FRA/ORD-84/17

TRACK DEGRADATION AT FAST

FAST Facility for Accelerated Service Testing

TRANSPORTATION TEST CENTER
PUEBLO, COLORADO 81001

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16. Abstract

This report describes the Track Degradation Experiment performed on the FAST track at the Transportation Test Center, near Pueblo, Colorado. The railroad industry's need to allocate resources more effectively has prompted strong interest in methods of predicting when track will degrade geometrically to the point where maintenance is necessary. Safety and reliability are dependent upon the condition of track and supporting structures.

Eleven segments of track were studied consisting of tangent and curve track with jointed and continuous welded rail on wood and concrete ties. The purposes of the study were to: 1) develop a method of quantifying track degradation and maintenance requirements relative to defined standards, 2) measure track degradation as a result of traffic, and 3) determine the feasibility of predicting the rate of track degradation under known operating conditions and maintenance practices.

A commercially available track geometry vehicle was used to obtain most of the data for this study. From the data, statistical calculations were made to quantify the degradation of the track segments and to permit correlation with maintenance data. Conclusions support the use of statistical calculations from track geometry data as a viable means of quantifying track degradation. However, the track degraded slowly, and although this was desirable from an operational standpoint, it precluded any firm conclusions about rate or predictability of degradation from this experiment.

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The Denver & Rio Grande Western Railroad Co.

DU-WEL Steel Products

Missouri Pacific Railroad Co.

Pandrol USA, Inc.

Union Pacific Railroad

Unit Rail Anchor Co.

In addition to these donations, the ballast, other fasteners, planning and labor to construct the necessary track were provided by the FRA through the FAST program. The FRA also provided funds to operate and maintain the FAST facility, and to collect and analyze the test data.

Contributions to the entire FAST program, which has benefitted the Track Degradation Experiment, have been provided by more than 150 other Railroads and Suppliers, a list of which is too long to include. The AAR has also contributed heavily to the FAST program planning and administration.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAR	Association of American Railroads
AREA	American Railway Engineering Association
CWR	continuous welded rail
DOT	Department of Transportation
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
IFAST	Interim Facility for Accelerated Service Testing
MGT	million gross tons
ORE	Office for Research and Experiments of the International Union of Railways
TSC	Transportation Systems Center

ABBREVIATIONS AND METRIC CONVERSIONS

%	percent	
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/hr	miles(s) per hour	= 1.609 km/hr
1 lb	pound	= 0.454 kg
1 kip	kilopound	= 453.59 kg
1 ton		= 0.907 metric tons

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4. Based on percentage of track with FRA Class 6 exceptions (freight train speed limit of 110 mph), the greater the standard deviation of selected parameters, the more likely specific geometric exceptions will occur. This was particularly true with profile and twist and to a lesser extent with cross-level. No correlation was found between FRA Class 6 alignment exceptions and alignment standard deviation based on 62-foot chord. It should be noted that there were no FRA Class 5 exceptions for any parameter on any segment at 160 MGT, (using revised FRA standard, effective November 1, 1982).

It is apparent that track degradation experiments at FAST must be somewhat limited in scope. However, because of the ability to control many of the factors influencing degradation, experiments at FAST should be continued as a part of a program including experiments on revenue service trackage. This can add materially to our knowledge of the mechanics of track degradation, which should, in turn improve the industry's ability to build and maintain a safer track structure at lower cost.

EXECUTIVE SUMMARY

The objectives of the FAST Track Degradation Experiment were: (1) to develop a method to quantify track degradation and required maintenance when operating a controlled consist on track built and maintained to defined standards; (2) using the method developed, measure the track degradation and maintenance required as a result of operating the FAST train; and (3) determine the feasibility of predicting degradation of track subjected to known operational and maintenance practices. Objective No. 1, to quantify track degradation and required maintenance, was achieved. The test track was originally constructed to FRA Class 6 standards, and, at 160 MGT, very little track degradation had taken place and very little maintenance was required. What track degradation and maintenance did take place were measured in accordance with Objective No. 2. Objective No. 3 of this first track degradation experiment was not attained, since insufficient track degradation at the FAST site occurred to provide the data necessary for predicting track degradation.

It is evident from this first track degradation experiment that many of the factors causing track degradation in the revenue service environment were not present in the FAST operation. These include (1) greater variation in train forces, e.g., acceleration and braking; (2) greater variation in the natural environment, e.g., freeze-thaw cycles and precipitation; (3) greater variation in rail, crosstie and ballast condition, (4) greater variation in subgrade characteristics, and (5) extensive and sometimes inconsistent rail and wheel lubrication.

The experiment appears to confirm the beliefs of many track engineers that a high quality track structure combined with well maintained mechanical equipment and well controlled train operation will result in reduced track deterioration, thus reducing maintenance of track and mechanical equipment. The fact that a good portion of this experiment was in the lubricated regime, as required by the Rail Metallurgy and Wheel Experiments, also impacted track degradation. Other FAST experiments indicate that proper lubrication not only reduces rail wear but also those longitudinal and lateral forces which contribute to geometric degradation.

While the track in this experiment did not degrade sufficiently to permit accurate prediction of future degradation, some conclusions can be drawn. It should be kept in mind that these conclusions are derived from highly controlled train operation in the FAST environment using a self-propelled EM80 track geometry car for the geometry car measurements. Correlation with various railroad operating environments is unknown. The conclusions are:

1. Degradation of track profile as measured by its standard deviation increased over the first 60 million gross tons and then stabilized or increased slightly to 160 MGT. The experiment was terminated at 160 MGT.

2. Degradation of alignment and rate of change of alignment do not appear to be directly related to accumulation of tonnage.

3. Degradation of gage, cross-level and twist in the test track was not sufficient in magnitude to indicate a correlation with tonnage.

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1.0 INTRODUCTION

Maintenance-of-way and structures expenditures for Class I Railroads in the United States exceeded $5 billion in 1982.(1) The effectiveness with which these funds are allocated is thought to vary greatly within the industry. Generally, past allocation of maintenance funds has been based on field experience and judgement not easily quantified, but good management practice requires a more objective process of allocation and the ability to evaluate the effectiveness of the use of resources.

The ability to predict when track can no longer fulfill its functional requirements would greatly improve maintenance planning. Thus, the allocation of scarce maintenance-of-way resources would be more effective, and accountability for expenditures would also improve.

In 1975, Punwani, Lundgren, and Martin (2) addressed the need for a series of Track Settlement and Maintenance Tests in their report to the FRA outlining a need in the U. S. for a Facility for Accelerated Service Testing (FAST). When FAST, called IFAST at the time, started operation in September 1976, a track maintenance experiment called "The Maintenance-of-Way Experiment" had been considered; however, due to the lack of a clearly defined experiment objective and problems in retrieval of the maintenance data, the experiment was never implemented.(3)

The second edition of the Track Train Dynamics Manual to Improve Freight Train Performance summed up the importance of track geometry. "Reliable train operations are dependent to a large extent on the condition of the track and supporting structures. Irregularities in track alignment, surface, and gage can cause damage to equipment and lading and, in extreme cases, may cause derailment."(4)

Most major U. S. Railroads use track geometry cars to measure track geometry and report the locations of major deviations from track standards. The Chessie was one of the first U. S. Railroads to see the benefits of the use of a track geometry car in the 1880's and later developed the more sophisticated RI-1 Geometry Car in 1936.(5) There have been many changes in the methods by which geometry cars collect and record the measured data. Originally the data were recorded on strip charts with exceptions marked by hand on the chart. In the last 20 years high speed microcomputers have been introduced in the data collection function, and the computer identifies locations where deviations exceed predetermined values. In addition to locating discrete problems, a tremendous amount of additional data is collected and is generally not being used. The Southern Railway has been able to use some of these additional data to help identify track segments for programmed or system gang maintenance and as a research and analytic tool.(6) In addition, other railroads and the FRA have begun to manipulate these data for use as a maintenance planning tool or to evaluate overall track quality.(7)

In 1980, the FAST Policy Committee, under the direction of Mr. W. W. Simpson of the Southern Railway, decided that the issue of degradation of the track structure--specifically geometric degradation as related to the operation of 100-ton cars with conventional trucks--should be addressed. The Policy Committee requested that Dr. W. J. Harris, Vice President, Research and Test Department of the Association of American Railroads, assemble an Ad-Hoc Committee of railroad engineering and track professionals to design an experiment that would produce the data requested by the Policy Committee. The Ad-Hoc Committee developed the experiment identified as the "Track Degradation Experiment."(3)

The Track Degradation Ad-Hoc Committee included the following indviduals:

- Mr. J. W. Brent, former Chief Engineer, Chessie System Railroads,
- Mr. R. F. Tuve, Manager, Quality Control Engineering, Norfolk Southern Corporation,
- Mr. W. J. Cruse, former Chief Engineer, Rock Island Railroad,
- Mr. T. B. Hutchinson, former Chief Engineer, Seaboard Coastline Railroad,
- Mr. G. A. Vandewater, Vice President, Great Lakes Region, Canadian National Railways,

The objectives of the experiment as defined by the Ad-Hoc Committee were as follows:

1. To develop a method to quantify track degradation and/or maintenance effort required when operating a controlled consist on track built and maintained to defined standards. This method would then be utilized when track and/or vehicle parameters were changed.

2. To measure, using the method developed, the track degradation and the maintenance required as a result of operating the FAST train consist and other train consists in subsequent phases of the FAST program.

3. To determine the feasibility of predicting the rate of track degradation when subjected to known operating and maintenance practices.

In the development of the experiment, the committee chose to concentrate on the measurement and quantification of the degradation of normally-measured parameters of track geometry. The committee also chose to gather other pertinent data which they thought might be useful in defining and predicting the degradation rate.(3)

2.0 DESCRIPTION OF THE EXPERIMENT

The Facility for Accelerated Service Testing (FAST) is located at the Transportation Test Center (TTC) in Pueblo, Colorado. The TTC, originally built and operated by the Federal Railroad Administration (FRA), was turned over to the Association of American Railroads (AAR) on October 1, 1982. The AAR has continued operation and management of the FAST program under contract with the FRA. FAST consists of a 4.8 mile test loop on which a test train of 9,500 trailing tons completes up to 120 laps daily. The result is accumulation of 0.5 to 1.2 million gross tons (MGT) of traffic on the FAST track daily. Figure 1 shows the general configuration of the FAST track and Figure 2 shows the FAST condensed profile.

Approximately 1.8 miles of the FAST track were used in the Track Degradation Experiment. Figure 3 shows that portion of the FAST track.

The test was divided into 11 segments. Three of the segments were in tangent track, four were in spiral track, two in a 3 degree curve, and two in a 4 degree curve. The experiment design matrix, Table 1, shows the detailed track construction of each of the 11 segments. Typical track construction photos showing wood ties with jointed rail, wood ties with CWR, and concrete ties with CWR are presented as Figures 4, 5, and 6 respectively.

2.1 TRACK CONSTRUCTION

Prior to the start of the experiment all 11 test segments were rebuilt with new or second-hand track material to the following standards:

Subgrade. Native construction subgrade material found at FAST consists of sand with small amounts of clay and silt. The subgrade under test segments 1-4 was constructed in 1972-1973 as part of the Train Dynamics Track at the TTC. The subgrade in segments 5-11 was constructed as part of the FAST construction program in 1976. During construction the placement of fill material and subgrade compaction were monitored very closely. The construction specification required compaction of all subgrades to a minimum of 95% of Modified Proctor. In addition to construction of a stable and well compacted subgrade, an 8 to 12 inch layer of subbase material was placed and compacted prior to track construction. The foundation on which the FAST track was placed was of very high quality.

Geometry. All track was constructed to standards such that better than 90% of the track was within FRA Class 6 for profile, surface, alignment, gage, superelevation, and twist.

Ballast. Minimum 12" deep below ties and minimum 12" shoulder. Ballast in segments 1, 2, 3, 4, 10, and 11 consisted of slag produced by a western steel producer, and was approximately an AREA No. 4 gradation. Ballast in segments 5, 6, 7, 8, and 9 was Wyoming Granite with an AREA No. 5 gradation.

Wood Ties. New AREA No. 5 mixed hardwood on 19.5 inch centers were used for wood tie trackage.

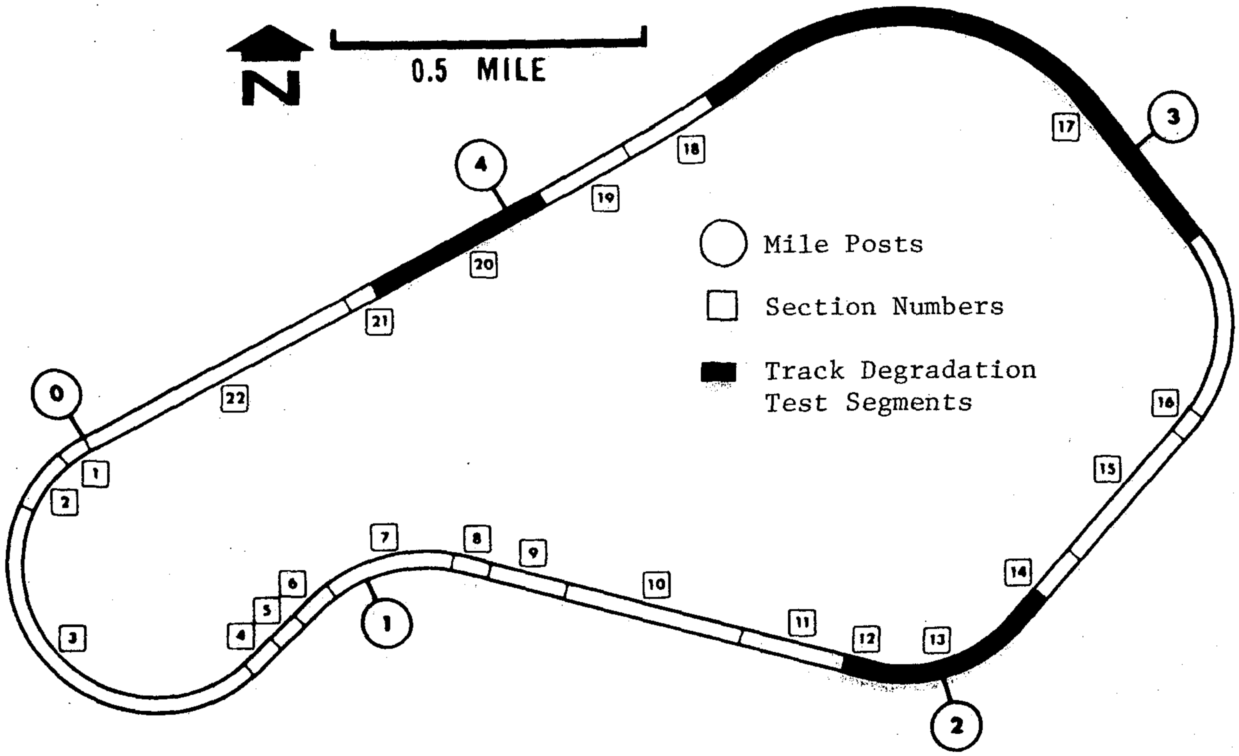

FIGURE 1. FAST TRACK CONFIGURATION.

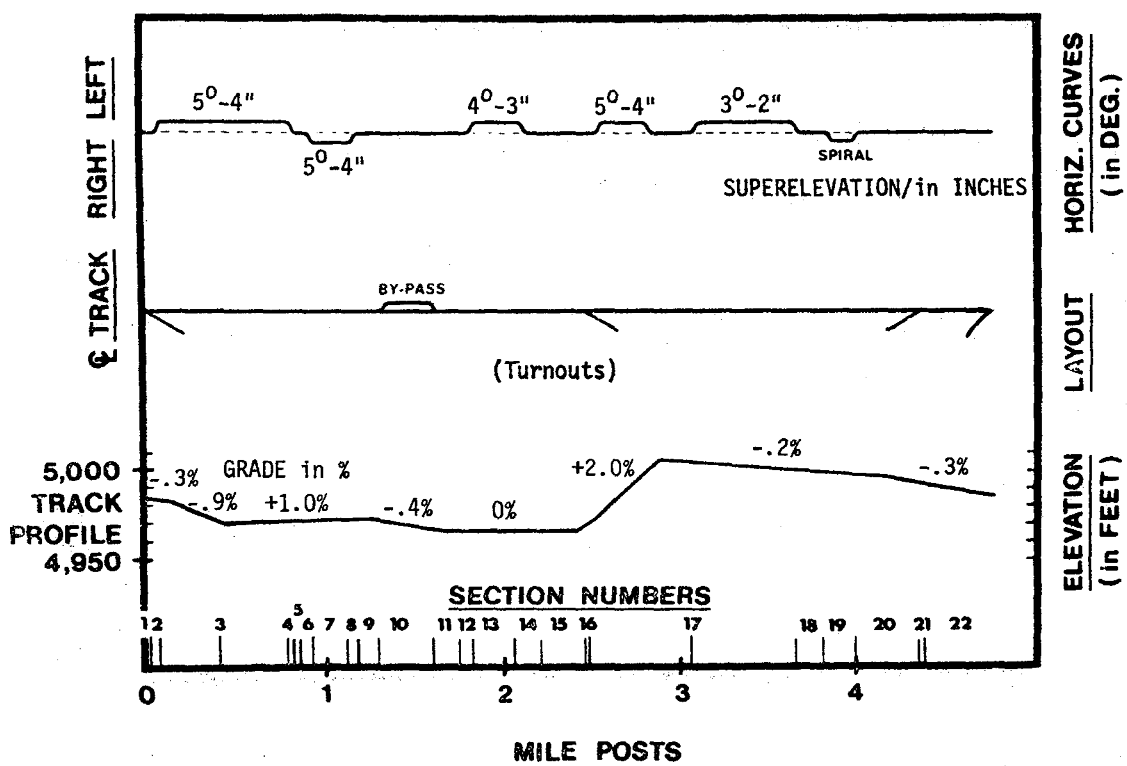

FIGURE 2. FAST CONDENSED PROFILE.

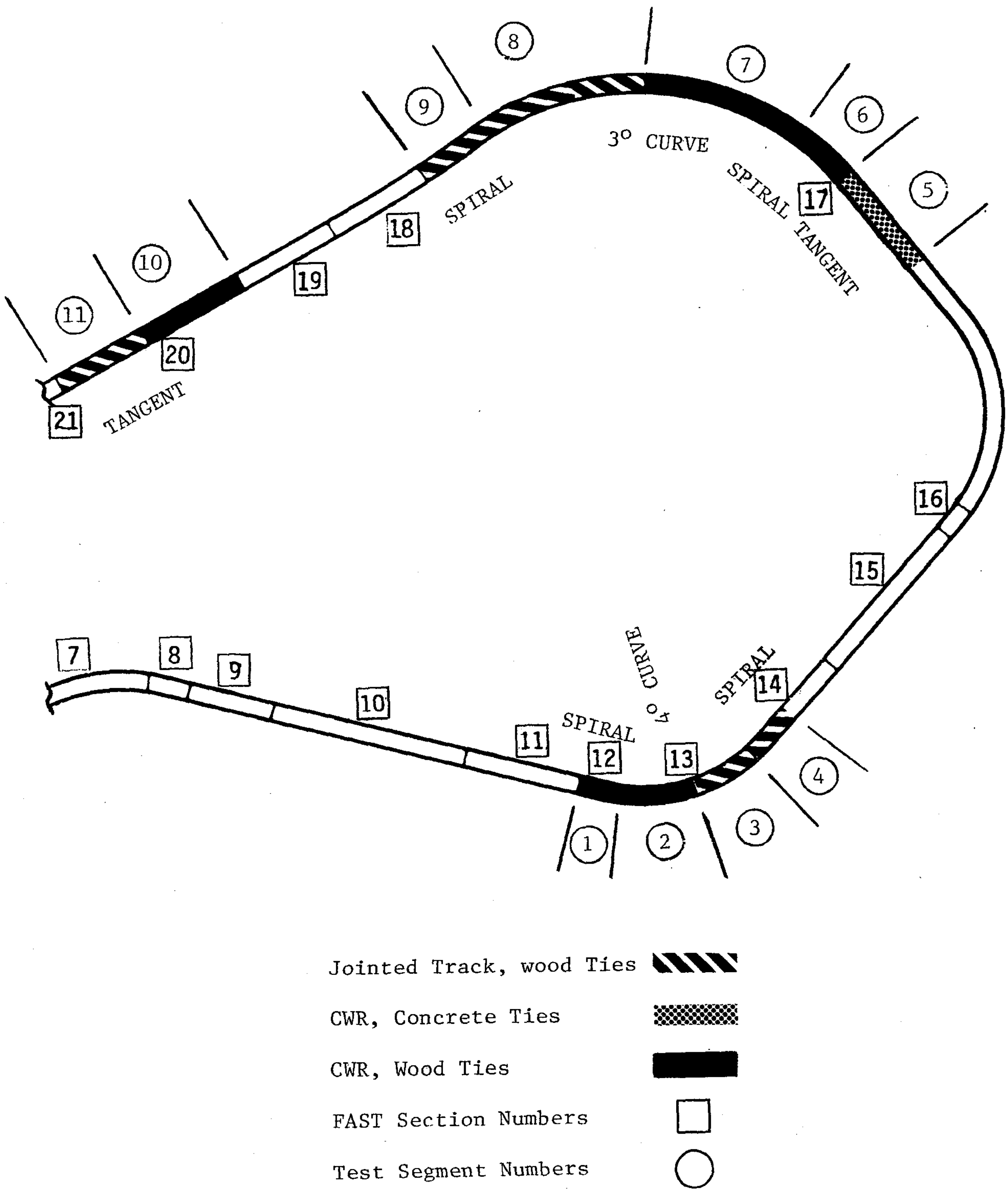

FIGURE 3. TRACK DEGRADATION TEST SECTIONS AT FAST.

TABLE 1. EXPERIMENT DESIGN MATRIX.

