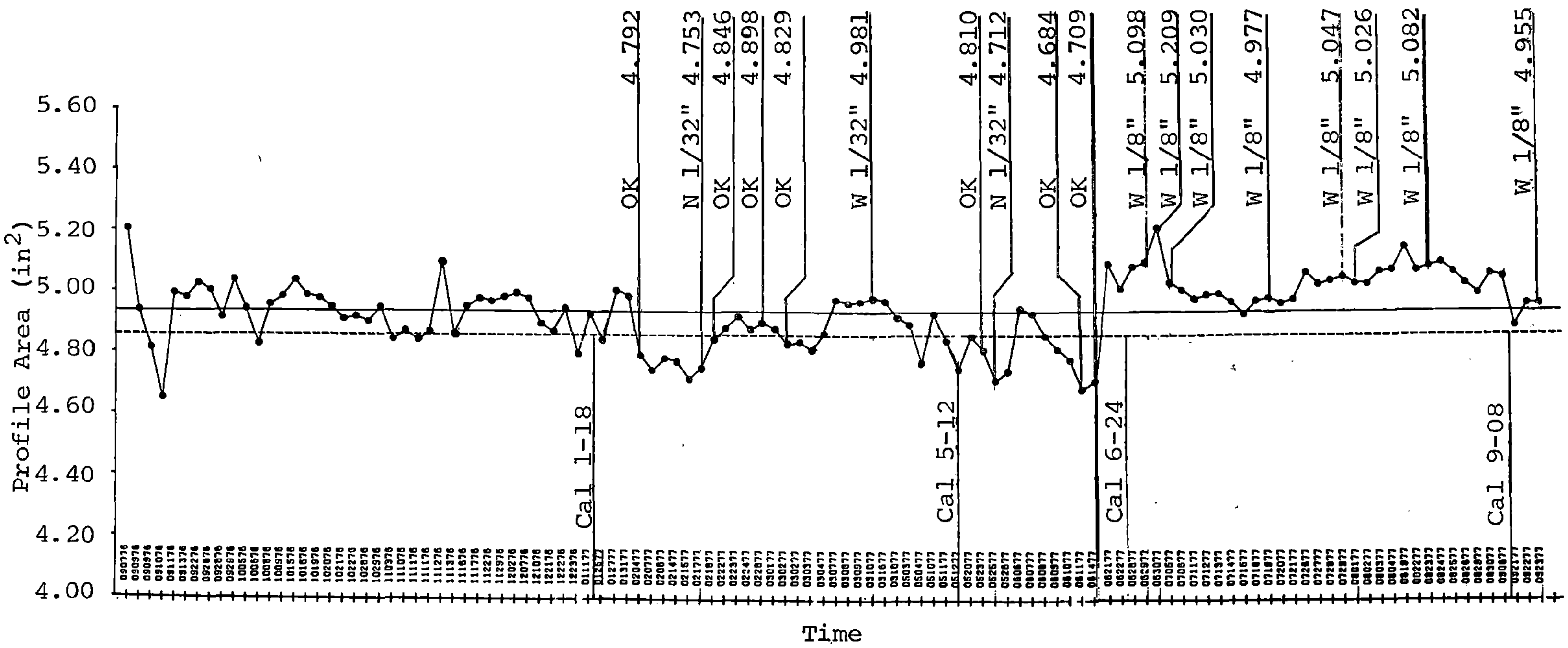


FIGURE C-3. PROFILOMETER 99 BEHAVIOR TREND.

82% of the profiles, and one operator alone was responsibile for 33% of the profiles. The ratings of these operators in terms of gross mean (OPGM) and their standard deviations and relation to the GGM are given in table C-1). Fortunately, the operator (D) who produced the greatest single number of profiles also produced about the most consistent profiles and the second smallest departure from the GGM. Regrettably, because different operators tended to specialize with different instruments, possible operator:instrument interactions cannot be determined. However, as can be observed in figure C-4, the profiles of the most frequent operator (D) were stable on instrument 99 but showed a tendency toward decreased gross head area for instruments 46 and 47 after the summer of 1977. The next most frequent operator (F) showed (figure C-5) large excursions throughout the entire period of the first metallurgy experiment on instrument 46 but very good control on that instrument afterwards. His performance on instrument 45 showed a fairly consistent decline in gross head area after the late fall of 1976. The only other operator (C) with any appreciable number of profiles to his credit seems to have worked primarily with instrument 99 (figure C-6). His performance was erratic at first but became steadier after midsummer of 1977.

