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Stress Measurements in Railroad Wheels via the Barkhausen Effect

Southwest Research Inst, San Antonio, Tex

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STRESS MEASUREMENTS IN RAILROAD WHEELS VIA THE BARKHAUSEN EFFECT

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16. Abstract

The feasibility of utilizing the Barkhausen Effect in ferromagnetic steels as a nondestructive means for ascertaining residual stresses in railroad wheels was investigated. Railroad wheels are generally manufactured with compressive stress distributions in the rim to impede the propagation of fissures or thermal cracks caused by brake applications. In service, these compressive stresses may gradually become tensile, thus increasing the potential for wheel failure. Specimens examined using the Barkhausen noise measurement technique included four new wheels and two used wheels. Stress measurements from this nondestructive technique were compared with stress values determined by a dissection method of strain relaxation. Qualitative consistency in these data were observed, although testing of a larger data base will be required to determine the utility of the Barkhausen noise measurement technique for identifying those wheels which are potentially hazardous because of tensile stress buildup.

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PREFACE

The research and testing studies documented in this report are one part of an investigation to evaluate the residual stresses in railroad wheels due to varying braking rates on passenger vehicles. The companies involved in the overall program included Southwest Research Institute, USS Engineers and Consultants, Inc., and the NASA Marshall Space Flight Center. Southwest Research Institute evaluated the Barkhausen effect under Contract DOT-TSC-713, U.S. Department of Transportation, Transportation Systems Center under the auspices of the Federal Railroad Administration, Office of Research and Development.

The work at SRI was carried out by Robert R. King, John R. Barton, and William D. Perry. The technical contract monitor was the late Jack W. Lyons of the Transportation Systems Center.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

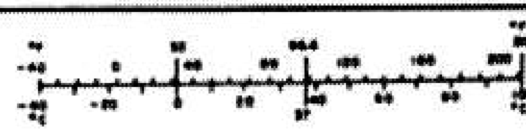


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

1. INTRODUCTION

Approximately 400 railroad wheel failures are encountered each year.[1] Although this represents a small fraction of the approximately 16,000,000 wheels in operation, the consequences of a few catastrophic wheel failures are so severe that solving this problem has been assigned a high priority by the Government and the railroad industry.

There is evidence which suggests that undesirable residual stress conditions developed by brake application are a dominant factor leading to the catastrophic failure of many railroad wheels. New wheels used in most railway passenger operations have a built-in failure prevention mechanism; namely, the development of residual compressive stresses in the rim of properly heat-treated wheels. These locked-in rim stresses are intended to impede the propagation of thermal cracks caused by heat generated from successive high-speed braking stops. Associated thermal cycling from such braking gradually reduces any protective compressive stresses which eventually become tensile, after which the wheel may be primed for failure when a critical crack has developed.

The manner in which stresses in a wheel rim change is dependent upon many factors such as: speed at which the wheel is operated, number of brake applications (especially during hard or emergency stops), initial compressive stress level of the wheel rim, etc. The rate of change of stresses with each of the influencing factors is unknown at this time, and the critical level for the tensile stresses in the wheel rim have not been determined. To gain a further understanding of the stress changing mechanisms in the wheel and to investigate techniques that are potentially feasible and useful for nondestructive evaluation of these stresses, the Federal Railroad Administration initiated on 28 August 1972 a research program to include an evaluation of the Barkhausen Noise Stress measurement technique being developed at Southwest Research Institute. This report summarizes the work accomplished under Contract DOT-TSC-713.

2. SUMMARY

The investigation included four new wheels and two used wheels which had been removed from service; one of the used wheels contained a thermal crack approximately 1.2 inches long. The six wheels were involved in a round-robin type activity involving Southwest Research Institute (SwRI), United States Steel Corporation (USSC), and Marshall Space Flight Center (MSFC). SwRI acquired Barkhausen noise data from each of the six wheels after which each wheel was returned to USSC where three of the new wheels were each placed on a dynamometer for high-speed simulated brake-stop testing. (Wheels were also routed to MSFC for investigating an ultrasonic method of residual stress measurement.) After stop testing, each of the three wheels was returned to SwRI for a second series of Barkhausen noise measurements. Following the measurements, they were returned to USSC for metallographic analysis including residual stress measurements obtained by a destructive strain relaxation method. Stress indications obtained nondestructively by the Barkhausen noise method were compared to the residual stress measurements obtained for each of the six wheels by the USSC.

A brief summary of significant results follows; a more detailed presentation, including a description of the Barkhausen method, illustrations showing the equipment, diagrams of the measurement locations, graphs and tabular presentations of data obtained on the program, discussions, and recommendations, appears in subsequent sections.

An overall appraisal suggests that the Barkhausen method offers a possible potential of providing means for rapid assessment of residual stress conditions in railroad wheels. However, results are not conclusive enough to warrant immediate development of equipment for routine use on wheels. It is emphasized that an extremely limited wheel "population" was examined: 4 new (3 wheels with different simulated braking conditions) and 2 used wheels were available. Furthermore, although one of the used wheels contained a significant thermal crack (1.2 inches long and 0.2 inch deep) and one of the new wheels developed two small surface cracks during the dynamometer experiments, no predictable wheel fractures occurred due to the simulated braking imposed upon the wheels. Accordingly, the results could not provide a basis of indicating at what level of residual stress or Barkhausen signature a wheel should be judged to be unsafe for service.

Nevertheless, a qualitative consistency was observed for limited locations on the rim between the Barkhausen results and the residual stresses determined destructively at USSC. Relatively minor stress changes occurred on the wheel rim regions and plate regions but major changes occurred on the tread regions. Specifically, Barkhausen values indicative of tensile stresses in excess of 50 ksi were obtained on the tread regions and compressive stresses in excess of 40 ksi were obtained on the sides of the rims for wheels after dynamometer experiments. Stress values obtained destructively at these same locations ranged from 50 ksi to 100 ksi tension and 0 ksi to 53 ksi compression, respectively. Prior to the dynamometer experiments, all of the rim regions were in compression. If these high tensile stresses in the tread region and the associated high Barkhausen values are indicative of values that could develop on the sides of the rims after tensile stresses have developed to a dangerous level in the rim, it should be relatively straightforward to specify a "GO, NO GO" criterion based on simple procedures using the Barkhausen method. One possible treatment of the Barkhausen data is presented to illustrate a potential criterion of identifying those wheels which are high risks for service applications.

Since the Barkhausen noise method is confined to the near surface region, possibly 0.01 to 0.02 inches deep, the applicability of the method to the railroad wheel stress problem may appear questionable. However, a recent comprehensive investigation* in which wheels were tested to fracture shows a correlation between values of residual stress indicated by X-ray diffraction and a strain relaxation method on railroad wheels that were subjected to drag braking tests in the laboratory. In addition, it is indicated that surface residual stresses obtained by using the X-ray diffraction method on the front side of the rim at a position 10 mm from the tread corner shows promise, when used with a fracture mechanics analysis, of predicting conditions (crack size and residual stress) that result in wheel fracture. Accordingly, it appears that the Barkhausen method — since it measures somewhat deeper than X-ray diffraction — is possibly applicable to stress measurement in railroad wheels, but extensive additional data will be required to provide an adequate base for assessing effectiveness of the method.

*"Residual Stresses in the Rim of a Railroad Solid Wheel Due to On Tread Braking and Their Effect on Wheel Failure," by Toshio Hirooka, Kuso Kasai, Seiichi Nishimura, Katsuyuki Tokimasa, International Wheelsets Congress, Paris, 4-7 June 1972 (Ref. 21).

3. DISCUSSION OF APPROACH

3.1 THE BARKHAUSEN PHENOMENON

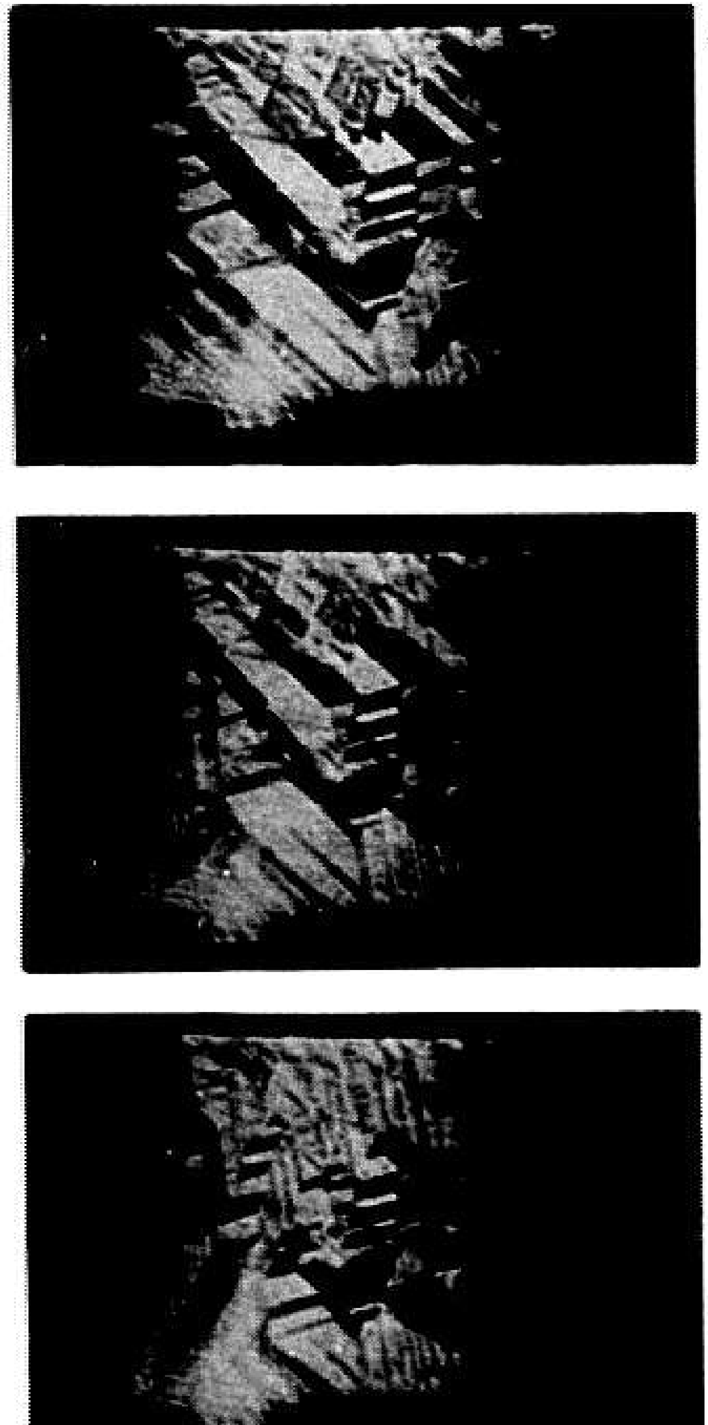
The fact that certain properties of ferromagnetic material are strongly stress sensitive has long been known. Suggestions that one or more of these might be made the basis of a practical stress measuring method were made as early as 1922.[2] Until recently, nothing practical came of these suggestions, perhaps because of the lack of any detailed understanding of the ferromagnetic state in general and, in particular, because of the lack of understanding of the complex way in which material composition, grain size and structure, and crystalline defect structure, as well as the state of mechanical stress, interact to affect any given measurable parameter of the ferromagnetic material. While it cannot be presently stated that this complex situation is fully understood, it is true that significant progress has been made in the past several years.

One phenomenon in particular affords an approach to the measurement of applied and residual stress in ferromagnetic materials: the Barkhausen effect.[3] In 1917, Barkhausen discovered that as a ferromagnetic specimen is magnetized by the application of an external magnetic field, the magnetization does not increase in a strictly continuous way but rather by small, abrupt, discontinuous increments now called Barkhausen jumps. It is now well established that such jumps are due principally to discontinuous movements of mobile boundaries between small sub-regions called magnetic domains in the macroscopic specimen. Each such domain is at all times very nearly magnetically saturated; an unmagnetized macroscopic specimen comprises a great number of domains which have randomly oriented directions of magnetization so that the average bulk magnetization is zero. The specimen becomes magnetized mainly by the growth in volume of favorably oriented domains at the expense of unfavorably oriented domains, the principal mechanism of growth being the physical movement of the walls or regions in which the alignment of atomic magnetic moments change rapidly between adjacent domains. It has been established that the direction and magnitude of mechanical stress to which a ferromagnetic specimen is subject strongly influences the detailed dynamics of the domain wall motion and thus correspondingly influences the Barkhausen effect.[4, 5, 6] In Figure 1 are several photographs made at Southwest Research Institute utilizing the Kerr magneto-optic effect to show magnetic domains on the surface of a single crystal of silicon-iron. These illustrate the manner in which domains change under the influence of applied stress.[7]

$0.6 \ \frac{kg}{mm^2}$

$1.22 \ \frac{kg}{mm^2}$

$1.84 \ \frac{kg}{mm^2}$



(Compressive Stresses Applied Horizontally)

MAG 5X

FIGURE 1. MAGNETIC DOMAINS ON SURFACE OF SILICON IRON CRYSTAL

3.2 STRESS MEASUREMENT BY MEANS OF THE BARKHAUSEN EFFECT

Utilization of the Barkhausen phenomenon to measure stresses in ferromagnetic parts requires instrumentation to excite the Barkhausen activity, to detect the Barkhausen activity, and to process the detected signal yielding a quantified stress indication. Figure 2 is a diagram of a rudimentary arrangement for exciting and detecting the Barkhausen effect. Figure 3 shows a cathode ray oscillogram of the voltage induced in the induction coil sensor during one complete reversal of the magnetization of the specimen. The direct output of the sensor can be described as a burst of pulses of somewhat random amplitude and temporal separation. The largest amplitude of this burst usually occurs near the center of the magnetic reversal cycle, and the maximum amplitude of the burst is especially sensitive to the state of stress in the specimen. Qualitatively, high amplitude processed signals (see Figure 4) are associated with tensile stresses and low amplitude with compressive stresses. The direction of stress can be determined approximately by orienting the probe to obtain a maximum signal amplitude, and this occurs when the probe axis is aligned along the maximum tensile stress axis. The method is confined to stresses in the near surface region but has some subsurface sensitivity, perhaps not deeper than 0.02 inches. In some cases, it can also be shown that the state of stress in the specimen is related to the area under the envelope of the Barkhausen burst. In this program, the envelope of the Barkhausen burst was recorded on a strip chart recorder as illustrated in Figure 4 and the peak amplitude of the envelope was measured as the significant stress indicator, since preliminary appraisal indicated best correlation on calibration specimens.

To obtain quantitative stress values using the Barkhausen noise technique, measurements must first be made upon a specimen for which the stress condition is known and whose material condition is similar to the part which is to be inspected. Typically, a graph is plotted relating the Barkhausen noise measurement to the stresses applied to the specimen. Such a graph with the applied stress values plotted along the abscissa typically has the shape of a lazy "S" for steels with the maximum slope in the range between 40 ksi compression and 50 ksi tension. This "calibration curve" is then used to relate a Barkhausen measurement made on the inspected part to a particular stress value for the measurement location.

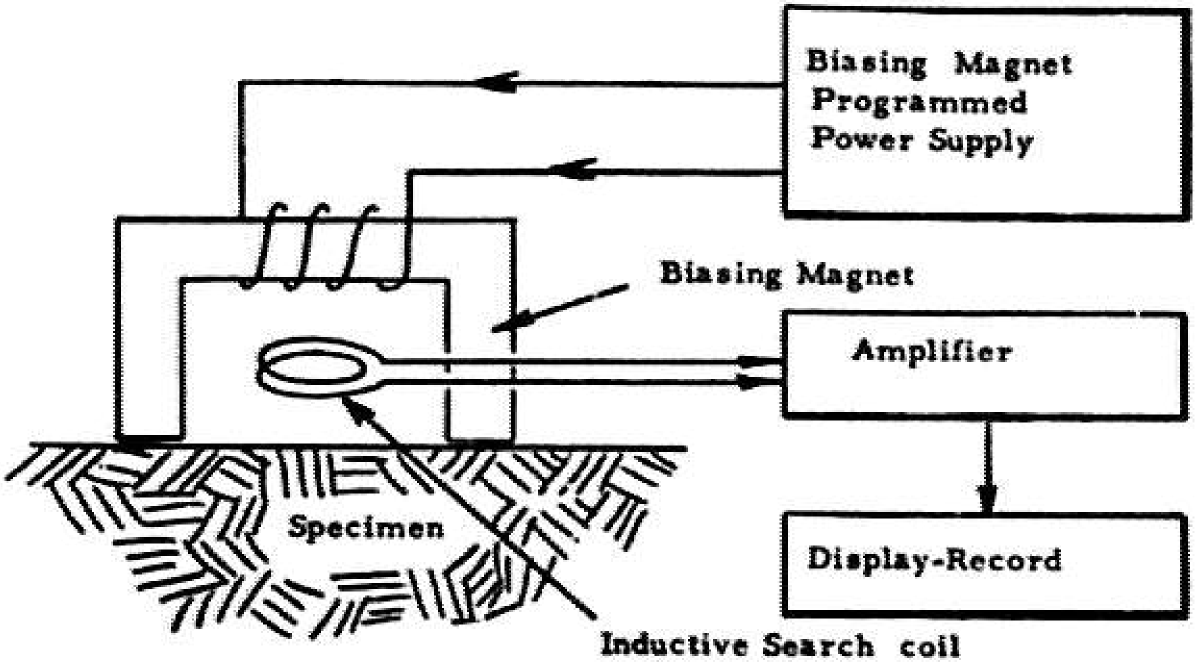
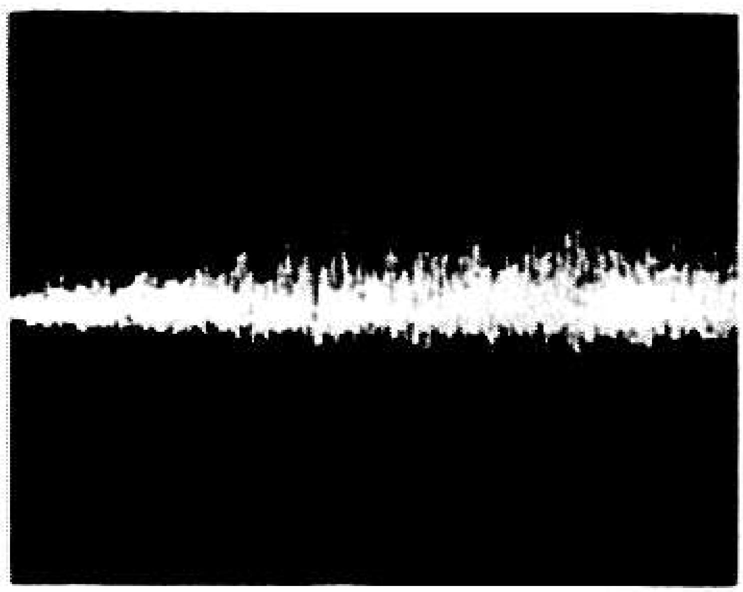
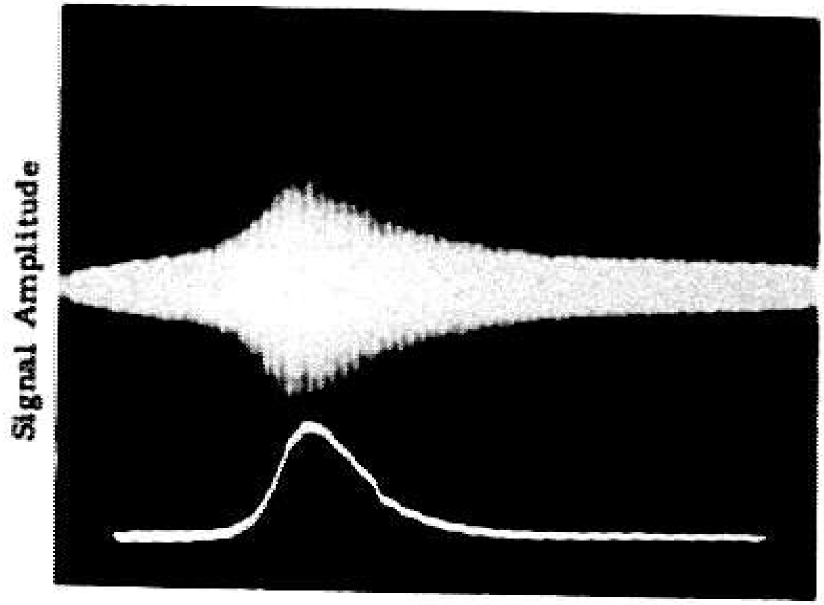


FIGURE 2. SCHEMATIC DIAGRAM OF THE ESSENTIALS FOR INDUCTIVELY SENSING THE BARKHAUSEN EFFECT



10 mv/cm vertical sensitivity
1 msec/cm sweep rate (horizontal)

FIGURE 3. TYPICAL BARKHAUSEN NOISE PULSES



Sweep Rate: 0.05 sec/cm

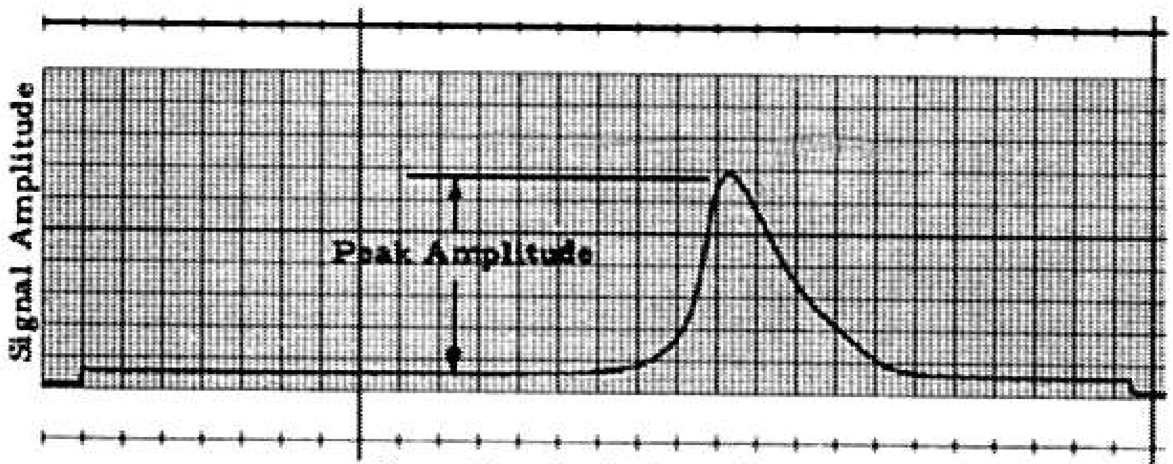


Chart Speed: 125 mm/sec

FIGURE 4. REPRESENTATIVE OSCILLOGRAM OF A BARKHAUSEN NOISE BURST AND ASSOCIATED PROCESSED SIGNAL INCLUDING A STRIP CHART RECORDING

4. EXPERIMENTAL IMPLEMENTATION

4.1 EXPERIMENTAL SCHEME

There were a number of tasks involved in pursuit of this program, some of which were run in parallel. The list of tasks, given below, presents the tasks in a logical sequence without regard to the actual scheduled order of the tasks.