TRACK CONSTRUCTION		CURVATURE				
RAIL AND TIE TYPE	OTHER CONSTRUCTION DETAILS	TANGENT	3° CURVE	4° CURVE	3° SPIRAL	4° SPIRAL
Jointed - Wood Ties	Segment No.	11	8	3	9	4
	Length	1,139'	1,063'	663'	600'	300'
	Grade	-0.2 to 0.3%	-0.2%	0%	-0.2%	0%
CWR - Wood Ties	Segment No.	10	7	2	6	1
	Length	1,139'	1,063'	663'	600'	300'
	Grade	-0.2 to 0.3%	-0.2%	0%	-0.2%	0%
CWR - Concrete Ties	Segment No.	5				
	Length	902'				
	Grade	-0.2				

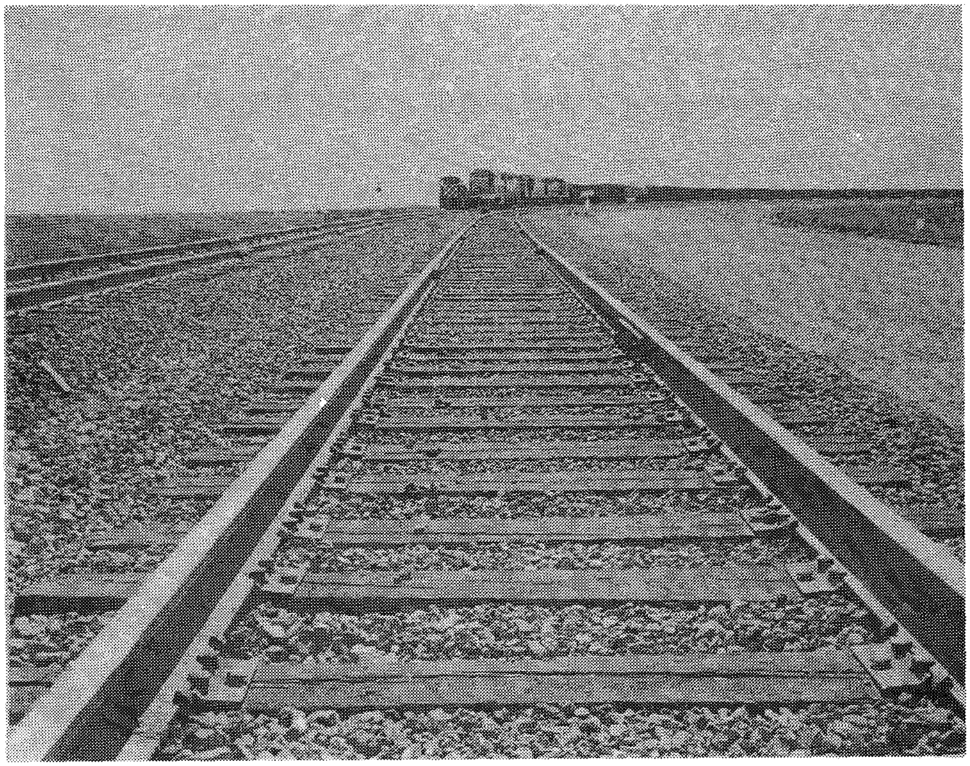

FIGURE 4. JOINTED RAIL ON WOOD TIES.

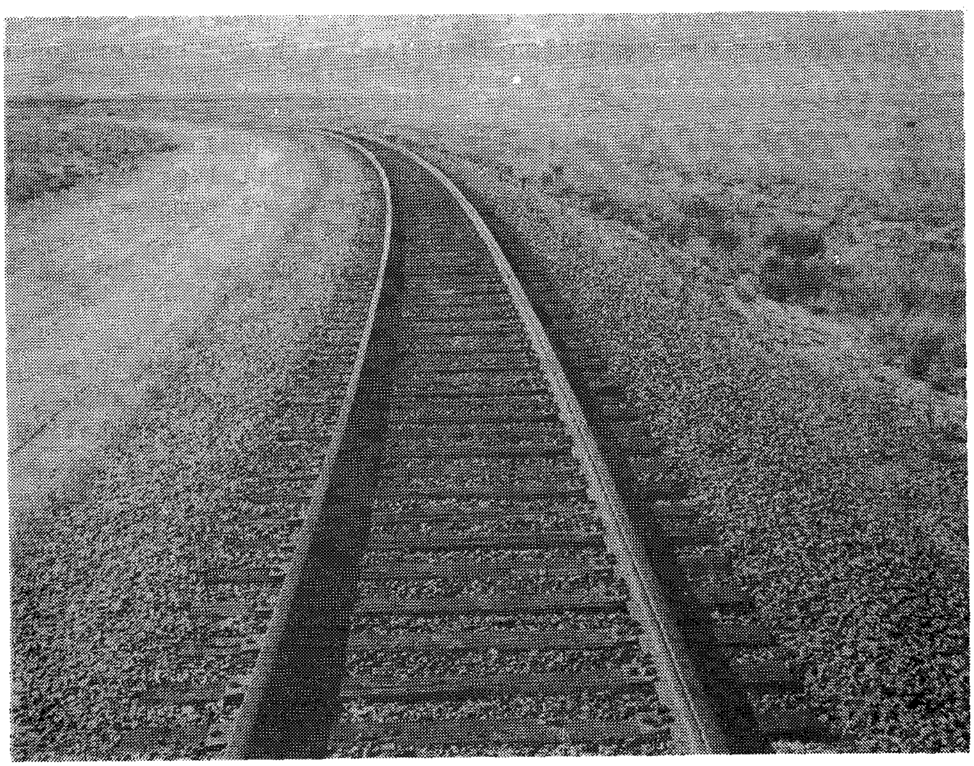

FIGURE 5. CONTINUOUS WELDED RAIL (CWR) ON WOOD TIES.

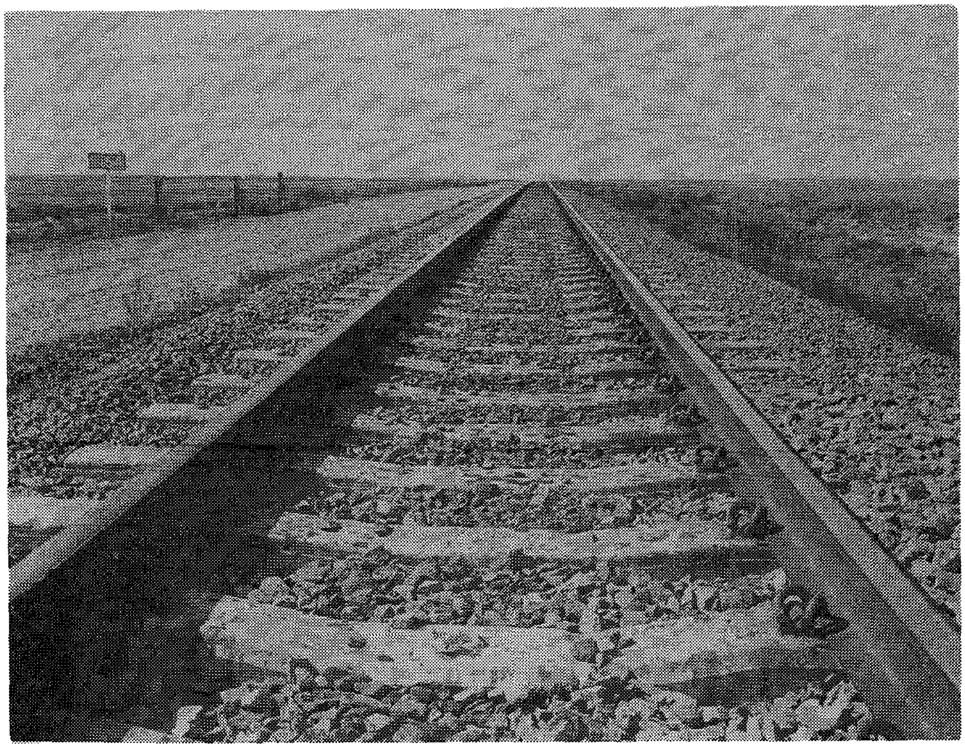

FIGURE 6. CONTINUOUS WELDED RAIL (CWR) ON CONCRETE TIES.

Concrete Ties. Second-hand select concrete ties previously used in a FAST experiment in near new condition installed with 24" center-to-center spacing were used for concrete tie trackage.

Rail. All new 133 lb and 136 lb rail (jointed and CWR) was installed on all tracks in the test. All rail was given an initial grinding per the FAST procedures with approximately 0.002 inch of steel removed .

Tie Plates. Standard AREA 14" plates with 1 in 40 cant. Both A and B punching were used.

Spikes. The spikes were AREA Standard 6" cut spikes, 4 spikes per plate installed on tangent track and 5 spikes per plate on curves and spirals. (At the wood to concrete tie transition, 15 wood ties were installed with 4 compression clips per tie in place of 4 rail spikes.)

Fasteners. On the concrete ties, new Pandrol clips, new insulators, and new compression pads were installed.

Rail Anchors. All new Unit anchors were used with CWR, box anchored every other tie. Jointed rail was box anchored every other tie except at and across from rail joints.

The resulting track was a very high quality structure with only minimal defects and no deteriorated components.

2.2 TRAIN OPERATION

Consist. Length of consist was maintained between 65 and 80 cars with an average of 70 cars in the train at any one time. Of the 70 cars, 4 were empties, 2 were loaded to 33 tons, and the remaining cars were fully loaded 100-ton capacity hoppers. The percentage of radial trucks in the train did not exceed 12.5% at any one time. Wheel mix varied daily and was not felt to impact the experiment. All cars were equipped with roller bearings. All cars were inspected daily during train operation and any cars containing AAR Field Manual Interchange Rules violations or FRA defects of any kind were bad ordered and repaired. The train did not contain any hollow or flat wheels. In addition, the Mechanical Experiments at FAST required measurements of a variety of car and truck components and resulted in the cars having the entire truck removed, disassembled and inspected as often as every three months or 11,000 miles. Thus, the mechanical equipment was better maintained than is normally the case in industry.

Operation. The train was operated around the loop approximately 50% in the clockwise direction and 50% in the counterclockwise direction. Braking, except to stop the train at the end of a shift, occurred during 5% of the train operation. The train maintained a very uniform speed as it traversed the 4.8 miles and did not normally vary more than 5 miles per hour from the 45 mph operating speed. The train speed was such that in curves the superelevation provided an underbalance condition.

Lubrication. The metallurgy and wheel experiments at FAST require very close monitoring of rail and lubrication. During normal lubricated running, a visible band of grease was maintained on the gage corner of the rail. Table 2 shows the Lubrication/Non-Lubrication cycles at FAST during the Track Degradation Experiment.

TABLE 2. TRACK DEGRADATION LUBRICATION CYCLE.

Lubrication Period	Start MGT	End MGT	Track Condition
1	0.0	6.4	Mixed Lubrication
2	6.4	22.4	Lubricated
3	22.4	22.8	Dry (No Lubrication)
4	22.8	132.0	Lubricated
5	132.0	152.3	Dry (No Lubrication)
6	152.3	160.0	Lubricated

2.3 MEASUREMENTS AND DATA REQUIREMENTS

Appendix A, taken from the Track Degradation Experiment Plan, shows the type of measurements taken and the frequency with which they were taken.

3.0 RESULTS AND DISCUSSION

3.1 TRACK GEOMETRY DEGRADATION

Track Geometry data were recorded by a Plasser EM-80 Track Geometry Car and provided the greatest portion of data studied in this experiment. The geometry car measured the profile, alignment, gage, cross-level, twist, and surface irregularity of the track at 1 foot intervals and recorded all the measurements on magnetic tape through the use of an on-board computer. Profile and alignment were measured at the mid-point offset of a 31-foot chord between the front and rear measuring axles of the geometry car. Surface irregularity was measured using a 12-foot chord. The other parameters were not chord offset dependent. A mathematical conversion was used to change the 31-foot chord offset data to 62-foot chord offset data.

It is important in any study of track geometry to understand what defect wavelengths have the greatest impact on train dynamics and how the geometry car measures those defects. Work done by ENSCO for the DOT indicates that the 62-foot midchord offset method does not adequately cover all the deviations of interest, due to the fact that certain wavelengths of deviations are masked. That work indicates that a measurement system which uses several different chord lengths could provide more complete descriptions of track alignment and profile.(8) An attempt was made to overcome this in regard to profile in this experiment by using the "standard" profile based on a 31-foot chord, and also the surface irregularity which was based on a 12-foot chord.

A second consideration is that the repeatability and accuracy (calibration error) of track geometry measurement become increasingly important when studying the geometry of high-quality track. Defects in the region of the noise level of the equipment will not be consistently detected, nor will their magnitude be accurately measured. These errors are less important on poor quality track.

It became apparent in the course of the experiment that calibration errors were being interpreted as track degradation. To randomize the effects of these errors, the track geometry car was recalibrated more frequently in the latter part of the experiment. (Refer to Appendix "B").

Listed below are the geometry parameters used in the experiment. If a parameter was not measured directly, it was calculated from other measured parameters.

1. PLR62: average of profile values for the left and right rails per the 62-foot chord definition.

2. PLR31: average of profile values for the left and right rails per the 31-foot chord definition.

3. PL62: profile values for the left rail individually per the 62-foot chord definition.

4. PR62: profile values for the right rail individually per the 62-foot chord definition.

5. ALR62: average of the alignment values for the left and right rails per the 62-foot chord definition.

6. AL62: alignment values for the left rail individually per the 62-foot chord definition.

7. AR62: alignment values for the right rail individually per the 62-foot chord definition.

8. ADEL: rate of change of alignment with respect to previous 62-foot point using averaged values for left and right rail.

9. SIL: surface irregularity values for the left rail individually using a 12-foot offset chord.

10. SIR: surface irregularity values for the right rail individually using a 12-foot offset chord.

11. GAGE: deviations of the track gage from 56.50 inches.

12. CL: value of cross-level or superelevation.

13. TW11: value of twist over an 11-foot chord.

14. TW20: value of twist over a 20-foot chord.

15. TWS: maximum value of twist within the previous 62-foot chord per the FRA definition.

The track geometry data were taken every 5 MGT during the experiment. This method provided between 200 and 1,200 actual measurements for each individual geometry parameter in each test segment (all measurements and calculations are in inches). The standard deviation, average squared deviation, maximum, mean, minimum, and percentage of track of lower quality than each of the FRA classes were then calculated for the group of measurements in each segment. The equations for standard deviation and average squared deviation are found below:

Equation for standard deviation:

$$\text{Standard Deviation} = SD = \sqrt{\frac{\sum_{i=1}^{n} (Yi - \bar{Y})^2}{n - 1}} \qquad (1)$$

where Yi = individual measurements and n = number of measurements.

Equation for average squared deviation:

$$\text{Average Squared Deviation} = \frac{\sum_{i=1}^{n} (Yi - \bar{Y})^2}{n} \qquad (2)$$

where $\bar{Y}$ = 0.00 for all measurements except gage, where $\bar{Y}$ = 56.50 inches.

Standard deviation is rapidly becoming the preferred statistic for evaluating track geometry measurements. A study by AREA Committee 32, Systems Engineering, found that of 25 railways surveyed worldwide, 17 developed an overall track geometry rating and 13 of these 17 railways use standard deviation as the basic statistic for developing the rating.(9). The Office of Research and Experiments (ORE) of the International Union of Railways has used standard deviation extensively in its studies of change in surface, cross-level, alignment and gage.(10 & 11) Research carried out by the China Academy of Railway Sciences indicates that the use of "over limit" or exception data combined with the standard deviation of track section provided a method of identifying those sections of railroad track that contained irregularities that were the greatest hazard to cars and equipment.(12) British rail goes so far as to include the standard deviation of a segment of track on the exceedance report produced by its Track Recording Coach and provided to the area track supervisor.(13)

Tuve and his collegues on the Southern Railway have been using the average squared deviation statistic, equation 2 above, and have found a close correlation between it and standard deviation. The logic for the use of the average squared deviation statistic is that the square of the distance a geometry defect displaces a wheel of a car is directly proportional to the energy transmitted to the car.(6)

Although the average squared deviation was calculated for each track geometry parameter, it is not discussed in detail in this report, since it is highly correlated with the standard deviation. Furthermore, without determining the association of the various track geometry parameters with freight car behavior, the superiority of one statistic over the other cannot be established.

The standard deviation data are first presented in detail. A correlation study of each geometry parameter with every other geometry parameter using the standard deviation is performed. A summary of the final FRA class exceptions is then presented, and a correlation of the FRA defects to standard deviation is developed for each test segment.

<u>Profile Average Left and Right - 62-Foot Chord (PLR62)</u>

Profile was recorded based on a 31-foot chord, measuring the profile on each rail individually, and a combined (average) profile of both rails was calculated. The individual and combined profiles were also calculated using a 62-foot chord.

The standard deviation of the profile of both rails for the entire test section using the 62-foot chord definition increased through 60 MGT and then leveled off through the remaining 100 MGT of the experiment (see Appendix C, Figure C-1).

Analysis of the individual segments indicates that each of the tangent segments reacted much the same as the combined average of all tangent segments, i.e., increasing degradation up to about 60 MGT with little or no change beyond that point (see Figure C-2).

The individual segments of curved track (see Figure C-3) responded in a slightly different manner than the tangent segments. While the two CWR segments showed little change after the initial settlement prior to 60 MGT, the jointed rail curved segments continued to show a slight increase in standard deviation of 62-foot profile throughout the experiment. Profile calibration problems and evidence of a rail lubrication effect prevent a definitive statement here.

Profile degradation in the spiral segments was not consistent throughout the experiment (see Figure C-4). Three of the four segments showed no increases in standard deviation beyond 60 MGT. One of the jointed rail spiral segments did show an increase in standard deviation of profile during the experiment. The cause of these differences is not known. Due to the small amount of profile degradation, the data was insufficient to make any quantitative comparisons between CWR and jointed rail on the two curves involved in the experiment.

As expected, the standard deviation of the profile of the spiral segments was greater than the standard deviation of profile in the tangent or curve track segments.

The initial rapid profile change experienced in the first 25 MGT of operation after construction in other FAST testing was noted by Leshchinski in 1982.(14) A sudden change in the data trend at the end of the experiment may be attributable to changes in calibration, or it may have been due to the non-lubricated operation between 132 and 152 MGT.

The geometry car used in this experiment measures the geometry parameters using a direct contact system, and thus changes in rolling resistance afforded by lubrication may also have impacted the geometry measurements. The exact nature of the impact of lubrication on track geometry or on the measurements of track geometry was not studied in this experiment.

Profile Average Left and Right - 31-Foot Chord (PLR31)

The profile measured using a 31-foot chord, Appendix D, Figures D-1, D-2, D-3, and D-4, resulted in changes that closely resembled the respective profiles measured using the 62-foot chord.

The general nature of the change in the profile of track, with an initial rapid increase in vertical degradation after maintenance followed by very little subsequent change in profile, is similar to the profile which British Rail has found with their track recording car.(15)

Alignment Average Left and Right - 62-Foot Chord (ALR62)

There was no degradation of alignment during the 160 MGT operation of the experiment. This lack of significant change in alignment appears to be at least partially attributable to the very uniform train operation, extremely high level of equipment maintenance, and the probable reduction in wheel/rail interface forces due to the generous rail lubrication (see Appendix E).

Rate of Change of Alignment - 62-Foot Chord (ADEL)

Due to the virtual absence of alignment change, the rate of change of alignment (ADEL) measurement was of little value and, as Appendix F indicates, did not demonstrate any change in this value. Furthermore, the rate of change of alignment was so low that measurement was to only one significant figure ruling out a sensitive analysis of the data.

Surface Irregularity - 12-Foot Chord (SIL & SIR)

Problems with the repeatability of the surface irregularity measurement resulted in excessive data scatter and a lack of confidence in the measurement until late in the experiment; consequently, the surface irregularity data were not analyzed.

Gage Variation from 56.50 Inches (GAGE)

There was no evidence of increasing gage variability observed during the experiment except in the spiral segments where a small but continuing increase in the gage standard deviation was apparent (see Appendix G). It appears that the tightly controlled and uniform train operation and high level of rail lubrication may have been major factors in this lack of degradation. (There is some evidence that the increasing gage variability in the spirals could be associated with the no-lube condition starting at 132 MGT.)

Cross-level Variation from Uniform (CL) and Twist (TW11, TW20, and TWS)

The collected data relating to cross-level and twist indicated only minor changes, the magnitude of which fell mostly within the noise level of the geometry car. These data would indicate no degradation of cross-level or twist throughout 160 MGT of operation (see Appendix H). This must be attributed to the extremely high quality and uniformity of the initial track structure and subgrade, climate, train operation and equipment maintenance.

Track Geometry as a Function of the Track Structure

Due to the limited replication in the experiment (refer to Table 1) there was little opportunity for sensitive testing of track variability associated with track curvature and track construction. The most sensitive test was a comparison of jointed rail vs welded rail on wood ties where there were five segments of each configuration. No significant difference in track variability could be associated with jointed vs welded rail based on any of the track geometry parameters measured. Termination of the experiment at 160 MGT did not expose the differences in welded and jointed rail observed in revenue service.

There were significant differences in the curve variable, i.e., tangent segments, 3-degree curves, 4-degree curves, and spirals. This was observable in the standard deviation of the average alignment (62-foot chord), gage, and crosslevel. There appears to be little difference in track variability between tangent and curve track up to 4-degrees, but the spirals, exhibited significantly greater variation throughout the experiment (Refer to Table 3). None of the profile and twist parameters showed significant differences in variability with respect to curvature.

TABLE 3. EFFECT ON CURVATURE ON TRACK GEOMETRY VARIABILITY.