Besides the instrument operator variability factor (which included error introduced during digitizing of the profiles), the random occurrence of phantom profiles also served to increase the variability in the data base. Phantoms are profiles which appear to be incorrectly labeled by tie number or date. They are most easily recognized in the low rail where different rail sections appear on the same tie number over a short period of time; i.e., 136 lb/yd, 132 lb/yd, 136 lb/yd over the course of only a few weeks or less. Phantoms of the same rail section type but different metallurgy cannot be recognized with any certainty except after an extended period of underlubricated service. It is not possible to estimate how many phantoms existed in the high rail population but, based on spot checks of the low rail profile population, it is hoped that one should account for less than 5% of the population.

TABLE C-1. OPERATOR GRAND MEAN VS GREAT GRAND MEAN.

	N	Area (in^2)	σ	%D
GGM	406	4.857	0.126	+ 2.6%
Operator				
A	12	4.887	0.10	+ 0.62%
B	10	4.817	0.12	- 0.82%
C	59	4.922	0.14	+ 1.34%
D	136	4.847	0.10	- 0.21%
E	22	4.933	0.12	+ 1.56%
F	94	4.812	0.14	- 0.93%
G	17	4.795	0.08	- 1.28%
H	45	4.876	0.14	+ 0.39%
I	11	4.865	0.10	+ 0.16%