Task 1: The initial task was to determine experimentally the instrumentation parameters for exciting and sensing the Barkhausen activity to provide the best sensitivity. It appeared that the Barkhausen signals from these experiments could be adequately processed utilizing the electronic parameters already incorporated in an existing Southwest Research Institute instrument.

Task 2: Select the points on the railroad wheels at which noise measurements would be made to reasonably map the Barkhausen response over the entire surface of each wheel.

Task 3: Adapt existing Barkhausen noise measurement instrumentation to incorporate the instrumentation parameters determined from Task 1 and the geometrical parameters determined in Task 2. This included the fabrication of special probes to fit the wheel contours at the various measurement locations as well as fixtures for holding the wheel and positioning the probe at each measurement location.

Task 4: Perform calibration experiments to relate the Barkhausen noise measurements to residual stress values in the railroad wheel material.

Task 5: Acquire Barkhausen noise data from each wheel in the program. This included duplicating the data on three wheels after the simulated service at the United States Steel Corporation. At each measurement location the probe was removed from the wheel and replaced five times. The mean value of the five measurements was taken as the true value. At each location Barkhausen noise measurements were acquired in the circumferential direction and in a direction perpendicular to that. This resulted in a total of 1,920 measurements for most wheels.

Task 6: Analyze the Barkhausen stress data and compare these data with the destructively determined stress values obtained by the United States Steel Corporation.

Because of the nature of the round-robin type experiment, the prolonged stop tests performed at USSC, and time consumed in shipping the railroad wheels, the performance of this program was extended over a period of approximately two years.

4.2 TEST SPECIMENS

The railroad wheels utilized in this investigation were of Section B-36, Class A, produced by the Standard Steel Division of the Titanium Metal Corporation of America. Figure 5 illustrates the locations selected for making Barkhausen measurements and the conventions of orientation which were adopted in this study. Figure 6 is a photograph of one of the wheels, illustrating the manner in which it was marked for locating the measurement points. Scribe lines were marked on the wheels with a vibrating etcher and highlighted with paint markings. These scribe lines facilitated repeatably locating the Barkhausen probe within approximately ±0.03 inches by means of alignment fixtures attached to the wheel.

It is important that we understand the physical and metallurgical characteristics of the wheels in order to properly interpret the Barkhausen noise data obtained from them. Therefore, the following discussion describes the wheels metallurgically, the manufacturing processes, and the service conditions of these wheels in the detail deemed pertinent to this investigation. In Table 1 are tabular descriptions furnished by the program monitor for each of the wheels selected for this investigation. The manufacture of the wheels used in this experiment involves the basic processes of rough-forming to shape, contour machining, heat treating, and shot-peening. Of these processes, the last two named are of particular interest to our study. The heat treatment is a rim-treatment designed to "build-in" compressive stresses in the rim of the wheels thereby minimizing the problems of crack propagation and explosive failures. The following heat treatment process was utilized for these wheels:[8]

Austinized: 1550°F (approximately 4.5 hours);
Rim Spray: 2.5 minutes (plate shielded from water spray);
Quench: 3 minutes in water;
Temper: 720°F (approximately 4.5 hours).

After the heat treatment process has been completed, the plate of the wheel is shot-peened per MIL-S-13165B. As applied to the subject railroad wheels, this standard requires that the wheel be peened to an Almen intensity of 0.012A2 to 0.016A2 using S-280 shot to full coverage. Also, the standard stipulates that areas not requiring peening shall be optional unless masking is specified. Full coverage has the definition that doubling the time of expor re will result in an increase in the Almen intensity number by less than 10 percent, which can be established by plotting a saturation intensity curve and assuring that the intensity falls to the right of the knee of the curve.

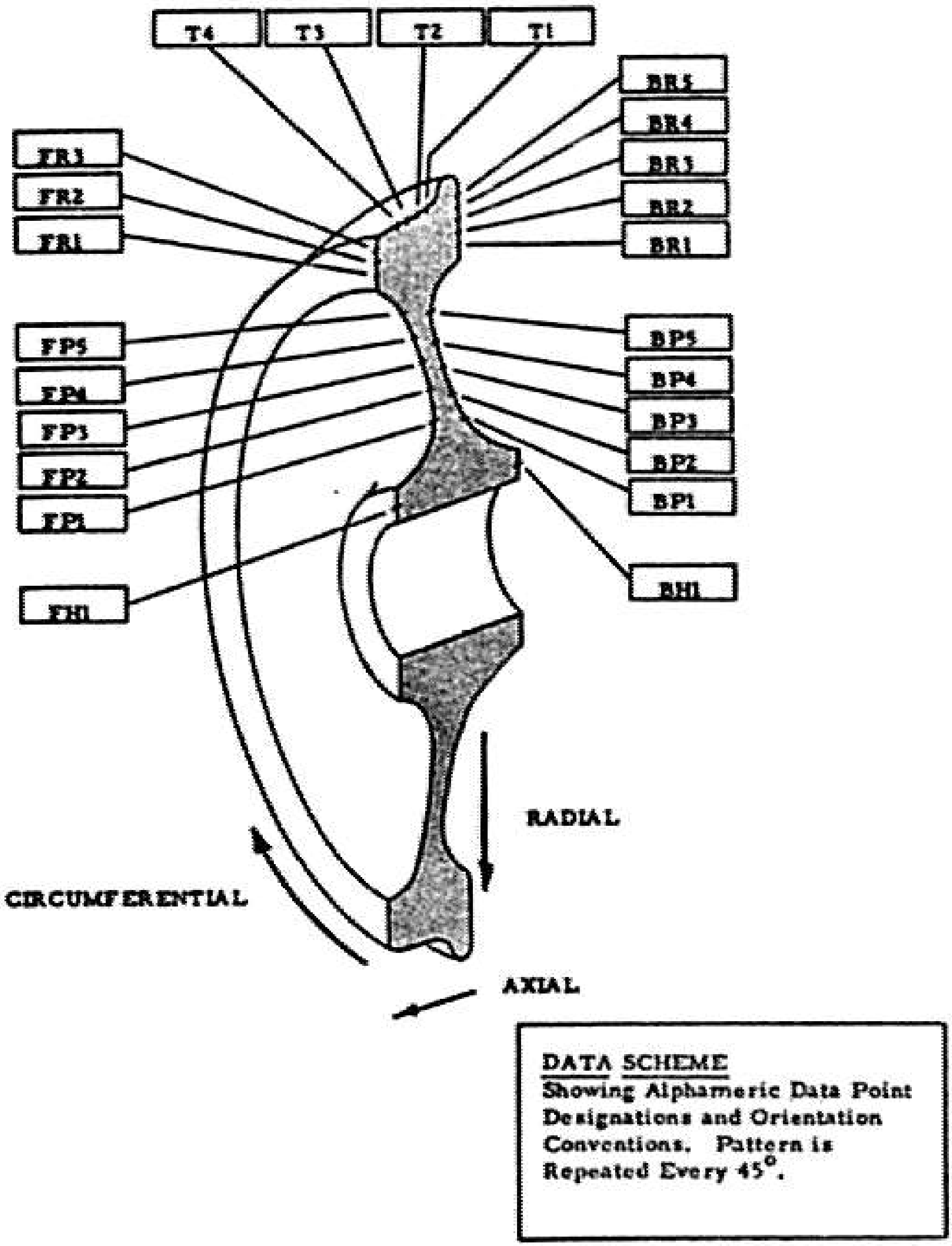


FIGURE 5. MEASUREMENT LOCATIONS AND ORIENTATION CONVENTIONS WITH ASSOCIATED DATA SCHEME DESIGNATIONS

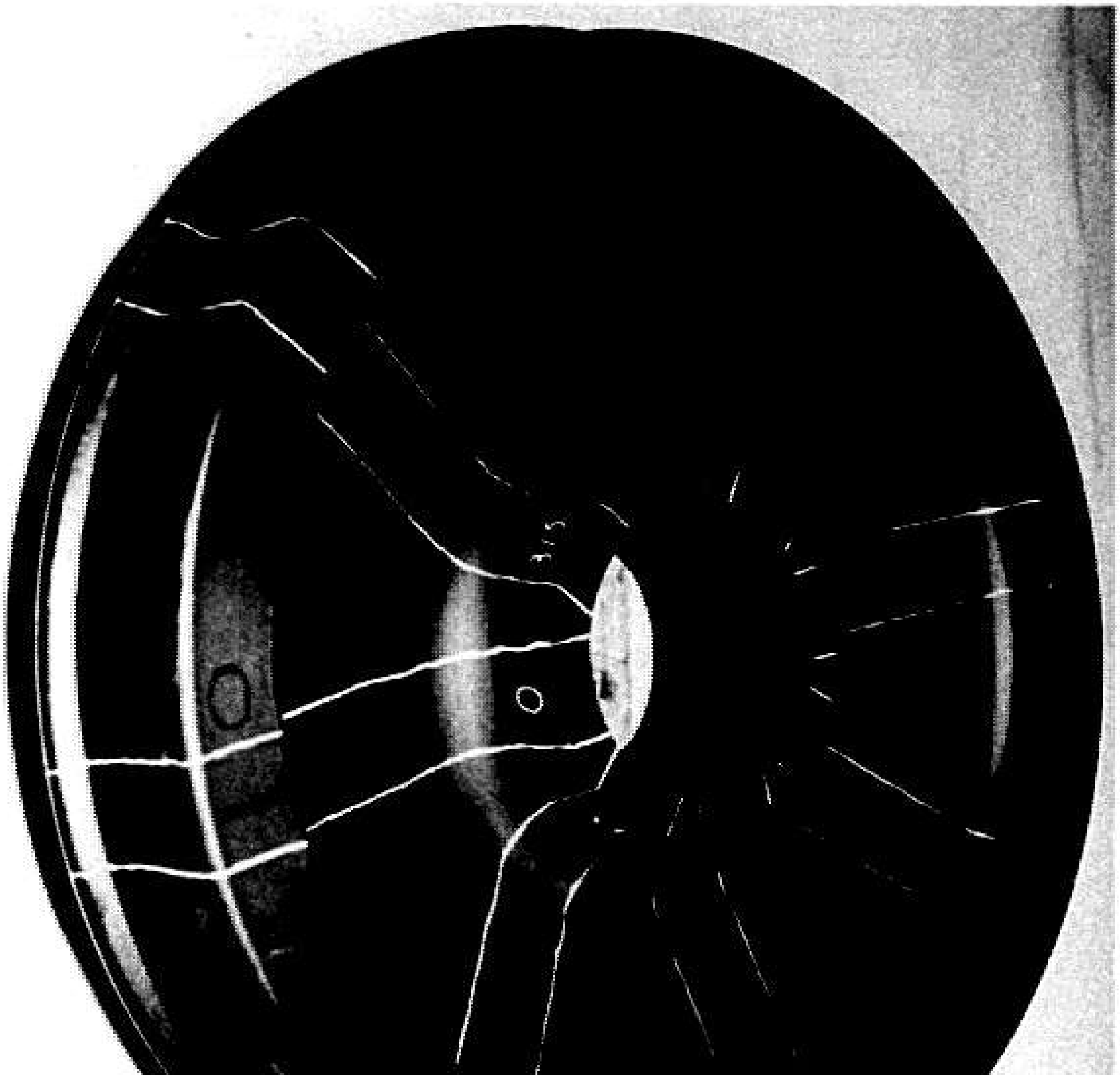


FIGURE 6. PHOTOGRAPH OF A TYPICAL WHEEL WITH MARKINGS OF MEASUREMENT LOCATIONS

TABLE 1.

WHEEL MANUFACTURING DATA(9)

Wrought Steel Wheels, Class A, 36", MW

I.D. No.	1	2	3	4	5	6
MFG. No.	2476A	2472A	2474A	2466A	10190A	10191A
Type	NEW	NEW	NEW	NEW	USED	USED
MFG.	Standard	Standard	Standard	Standard	Standard	Standard
Date MFG.	1/72	1/72	1/72	1/72	1/71	1/71
Tape	233	235	235	233	237	237
AAR SPEC		M-107-70			M-107-67	
Heat No.		K3103			9304	
Chemical Analysis		C 0.41 Si 0.3 P 0.023 Mn 0.78 S 0.34			C 0.39 Si 0.28 P 0.026 Mn 0.71 S 0.04	
BHN		262			262	

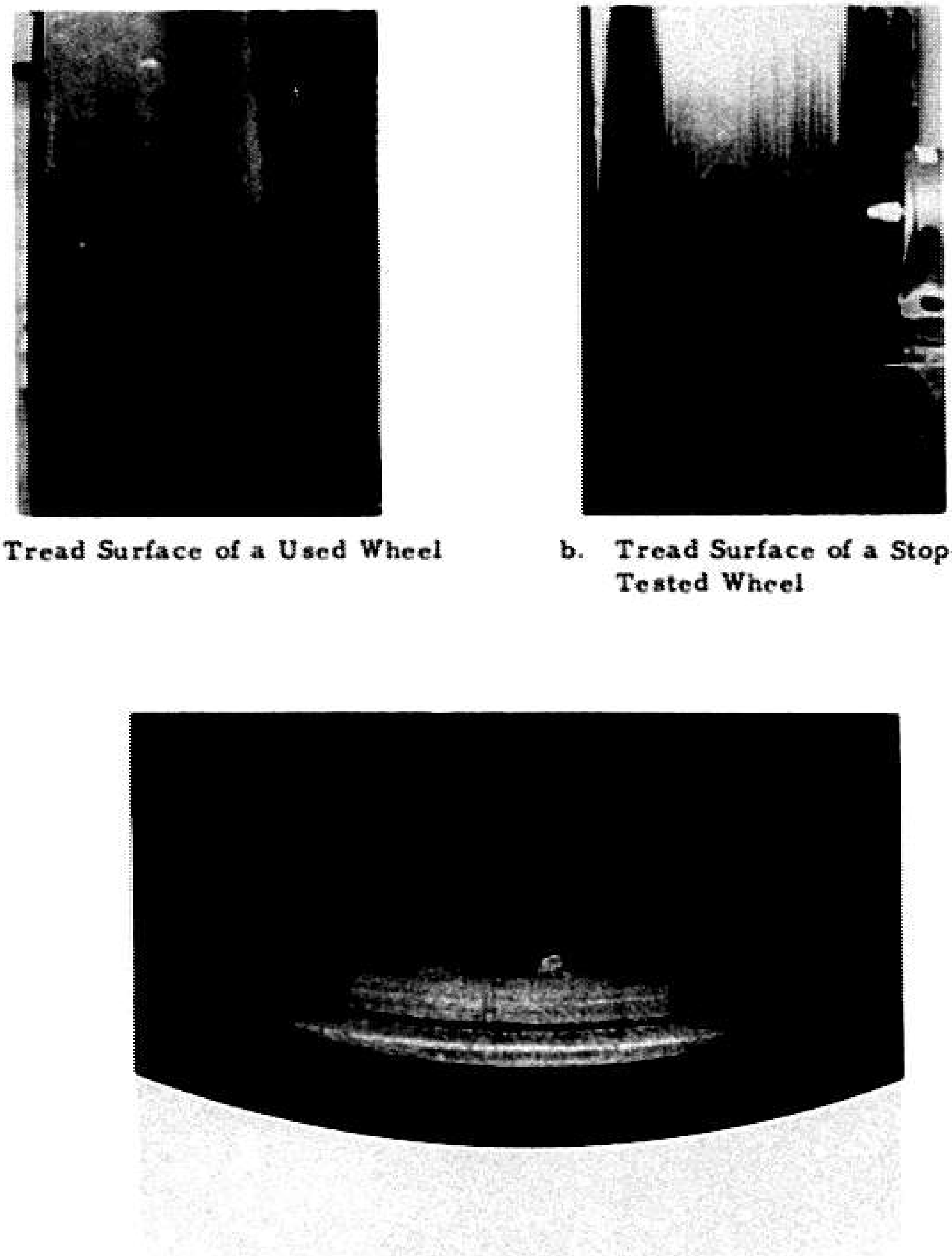
An important factor of this shot-peening procedure to the Barkhausen stress measurement is that only the plate and plate fillets are specified to receive full coverage shot-peening. The sides of the rim, which will be shown to be of considerable importance to the determination of the service condition of a wheel, receive only the uncontrolled scatter from the shot-peening of the plate. The results of this design specification to the Barkhausen stress measurements on the rim will be commented upon later in this report.

As noted in the previous discussion of the Barkhausen phenomenon, the noise measurement is principally from the surface layer of the test article. Thus, it is pertinent that we note the surface material condition for the various areas of each wheel. Figure 7 illustrates some of the major surface finishes from various regions of the specimens, both before and after stop-test. Additionally, Figure 8 illustrates the thermal fatigue crack which existed in wheel No. 6 (10191A) causing its removal from service. The crack was approximately 1.2 inches long and 0.2 inches deep.

Unexpectedly, the first new wheel stop tested on the USSC dynamometer failed to develop any thermal cracks after being subjected to 300 stops (more than three times the number of stops received by the used wheels, one of which had already developed a thermal crack in the tread during service). Therefore, the stop test program conducted by the USSC was revised as shown in Table 2.