STANDARD DEVIATION AT 160 MGT, INCHES

Track Geometry Parameters	Tangent (Average of Two Test Segments)	3° Curve (Average of Two Test Segments)	4° Curve (Average of Two Test Segments)	Spiral (Average of Four Test Segments)
Avg. Alignment, 62-Foot Chord	.076	.116	.134	1.028
Gage	.054	.063	.055	.088
Cross-level	.140	.117	.132	.561
Profile & Twist	No significant differences			

3.2 CORRELATION OF THE VARIOUS GEOMETRY PARAMETERS USING THE STANDARD DEVIATION

Table 4 shows the simple correlations of various parameters calculated using the standard deviation. Each correlation used 284 data points. Track geometry measurements were taken every 5 MGT for each of the 11 segments yielding 286 points disregarding data gathered prior to track geometry car modifications at 20 MGT; two points were deleted for invalid data. Interpretation of these correlations is given in the following paragraphs.

Surface

Good correlations were found between average profile and the profile of the individual rail, indicating that the average measurements would be sufficient. Average profile using the 62-foot chord correlated with the 31-foot chord, indicating either would suffice. Scattergrams showing the relationship are shown in Appendix I. Average profile correlated reasonably well with cross-level, indicating that low joints can cause changes in profile and cross-level simultaneously. This relation is shown in Appendix J. The standard deviation of the average profile was only moderately correlated with the standard deviation of the average alignment.

The conspicuous clustering of the data displayed in Appendix J, as well as Appendices K, L, and M is due to the very substantial difference in spiral standard deviations compared to the tangent and curve data. (Refer, for example, to Figure H-1.) The left cluster in Figure J-1 contains all the tangent and curve data and the right cluster contains the spiral data. The absence of degradation in cross-level accentuates the cluster effect.

TABLE 4. CORRELATION COEFFICIENTS OF TRACK GEOMETRY DATA USING STANDARD DEVIATION STATISTIC, 20 TO 160 MGT.

	PLR62	PLR31	PL62	PR62	ALR62	AL62	AR62	ADEL	GAGE	CL	TW11	TW20
PLR31	0.75											
PL62	0.87	0.57										
PR62	0.92	0.76	0.63									
ALR62	0.62	0.51	0.61	0.53								
AL62	0.62	0.51	0.61	0.53	1.00							
AR62	0.62	0.51	0.61	0.53	1.00	1.00						
ADEL	0.57	0.57	0.50	0.49	0.77	0.77	0.78					
GAGE	0.50	0.43	0.40	0.48	0.79	0.79	0.80	0.72				
CL	0.71	0.55	0.67	0.63	0.98	0.98	0.98	0.73	0.76			
TW11	0.29	0.25	0.31	0.27	0.36	0.36	0.35	0.25	0.35	0.38		
TW20	0.42	0.20	0.58	0.25	0.49	0.49	0.49	0.26	0.29	0.50	0.59	
TWS	0.31	0.39	----	0.48	0.35	0.35	0.35	0.17	0.47	0.42	0.51	0.22

Note: All correlations are significant at the .999 level or above.

Alignment, Gage and Cross-Level

Average alignment correlated almost perfectly with alignment of the left and alignment of the right rails. This relationship is displayed in the scattergrams found in Appendix K.

The correlation between alignment and gage that Hamid and Yang found in their work for the FRA, (8) also occurred at FAST. It seems reasonable to expect that when problems occur in gage, corresponding problems will occur in alignment (refer to Appendix L).

High correlation also exists between average alignment and cross-level as demonstrated in Appendix M. Correlation was not unexpected, particularly in the curves where the alignment and cross-level change simultaneously due to the design and surfacing of the curve. The alignment and cross-level both change gradually in the spiral and are continuously non-zero in the full body of the curve and tangent track.

The magnitude of the rate of change of alignment (ADEL) was too small to be accurately measured by the track geometry car. It was not a useful parameter in this test.

3.3 FRA CLASS 6 GEOMETRY EXCEPTIONS

In addition to the standard deviations discussed above, the percentage of track in each of the 11 test segments not meeting current FRA Class 6 geometry standards at 160 MGT was calculated. This is presented in Tables 5 and 6. Although there is evidence of higher FRA defect levels in the spirals at 160 MGT, the inconsistent pattern prevents a clear assignment of cause.

Correlation of Standard Deviation with FRA Exceptions

Table 7 shows the significant correlations of the various parameter standard deviations at 160 MGT with the percentage of track having FRA Class 6 exceptions at 160 MGT. The best correlations were found with profile and twist. The significant correlations support the hypothesis that standard deviation is an indicator of the likelihood of the presence of individual track exceptions to a standard, FRA or otherwise. The best relationships were found to be exponential. This was not unexpected. If the above hypothesis is true, below some given value of the standard deviation, there would be no exceptions to a standard providing the distribution of the measurements does not deviate too far from a normal distribution. Futhermore, the curve would go through the origin regardless of the distribution. Conversely, above some level of the standard deviation, the percentage of track exceeding the standard would increase rapidly. Refer to Appendix N for graphical displays of the significant relationships found.

There were some anomalies in these findings. For example, profile right showed a much better correlation than profile left. This would leave one to believe that there was some repeatability problem associated with the profile left measurement. There was no correlation between either alignment measurement and the corresponding FRA alignment specification. This is an indication of a problem that merits further research.

TABLE 5. PERCENTAGE OF TRACK WITH FRA CLASS 6 EXCEPTIONS AT 160 MGT FOR PROFILE AND ALIGNMENT.

TRACK CONSTRUCTION		CURVATURE				
RAIL AND TIE TYPE	OTHER CONSTRUCTION DETAILS	TANGENT	3° CURVE	4° CURVE	3° SPIRAL	4° SPIRAL
	SEGMENT NO.	11	8	3	9	4
Jointed-Wood Ties	Profile left	1.5	0.7	2.6	10.7	4.3
	Profile right	0.8	2.0	1.5	7.3	
	Alignment left				17.3	16.3
	Alignment right		1.1		19.2	18.7
	SEGMENT NO.	10	7	2	6	1
CWR - Wood Ties	Profile left	2.7	0.8		1.7	
	Profile right	0.7			2.5	6.7
	Alignment left	1.7		0.3		
	Alignment right	1.6	0.4	2.6	1.8	
	SEGMENT NO.	5				
CWR - Concrete Ties	Profile left					
	Profile right					
	Alignment left					
	Alignment right					

Note: Blank denotes a value of zero.

TABLE 6. PERCENTAGE OF TRACK WITH FRA CLASS 6 EXCEPTIONS AT 160 MGT FOR TWIST, SUPERELEVATION, AND GAGE.

TRACK CONSTRUCTION		CURVATURE				
RAIL AND TIE TYPE	OTHER CONSTRUCTION DETAILS	TANGENT	3° CURVE	4° CURVE	3° SPIRAL	4° SPIRAL
	SEGMENT NO.	11	8	3	9	4
Jointed-Wood Ties	Twist					28.3
	Superelevation		1.6	1.0		8.3
	Gage					
	SEGMENT NO.	10	7	2	6	1
CWR - Wood Ties	Twist	2.7				11.0
	Superelevation		0.5	0.3	1.0	3.0
	Gage					
	SEGMENT NO.	5				
CWR - Concrete Ties	Twist	2.8				
	Superelevation					
	Gage					

Notes: (1) There were no gage FRA Class 6 exception at 160 MGT using the FRA standards effective November 1, 1982

(2) Blank denotes a value of zero.

TABLE 7. CORRELATION OF PARAMETER STANDARD DEVIATION AT 160 MGT WITH PERCENTAGE OF TRACK HAVING FRA CLASS 6 EXCEPTIONS AT 160 MGT.

Parameter	Correlation Coefficient	Significance Level	Relationship	Graphic Display Appendix #
Profile Right, 62-Foot Chord	.96	.9999	Exponential	N-1
Profile Left, 62-Foot Chord	.79	.998	Exponential	N-2
Twist, 20-Foot Chord	.73	.994	Exponential	N-3
Cross-Level	.58	.97	Linear	N-4
Alignment Left, 62-Foot Chord	NS*			
Alignment Right, 62-Foot Chord	NS*			

*Not Significant at .95 or above.

3.4 GROUND REFERENCE SURVEY TO BENCHMARK

The entire track structure settled approximately 0.75" after construction through the end of the experiment. There was no isolated extreme settlement in any of the test segments. There was no significant lateral displacement of the track during the experiment.

3.5 TRACK MODULUS

Track modulus data were accumulated at 0, 5, 100, and 160 MGT during the experiment. As expected the track deflection was minimal for the "new" track fasteners. At 160 MGT the wood tie track deflected significantly during the initial loading, apparently due to voids between rail, ties, ballast and the "worn" track fasteners but with very high resistance to deflection at the higher loads. It appears that the strength of the ballast and subgrade did not change. Representative load deflection curves are found in Appendix O.

The representative load deflection curves for the concrete tie track indicate that the track reacted basically the same at 5 MGT as at 160 MGT. This again indicates an absence of subgrade or ballast problems.

The absence of changes in the track modulus for both the wood and concrete sections demonstrate the high quality of the track structure at FAST.

3.6 TRACK MAINTENANCE LABOR

Table 8 shows the labor by segment and total labor to maintain the wood tie segments. The total labor required to maintain the wood tie segments less initial cleanup after construction, less rail replacements due to a string of defective rail and less signal repairs was 111 manhours over the 160 MGT. The jointed rail required more maintenance than the CWR, and the curves and spirals combined required more maintenance than tangent track. However, the inconsistent patterns in the maintenance labor, e.g., no maintenance in the welded spirals and lower maintenance in the 3° welded-rail curve than the welded-rail tangent track, prevent conclusive statements here.

3.7 TRACK MAINTENANCE MATERIAL

With the exception of 91 lineal ft of defective rails replaced (52 ft in the welded rail 4° curve and 39 ft in the welded 3° curve, having no apparent relationship to the track degradation experiment), virtually no material was used over the entire accumulation of 160 MGT. There were no replacements of rail anchors, ballast, fasteners, pads, spikes, crossties, or insulators. One tie plate was replaced, nine bolts were replaced, and 11 joint bars were replaced. Five of the nine bolts and nine of the 11 joint bars involved the two segments with the substantial replacement of rails. This further documents the minimum amount of maintenance required during the course of the experiment due to the lack of appreciable degradation.

TABLE 8. TRACK MAINTENANCE VS TRACK CONFIGURATION (WOOD TIE SECTION ONLY)

RAIL TYPE	STATISTIC	CURVATURE: TANGENT	3° CURVE	4° CURVE	3° SPIRAL	4° SPIRAL	TOTALS
Jointed	Segment Length, ft	1139	1063	663	600	300	3765
	Manhours Maintenance	3.7	15.6	14.8	34.1	4.7	72.9
	Manhours/ 1000 ft	3.2	14.7	22.3	43.1	43.1	19.4
Welded	Segment Length, ft	1139	1063	663	600	300	3765
	Manhours Maintenance	11.7	8.0	13.7	0	0	33.4
	Manhours/ 1000 ft	10.3	7.5	20.7	0	0	8.86
	Average Manhours/ 1000 ft	6.8	1.1	21.5	21.6	21.6	

4.0 CONCLUSIONS AND SUMMARY

The track in the Track Degradation Experiment did not degrade sufficiently to permit prediction of future degradation. This emphasizes the first conclusion to be drawn from this experiment: Given an initial high-quality track, the natural environment prevailing at FAST, uniform train forces and high maintenance standards on critical car components, track will degrade very slowly. The following conclusions are based on the limited degradation that did occur over the 160 MGT test interval:

1. The standard deviation and the average squared deviation are both highly correlated with the concentration of track geometry exceptions as reflected in FRA profile and twist requirements for Class 6 track. The standard deviation is a fair indicator of FRA cross-level exceptions. The standard deviation is not correlated with FRA Class 6 alignment exceptions. The lack of correlation with alignment exceptions may be associated with the quality of the alignment measurement by the track geometry car or differing definitions of alignment.

2. Degradation of track profile as measured by its standard deviation using either a 62-foot chord or a 31-foot chord increased over the first 60 million gross tons and then stabilized or increased only slightly to 160 MGT.

3. The track did not degrade with respect to twist, cross-level, alignment or rate of change of alignment in terms of the standard deviation of each of these parameters. That is, the standard deviation did not increase during the test period. There is slight evidence of twist degradation using the 62-foot chord definition, but severe data scatter prevents drawing a firm conclusion.

4. Variability of gage as measured by the standard deviation increased slightly for the spiral segments but remained constant for the tangent and curved segments.

5. At the termination of the experiment (160 MGT), there were no FRA track Class 5 exceptions in any test segment for any test parameter.

6. There is some evidence of an increasing rate of track degradation during the non-lubrication portion of the experiment. Rail lubrication affects the energy input to the total track structure and may also impact the rate of geometric degradation of that track.

7. There were serious track geometry car calibration and repeatability problems in the range of the track degradation occurring during the experiment. The problem was common to all parameters and prevented utilization of the surface irregularity data altogether.

8. The following correlations of the standard deviations of the individual track geometry parameters were found:

   a. There was modest correlation (correlation coefficient .63) between the left profile and the right profile but a high correlation (correlation coefficient .87 and .92) of each with the average profile. The standard deviation of the average profile would therefore be a good indicator of track profile condition.

b. The standard deviation of the left rail alignment was virtually identical to that of the right rail alignment (correlation coefficient .998). Hence, the standard deviation of the average alignment is an excellent indicator of alignment condition.

c. The standard deviations of the average alignment, cross-level, and gage were all highly correlated with each other. This would indicate that the development of a "track quality index" would require inclusion of only one of these parameters.

d. The magnitude of the rate of change of alignment was too small to be accurately measured by the track geometry car. It was not a useful parameter in this test.

e. The standard deviation of twist measured with either the 11-foot chord, the 20-foot chord, or the 62-foot chord was not highly correlated with the other track geometry parameters in this test.

f. The standard deviation of the average profile was only moderately correlated with the standard deviation of the average alignment (correlation coefficient .62). Therefore a "track quality index" should probably consider both profile and alignment.

Since car response was not measured in this experiment, there was no way to measure the relative importance of the above parameters. Consequently, there was no opportunity to develop a track quality index. Based on the correlations summarized above, however, one would anticipate such an index to contain principally a profile element, an alignment element, and a twist element.

9. With very few exceptions, the conclusions summarized above--based on the standard deviation--also apply to the average squared deviation. The principal exception was that the average squared deviation of twist and alignment was better correlated than the corresponding correlations with the standard deviation. Since car forces were not measured, the preferred statistic, standard deviation vs average squared deviation, could not be determined. This also applies to the preferred chord length for twist and profile measurements.

10. The rail in this test did not corrugate, indicating no effect of track degradation on corrugation over the range of degradation that occurred.

5.0 RECOMMENDATIONS

It is recommended that the following be studied further:

1. The impact on track degradation of truck design, wheel and truck condition, train braking and acceleration, train speed, and track lubrication.

2. Track geometry measurement techniques that assure repeatability of data within the limits being studied.

3. The effect of variations in track geometry parameters on freight car behavior. This is an essential element in developing a track quality index (TQI) weighting and combining the significant track geometry parameters.

4. The impact of initial track condition and geometric irregularities on the rate of track degradation.

It is also recommended that for those studies carried out at FAST, the testing be done in such a manner as to permit comparison with the revenue service environment.

It can be seen that track degradation experiments at FAST are limited in scope. Consequently, they should be part of a series of experiments that includes some carried out in revenue service where those factors causing more rapid track degradation are present. The impact of track condition, the impact of mechanical equipment condition, and the effect of lubrication on track degradation need to be studied further.

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APPENDIX A

SUMMARY OF MEASUREMENT AND DATA REQUIREMENTS

APPENDIX A

SUMMARY OF MEASUREMENT AND DATA REQUIREMENTS

A REFERENCE PARAGRAPH	B MEASUREMENTS	C FAST REFERENCE	D EQUIPMENT OR INSTRUMENTATION	E MEASUREMENT LOCATION	F SCHEDULE
<u>5.1</u>	Track Geometry	TMP2-013	EM-80-C	Continuous thru Test Segments	Initially; 7 ± 2 MGT and after each operating run
Profile	Maximum vertical mid-ordinate of a 62' chord and 31' chord				
Surface Irregularity	Loaded Profile				
Alignment	Maximum horizontal mid-ordinate of a 62' chord				
	Rate of change of alignment with respect to previous 62' point				
Gage	Deviation from 56.5"				
Superelevation (Cross-level)	Difference from 0" between rails				
Twist	Rate of change of cross-level or superelevation in 11 feet and 20 feet and previous 62' chord per FRA definition				

APPENDIX A (Continued)

SUMMARY OF MEASUREMENT AND DATA REQUIREMENTS

A REFERENCE PARAGRAPH	B MEASUREMENTS	C FAST REFERENCE	D EQUIPMENT OR INSTRUMENTATION	E MEASUREMENT LOCATION	F SCHEDULE
5.3 Rail Wear	High Rail Gage Point Wear Low Rail Metal Flow Head Height Loss (both rails)	Rail Wear Experiment SO-024 SO-025 SO-036	Gage Point, Metal Flow & Head Height Snap Gages	See 5.3	See 5.3
5.4 Rail Corrugation	Depth, wave length, and frequency	Experiment TE-5	Loram Rail Corr. Analyzer	Continuous through all test segments	Same as TE-5
5.5 Ground Reference Survey to Benchmark	Longitudinal, Lateral & Vertical Location of each rail in reference to Benchmark	S-002	As required by FAST Procedure S-002	50 foot stations on curves 100 foot stations on tangent	Initial, 7 ± 2 MGT & 40, 80, 120, & 160 MGT
5.6 Track Modulus	Deflection vs. Load	S-035	As required by FAST Procedure S-035	Near mid-point of segments 2, 4, 6, 7, & 9 and at 5 evenly spaced points in seg. 11	Initial, 7 ± 2 MGT, 100 MGT & final

APPENDIX A (Continued)

SUMMARY OF MEASUREMENT AND DATA REQUIREMENTS

A REFERENCE PARAGRAPH	B MEASUREMENTS	C FAST REFERENCE	D EQUIPMENT OR INSTRUMENTATION	E MEASUREMENT LOCATION	F SCHEDULE
5.7 Track Walker Reports	Observations of track conditions		Record on forms per Experiment Plan	Segments 1 through 11	Daily
5.8 Lateral and Vertical Loads	Lateral and Vertical Loads applied to the track		Instrumented wheel set	Continuous through all test segments	7 ± 2 MGT 100 MGT and final
5.9 TORS	Speed Throttle Position Brake Pressure Reduction		TORS	Continuous through all test segments	Initial, 7 ± 2 MGT, 100 MGT & final
5.10 Maintenance Records	Labor and Material		Record on forms per Experiment Plan	Wherever work performed in test segments	Same day work performed
5.11 Weather Records	Inches of precipitation Temperature in degrees F. Humidity Wind Direction Wind Velocity		Weather Station	FAST	Continuous

APPENDIX B

TRACK GEOMETRY CAR RECALIBRATION POINTS.

EM-80 RECALIBRATIONS

DATE	MGT
3/22/82	23 MGT
1/21/83	100 MGT
2/17/83	113 MGT
4/12/83	134 MGT
6/14/83	143 MGT
6/15/83	147 MGT

APPENDIX C

STANDARD DEVIATION OF AVERAGE PROFILE 62-FOOT CHORD VS MGT.

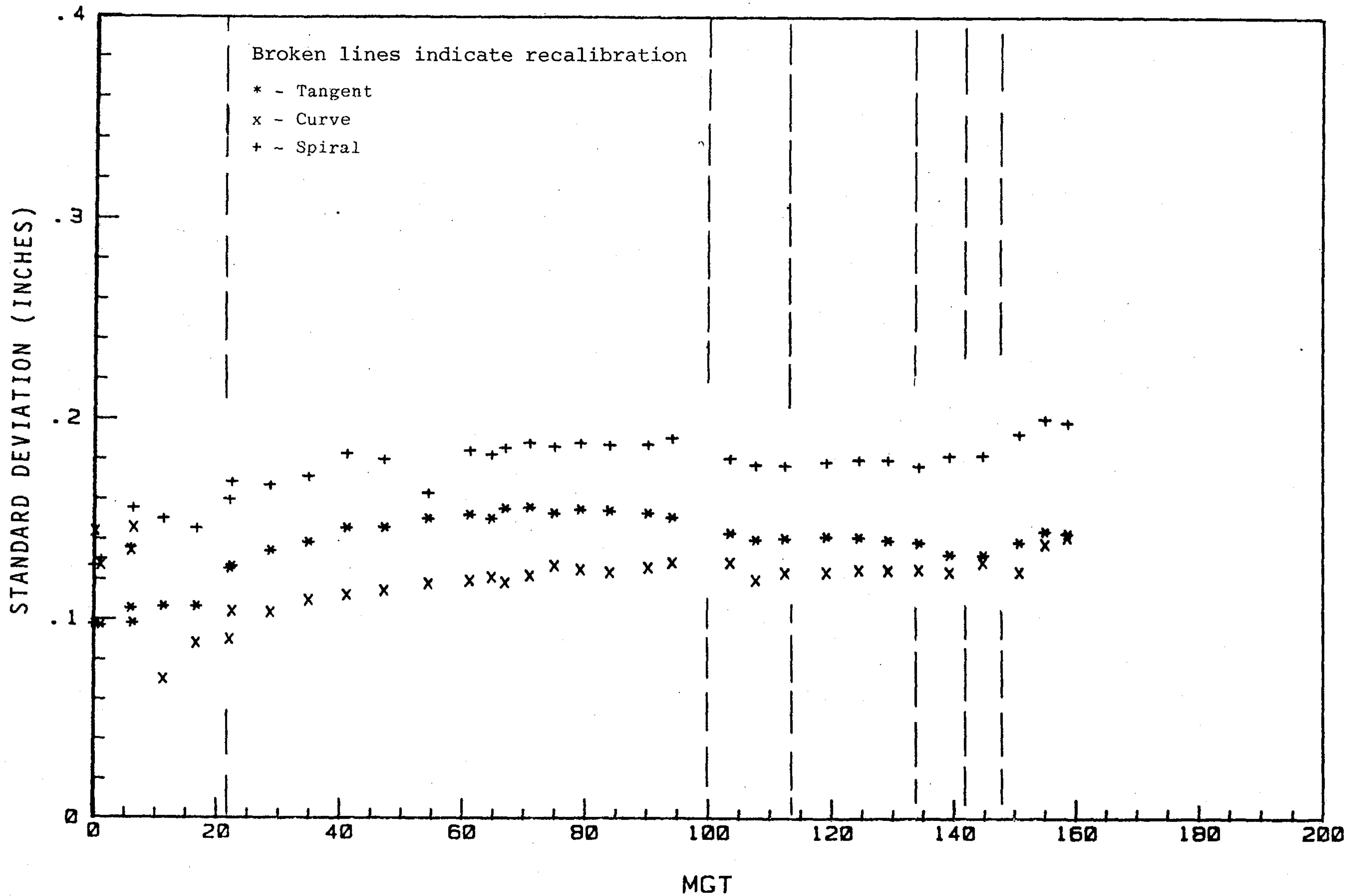


FIGURE C-1. AVERAGED STANDARD DEVIATION OF PLR62 (AVERAGE PROFILE 62-FOOT CHORD) VS MGT FOR ALL TEST SEGMENTS.