%D = Departure from GGM
N = Number of observations
σ = Standard deviation

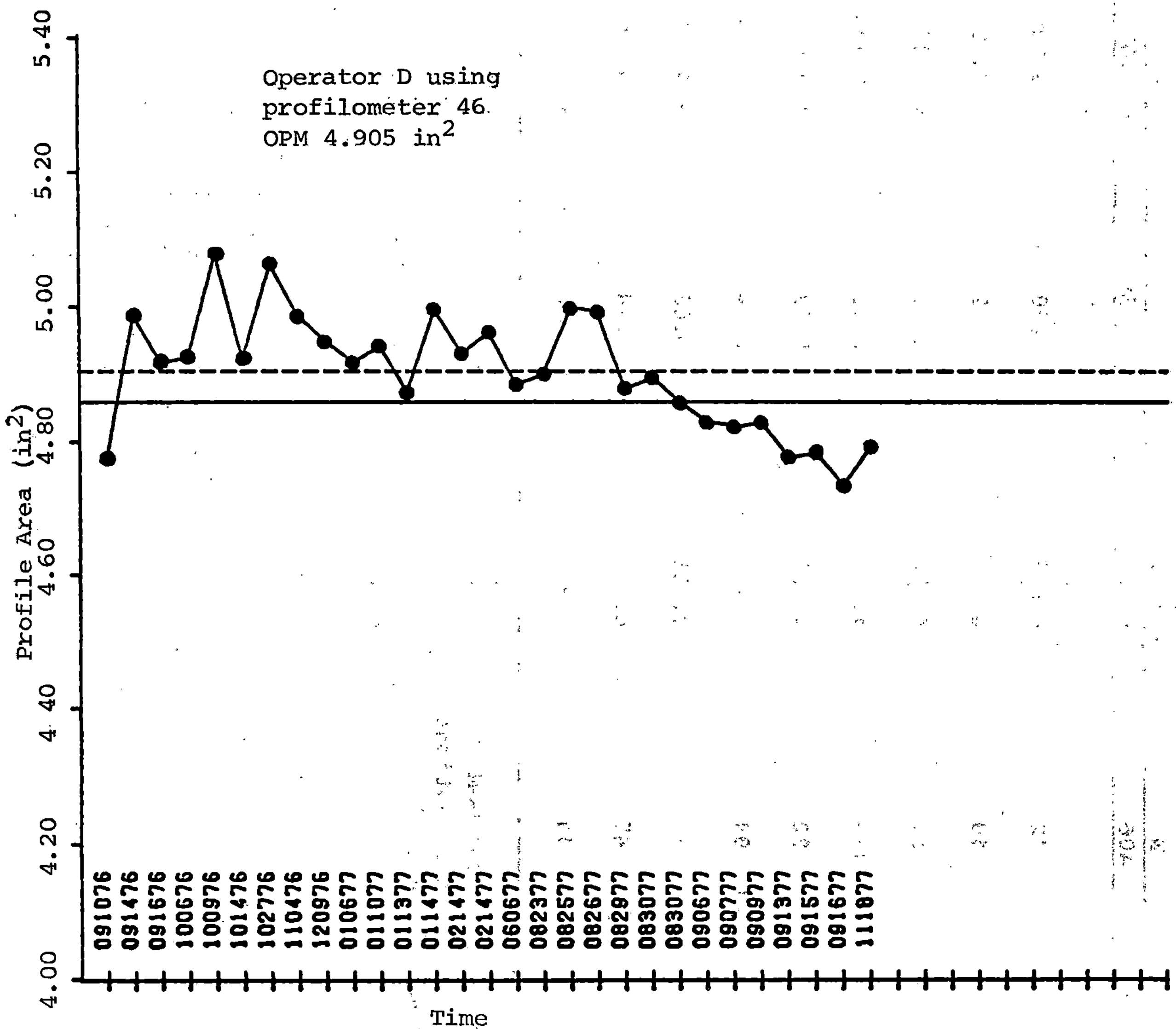


FIGURE C-4. OPERATOR "D".