4.3 INSTRUMENTATION AND TEST APPARATUS

Southwest Research Institute has developed a number of different equipments based on the Barkhausen noise phenomenon to measure residual or applied stresses in ferromagnetic materials. These equipments have varied from special-purpose laboratory instruments to field portable equipment suitable for use in production quality control. In the railroad wheel program adaptations of existing equipment included: (1) modification of a field useable, portable equipment to a sensitivity equal to the present best laboratory instruments; (2) design and fabrication of a detecting head configuration to meet the special requirements of the railroad wheel inspection. Figure 9 is a photograph of the specially designed hand-held probe used to acquire data from the wheels. The probe has interchangeable magnetic pole tips which facilitate matching the contour of the wheel at various measurement points. In Figure 10, the equipment is shown being used to acquire Barkhausen noise data from a point on the rim of a railroad wheel. The aligning fixtures shown in the figure were used to position the probe repeatably within approximately ± 0.03 inch. Also shown in this figure is the holding device which allowed the operator to rotate the wheel to various measurement locations and lock the wheel in the desired orientation.



a. Tread Surface of a Used Wheel

b. Tread Surface of a Stop-Tested Wheel

c. Rim Surface of a Typical Wheel

FIGURE 7. PHOTOGRAPHS SHOWING WHEEL SURFACE FINISHES OF VARIOUS WHEELS

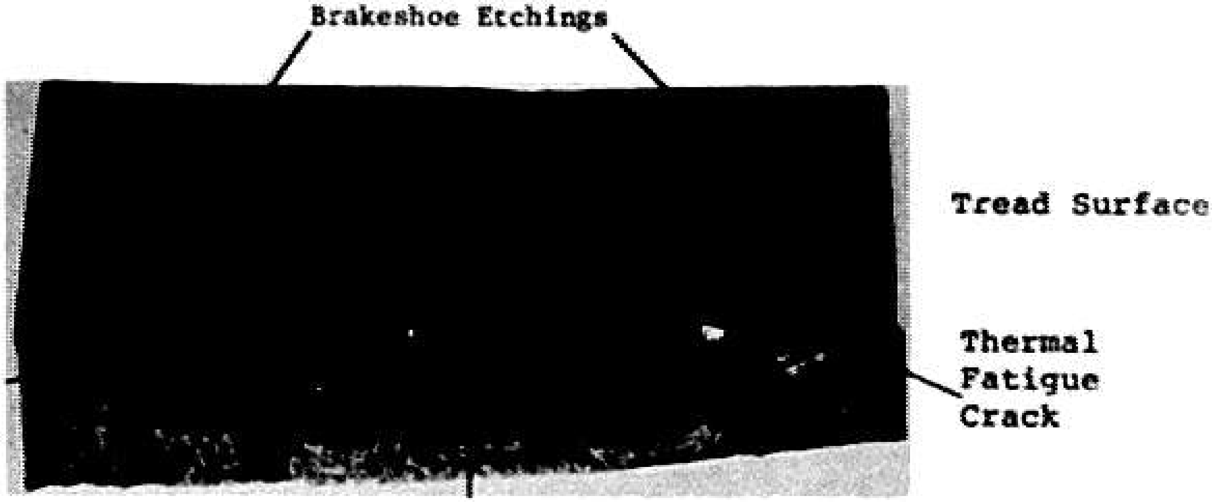
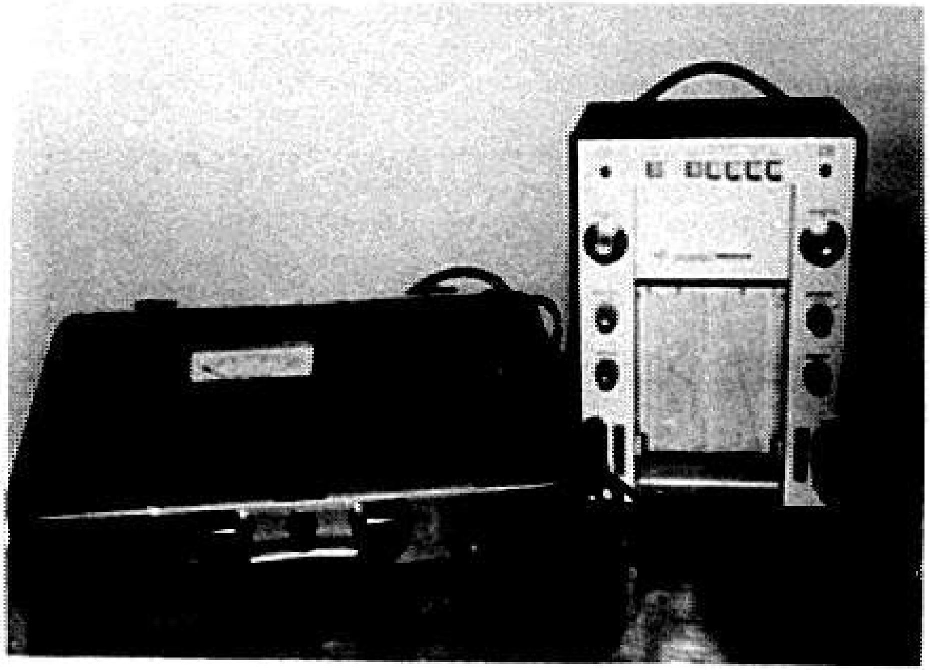


FIGURE 8. THERMAL FATIGUE CRACK IN TREAD SURFACE IN USED WHEEL NO. 5 (10191A)

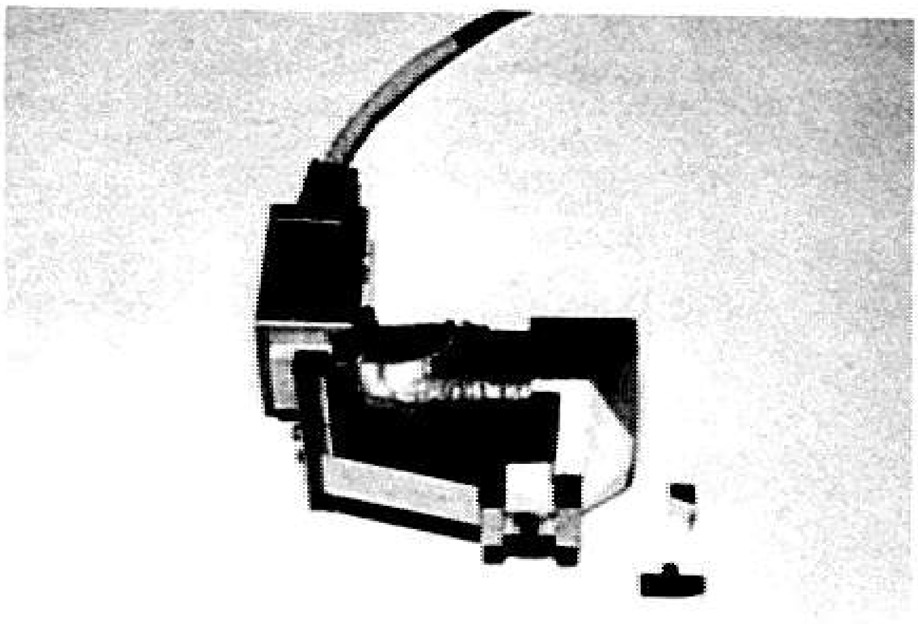
TABLE 2.

BRAKE-TEST PROGRAM AT USSC[10]

Wheel No.	History of Wheel Condition Prior to Residual Stress Testing
1 (2476A)	New wheel subjected to 300 simulated energency brakings from 130 mph.
2 (2474A)	New wheel subjected to 2424 speed-control brakings from 100 mph to 50 mph.
3 (2472A)	New wheel subjected to 120 speed-control brakings from 45 mph to 10 mph, and 110 emergency stops from 130 mph (10 with worn shoes).
4 (2466A)	New wheel in as-produced condition.
5 (10191A)	Used wheel with service life of 100,734 miles in which one thermal crack developed during service.
6 (10190A)	Used wheel (mate to Wheel No. 5) exhibiting no thermal cracks.



a. Electronic Signal Processor and Chart Recorder



b. Barkhausen Noise Probe

FIGURE 9. BARKHAUSEN NOISE MEASUREMENT INSTRUMENTATION

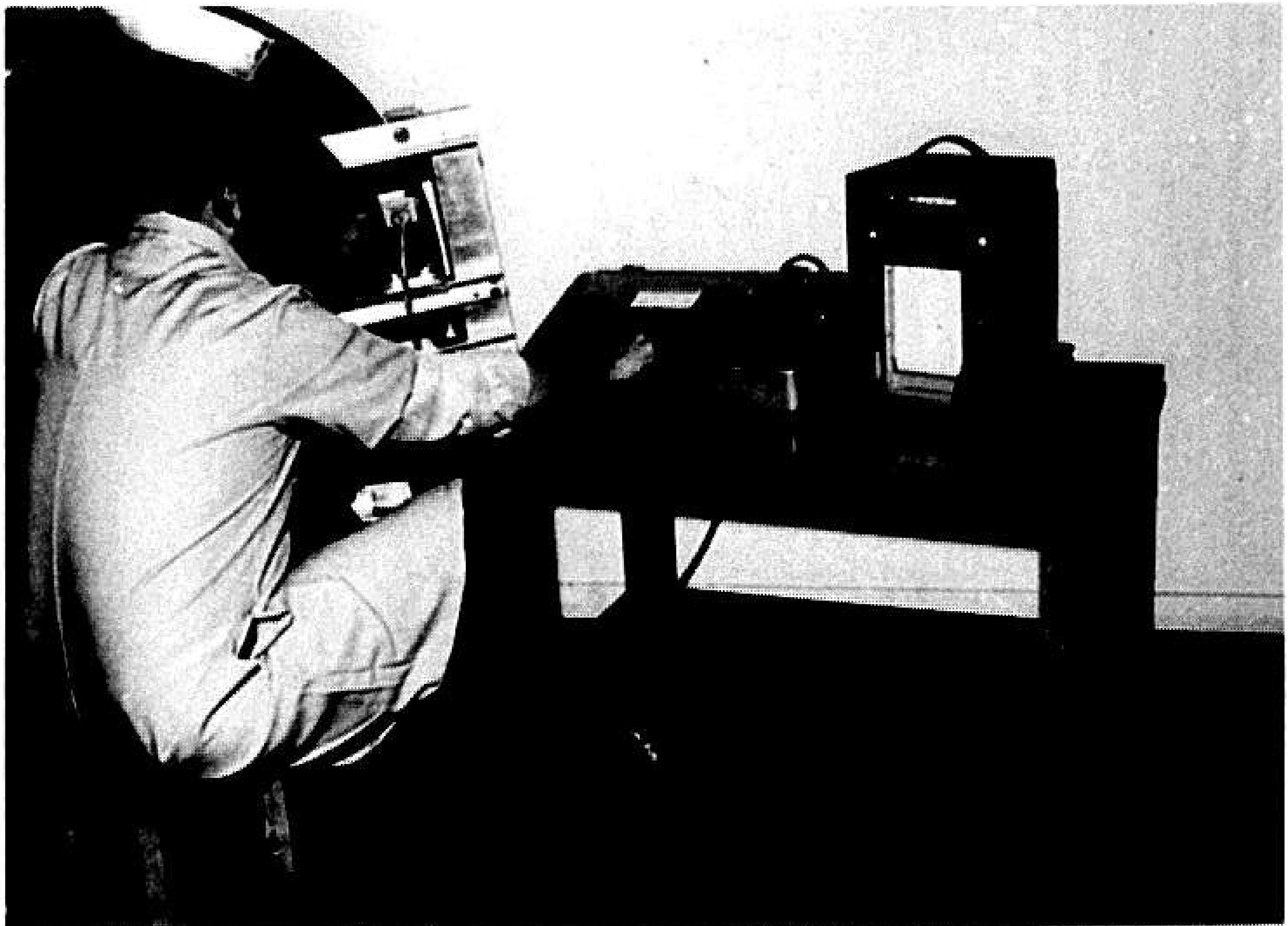


FIGURE 10. ACQUISITION OF BARKHAUSEN DATA ON RIM OF A RAILROAD WHEEL

5. EXPERIMENTAL RESULTS AND ANALYSIS

5.1 PRELIMINARY INVESTIGATIONS

The initial phase of this program involved the determination of values for the Barkhausen instrumentation variables which relate to the excitation of the Barkhausen activity within the inspection part and to sensing that activity. From past experience, it was considered that there were two factors which should primarily be considered. First to be evaluated was the strength of the magnetic field used to excite the Barkhausen activity. Secondly, the size of the induction coil used to sense the Barkhausen activity was evaluated along with a very brief investigation to determine the allowable liftoff (spacing between the induction coil and the inspection part). These investigations were made using existing laboratory hardware, an existing portable Barkhausen noise stress measurement unit fabricated by Southwest Research Institute, and various existing Barkhausen probes having different size induction coils.

At this point in the program, no specimens had been received on which to make Barkhausen noise measurements. Therefore, measurements were made on a fractured railroad wheel already at Southwest Research Institute, a 3-foot section of new rail, a 3-foot section of used rail, and two wheels which were obtained on loan from the Southern Pacific Railroad Company. The measurements made on these specimens were exploratory and interpretation of the data was based, primarily, upon past experience with the probes and equipments. The following decisions resulted from this effort:

(1) A relatively large probe coil size was selected because such a coil senses more of the Barkhausen activity, thereby requiring less amplification, and because such a probe is less sensitive to positioning on the surface of the specimen.

(2) The maximum magnetizing current available from an existing Barkhausen instrument was used to excite the Barkhausen activity because the large thickness of the railroad wheels tends to reduce the magnetic flux density in the region of the surface material near the induction sensing coil, and thereby tends to decrease the amplitude of the Barkhausen signature.

(3) It was decided that no magnetic feedback would be employed in the instrumentation. "Magnetic feedback" refers to monitoring the magnetic field component tangent to the surface of the measurement point and using this information in a feedback control loop to alter the current to the magnetizing coil in a predetermined pattern. The "magnetic feedback" technique was not incorporated in this program because the

required instrumentation is complex and experience with the technique is very limited.

From these decisions, design specifications were determined from which probes were fabricated, and modifications were made to an existing Barkhausen instrument which was used to acquire all the Barkhausen noise data in the remainder of the program.

5.2 CALIBRATION DATA

To relate the Barkhausen noise measurement to actual levels of stress in the inspected part, a calibration curve must be established from material similar to that part. Generally, in programs such as this, a calibration curve is obtained from a simple cantilever beam specimen that has been fabricated from material similar to the test part. This was the starting point for the calibration experiment on this program. Initially, a curve is established which relates the Barkhausen noise measurement as a function of the calculated stress applied to cantilever beam specimens. Figure 11 illustrates such a curve obtained from one sample of railroad wheel material. The details for establishing this curve are contained in Appendix C. It will be noted that the Barkhausen stress indication varies significantly with stress. Compressive stresses correspond to low values of the measured Barkhausen noise, whereas tensile stresses correspond to higher values of the Barkhausen noise. Also, it should be noted that the Barkhausen noise measurement is most sensitive to stress changes within the range of approximately -50 to +40 ksi. Beyond this region, the Barkhausen stress measurement varies only slightly with stress.

In Figure 11, Barkhausen noise measurements decrease to values on the order of 4 or 5 units for high compression, whereas on the railroad wheels noise measurements as low as 1 or 2 units in the plate regions and values less than 1 on the tread of used wheels are obtained. This apparent discrepancy led to the design of a calibration experiment involving much thicker specimens, and eventually, to an extensive calibration effort. Listed sequentially below are all the experimental efforts to obtain a valid calibration curve and to better understand the complexities of the railroad wheel material. Data from these experiments are included in Appendix C along with a brief discussion.

5.3 CALIBRATION EXPERIMENTS

(1) Cantilever Beam Experiment: thick beams (1" thick) shot-peened on one side and ground on the opposite side with stock removal performed incrementally until the beam was reduced to approximately 1/8" thick.

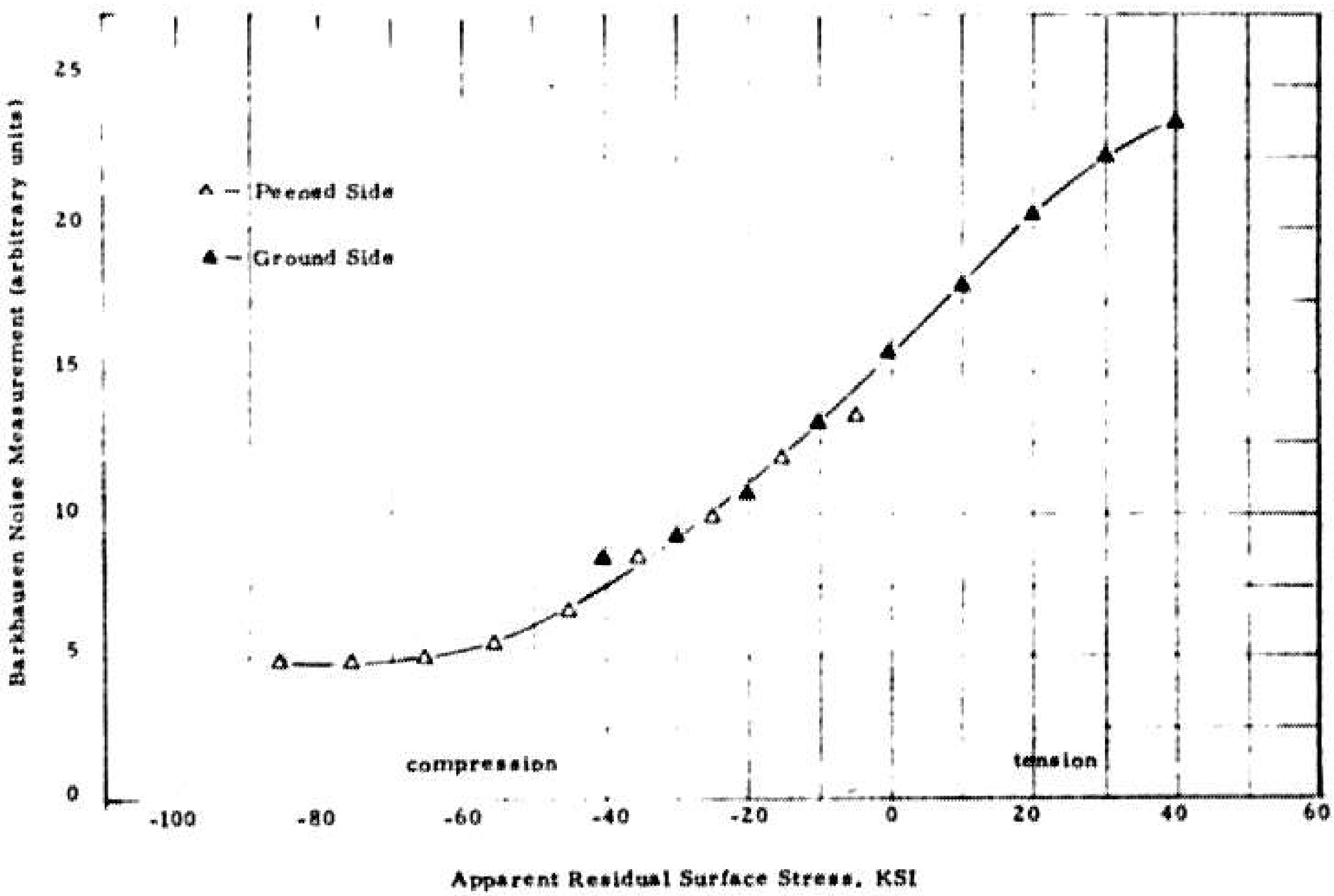


FIGURE 11. BARKHAUSEN NOISE CALIBRATION CURVE FROM SPECIMEN SS-1f
(See Appendix C for description of calibration specimen.)

(2) Cantilever Beam Experiment: 1" thick beam shot-peened on one side and ground on the opposite side.

(3) Uniaxial Compression Test: 1-1/4" thick specimens ground on one side and shot-peened on the opposite side, placed in uniaxial compression.

(4) X-Ray Diffraction: specimen shot-peened on one side and ground on the opposite side, approximately 1-1/4" thick.

(5) X-Ray Diffraction: 1/8" thick ground and stress relieved specimen.

(6) Strain Relaxation: holes surrounded by a strain gage rosette were drilled in a railroad wheel in a manner facilitating stress relief and calculation of the surface stress for each location.

(7) Shot-Peened Samples: five samples of railroad wheel material were shot-peened to different Almen intensity levels.

5.4 COMMENTS ON DATA INTERPRETATION

It is important to review the implications from the calibration experiments before entering into the presentation and analysis of the Barkhausen noise data from the railroad wheels. There are at least two results from the calibration experiments which deserve discussion. This discussion will simultaneously illustrate some of the complexities associated with Barkhausen noise measurements in the railroad wheel material and help to clarify the apparent discrepancies associated with the data to be presented in the next section of this report.