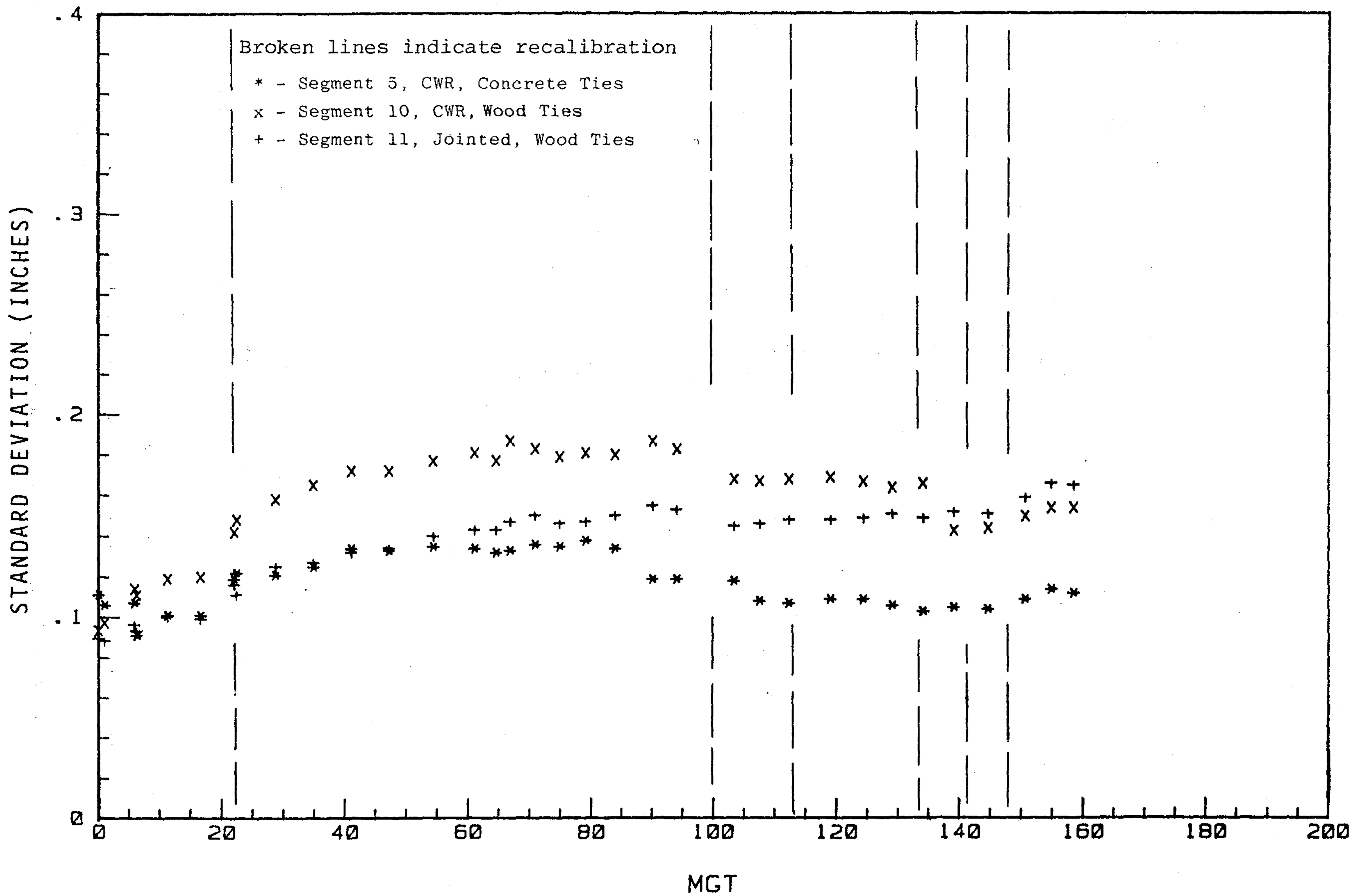


FIGURE C-2. STANDARD DEVIATION OF PLR62 (AVERAGE PROFILE 62-FOOT CHORD) VS MGT FOR TANGENT TEST SEGMENTS.

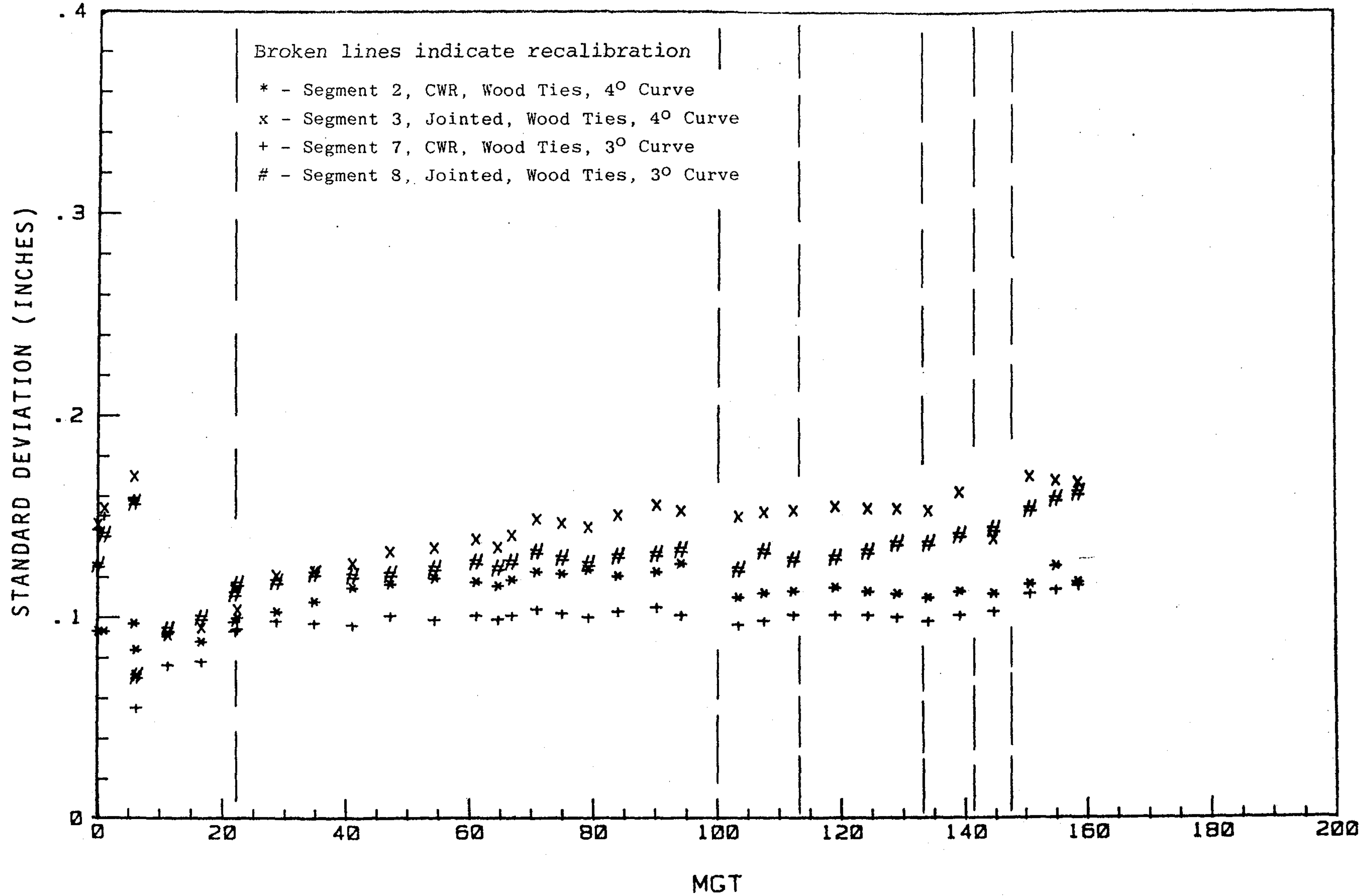


FIGURE C-3. STANDARD DEVIATION OF PLR62 (AVERAGE PROFILE 62-FOOT CHORD) VS MGT FOR CURVED TEST SEGMENTS.

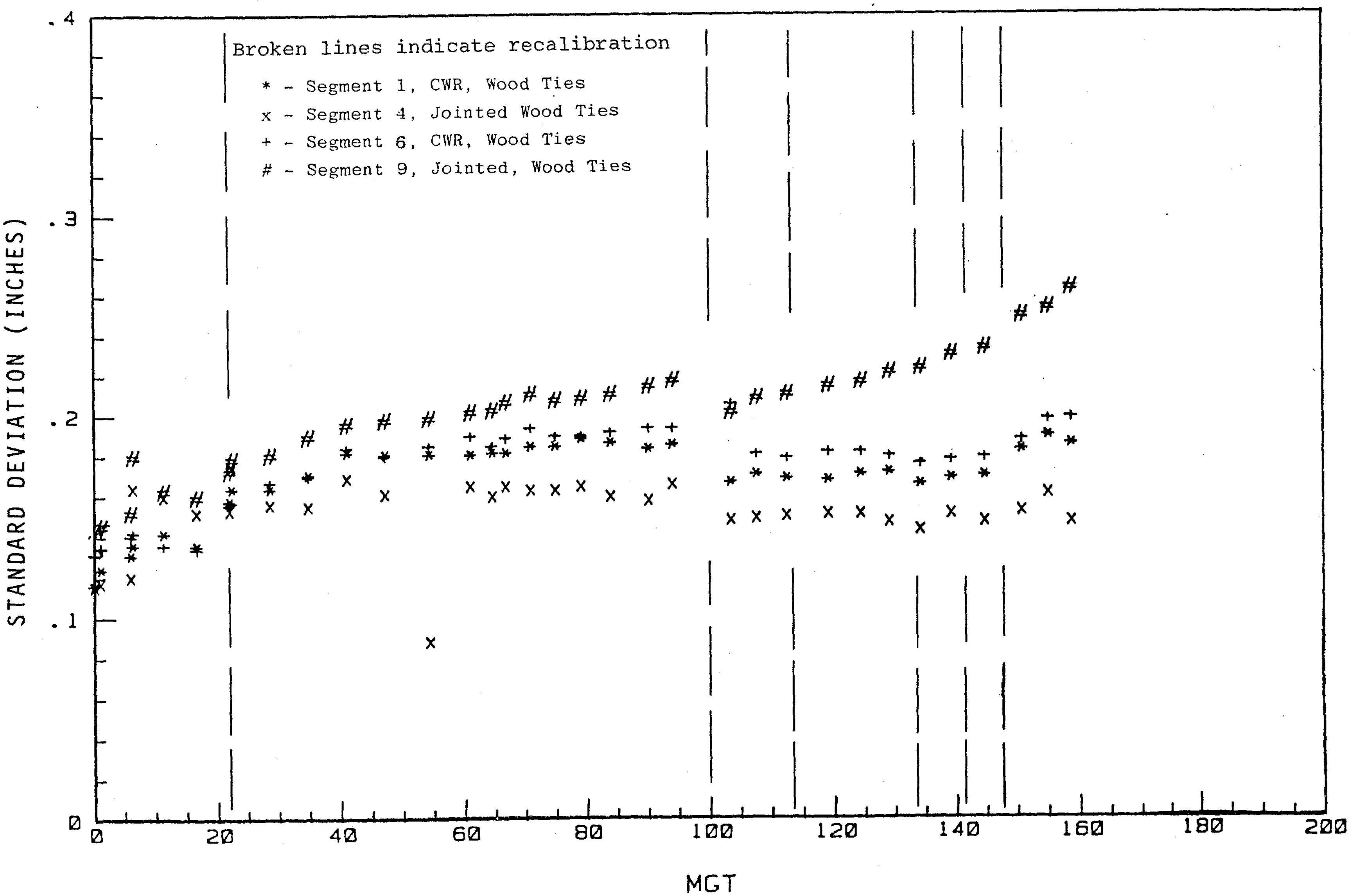


FIGURE C-4. STANDARD DEVIATION OF PLR62 (AVERAGE PROFILE 62-FOOT CHORD) VS MGT FOR SPIRAL TEST SEGMENTS.

APPENDIX D

STANDARD DEVIATION OF AVERAGE PROFILE 31-FOOT CHORD VS MGT.

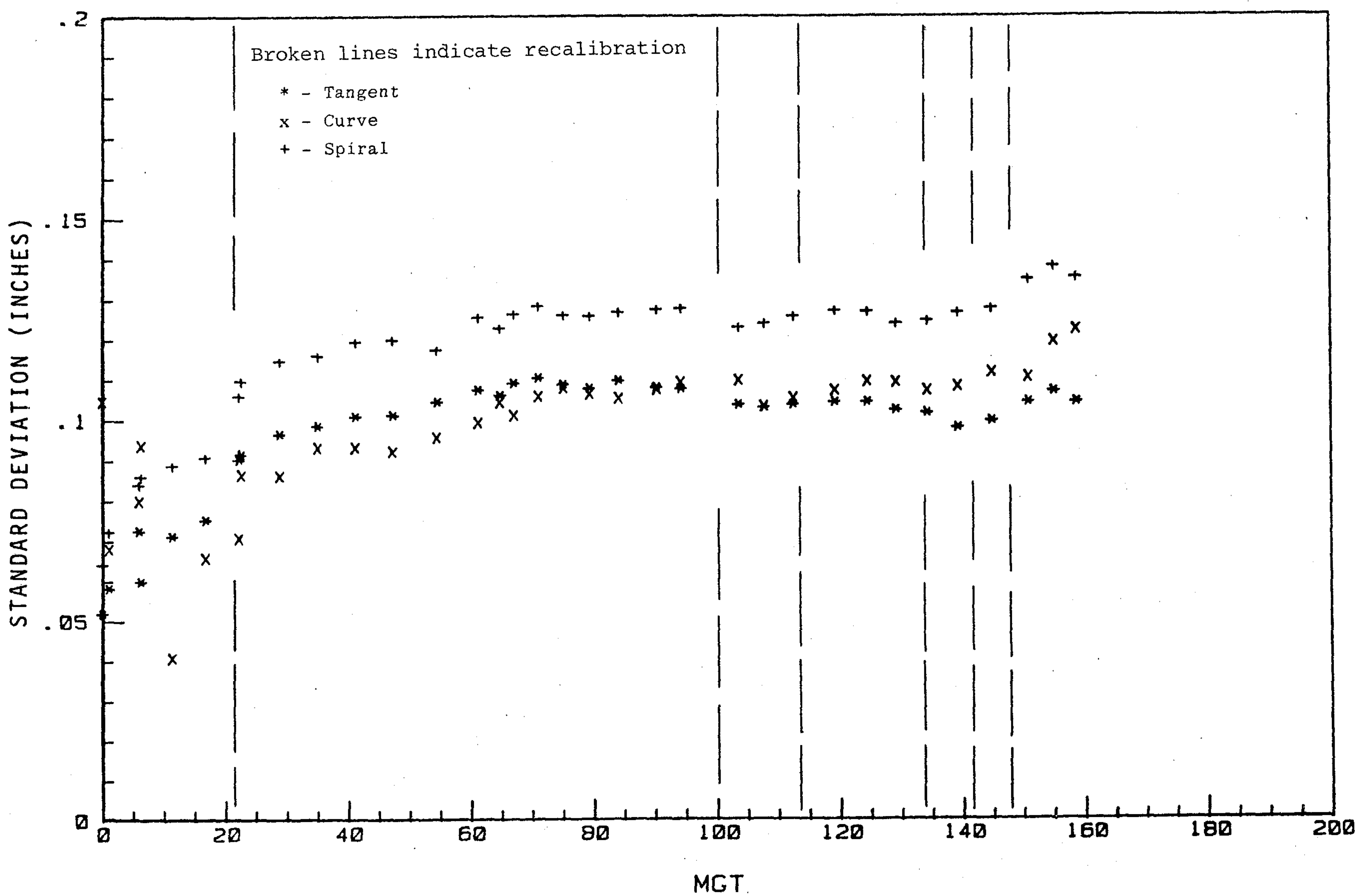


FIGURE D-1. AVERAGED STANDARD DEVIATION OF PLR31 (AVERAGE PROFILE 31-FOOT CHORD) VS MGT FOR ALL TEST SEGMENTS.

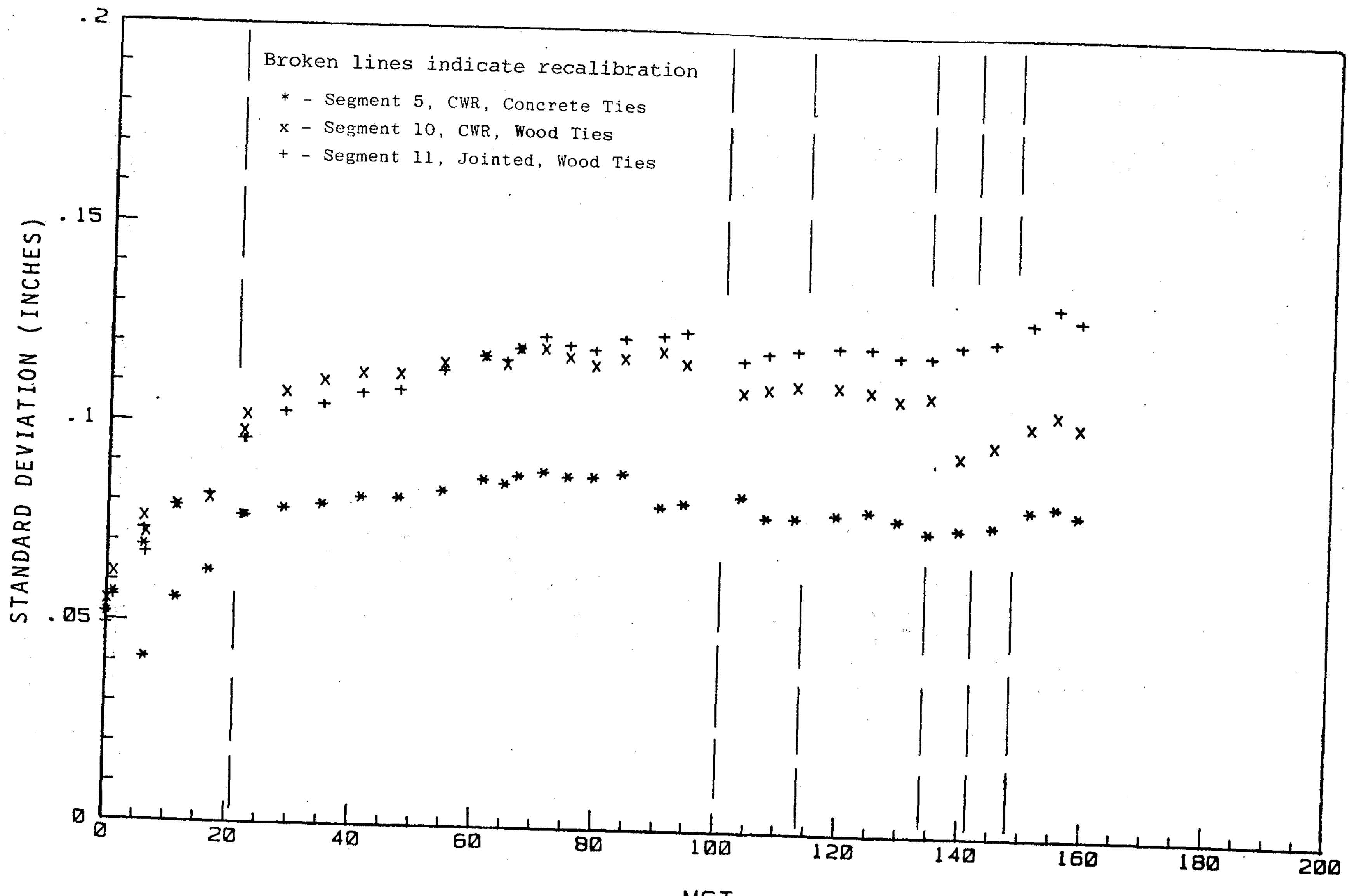


FIGURE D-2. STANDARD DEVIATION OF PLR31 (AVERAGE PROFILE 31-FOOT CHORD) VS MGT FOR TANGENT TEST SEGMENTS.