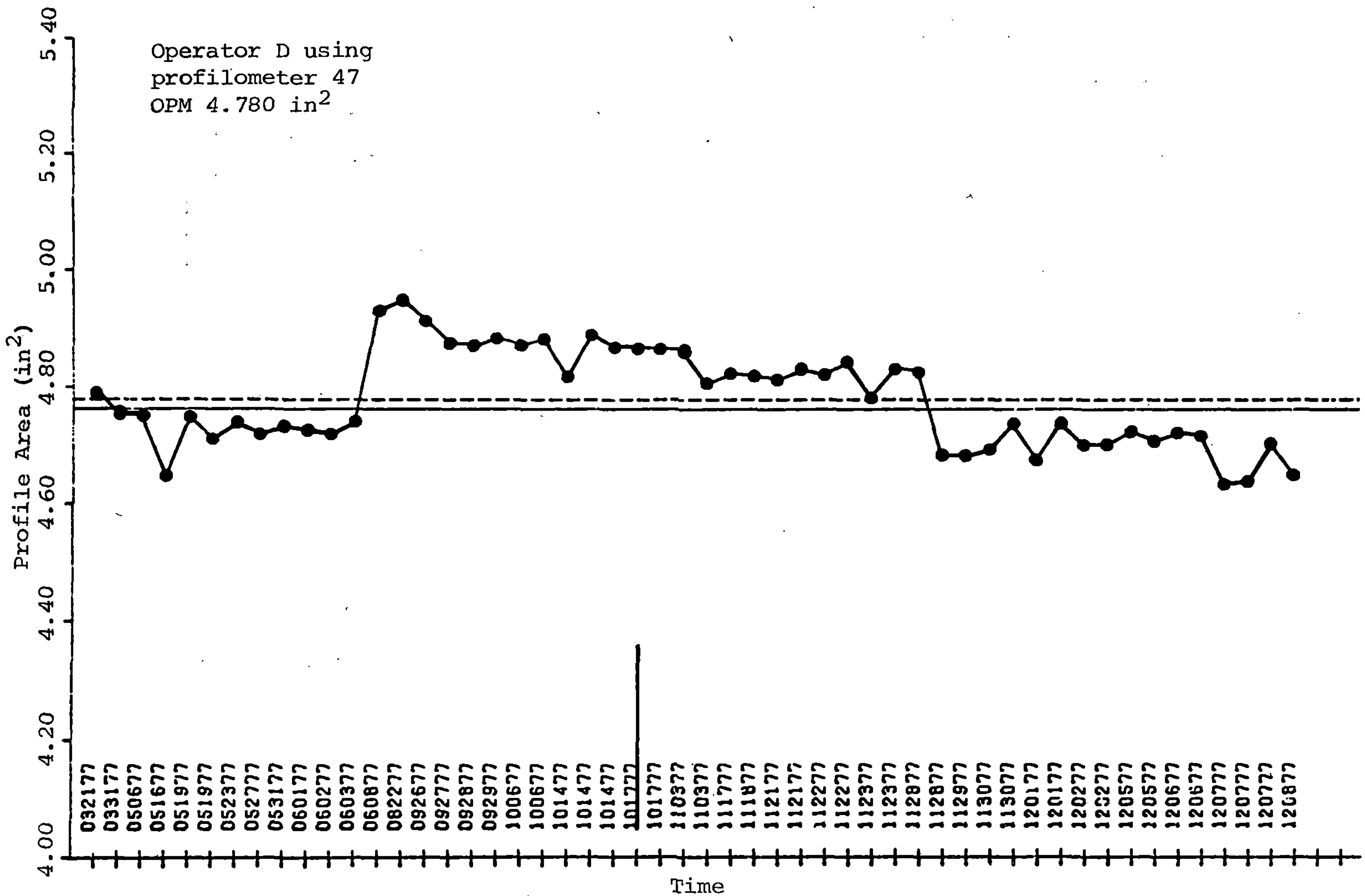


FIGURE C-4. OPERATOR "D", CONTINUED.