The results of the shot-peening intensity experiment discussed in Appendix C indicate that the amplitude of the Barkhausen noise measurement decreases only very slightly with increased peening intensity (in the peening range specified for the manufacturer of railroad wheels inspected in this program). Thus, one might expect all shot-peened regions of a new wheel to exhibit Barkhausen noise measurements of approximately equal amplitudes. Additionally, the lowest Barkhausen noise measurement obtained in all the calibration experiments from shot-peened regions was on the order of 5 units. Examination of the Barkhausen noise measurement made on the new wheels before brake testing, indicates that the majority of the data from the plate regions lie in the range from 1 to 6 units while the data from the rim usually lie within the range of 4 to 12 units. Thus, it has been found that there is neither a uniform Barkhausen noise amplitude from different shot-peened regions nor is the Barkhausen noise amplitude always greater than 5 units as would be expected from examination of the calibration curve shown in Figure 11. The following analogy is proposed as a simplified explanation for this apparent discrepancy.

In the manufacture of the railroad wheels utilized in this program, the rims are placed in compression by a quenching process (previously outlined in the description of test specimens). This same procedure also places the plate in tension. Onto these stress distributions are imposed the compressive stresses generated by the subsequent shot-peening process. Thus, in the rim the material is compressively stressed at the surface with the underlying material also in compression while in the plate, the surface layer is in compression with the underlying material in tension. Steel has a magnetic permeability which is sensitive to the stress within the material such that the permeability is increased in regions which are highly tensioned. Assuming that the shot-peening intensity is nearly uniform over both the plate and rim, we would expect that in the plate more of the excitation flux would be drawn into the underlying tensile layer and away from the surface layer, thereby reducing the Barkhausen activity sensed with an induction coil sensor as compared to similarly stressed material with an underlying compressive layer.

If the above hypothesis is valid, it is possible that instrumentation incorporating "magnetic feedback" would render significantly improved stress determinations on the railroad wheels. The term "magnetic feedback" implies the addition of a magnetic sensor placed near the induction coil sensor of the Barkhausen probe such that it is sensitive to the tangential component of a magnetic field very near the surface of the specimen. The flux measured by the auxiliary sensor is indicative of the magnetization of the near-surface layer of the specimen material. A signal from this auxiliary sensor can be utilized in the electronic processor to magnetically cycle the near-surface material in a predetermined, uniform manner independent of the condition of the subsurface material.

It must be emphasized that although insufficient control of the excitation field may have decreased the accuracy of a stress determination made from the Barkhausen noise measurements, it is still possible to make an evaluation of the technique for measuring stresses in railroad wheels, as will be shown in the next section of this report.

5.5 WHEEL DATA AND ANALYSIS

As was previously indicated, Barkhausen noise measurements were obtained from each of 24 geometrically unique locations on the wheel profile. This pattern of location was repeated along each of 8 radii, equally spaced around the wheel. Since measurements were also obtained in two directions, a total of 1,920 measurements were made on each wheel. The data obtained are presented in Appendix A, as a series of computer-generated graphs showing the total range, mean value, and standard deviations for the noise measurement obtained from each series of locations. Additionally, the results of the destructive stress determinations made by the U. S. Steel Corporation and forwarded to Southwest Research Institute are reproduced in Appendix B for convenient reference. To facilitate comparison of these data, Table 3 contains both the circumferential and radial Barkhausen noise measurements and the destructively determined stress values for the rim and tread surfaces at 0° and 180° locations. In this table, the Barkhausen noise measurements are associated with the destructively determined stress values obtained at approximately corresponding locations on the wheel.

It is emphasized that when comparing the data of Table 3, allowances must be made for differences inherent to each of the two measurement techniques. One particular example of these differences is associated with the size of the material sample from which a stress determination is made. The Barkhausen activity to which the probe responds is essentially a near-surface phenomenon. The inductive coil which senses the Barkhausen activity covers an area of 0.1 inch x 0.1 inch projected onto the surface of the test piece. In contrast, the strain relaxation method utilized by the U. S. Steel Corporation averaged the distribution of tangential residual stresses in the outer 1-inch thick layer of material on the tread and rim faces. Single element electrical resistance foil strain gages with a 1/8-inch gage length were cemented to the wheel rim surfaces after which 1-inch square by 2-inch long sections with a strain gage on one surface were saw cut from the wheel and final measurements were made from the strain gages. The relaxation strains measured by the gages were utilized to calculate the residual stress values. A similar technique was utilized in the plate regions. Consequently, it may be presumed that the Barkhausen noise measurement technique is significantly more sensitive to stress gradients than is the stress relaxation technique. Also, one would expect the Barkhausen noise measurement technique to be influenced to a greater degree by any surface treatments to a wheel or to service conditions which might alter the surface of a wheel.

An overall appraisal of the data in Table 3 discloses qualitative consistency in the Barkhausen data base. Those regions of the wheel in which the surface material experienced cold working; namely, the shot-peened regions and the tread surface of the used wheels exhibited low Barkhausen noise indications, indicative of the compressive stresses introduced into the material by cold working. The tread regions of the wheels which experienced simulated service exhibited Barkhausen noise

TABLE 3.

COMPARISON OF BARKHAUSEN DATA AND USSC STRESS VALUES

Wheel Description	[illegible]
Wheel No. 1 [illegible]	[illegible]
Wheel No. 2 [illegible]	[illegible]
Wheel No. 3 [illegible]	[illegible]
Wheel No. 4 [illegible]	[illegible]
Wheel No. 5 [illegible]	[illegible]
Wheel No. 6 [illegible]	[illegible]

* [illegible]

measurements which were generally of much higher magnitude. This is consistent with the development of tensile stresses from thermal cycling resulting from the brake stop testing in the absence of rolling against a rail. Although the wheel sample for this program was rather small, containing only two used wheels of limited service life and several wheels with simulated service, the Barkhausen noise measurements from these wheels covers a broad range from very low values obtained in the plate regions up to an indication of 22.7 units corresponding to a very high tensile stress (position T1, Wheel No. 1). This fact is indicative that the Barkhausen noise measurement technique is indeed sensitive to the full range of stresses as indicated by the calibration curve in Figure 11 and establishes the capability of the technique for detecting conditions of high surface tensile stress.

It is observed that Barkhausen noise measurements obtained from the plate region of the wheel are generally very low and exhibit little change with simulated service. This fact can be shown to be consistent with the state of the wheel as follows. A newly manufactured wheel is heat treated and subsequently shot-peened such that the core of the plate is in high tension with the surface layers in compression. Barkhausen noise measurements made on the plate of such a new wheel are low in magnitude, indicative of the compressive surface stresses. The changes which are induced by service operation of such a wheel presumably would cause the core of the plate to become less tensile while the surface layers of the plate would become more compressive. Barkhausen noise measurements repeated on such a used wheel after service would again exhibit readings of low magnitude in the plate showing little change. This is consistent with the shape of the calibration curve as shown in Figure 11, since the readings would be in a region of the curve with little slope.

As might be expected, the greatest changes in the Barkhausen noise measurements before and after simulated service are observed in measurements made on the tread surfaces of the wheels which experience the greatest mechanical and thermal working. The USSC residual stress measurements made on wheel No. 4 indicate that the tread stresses may be expected to be on the order of 50 ksi compression for a new wheel while measurements similarly made on wheel Nos. 1, 2, and 3 indicate that after simulated service the stress in the tread generally has increased on the order of 120 ksi or more toward tension. The change in the Barkhausen noise measurements before and after service for wheels Nos. 1 and 3 are observed to frequently be on the order of 10 units in the tread region. However, for wheel No. 2, the changes are much smaller and in some instances, the indication is in the direction opposite to that anticipated. We can only surmise that the different type of brake application for wheel No. 2 has resulted in a significantly different surface stress condition for that wheel which is subsequently reflected in the Barkhausen noise measurements, but not in the stress determinations made by the strain relaxation method which is more sensitive to material lying deeper in the tread.

Besides the differences inherent to each of the measurement techniques for which data are tabulated in Table 3, there are other factors for apparent discrepancies in those data. These are:

(1) The locations at which the Barkhausen noise measurements were made may not be in exact correspondence to the locations at which the destructive stress determinations were made.

(2) Lack of control of the rate of change of the magnetic field in the vicinity of the induction coil sensor may have allowed variations in the noise measurement which, to a degree, makes relating data from different regions of the wheel to be inexact.

(3) Other real differences may exist in the Barkhausen phenomenon due to unknown or uncontrolled material variation from wheel to wheel.

(4) Real errors may exist in either the Barkhausen noise data or the destructively determined stress values.

Much attention was given to the identification of a subset of the Barkhausen noise data which could be readily related to the service condition of a wheel. Data from the plate region of the wheel appeared not to change significantly with service on the wheel; therefore, it was discounted. The tread regions were similarly discounted since the material in these regions continually experiences wear, rolling, and brake applications which tend to alter the surface material making interpretation of Barkhausen noise data from this region unreliable. However, the data obtained from the rim surfaces appears to exhibit significant changes, especially in the regions nearest the tread. One might expect data from such rim extremities to be closely related to changes in the hoop stresses, and in fact the data from the back rim surface appears to vary in a manner resembling the stress changes to be expected with increased service of a wheel. The following paragraphs briefly demonstrate a treatment of these data which might possibly be used to predict the serviceability of a railroad wheel. However, it is cautioned that the validity of the treatment can only be substantiated by an extension of the data base.

Increased service life on a wheel tends to decrease the built-in compressive stresses in the rim; one would therefore expect the

Barkhausen readings to increase with service life. Such stress changes would be expected to be greatest at locations nearest the tread of the wheel, that is, the portion of the wheel which is nearest the material most affected by normal service operations. Accordingly, the stress gradient on the back rim near the tread is of interest. The difference between the Barkhausen stress indication obtained from positions BR5 and BR4, respectively, is directly related to the stress gradient of interest. Table 4 tabulates these data and orders the wheels according to the increased magnitude of the stress gradient indicated by the Barkhausen noise measurements. Also tabulated are the number of stops experienced by each wheel. One notes that the resulting order of the wheels corresponds to the increased number of hard stops. Although this result is indeed encouraging, it fails to distinguish the two cracked wheels and it seems to be unresponsive to service conditions other than hard stops.

To examine the validity of this approach to the data analysis, a similar tabulation is made in Table 5, utilizing the results of the U. S. Steel destructive stress determinations. It should be noted that in Table 5 the two cracked wheels are distinguished by their occurrence at the extreme end of the table. Also, the wheels seem to be ordered generally according to their overall service life experience. Better control of the magnetic field used to excite Barkhausen activity in the railroad wheel material might have resulted in better correspondence of the data as presented in Tables 4 and 5.

It should be noted that the stress gradient indicated by the Barkhausen noise measurements made near the tread on the front rim surface of the wheel tends to be opposite those corresponding gradients on the back rim face. This suggests a slight twisting of the rim. However, no dimensional measurements were made in the present experiment to test this hypothesis.

TABLE 4.

COMPARISON OF BACK RIM STRESS GRADIENTS
FROM BARKHAUSEN DATA

Wheel No.	Condition	No. Hard Stops	No. Control Brakings	Difference in Barkhausen Noise Average Indications at BR4-BR5
3 (2472A)	New	0	0	-3.2
2 (2474A)	New	0	0	-1.2
4 (2466A)	New	0	0	0
2 (2474A)	* Cycled (Cracked)	0	2424	0
1 (2476A)	New	0	0	+0.8
6 (10190A)	Used	85	?	+1.6
5 (10191A)	Used (Cracked)	85	?	+1.6
3 (2472A)	Cycled	110	120	+2.0
1 (2476A)	Cycled	300	0	+2.8

* This wheel cracked at two locations which had been drilled for the installation of thermocouples.

TABLE 5.

COMPARISON OF BACK RIM STRESS GRADIENTS FROM USSC DATA

Wheel No.	Condition	No. Hard Stops	No. Control Brakings	USS Stress Averages (ksi)		
				Near BR4	Near BR5	Difference
4 (2466A)	New	0	0	-56.2	-53.8	+ 2.4
7 (10190A)	Used	85	?	- 9.7	+47.9	+57.5
1 (2476A)	Cycled	100	0	-19.8	+33.8	+58.5
3 (2472A)	Cycled	110	120	+10.8	+60.7	+71.5
6 (10191A)	Used(Cracked)*	85	?	-39.5	+47.9	+87.4
2 (2474A)	Cycled(Cracked)	0	2424	-37.0	+62.4	+99.4

*This wheel cracked at two locations which had been drilled for the installation of thermocouples.

6. CONCLUSIONS AND RECOMMENDATIONS

As a result of the investigations conducted:

1. It has been determined that the Barkhausen phenomenon is sufficiently strong in the railroad wheel material to yield Barkhausen stress indications of adequate sensitivity and magnitude for possible utilization as a good stress indicator. Circumferential values ranged from approximately 0.6 (greater than 50 ksi compression) on the tread of a used wheel to 22.7 (greater than 50 ksi tension) on the tread of a wheel after repeated simulated stops.

2. It has been demonstrated that Barkhausen stress measurements can be made on these wheels with excellent repeatability utilizing simple probe positioning devices and associated instrumentation suggesting that a field portable equipment is indeed feasible. No preparation of the measurement locations are required except for removal of excessive oil and dirt build-up.

3. Even though significant Barkhausen noise variations are encountered from wheel to wheel and at different locations on each wheel, a qualitative appraisal indicates reasonable agreement with actual wheel stress conditions existing in the near-surface regions (as inferred from the manufacturing and processing procedures, wheel service conditions, and the data from USSC). Comparison of residual stress by the Barkhausen technique and by a destructive method indicated significant differences since the Barkhausen are surface measurements and residual stress measurements were from three-dimensional wheel segments.

4. The back rim surface nearest the tread has been, tentatively, identified as a region which may be utilized in determining the service condition of a wheel (see Table 4). However, a more extensive data base is required to establish whether this or other regions would provide the best measurement locations. Furthermore, the possibility of using one or more measurement locations near the rim and a measurement direction (perhaps radial) where stress changes only slightly with service as a "built-in-reference" should be considered.

5. Although no X-ray diffraction measurements were made on wheels during this program the extensive X-ray diffraction data, in conjunction with the wheel fractures and fracture mechanics analysis of reference 21 provide strong evidence that residual surface stress measurements made on the front side rim of wheels are a promising method of forecasting wheel life.

6. Since no wheel fractures were produced the results could not provide a basis for determining at what level of residual stress or Barkhausen signature a wheel should be judged to be unsafe for service.

7. The results from these preliminary experiments were not conclusive enough to warrant immediate development of Barkhausen equipment for the routine inspection of wheels.

The following recommendations are made:

1. It is recommended that the present data base be extended to a significantly larger number of wheels, perhaps several hundred, to facilitate relating the Barkhausen surface stress levels to the remaining serviceability of the wheels. Future programs to extend the data base should include wheels covering a much broader range of service life. It is possible that such data could be accumulated at a major overhaul facility.

2. It is further strongly recommended that future efforts incorporate magnetic feedback features in the Barkhausen instrumentation to minimize variations caused by measurement region geometry, material permeability gradients, and shot-peening.

APPENDIX A

BARKHAUSEN NOISE DATA

The Barkhausen noise data acquired in this program are presented here in a series of computer generated graphs. The measurement locations are shown in Figure A-1 which indicate the alpha-numeric designations for each location along with the corresponding numeric code utilized in the computer plots.

At each measurement location, five Barkhausen noise measurements were made in a circumferential direction. The average value for these five measurements was taken as the true Barkhausen noise measurement for the location. A similar procedure was followed for measurements made in a direction perpendicular to the circumferential direction. The repeatability of the Barkhausen noise measurement was usually within 5 percent of the average value for the five measurements made at each location.

A computer program was devised to average the five Barkhausen noise measurements from each location, and group the data from symmetrical locations from different wheel radii in bar graphs as shown in Figures A-2 through A-19. The series of asterisks associated with a particular location represent the range of Barkhausen noise measurement acquired along the different radii. The zero associated with each series of asterisks denotes the mean value for the particular set of data, and the "greater than" and "lesser than" symbols indicate the standard deviations from the mean value.