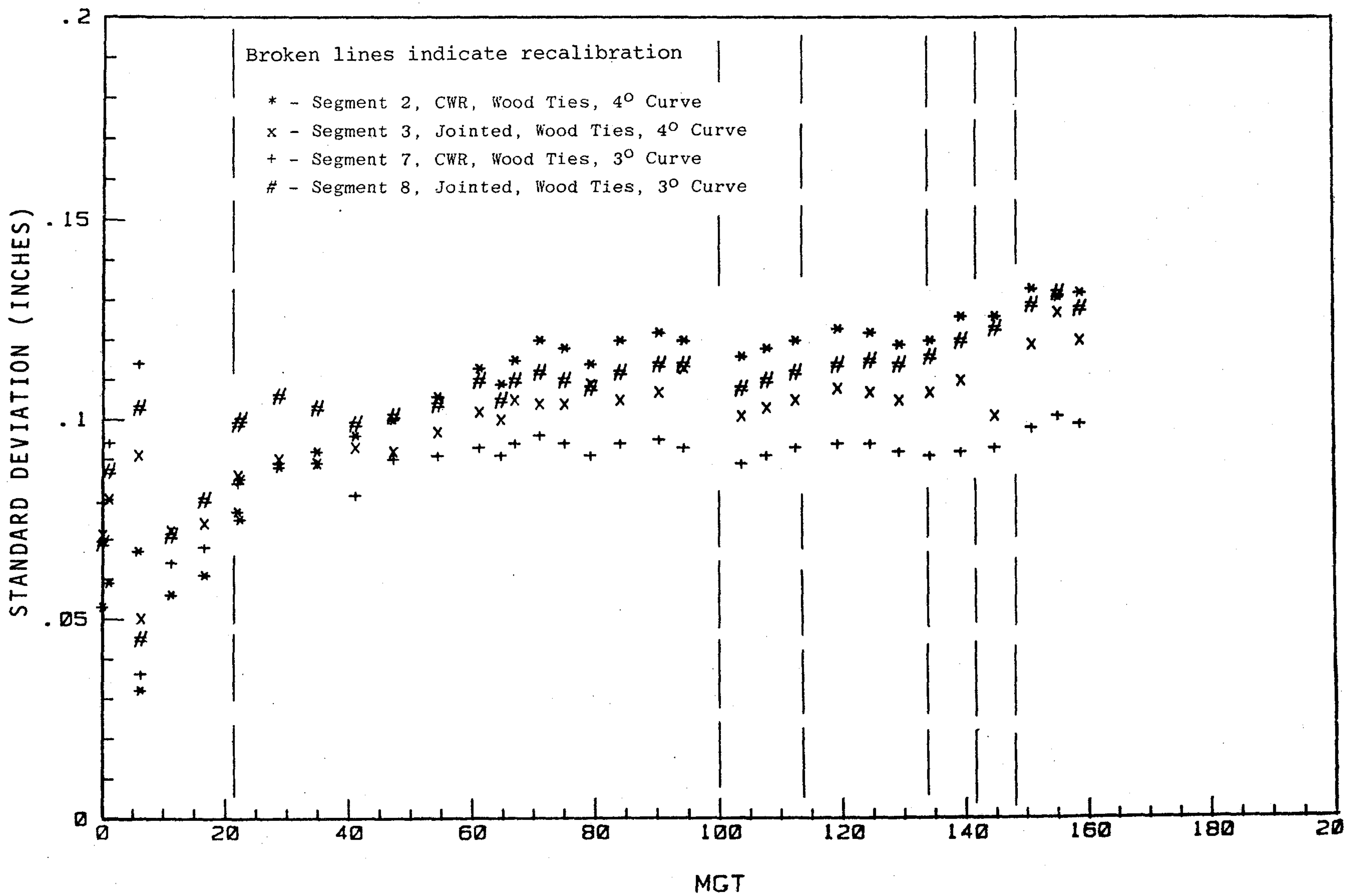


FIGURE D-3. STANDARD DEVIATION OF PLR31 (AVERAGE PROFILE 31-FOOT CHORD) VS MGT FOR CURVED TEST SEGMENTS.

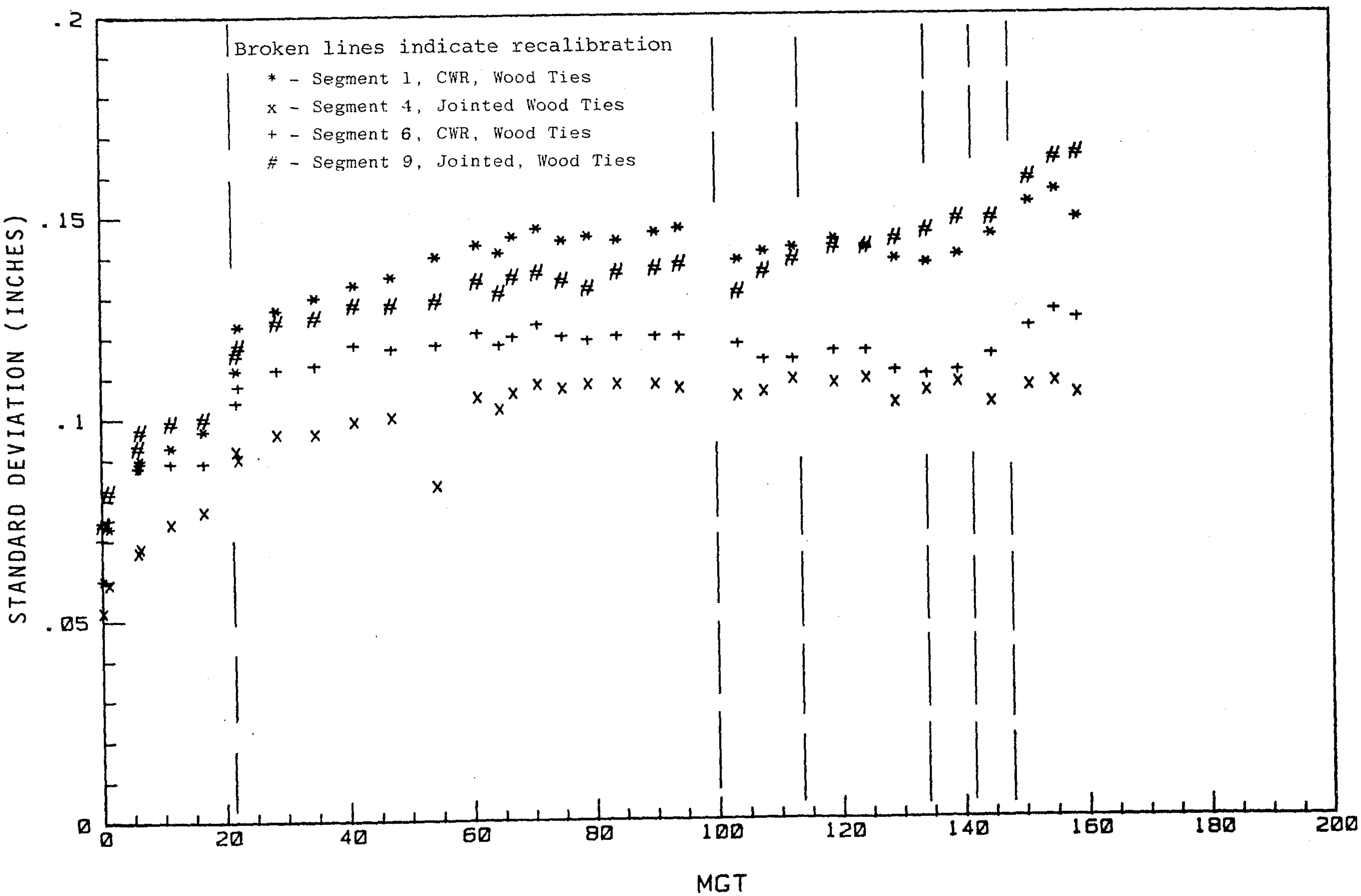


FIGURE D-4. STANDARD DEVIATION OF PLR31 (AVERAGE PROFILE 31-FOOT CHORD) VS MGT FOR SPIRAL TEST SEGMENTS.

APPENDIX E

AVERAGED STANDARD DEVIATION OF AVERAGE ALIGNMENT 62-FOOT CHORD VS MGT.

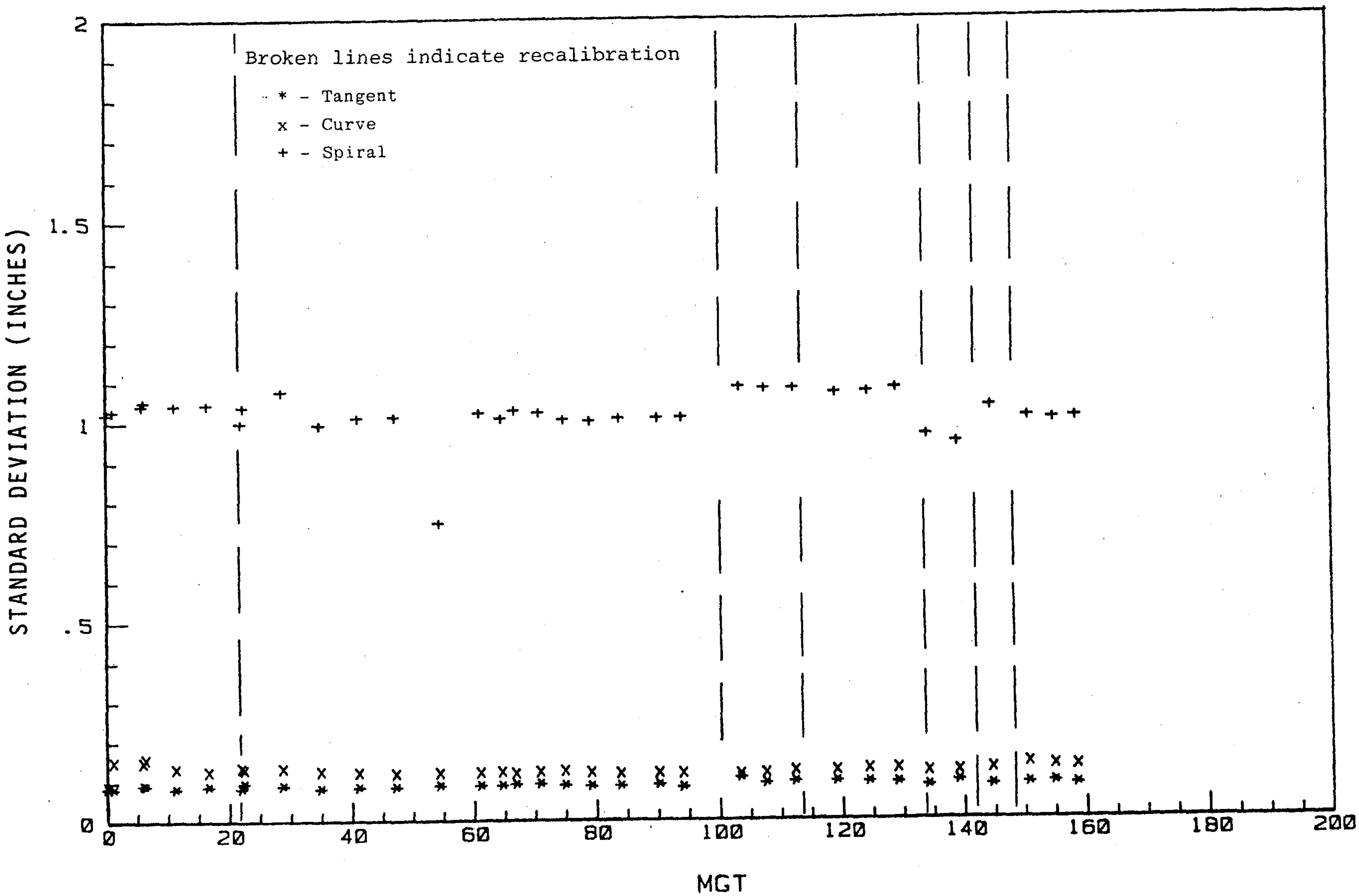


FIGURE E-1. AVERAGED STANDARD DEVIATION OF ALR62 (AVERAGE ALIGNMENT 62-FOOT CHORD) VS MGT FOR ALL TEST SEGMENTS.

APPENDIX F

AVERAGED STANDARD DEVIATION OF RATE OF CHANGE OF ALIGNMENT VS MGT.

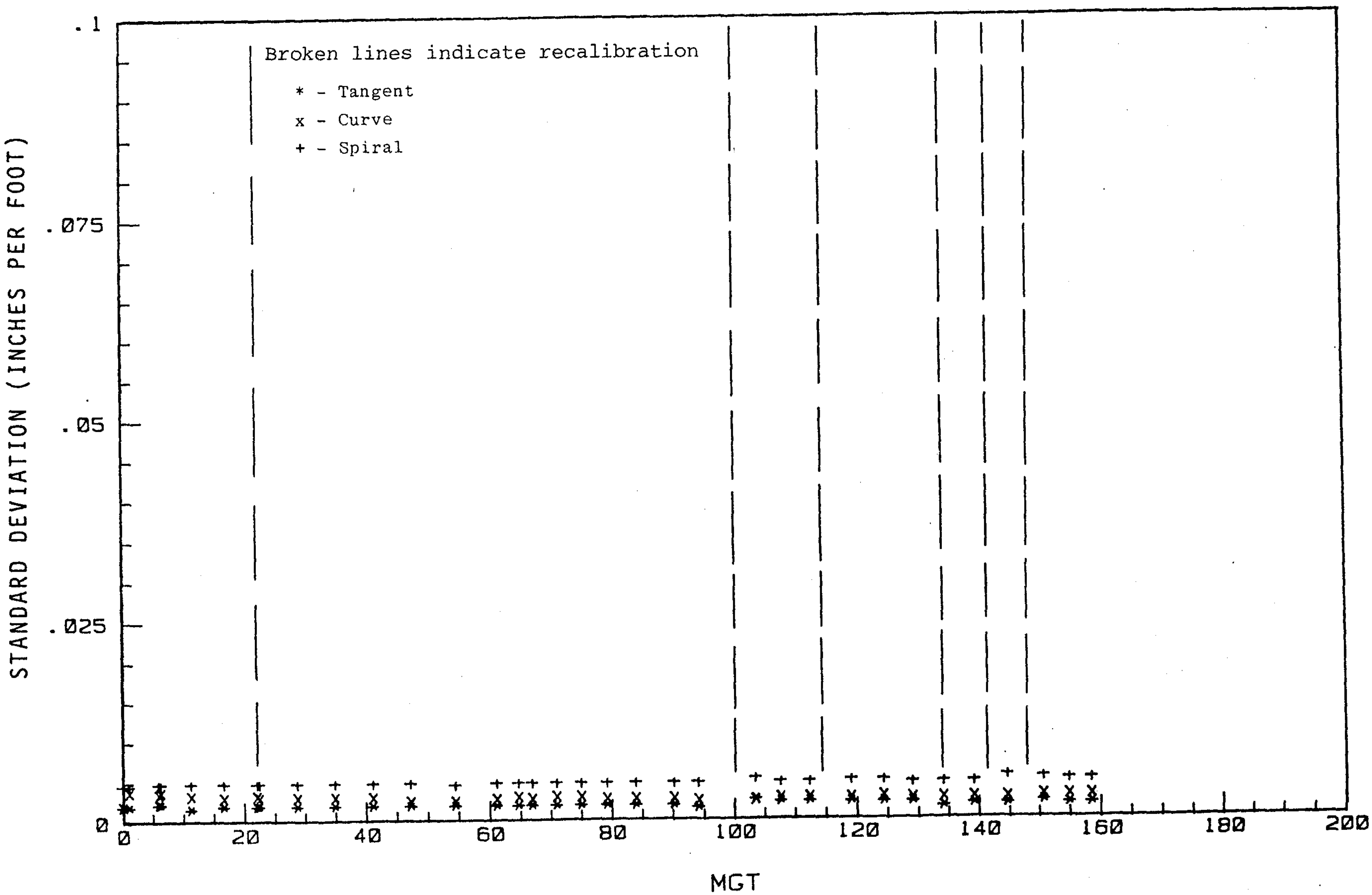


FIGURE F-1. AVERAGED STANDARD DEVIATION OF ADEL (ALIGNMENT RATE OF CHANGE) VS MGT FOR ALL TEST SEGMENTS.

APPENDIX G

AVERAGED STANDARD DEVIATION OF GAGE VS MGT.

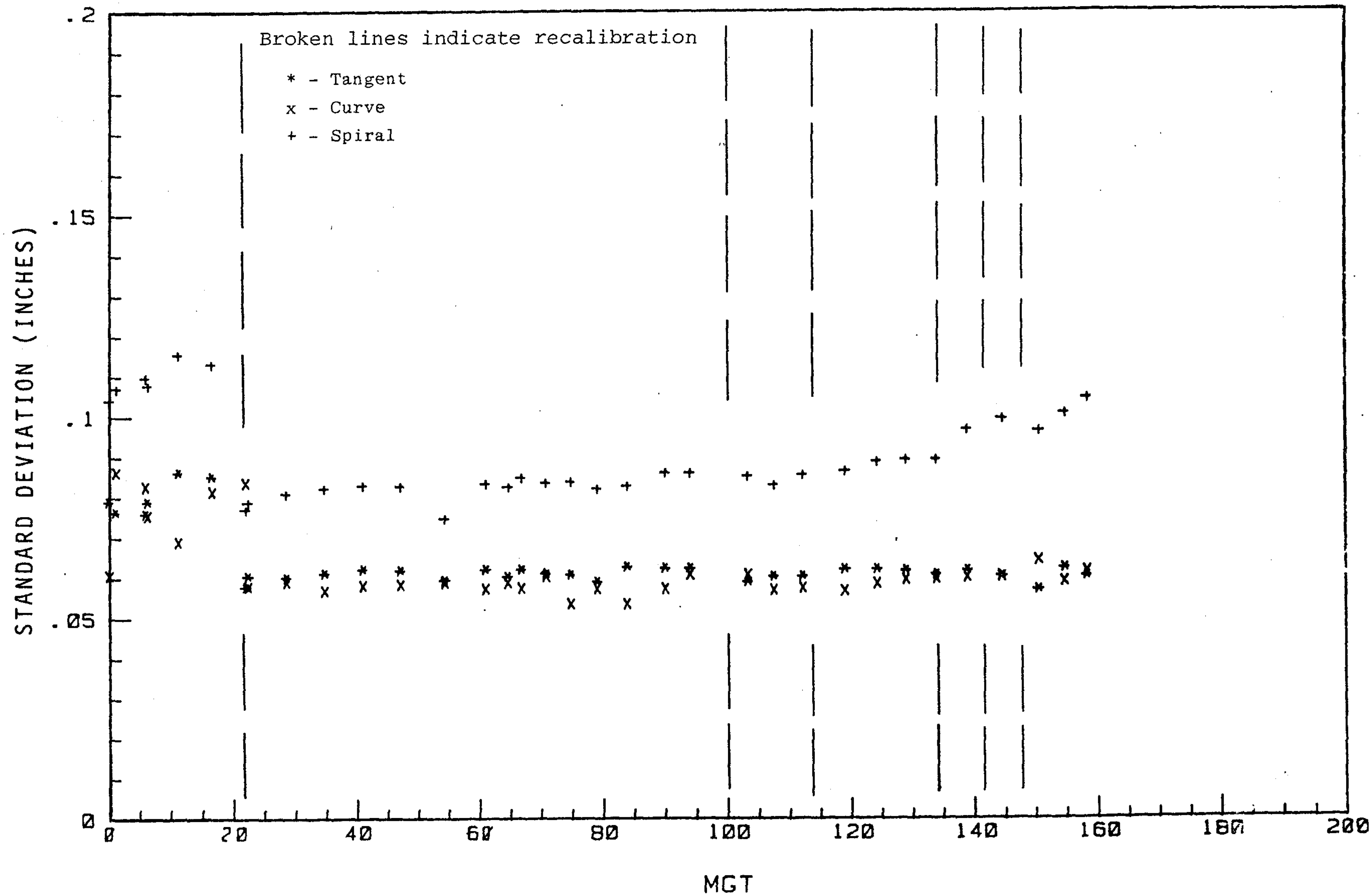


FIGURE G-1. AVERAGED STANDARD DEVIATION OF GAGE VS MGT FOR ALL TEST SEGMENTS.

APPENDIX H

AVERAGED STANDARD DEVIATION OF CROSS-LEVEL VS MGT.