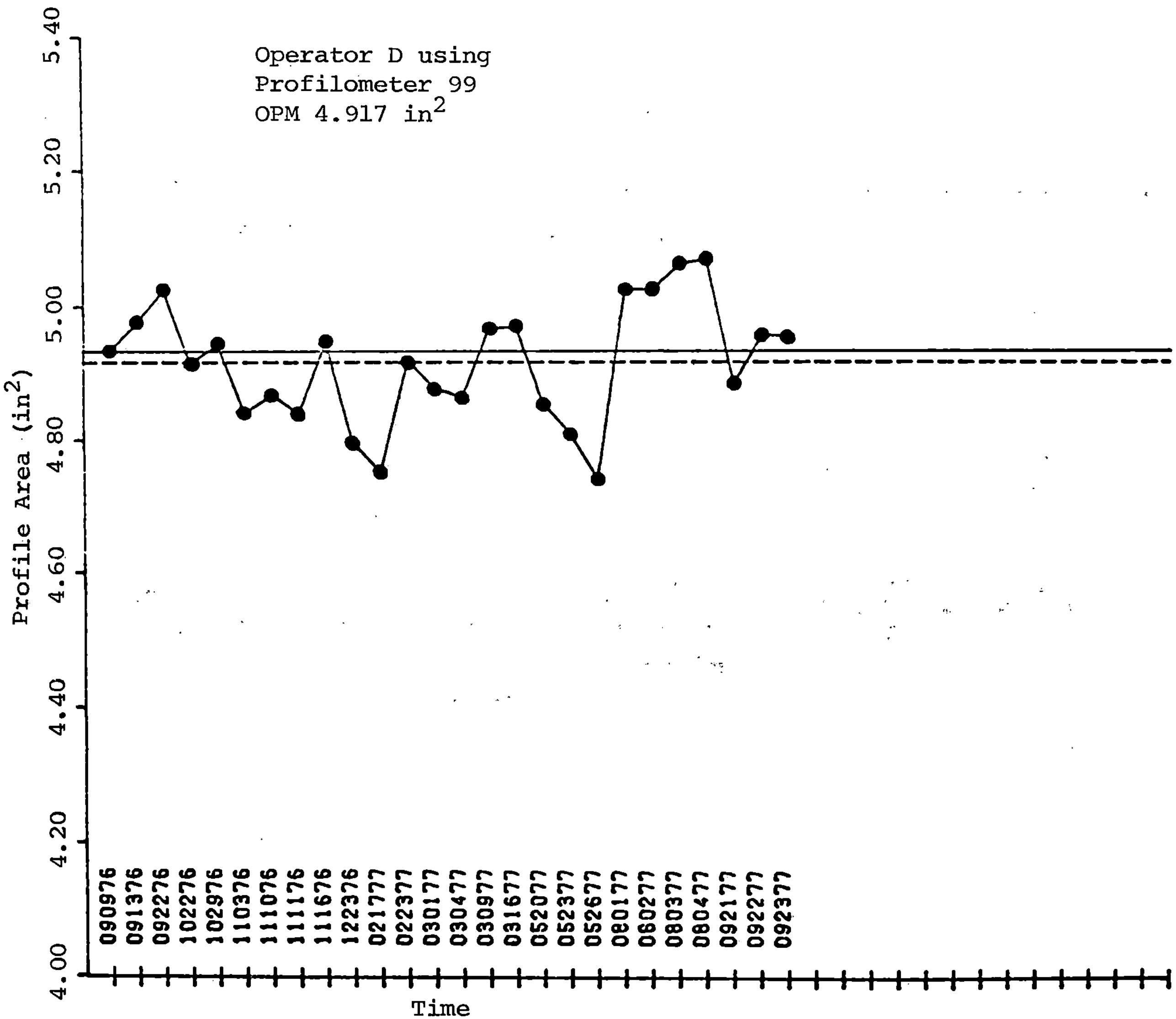


FIGURE C-4. OPERATOR "D", CONTINUED.

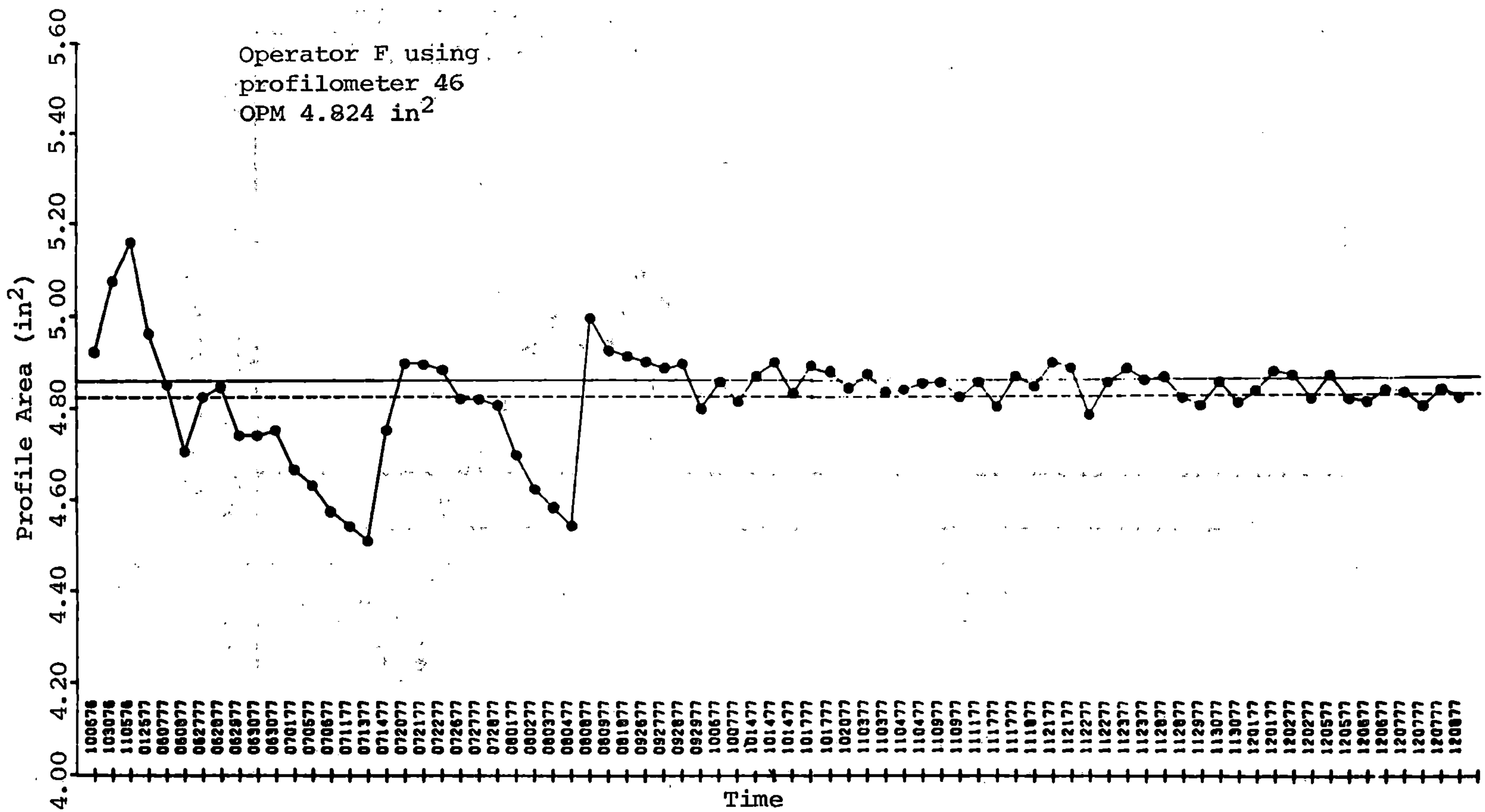


FIGURE C-5. OPERATOR "F".