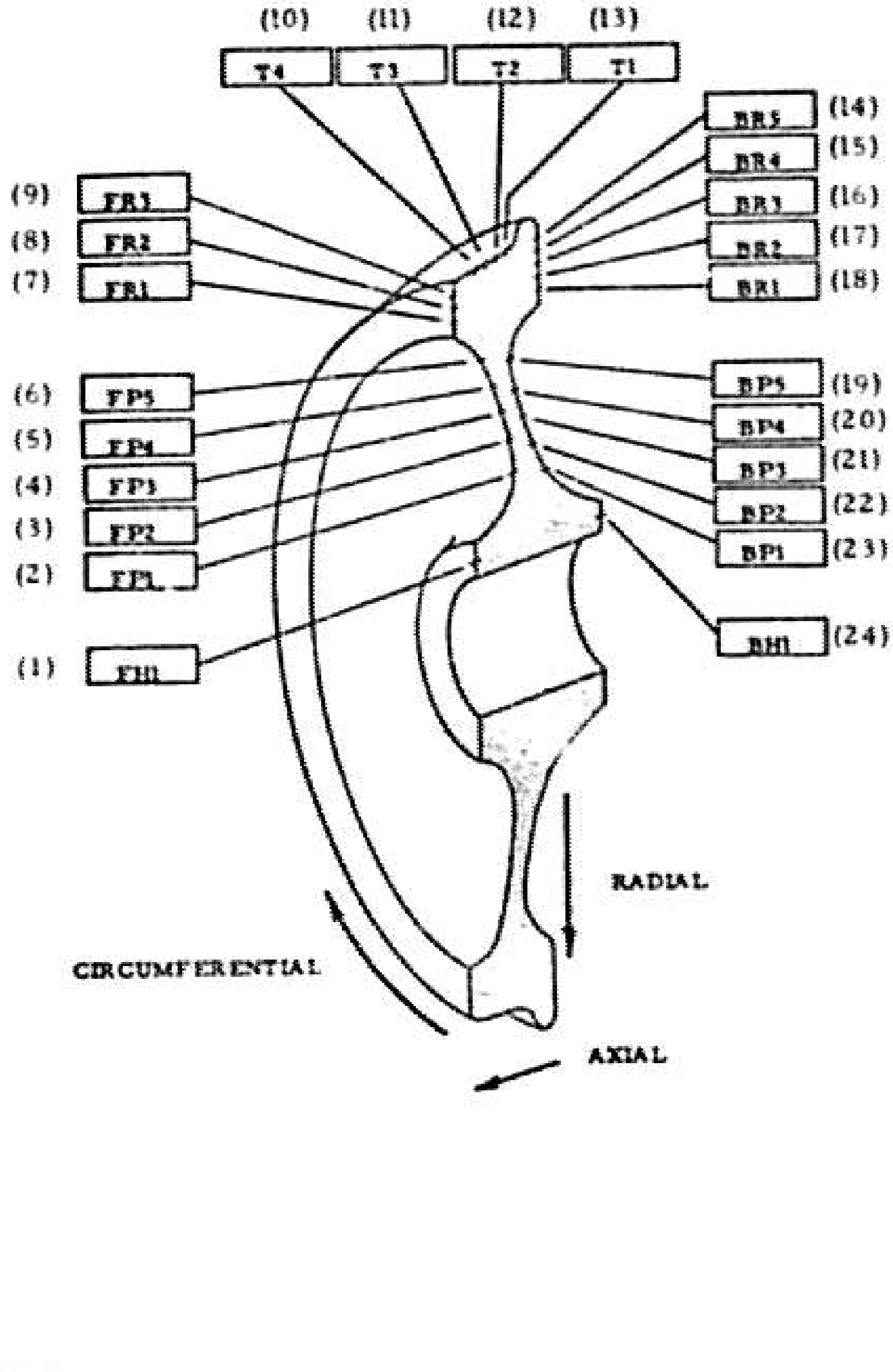


FIGURE A-1. MEASUREMENT LOCATION DESIGNATIONS FOR COMPUTER GRAPHS

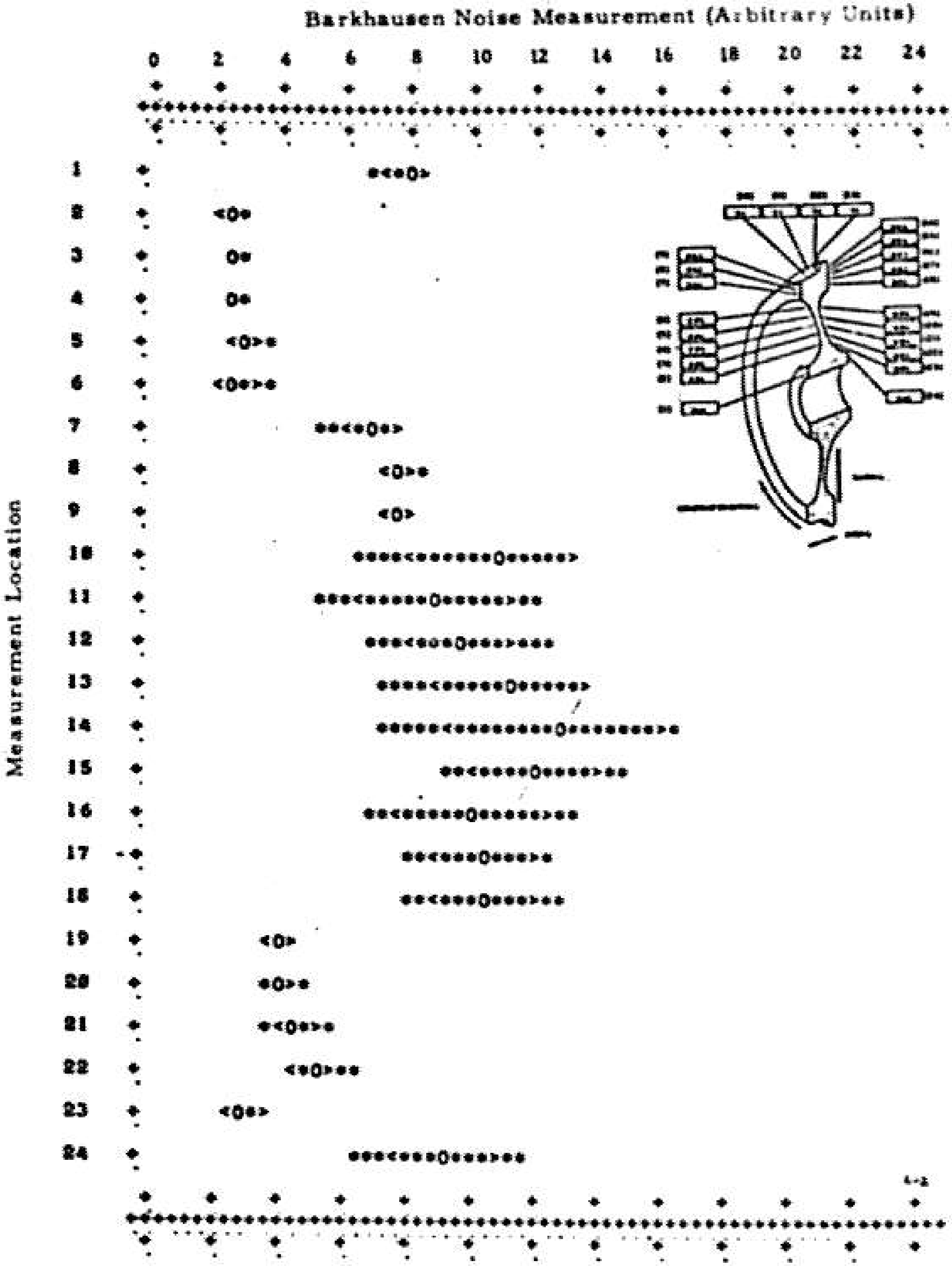


FIGURE A-2. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 1 (2476A), NEW

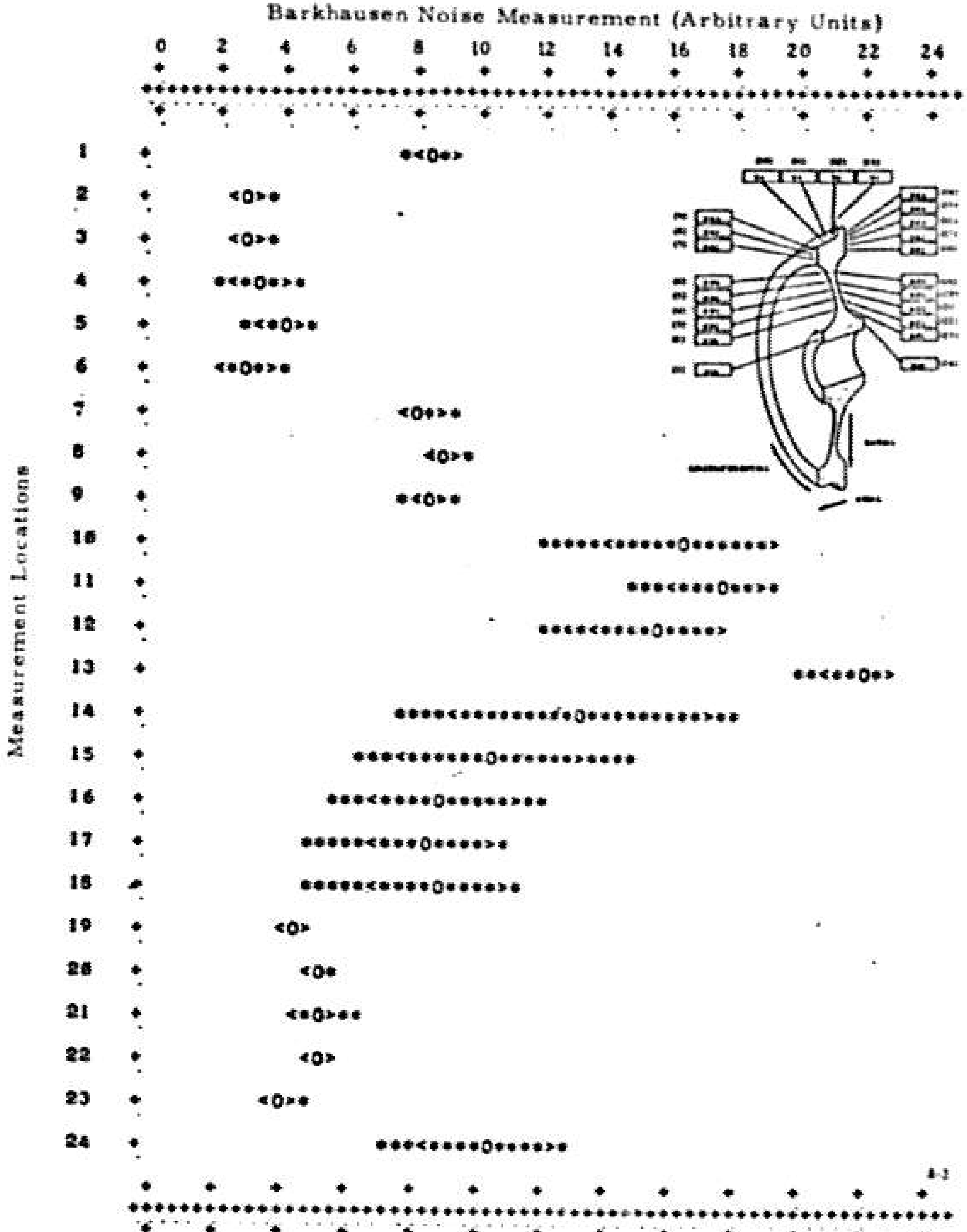


FIGURE A-3. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 1 (2476A), BRAKE TESTED

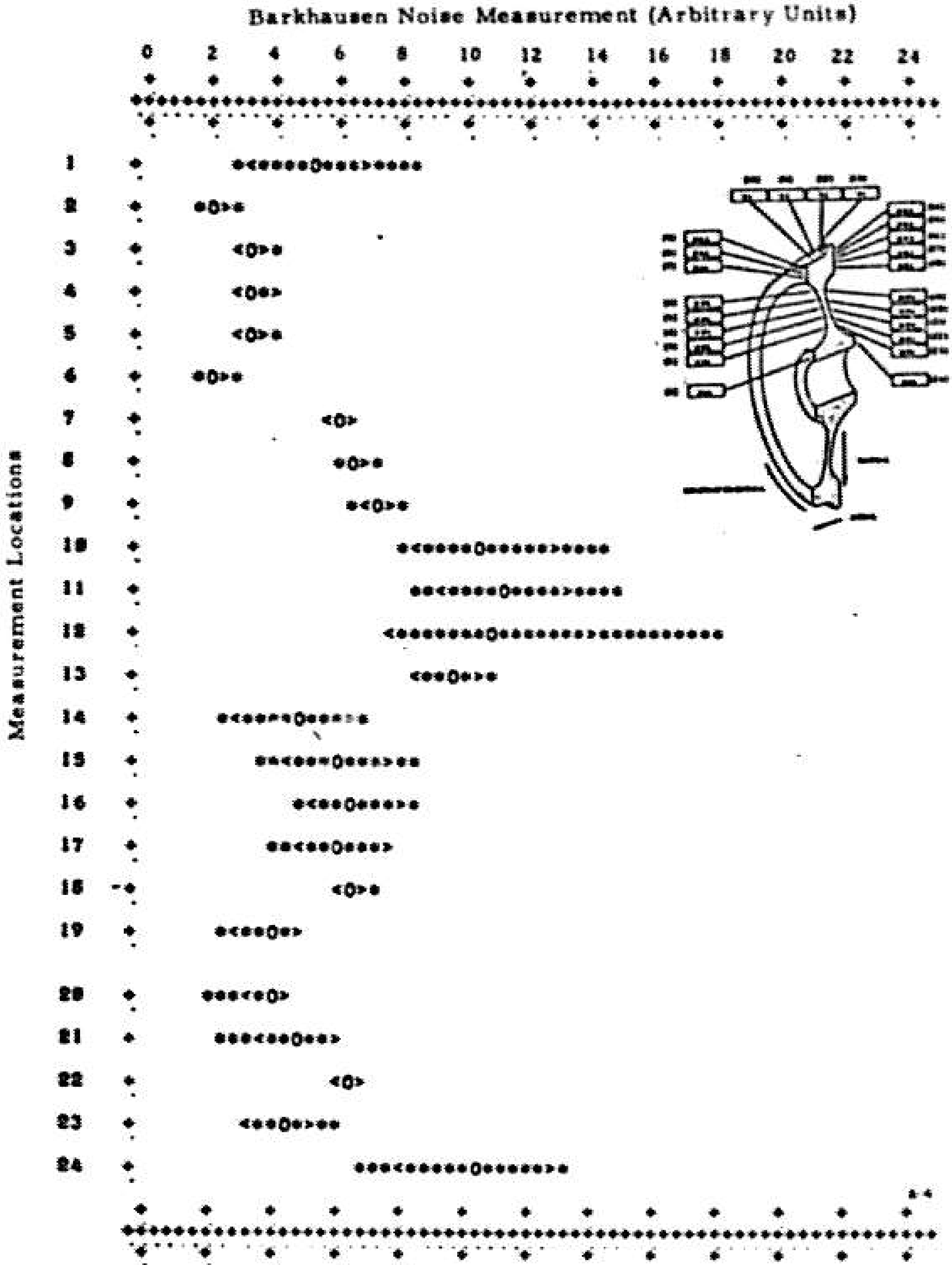


FIGURE A-4. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 2 (2474A), NEW

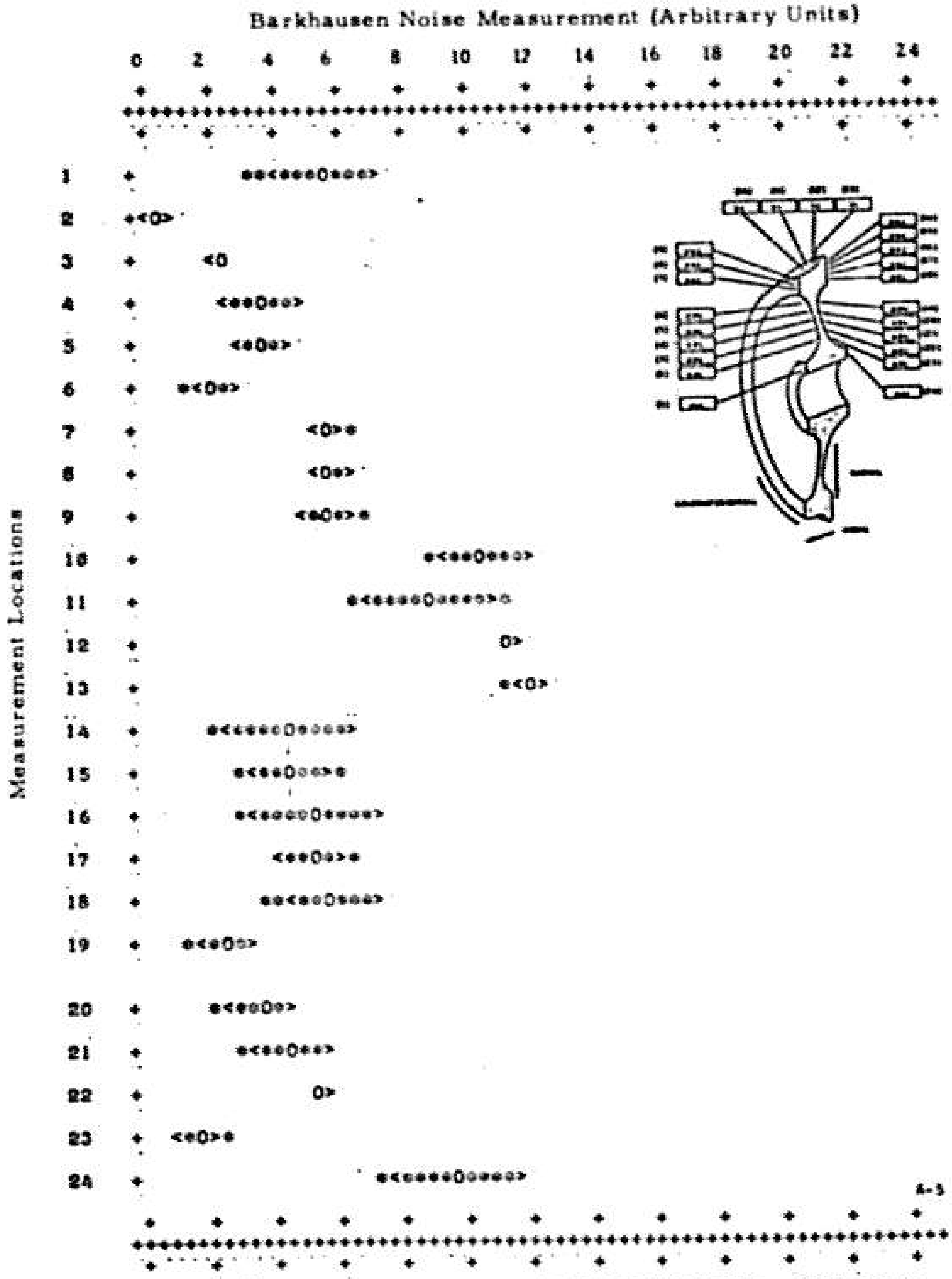


FIGURE-A-5. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 2 (2474A). BRAKE TESTED

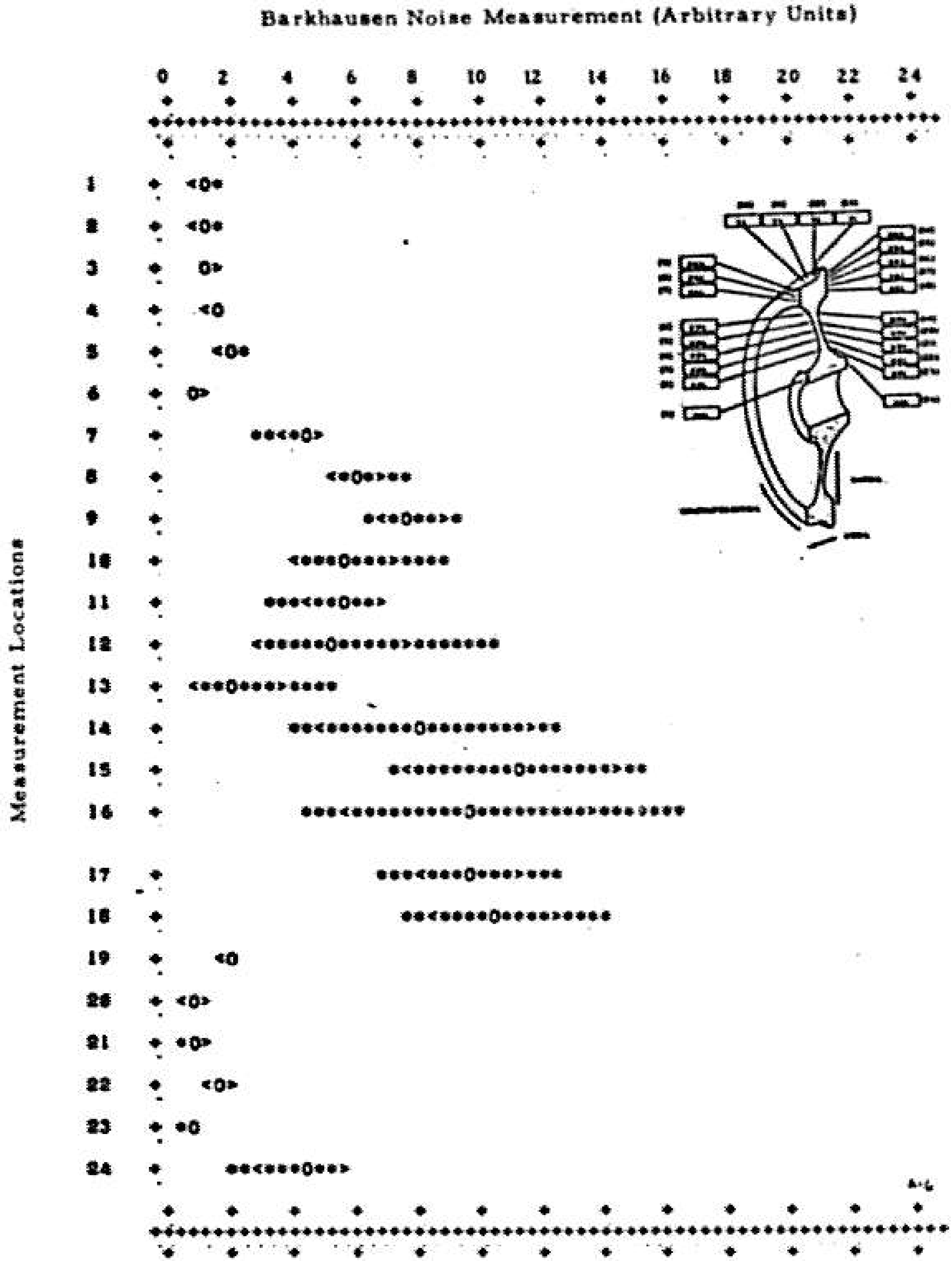


FIGURE A-6. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 3 (2472A). NEW

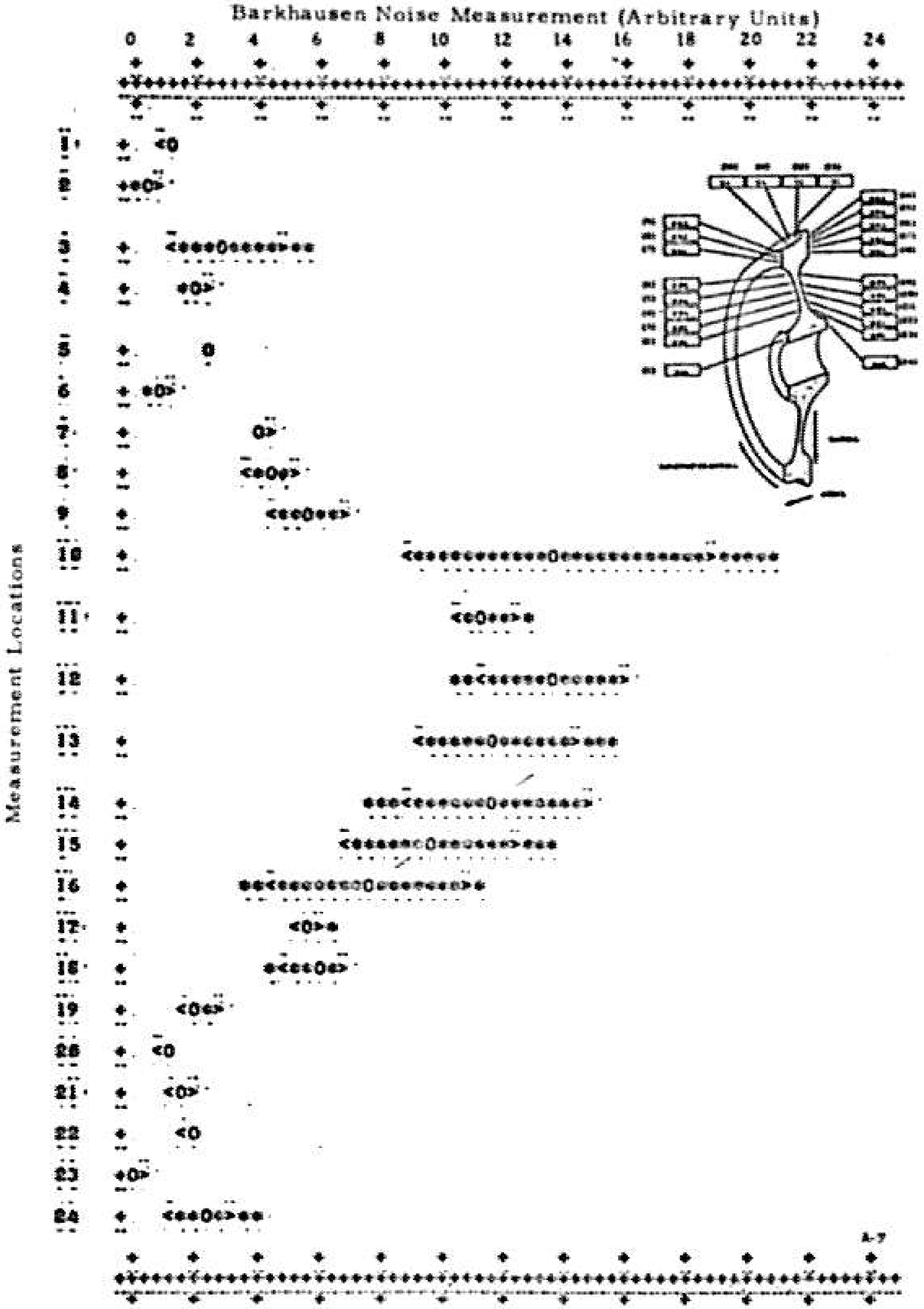


FIGURE A-7. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 3 (2472A), BRAKE TESTED