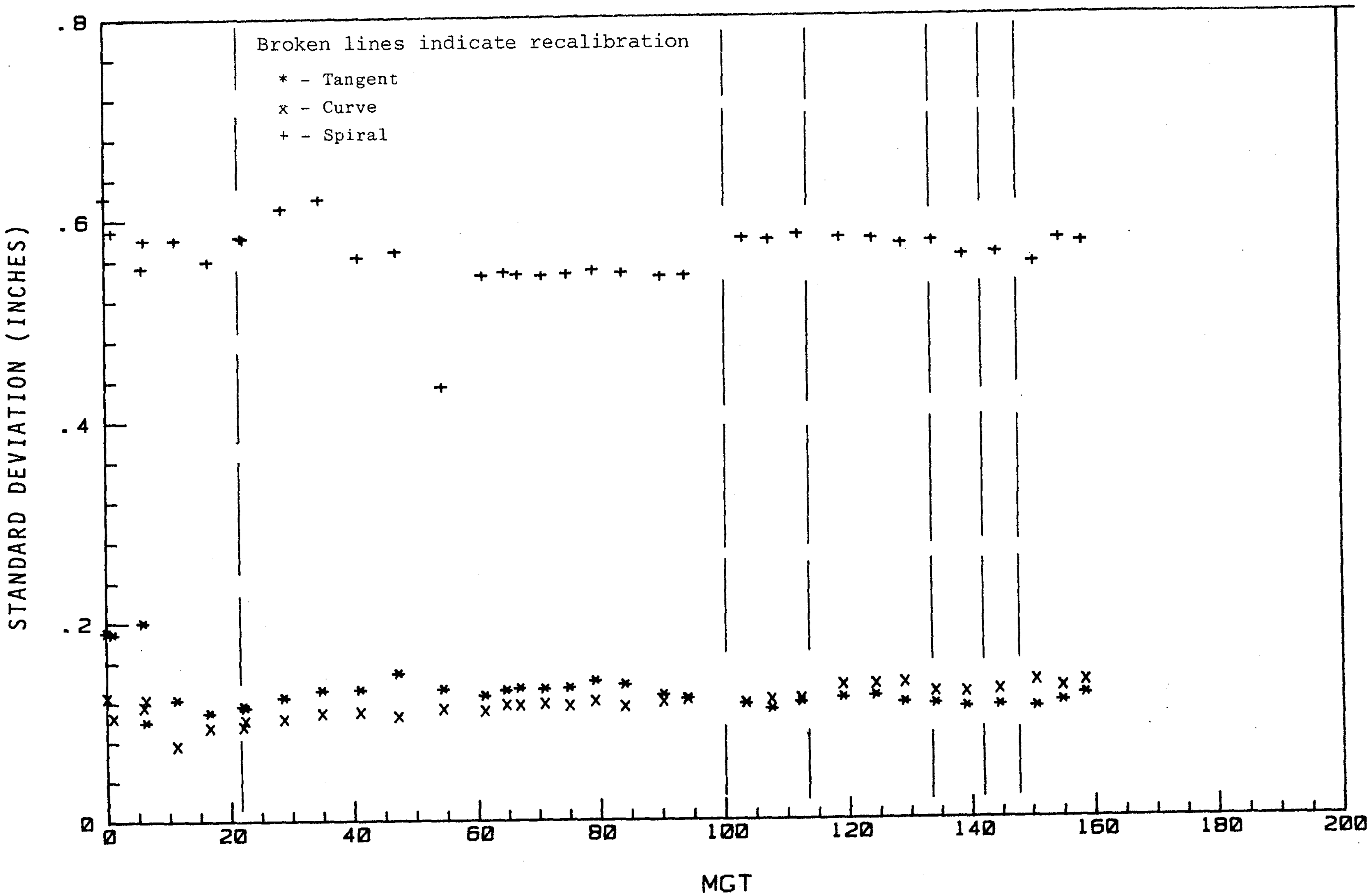


FIGURE H-1. AVERAGE STANDARD DEVIATION OF CROSS-LEVEL FOR ALL TEST SEGMENTS.

APPENDIX I

CORRELATION OF STANDARD DEVIATION, AVERAGE PROFILE 62-FOOT CHORD VS LEFT, RIGHT, AND 31-FOOT CHORD PROFILE.

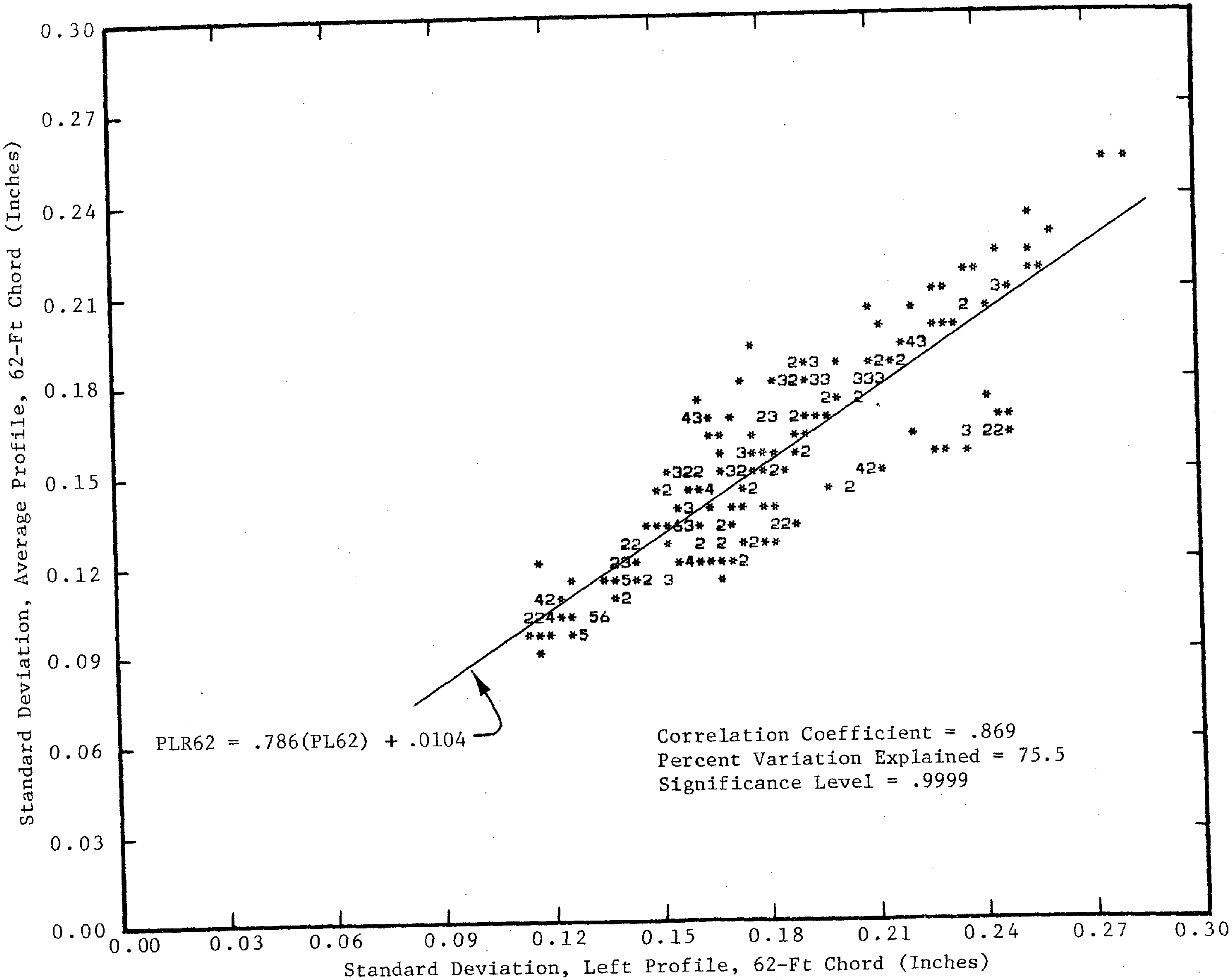


FIGURE I-1. STANDARD DEVIATION, AVERAGE PROFILE VS LEFT PROFILE, 62-FOOT CHORD.

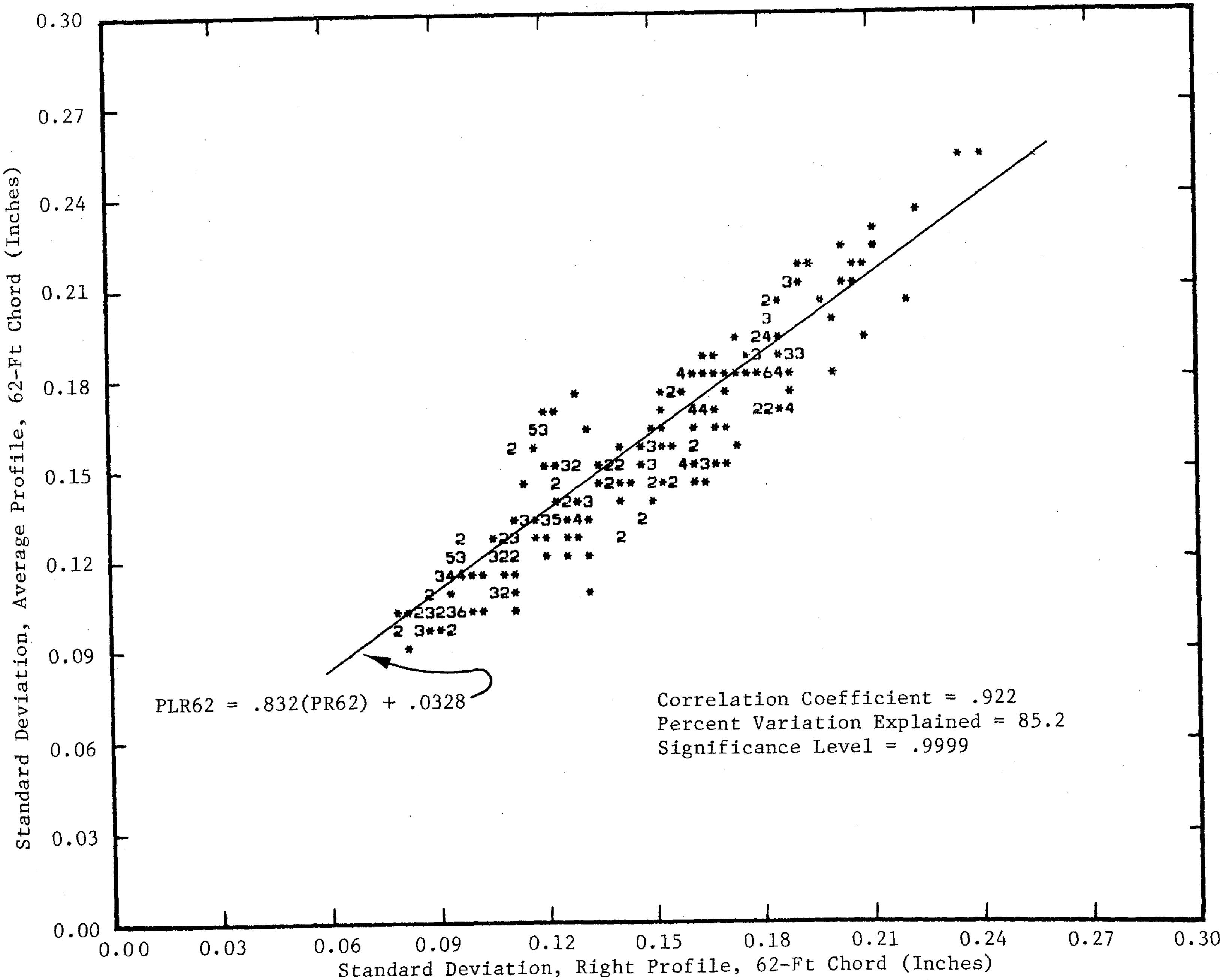


FIGURE I-2. STANDARD DEVIATION, AVERAGE PROFILE VS RIGHT PROFILE, 62-FOOT CHORD.

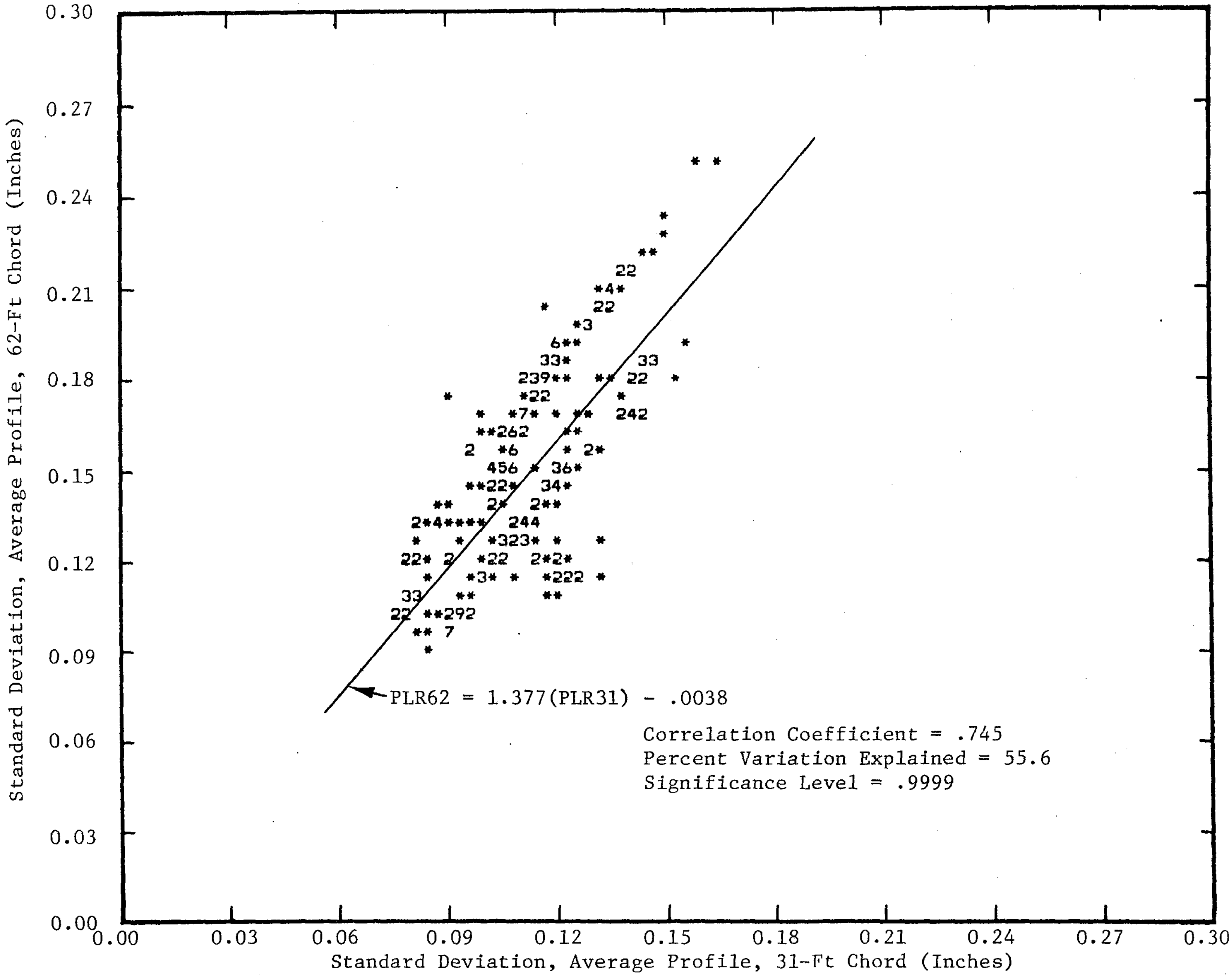


FIGURE I-3. STANDARD DEVIATION, PLR62 VS PLR31.

APPENDIX J

CORRELATION OF STANDARD DEVIATION, AVERAGE PROFILE 62-FOOT CHORD VS CROSS-LEVEL.

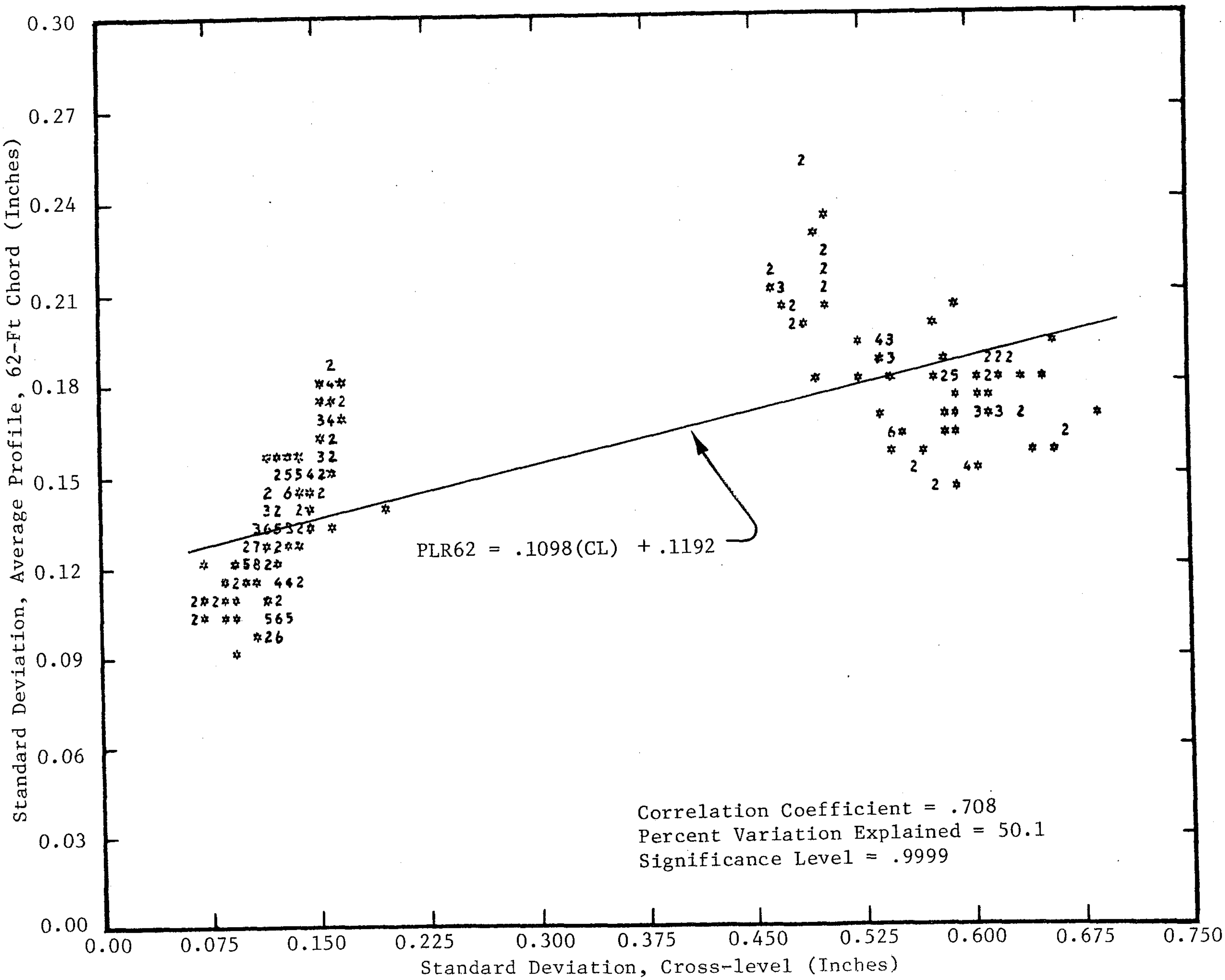


FIGURE J-1. STANDARD DEVIATION, AVERAGE PROFILE 62-FOOT CHORD VS CROSS-LEVEL.

APPENDIX K

CORRELATION OF STANDARD DEVIATION, AVERAGE ALIGNMENT 62-FOOT CHORD VS LEFT AND RIGHT RAIL ALIGNMENT.

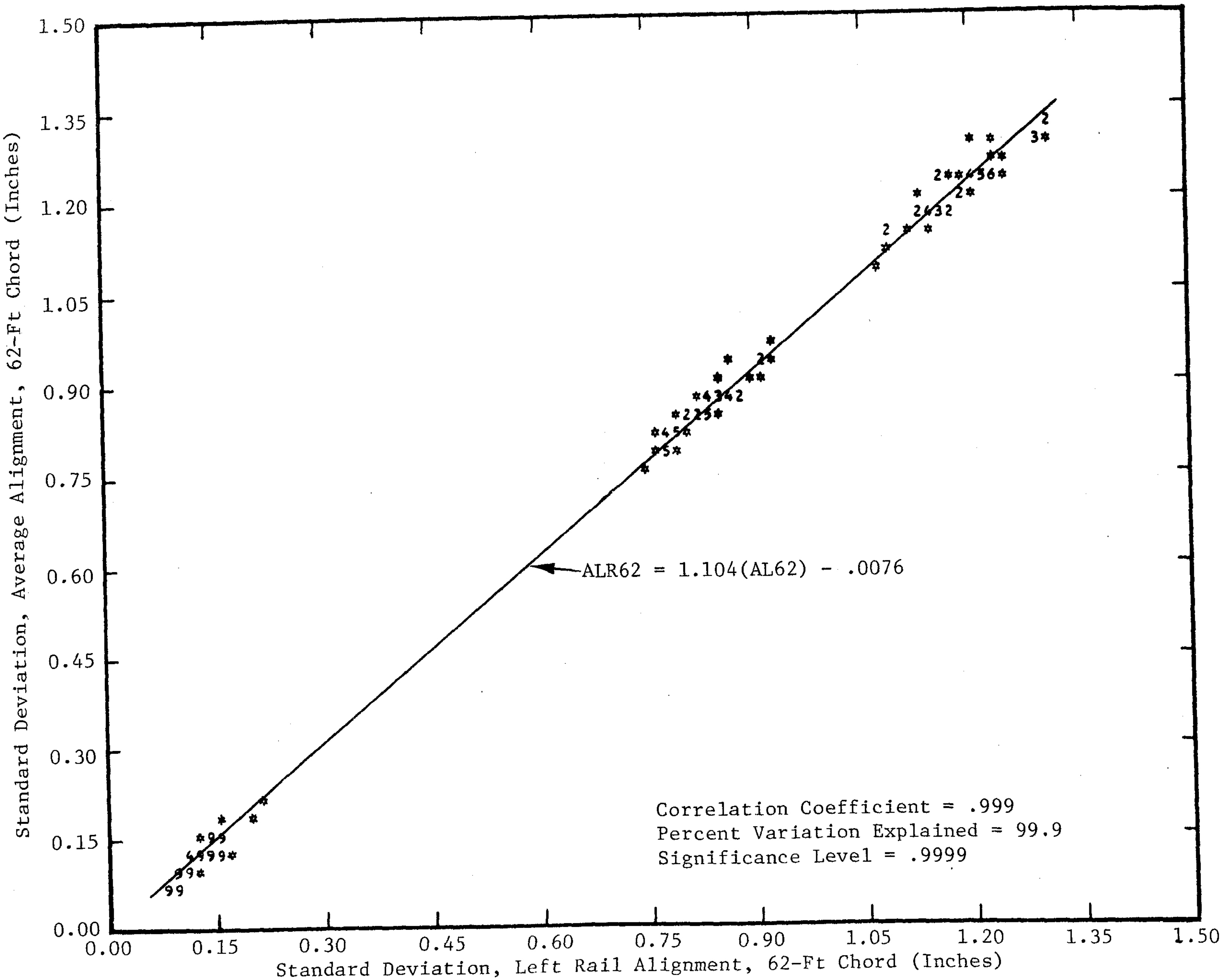


FIGURE K-1. STANDARD DEVIATION, AVERAGE ALIGNMENT 62-FOOT CHORD VS LEFT RAIL ALIGNMENT.