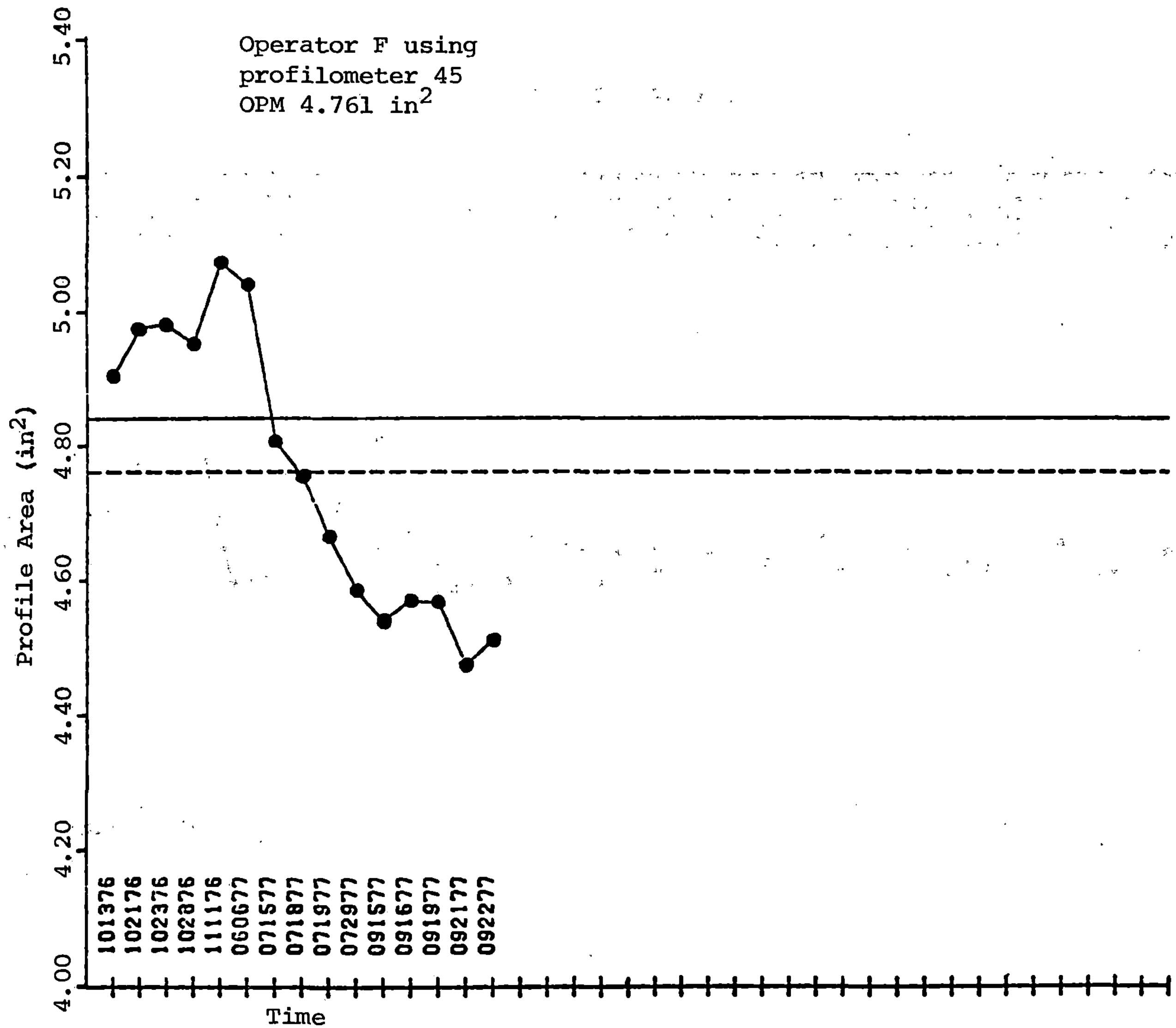


FIGURE C-5. OPERATOR "F", CONTINUED.