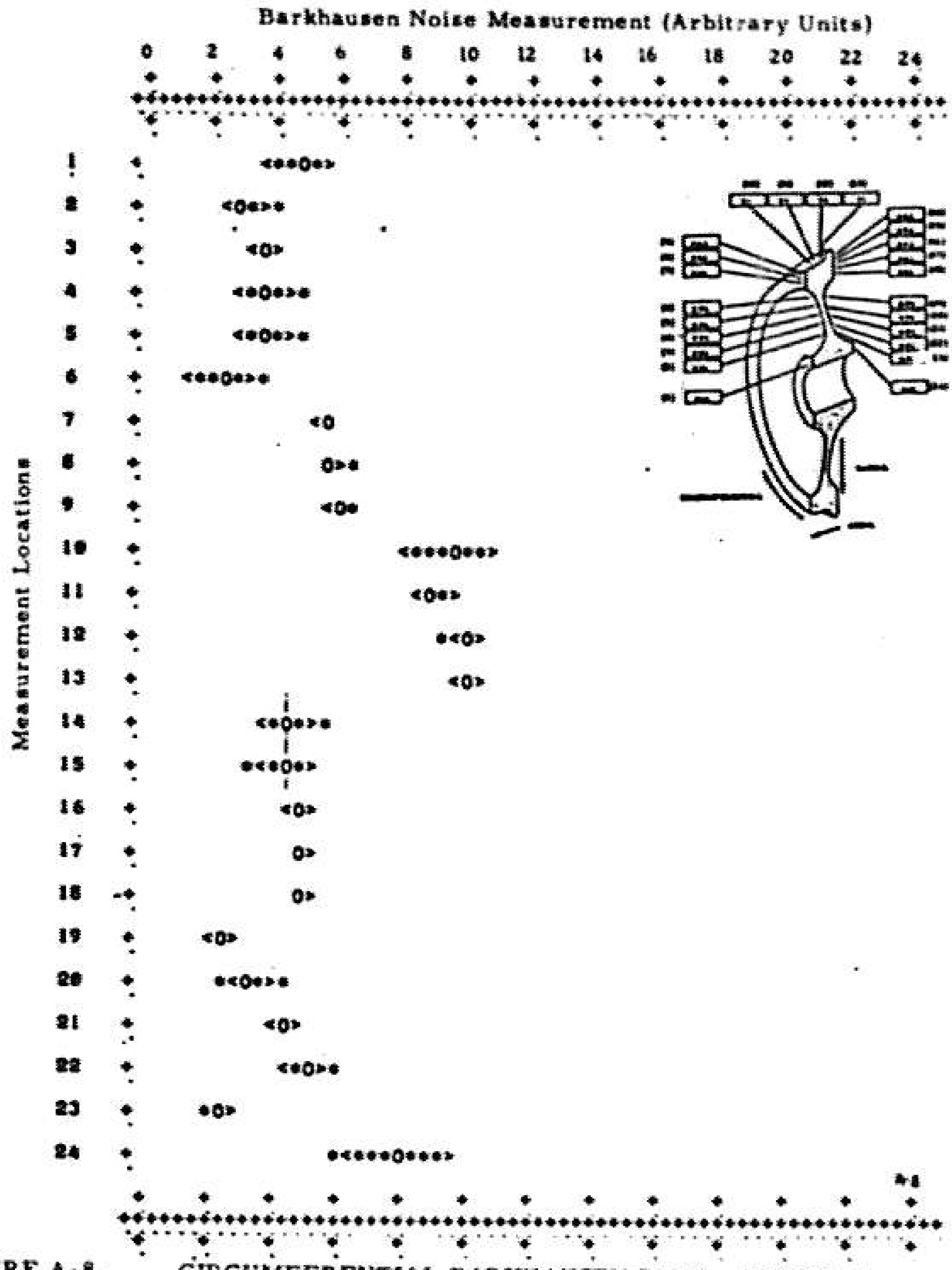


FIGURE A-8. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 4 (2466A), NEW

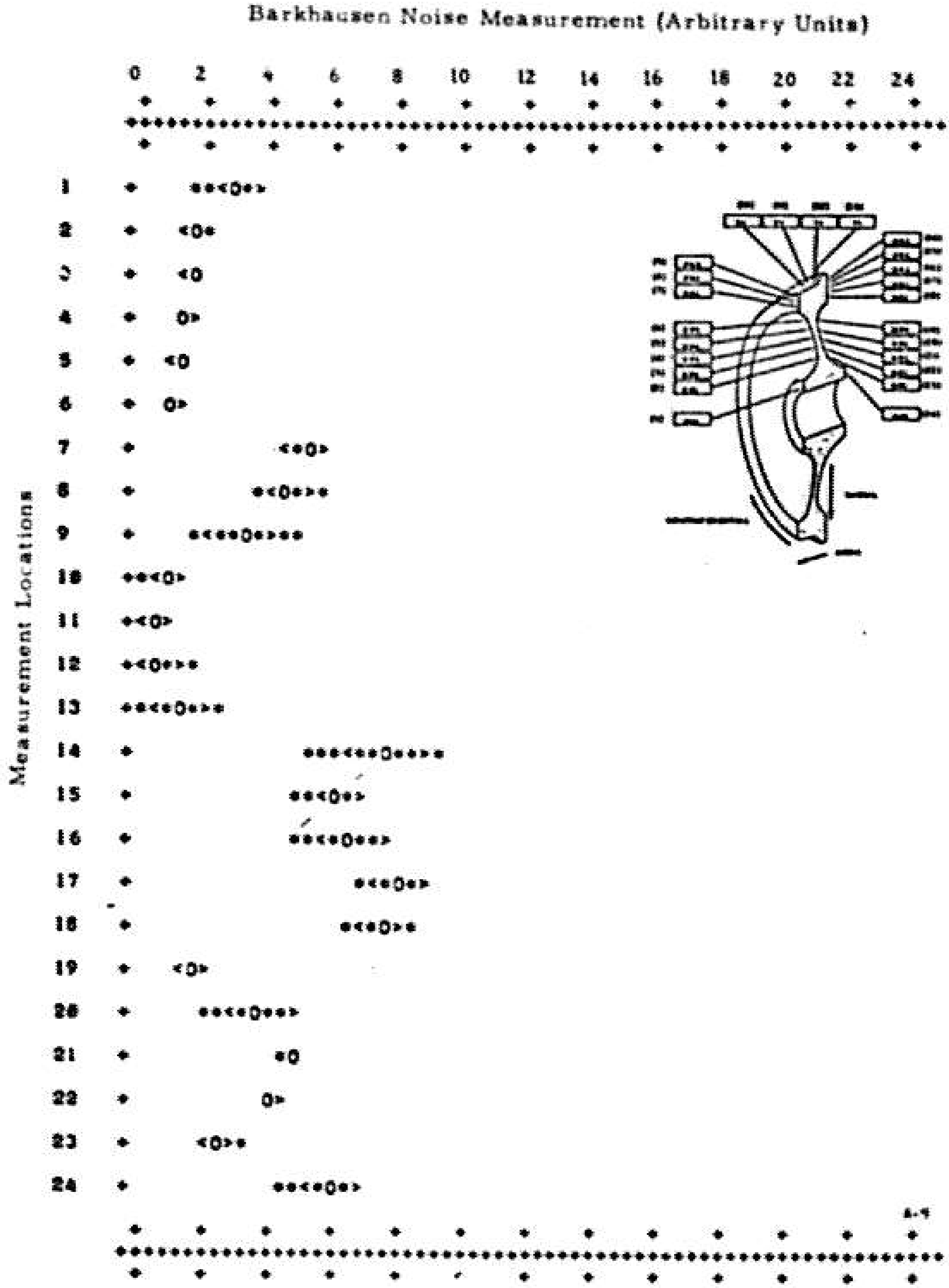


FIGURE A-9. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 5 (10191A), USED (CRACKED)

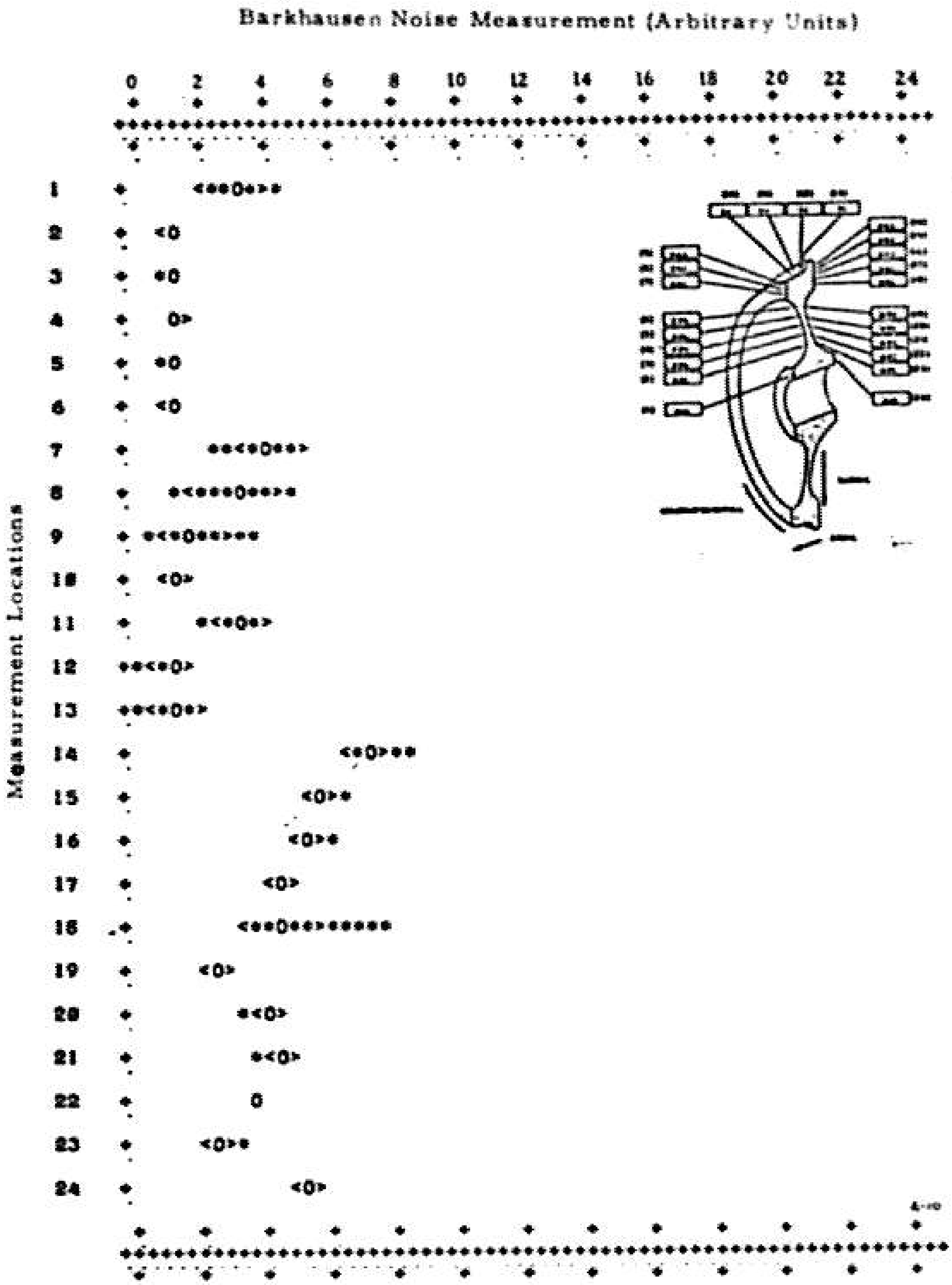


FIGURE A-10. CIRCUMFERENTIAL BARKHAUSEN DATA - WHEEL 6 (10190A), USED

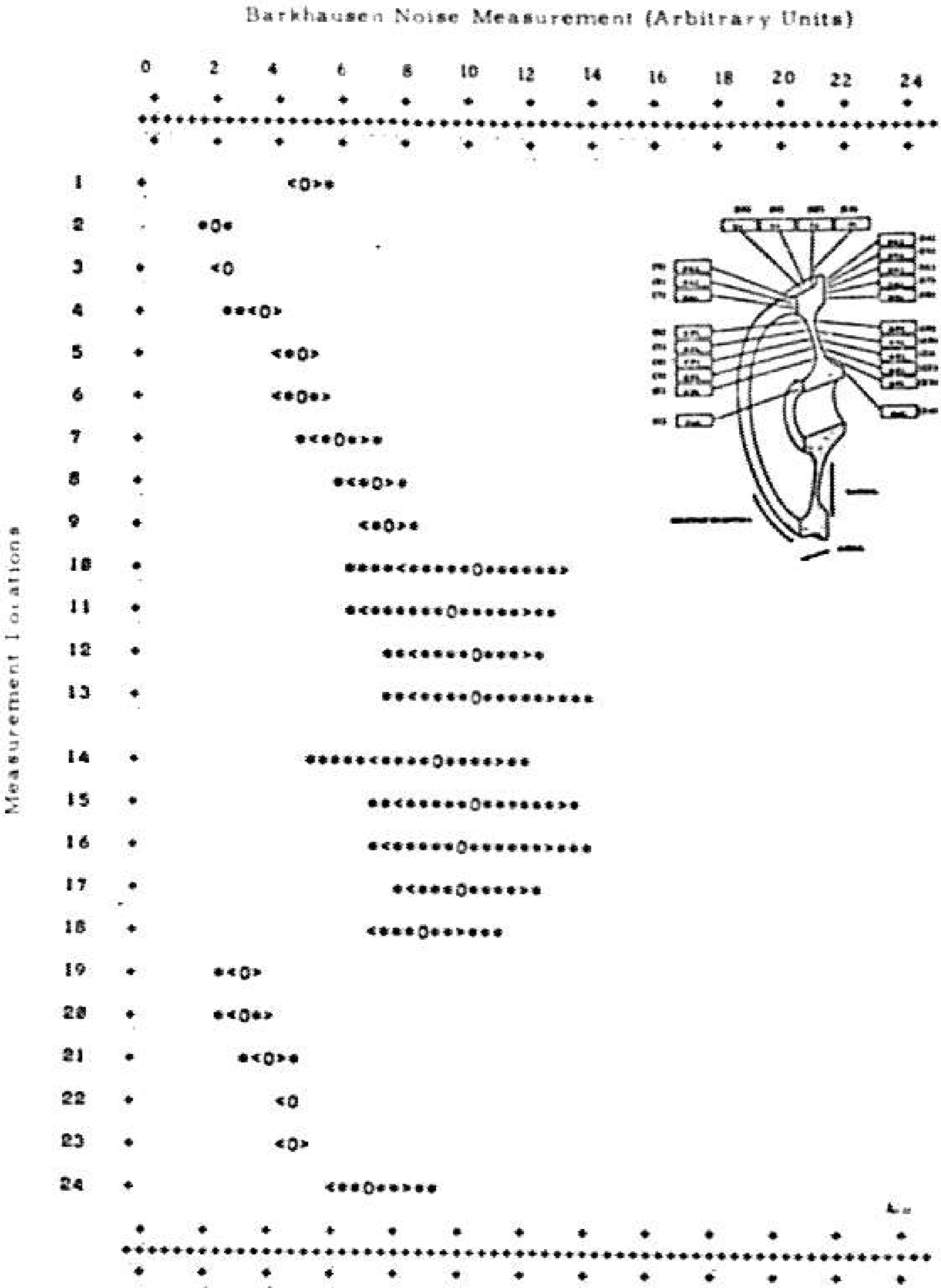


FIGURE A-11. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 1 (2476A) NEW

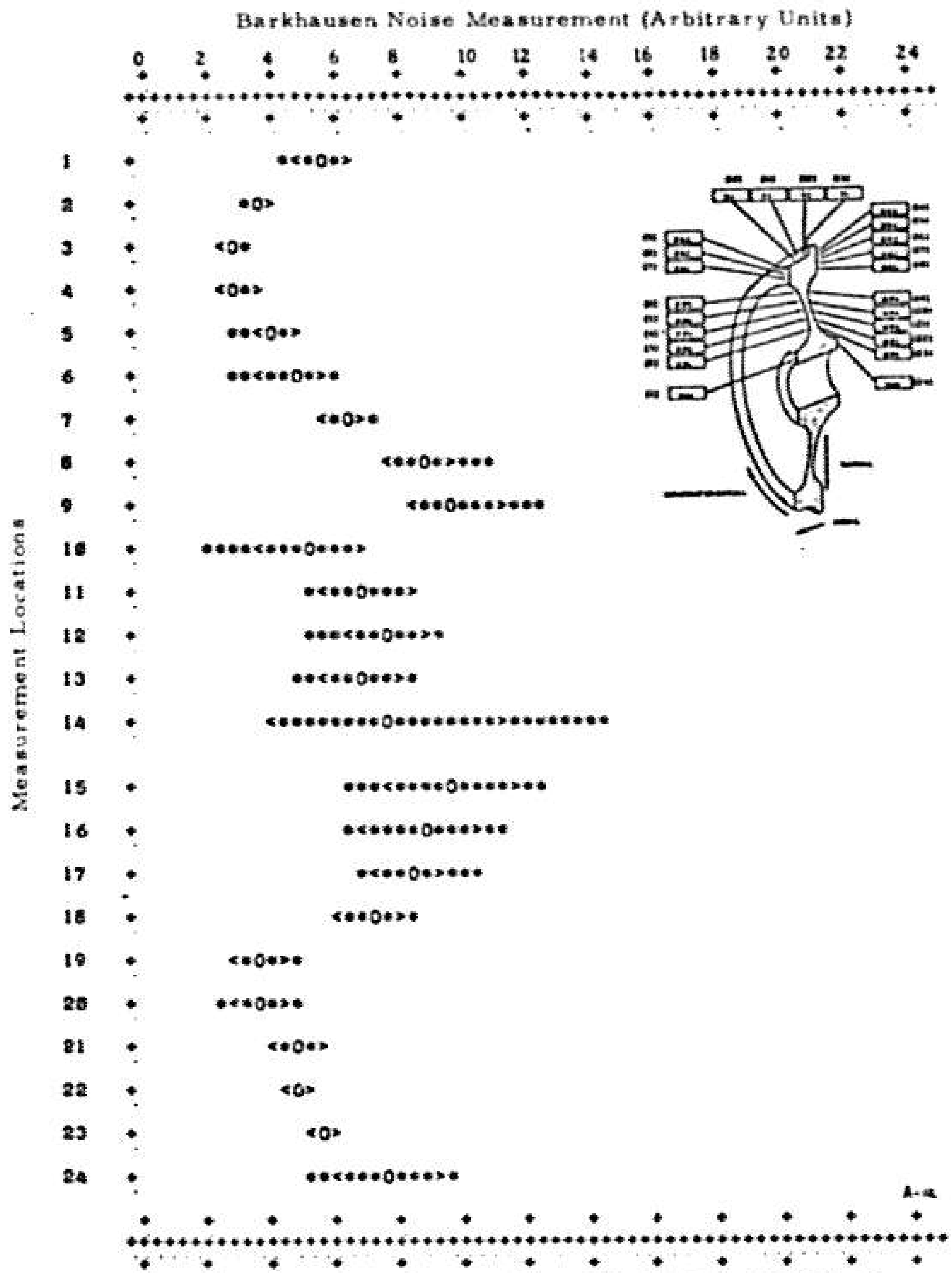


FIGURE A-12. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 1 (2476A), BRAKE TESTED