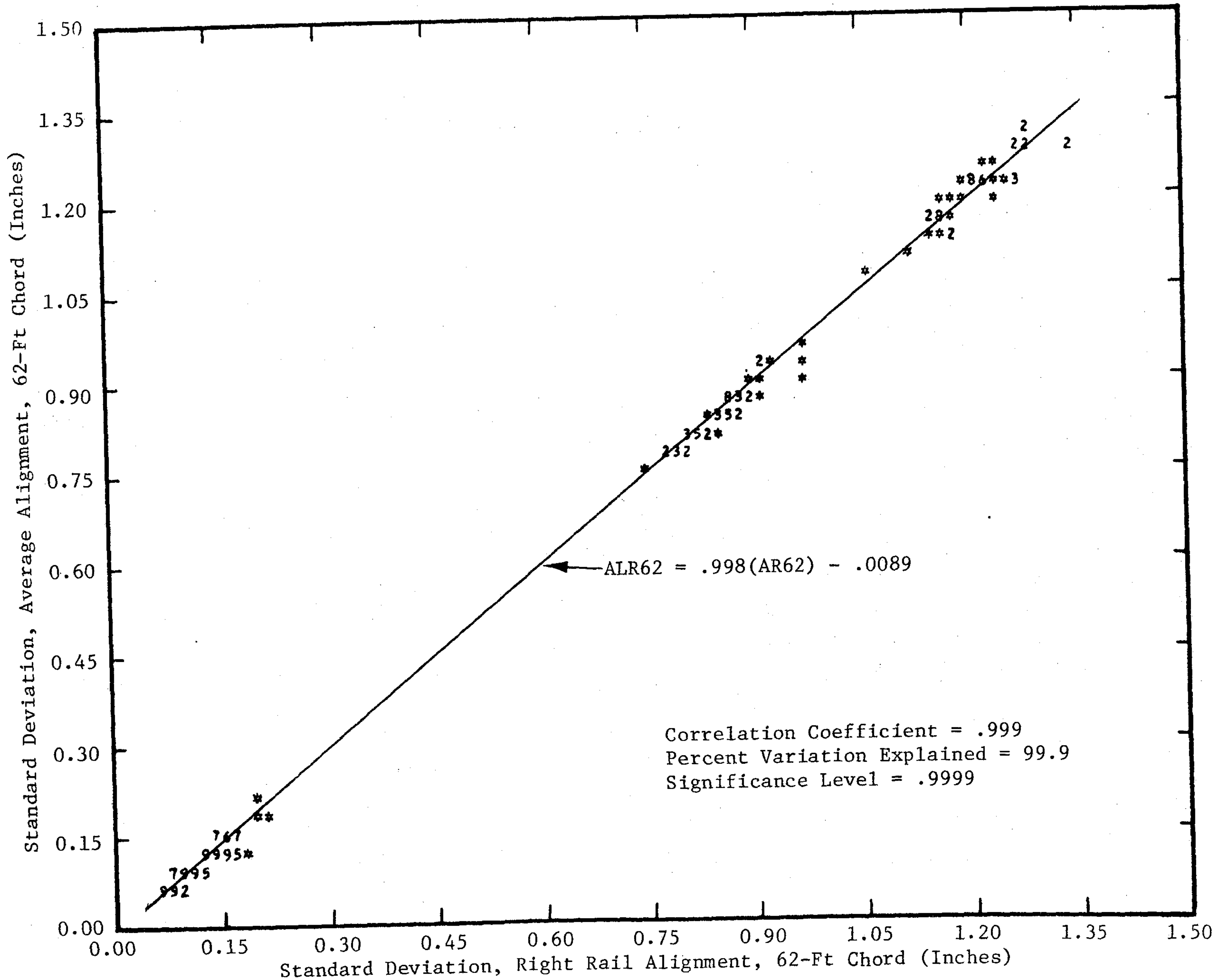


FIGURE K-2. STANDARD DEVIATION, AVERAGE ALIGNMENT 62-FOOT CHORD VS RIGHT RAIL ALIGNMENT.

APPENDIX L

CORRELATION OF STANDARD DEVIATION, AVERAGE ALIGNMENT 62-FOOT CHORD VS GAGE.

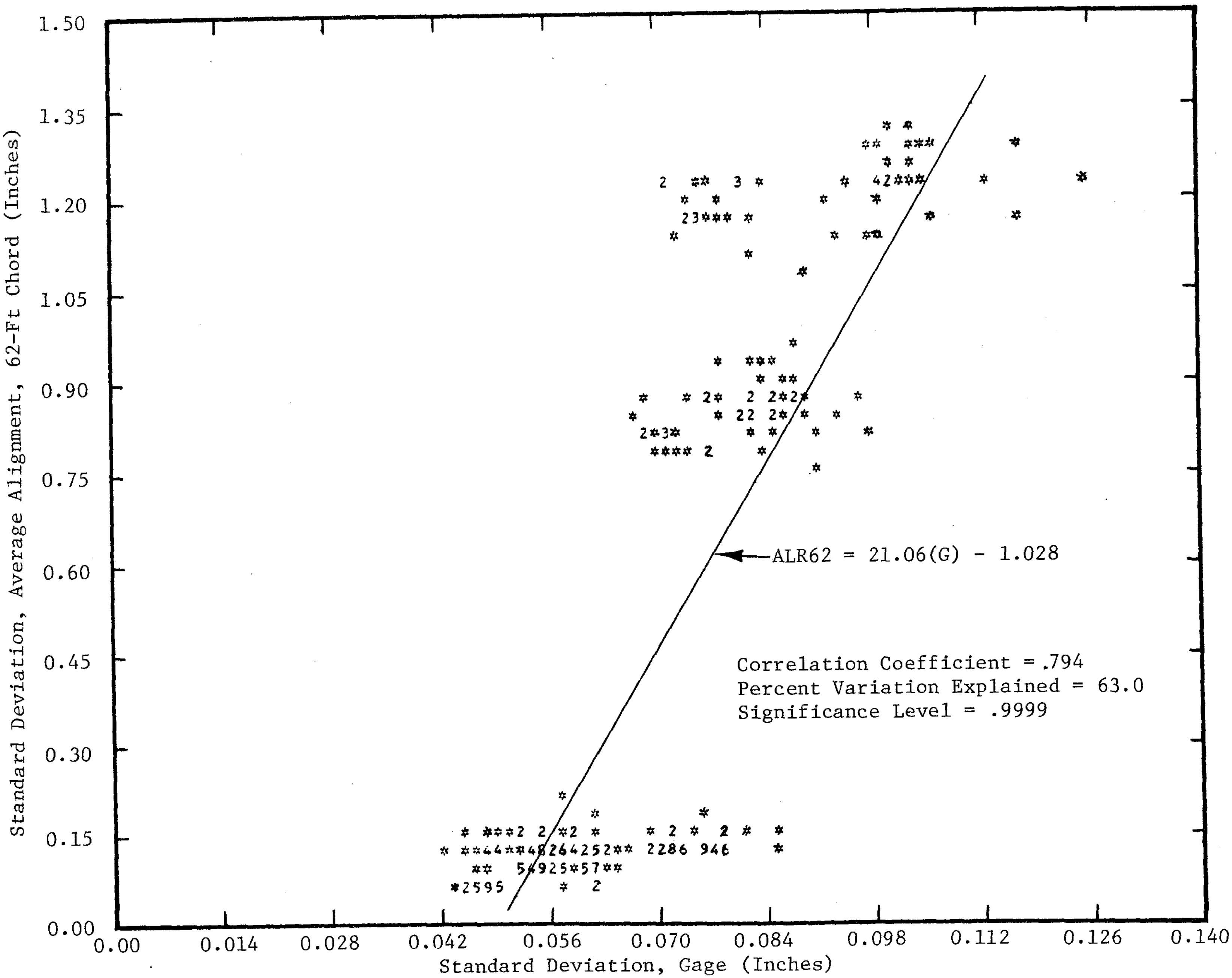


FIGURE L-1. STANDARD DEVIATION, AVERAGE ALIGNMENT 62-FOOT CHORD VS GAGE.

APPENDIX M

CORRELATION OF STANDARD DEVIATION, AVERAGE ALIGNMENT 62-FOOT CHORD VS CROSS-LEVEL.

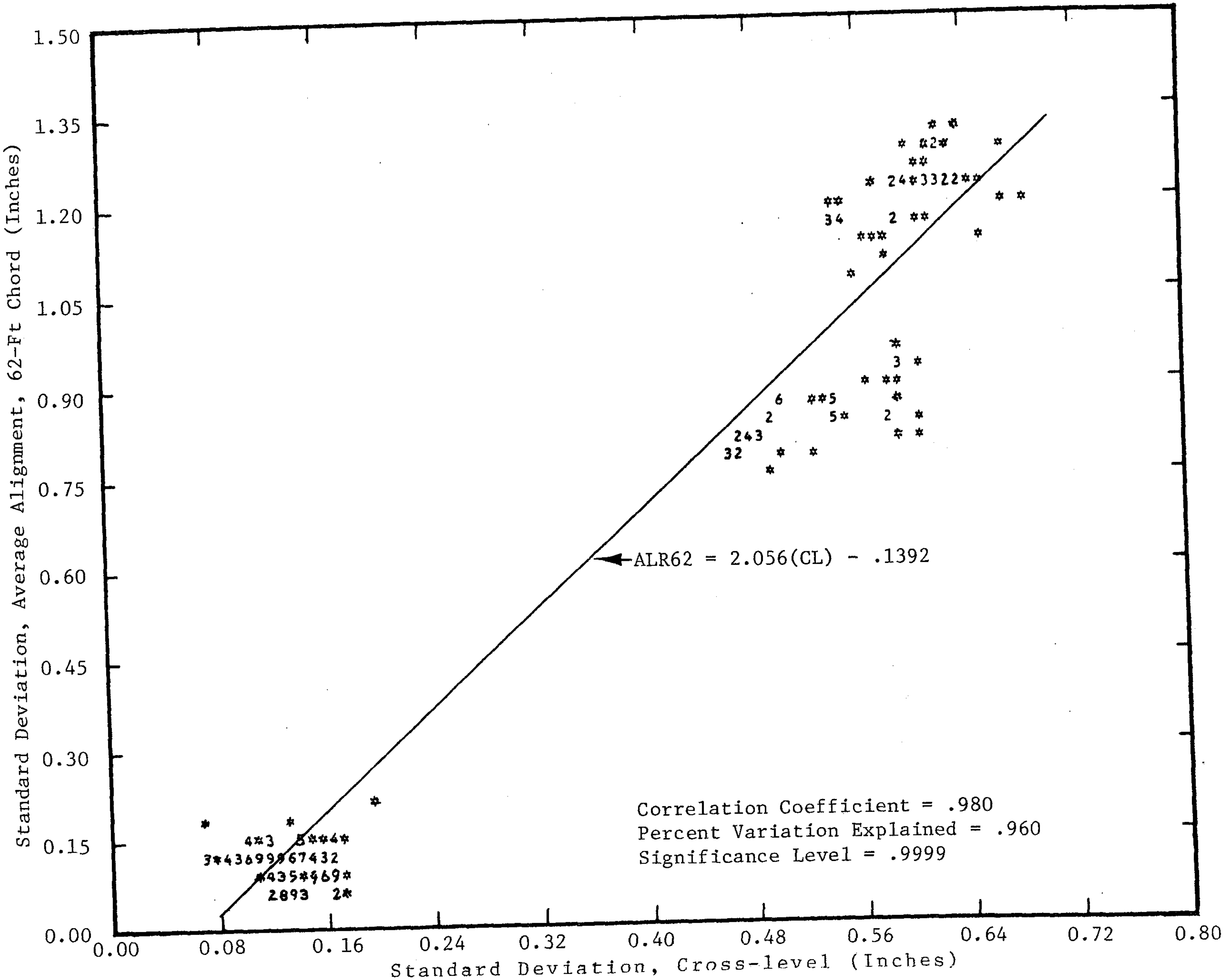


FIGURE M-1. STANDARD DEVIATION, AVERAGE ALIGNMENT 62-FOOT CHORD VS CROSS-LEVEL.

APPENDIX N

CORRELATION OF STANDARD DEVIATION OF GEOMETRIC PARAMETERS VS FRA CLASS 6 EXCEPTIONS

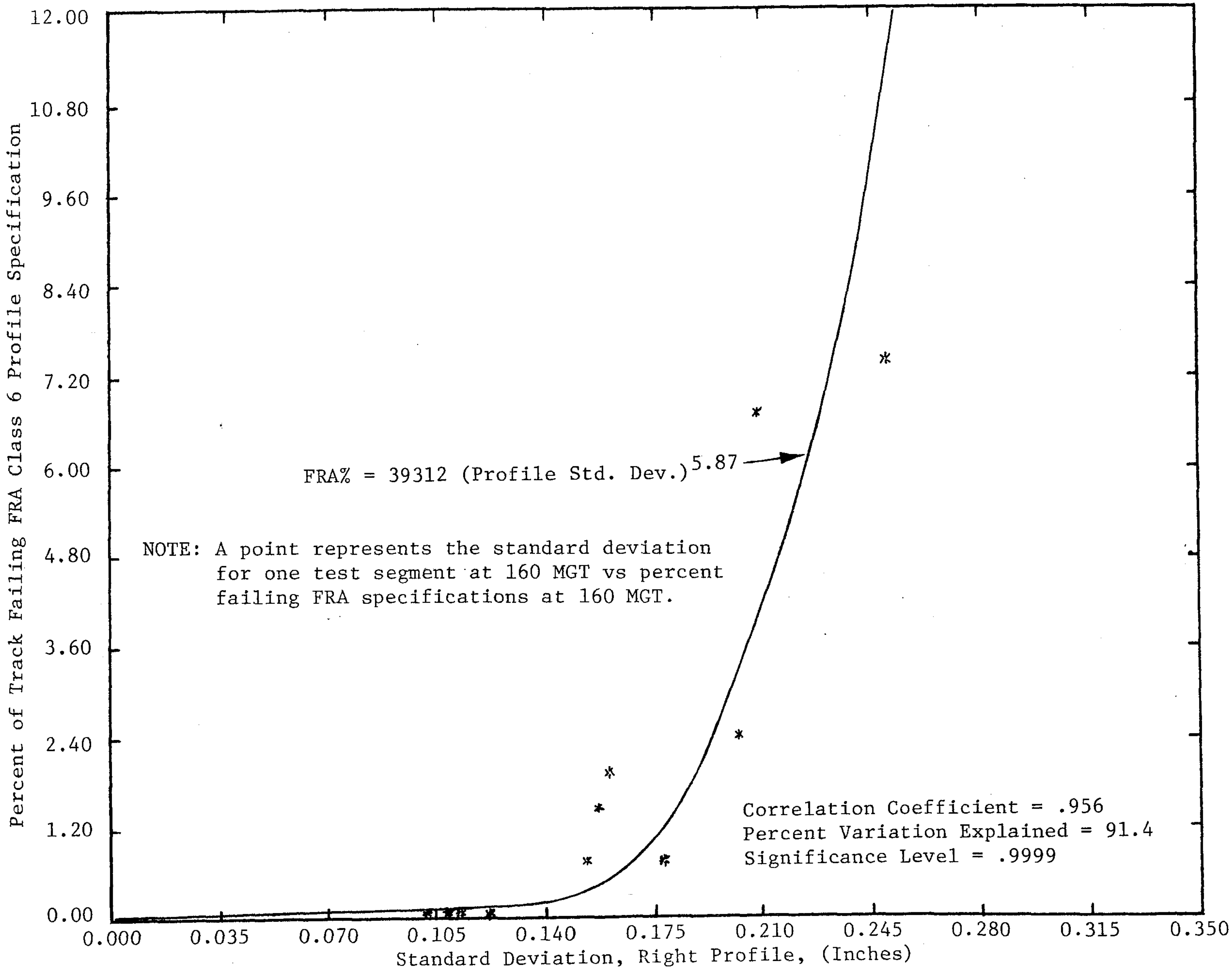


FIGURE N-1. STANDARD DEVIATION, RIGHT PROFILE VS FRA CLASS 6 EXCEPTIONS.

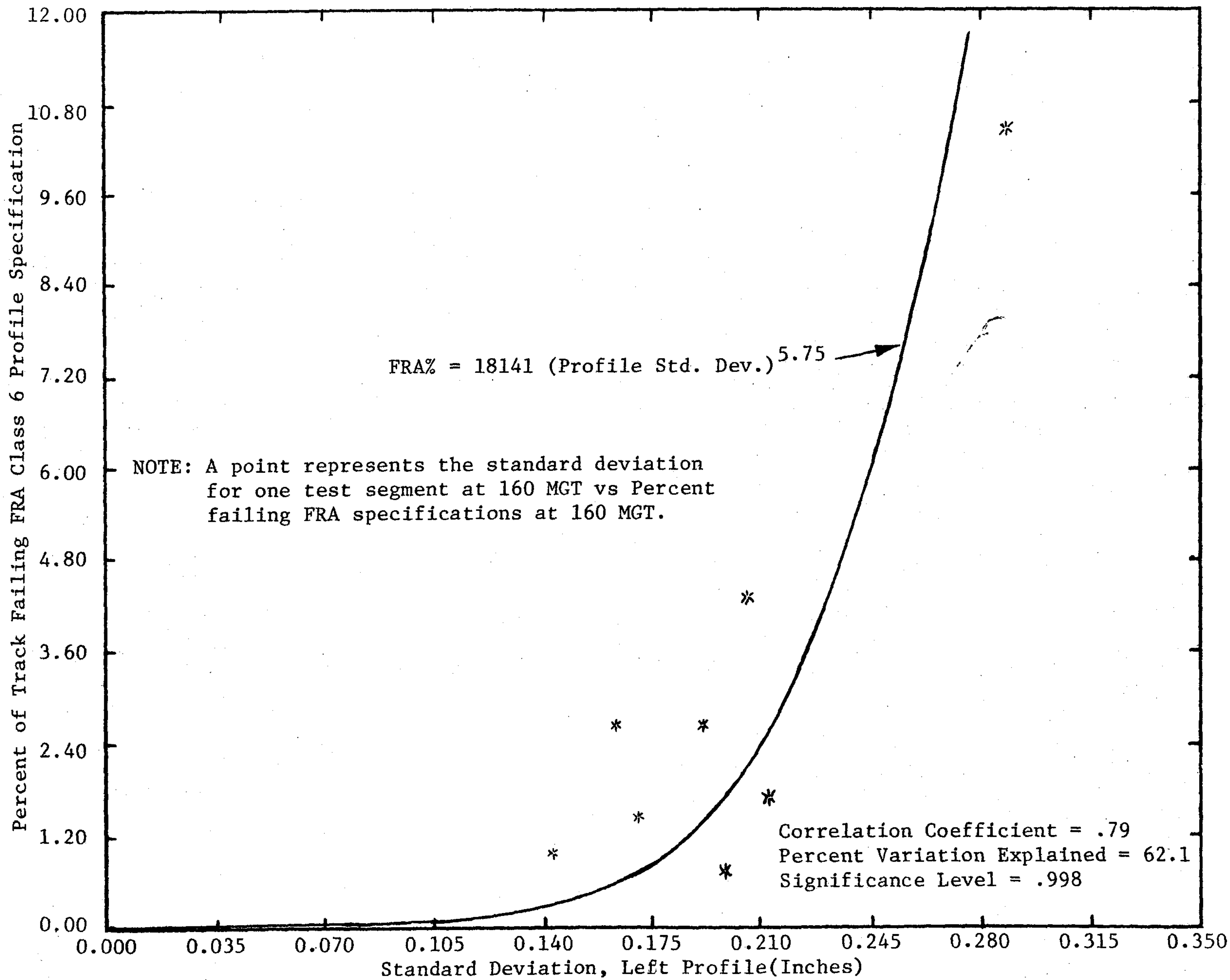


FIGURE N-2. STANDARD DEVIATION, LEFT PROFILE VS FRA CLASS 6 EXCEPTIONS.