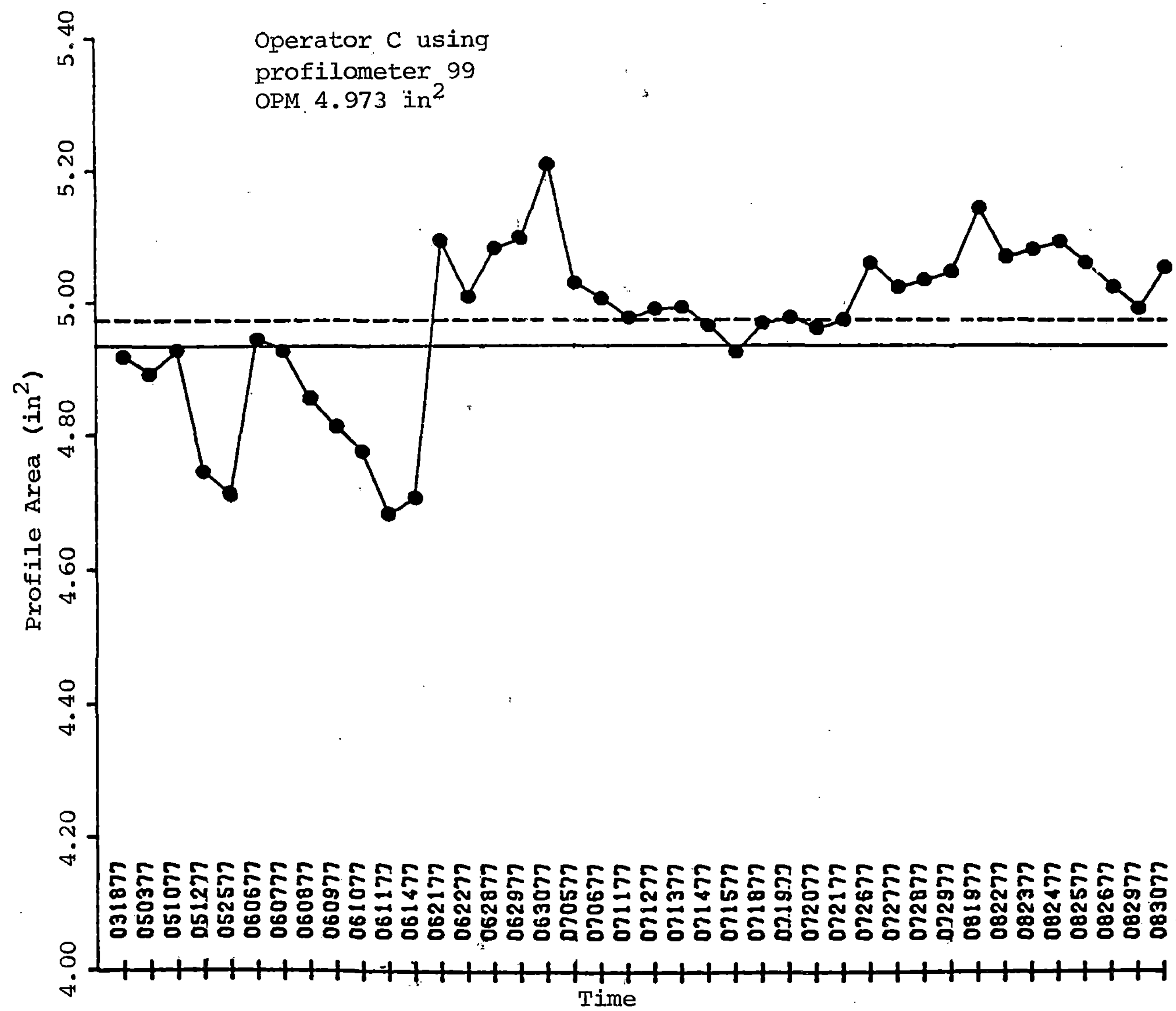


FIGURE C-6. OPERATOR C.

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