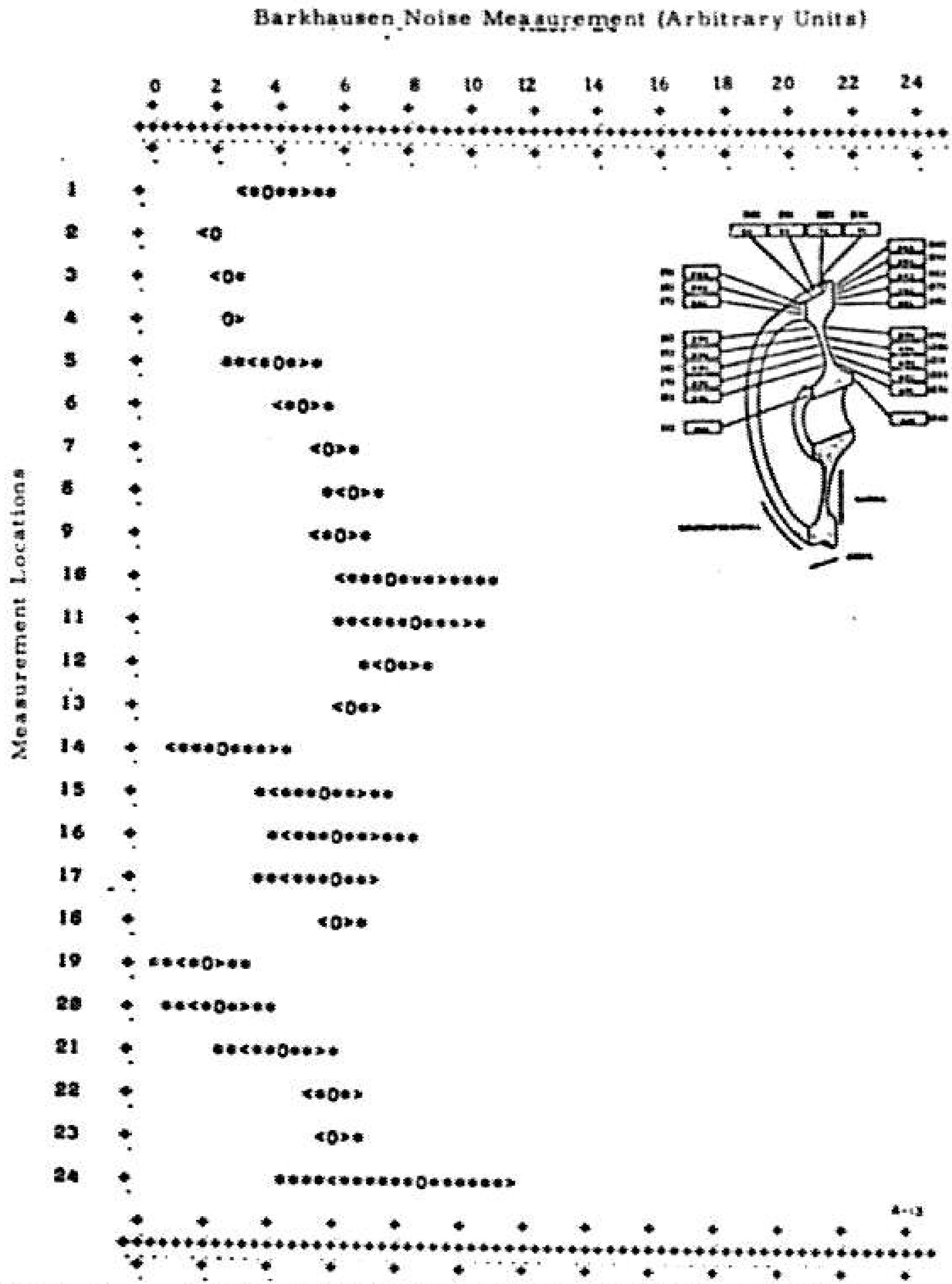


FIGURE A-13. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 2 (2474A), NEW

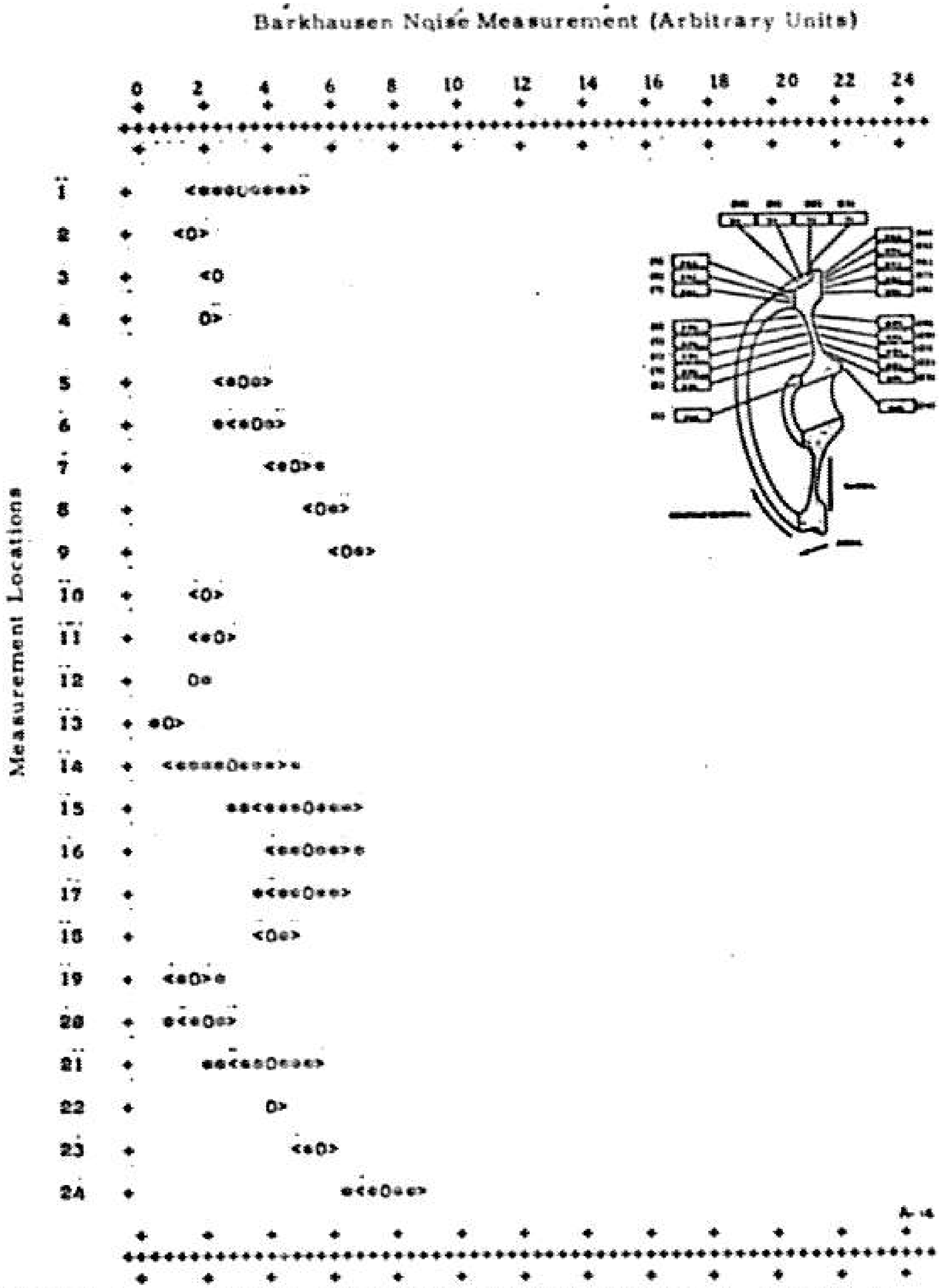


FIGURE A-14. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 2 (2474A), BRAKE TESTED

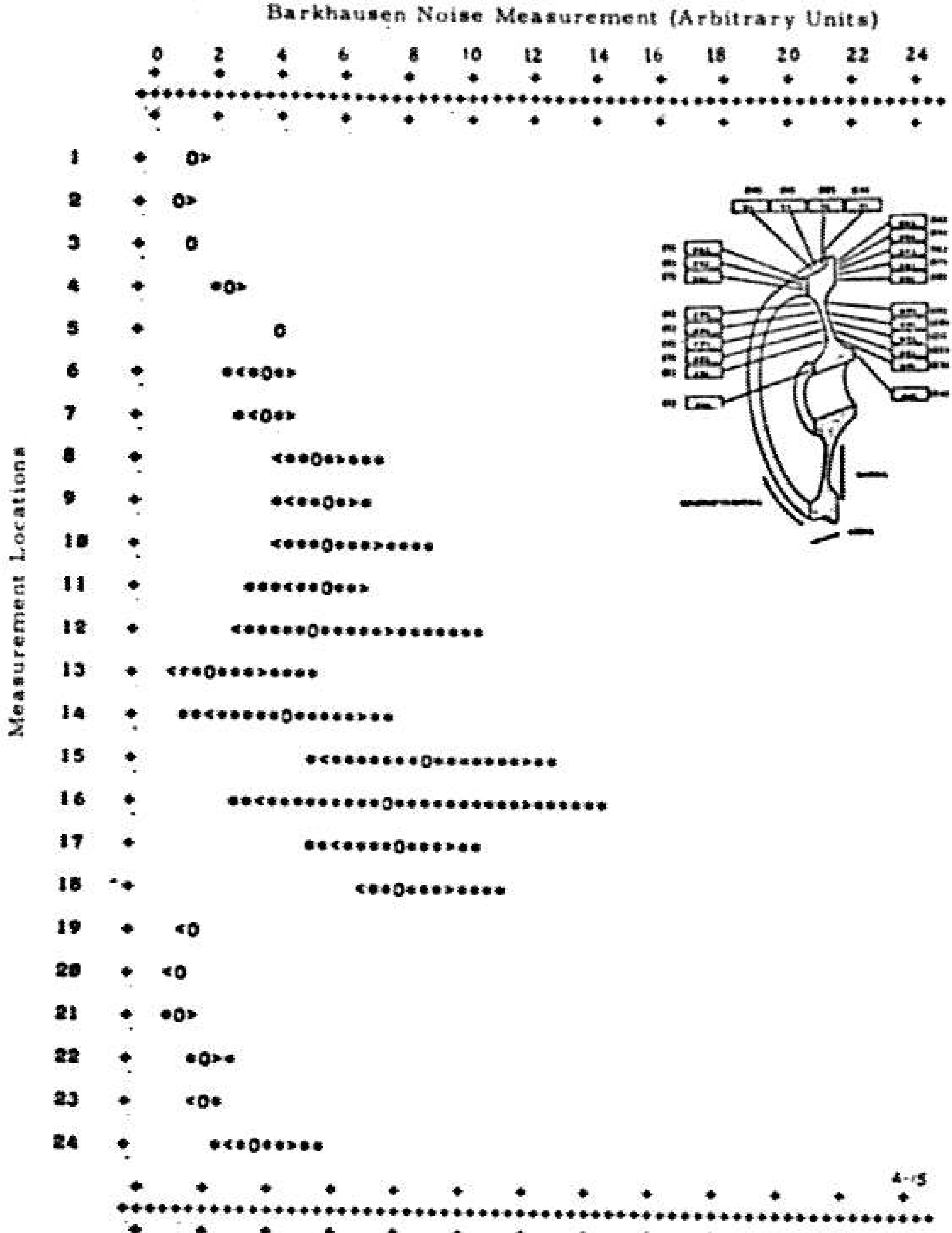


FIGURE A-15. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 3 (2472A), NEW

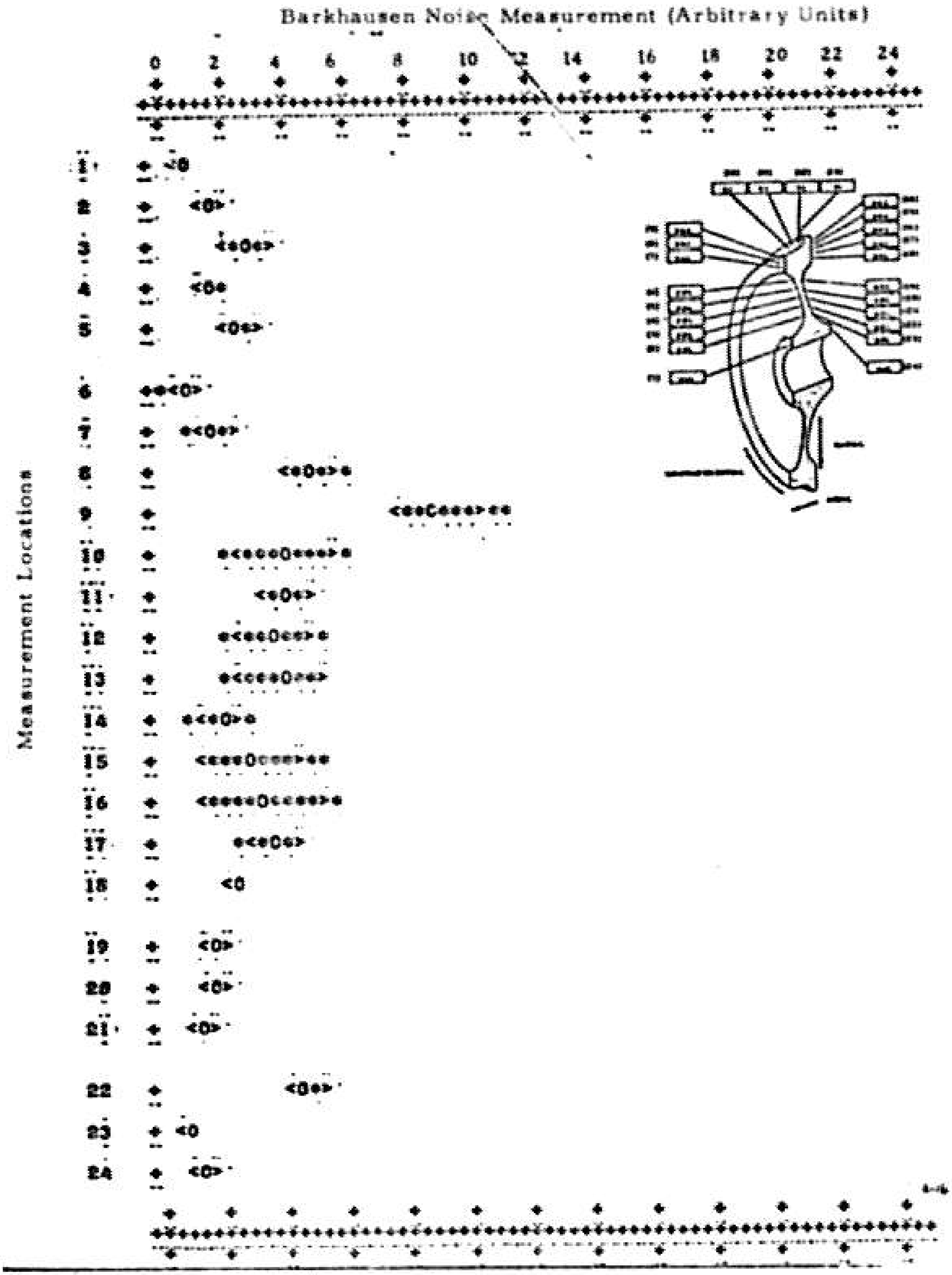


FIGURE A-16. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 3 (2472A), BRAKE TESTED