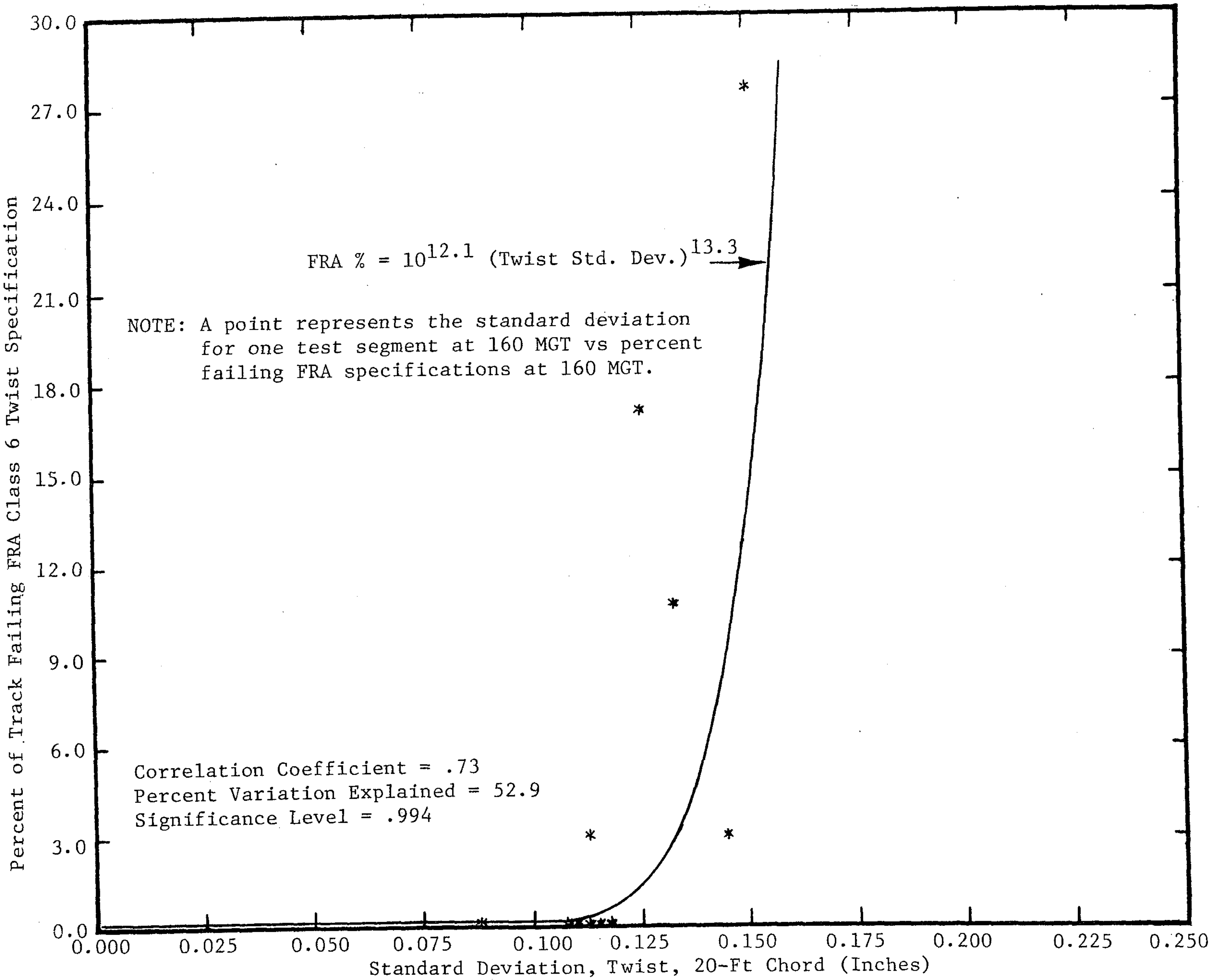
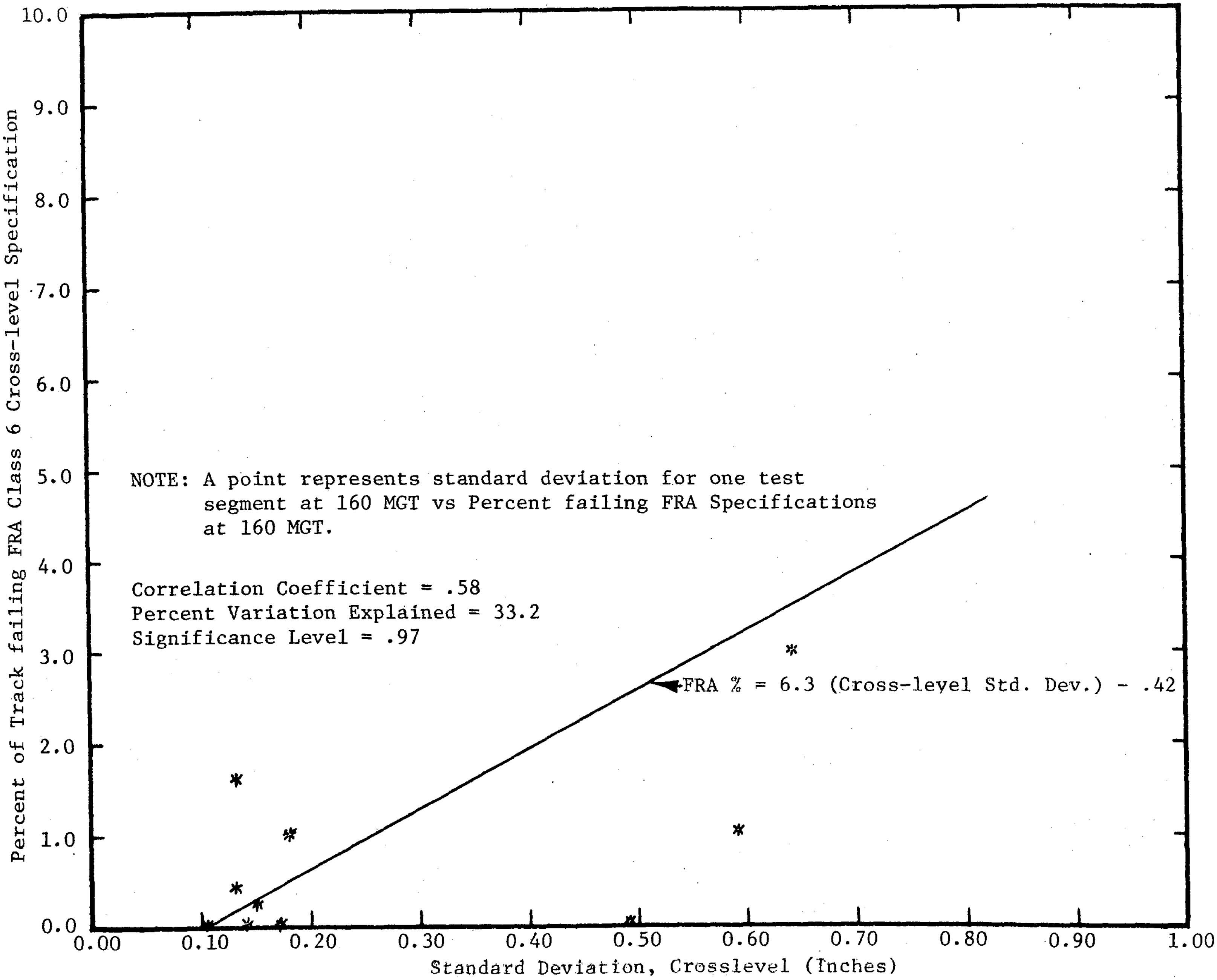


FIGURE N-3. STANDARD DEVIATION, TWIST VS FRA CLASS 6 EXCEPTIONS.



APPENDIX N-4. STANDARD DEVIATION, CROSS-LEVEL VS FRA CLASS 6 EXCEPTIONS.

APPENDIX O

TRACK MODULUS CURVES

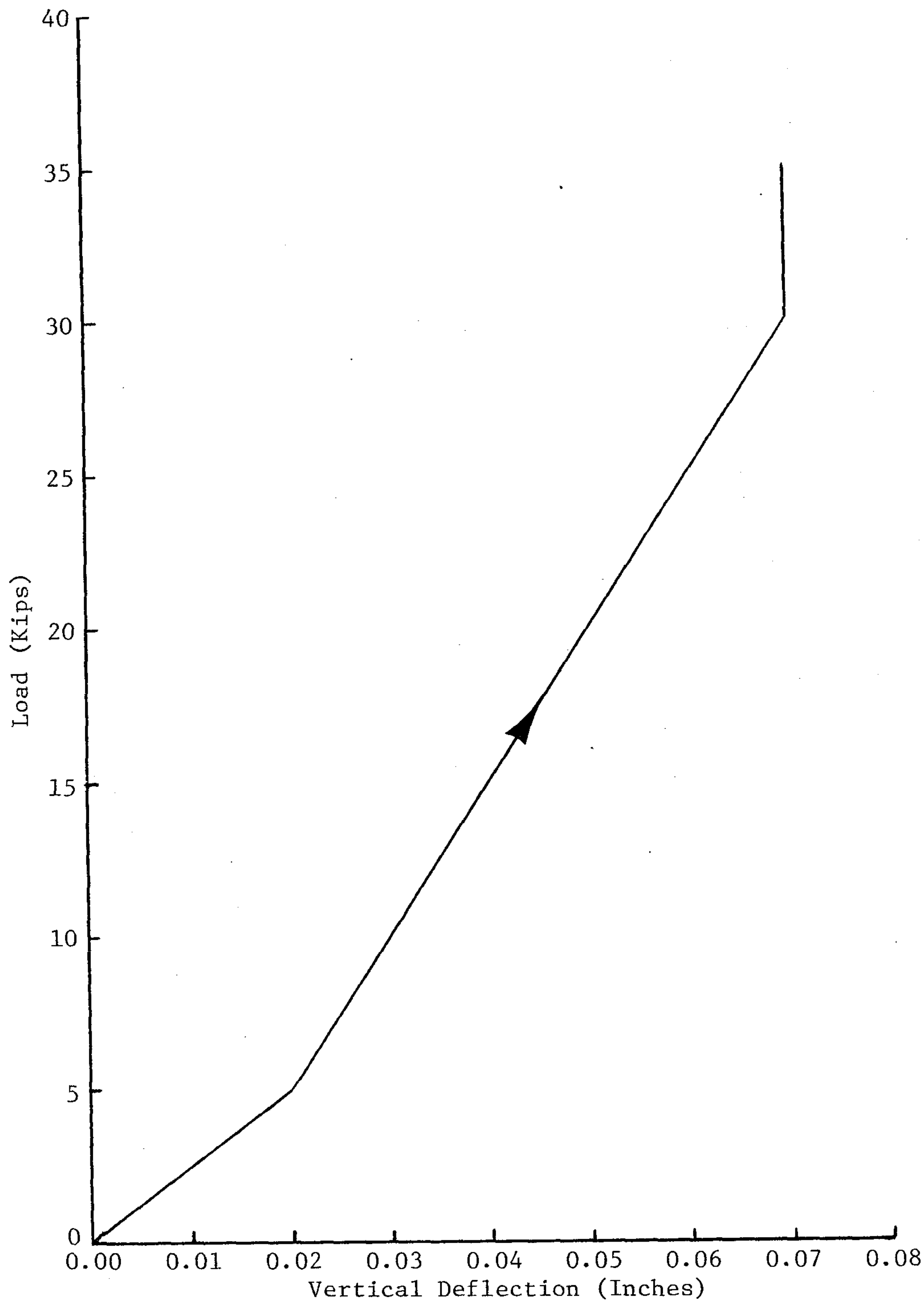


FIGURE O-1. LOAD VS DEFLECTION 5 MGT, WOOD TIES.

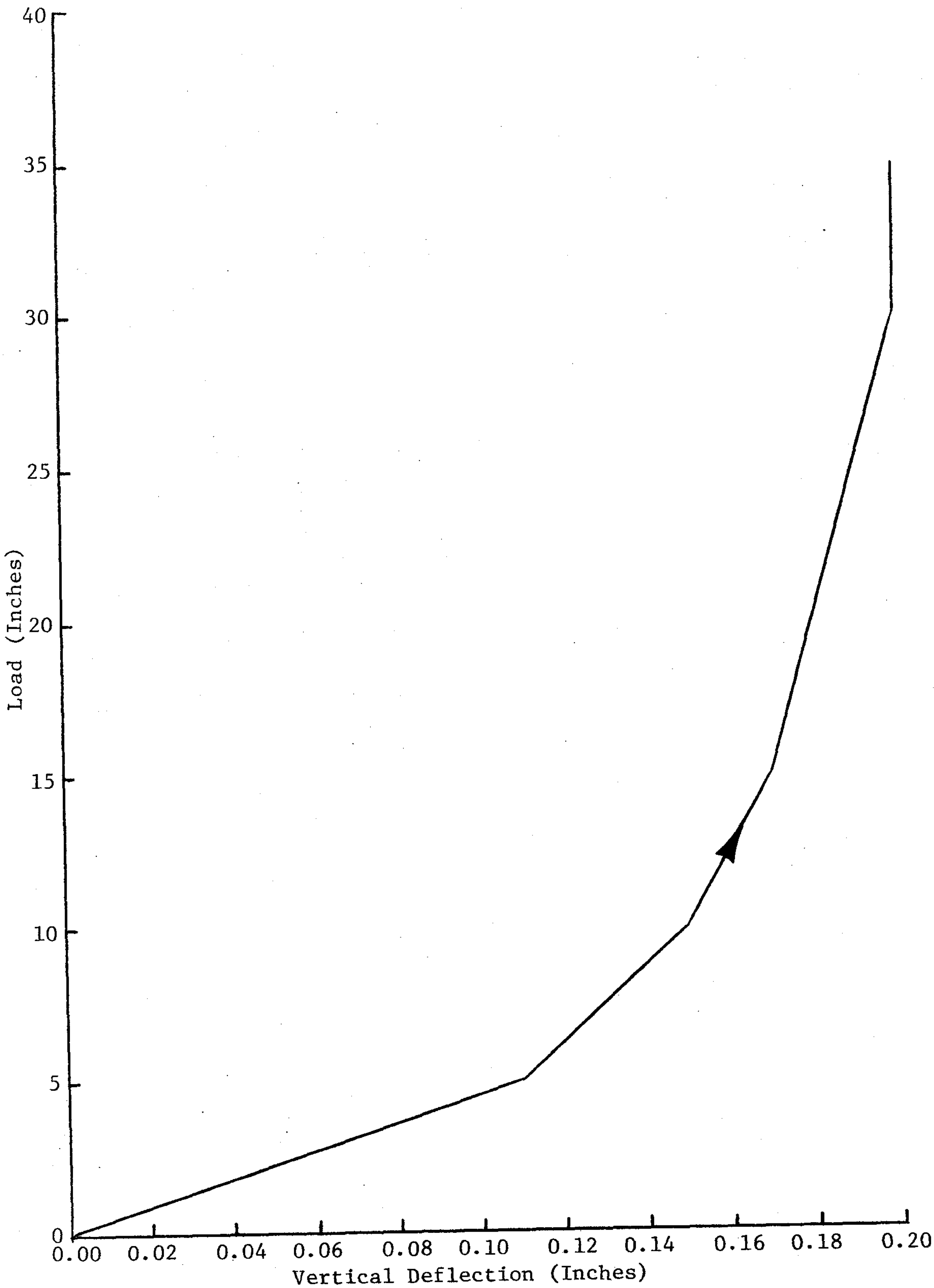


FIGURE O-2. LOAD VS DEFLECTION 160 MGT, WOOD TIES.

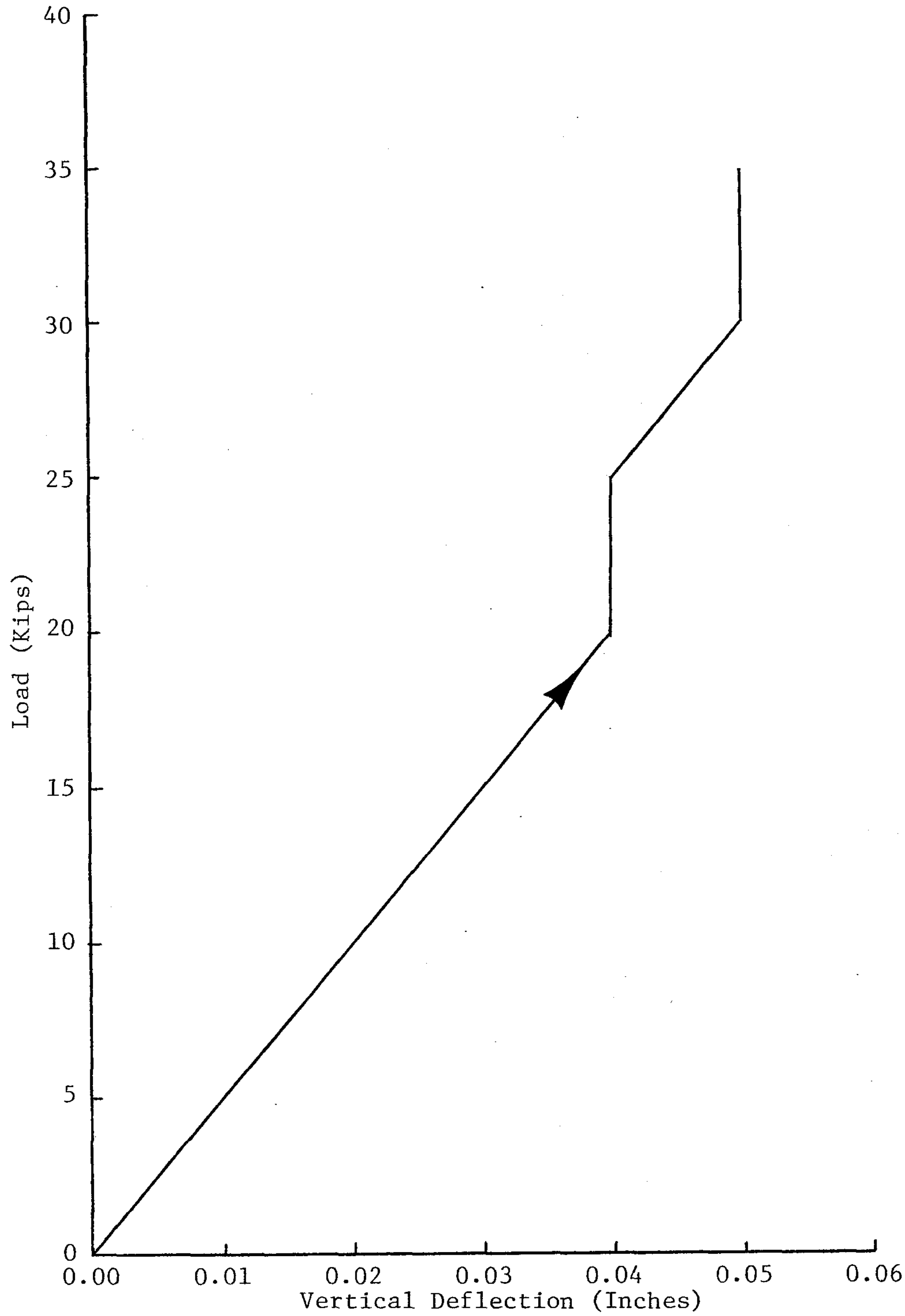


FIGURE 0-3. LOAD VS DEFLECTION 5 MGT, CONCRETE TIES.

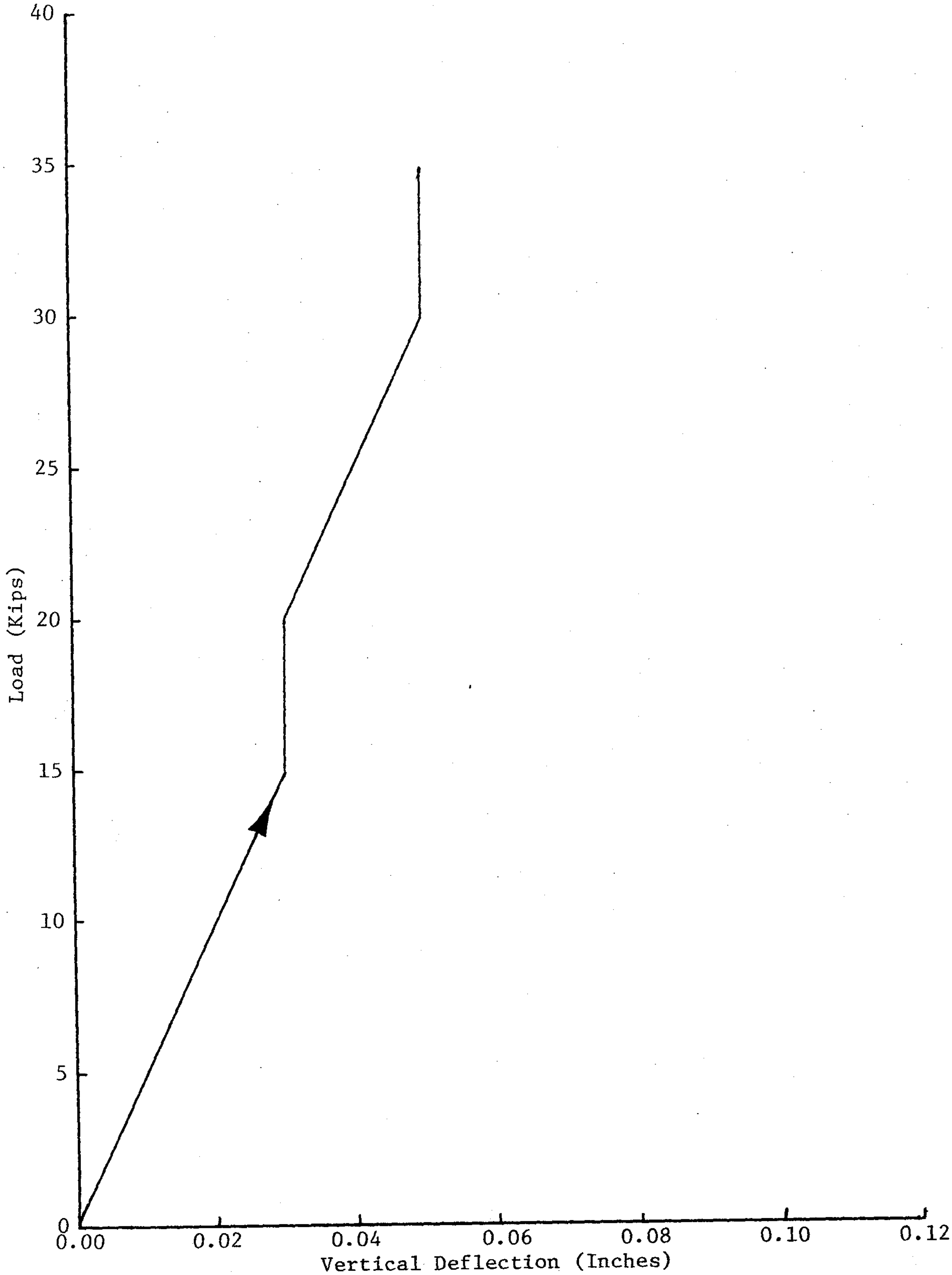


FIGURE 0-4. LOAD VS DEFLECTION 160 MGT, CONCRETE TIES.