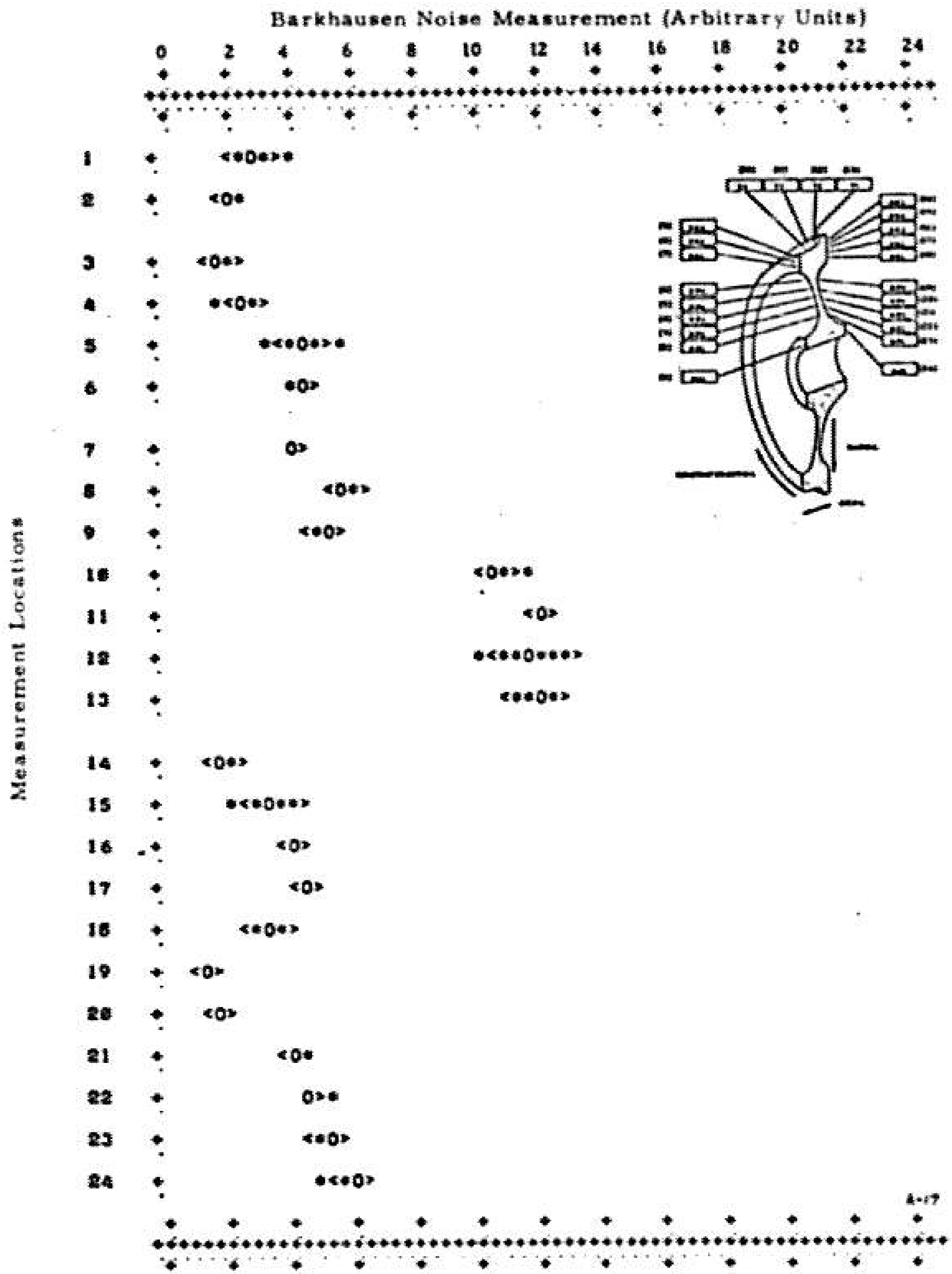


FIGURE A-17. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 4 (2466A). NEW

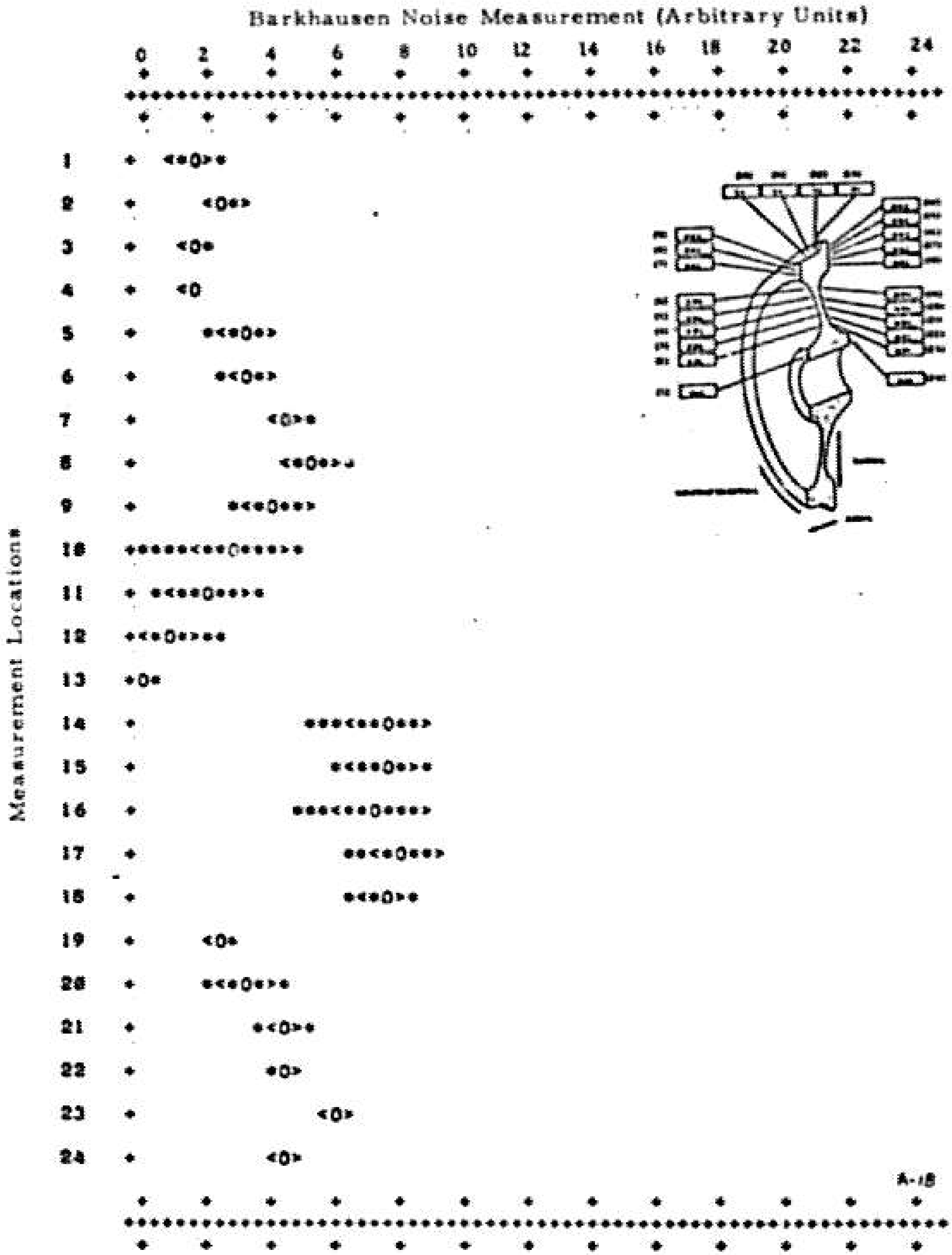


FIGURE A-18. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 5 (10191A), USED (CRACKED)

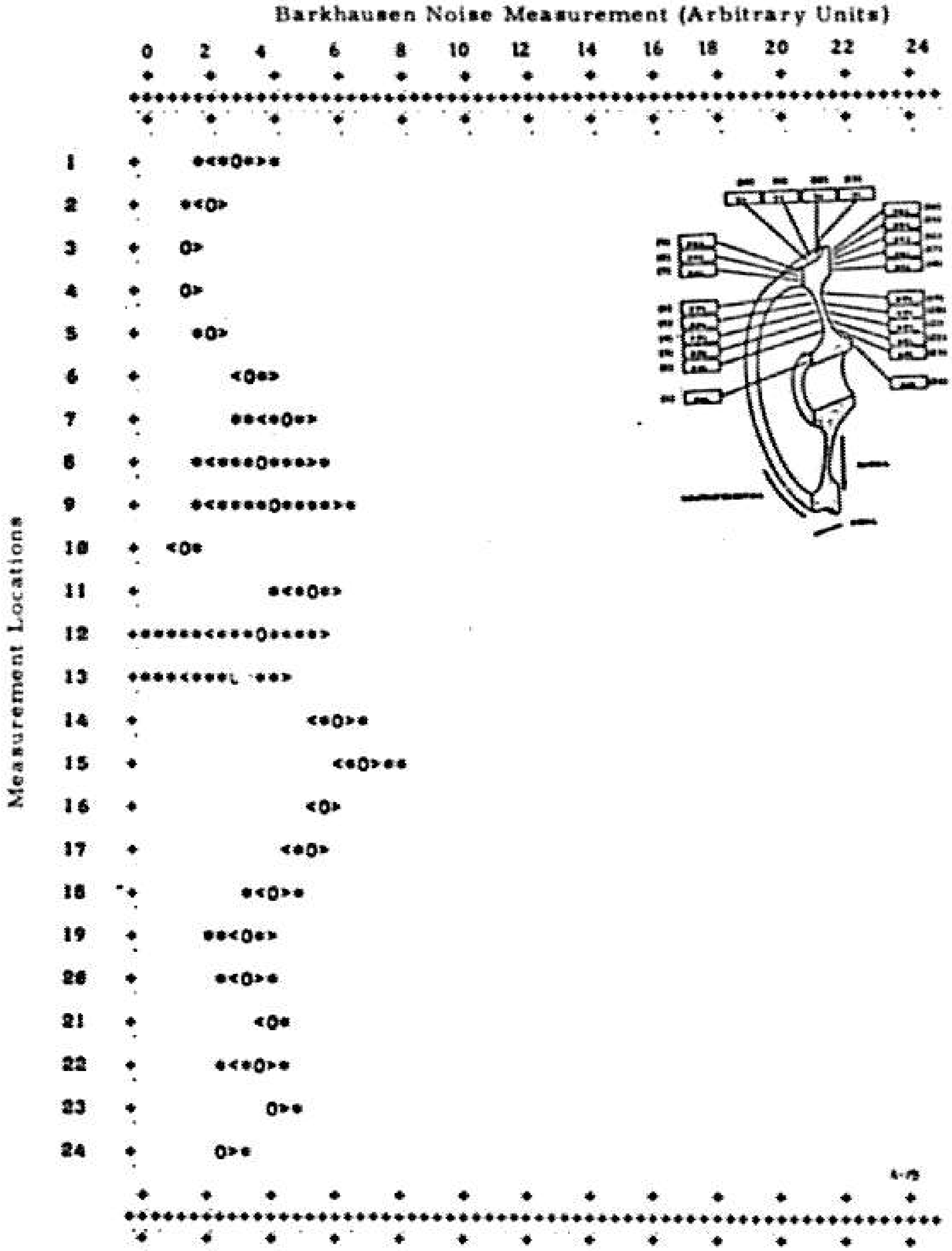


FIGURE A-19. RADIAL AND AXIAL BARKHAUSEN DATA - WHEEL 6 - (10190A): USED

APPENDIX B

DESTRUCTIVELY DETERMINED STRESS DATA

The data contained in this appendix were obtained by the United States Steel Corporation under Contract DOT-TSC-712 and furnished to Southwest Research Institute by the Contracting Officer's technical representative.

Figure B-1 is a sketch of the location of strain gages on the railroad wheels which were employed to determine the stresses in various regions of the wheels. To measure the distribution of tangential residual stresses in the outer 1" thick layer of the rim, single element, electrical resistance, foil, strain gages with 1/8" gage lengths were cemented to the wheel rim surfaces. One-inch square by 2-inch long sections with the strain gage on one surface were then saw cut from the rim and strain measurements were made from the gages. Using the accepted value of 30 million psi for Young's modulus, the tangential residual stresses were calculated from the relaxation strain.

The residual stresses at the bases of the back rim plate fillet and front hub plate fillet were measured by means of 45° rectangular, stacked rosette, electrical resistance, foil, strain gages with 1/4" gage lengths. The strain gages were cemented to the wheel plate from which 2-1/2" square by plate thick sections were sawed. The principal residual stresses were calculated from the measured relaxation strain.[11]

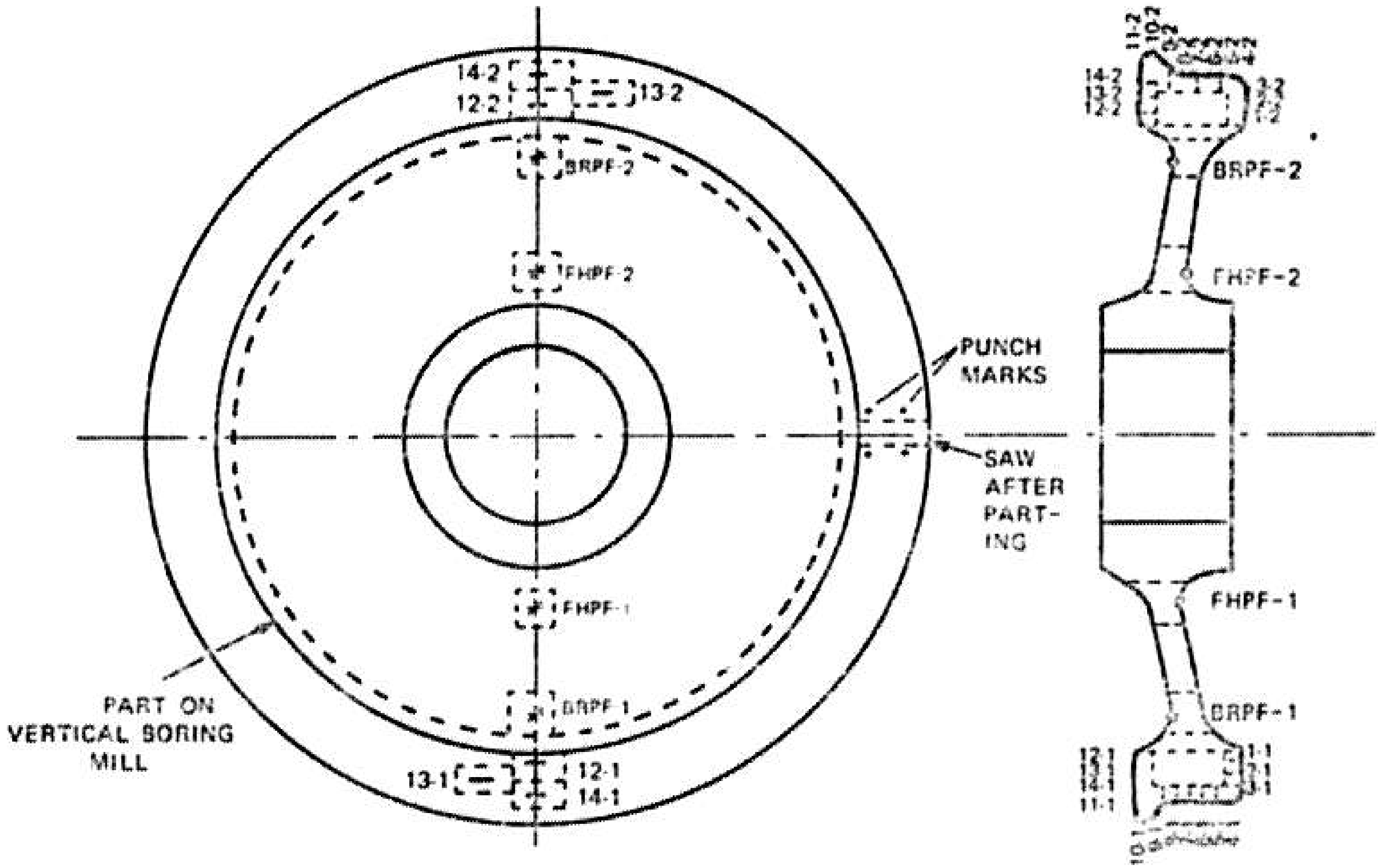


FIGURE B-1. LOCATIONS OF STRAIN GAGES ON SECTION B-36 WHEELS

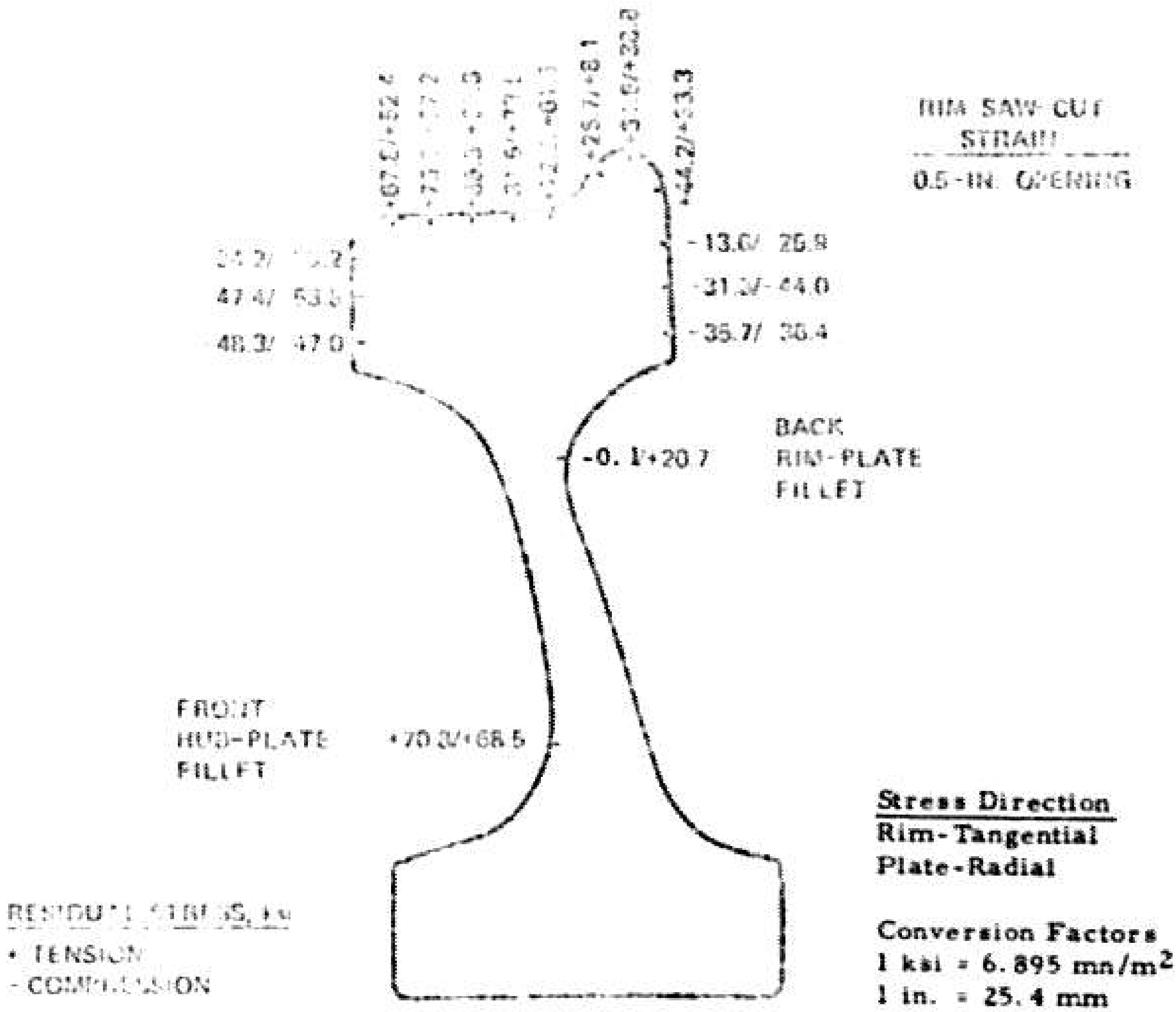


FIGURE B-2. INDICATED RESIDUAL STRESSES IN NEW WHEEL NO. 1 (1-72-S-2476-A) AFTER 300 SIMULATED EMERGENCY STOPS

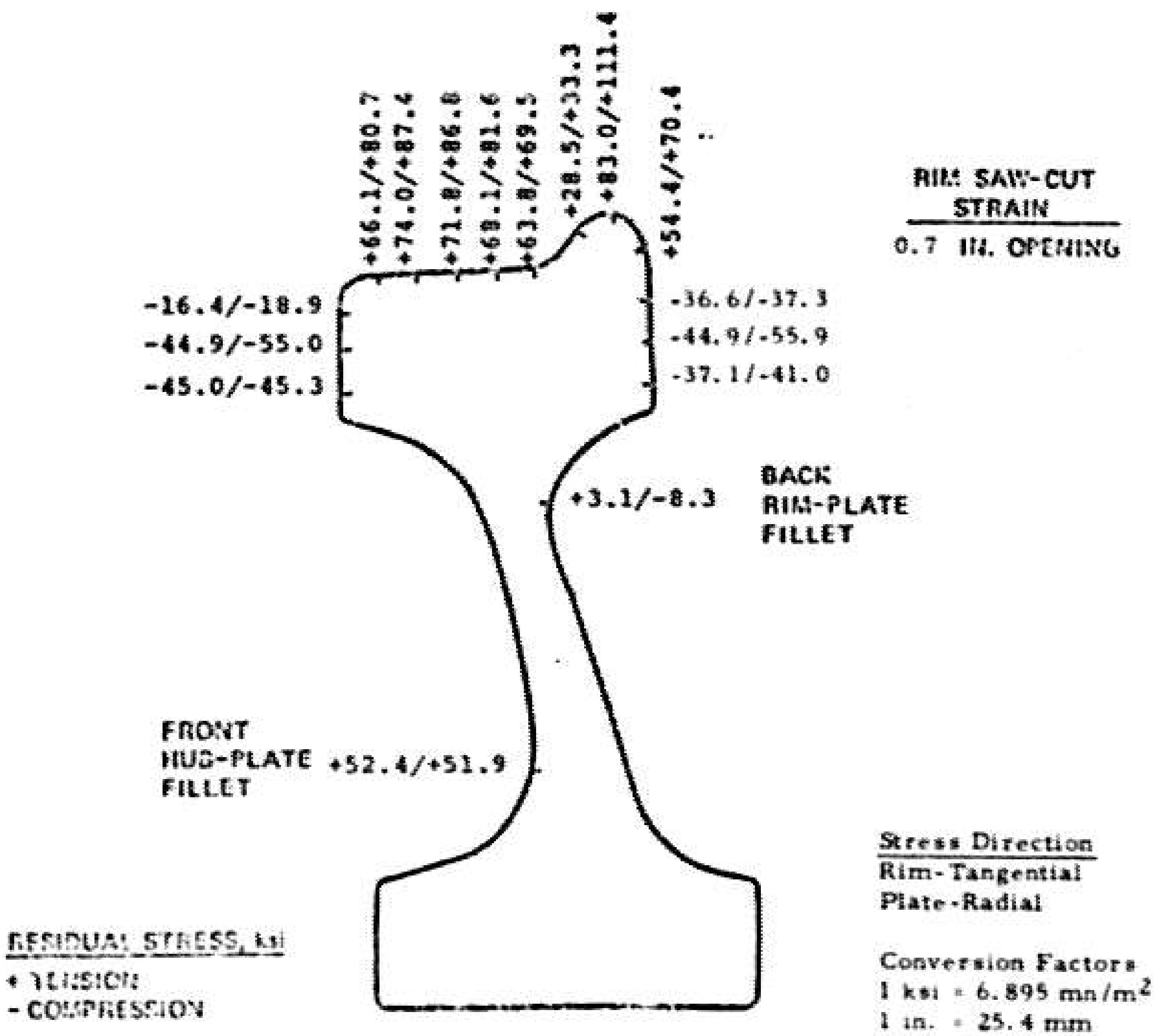


FIGURE B-3. INDICATED RESIDUAL STRESSES IN NEW WHEEL NO. 2 (1-72-S-2474-A) AFTER 2424 SPEED CONTROL BRAKINGS FROM 100 TO 50 MPH

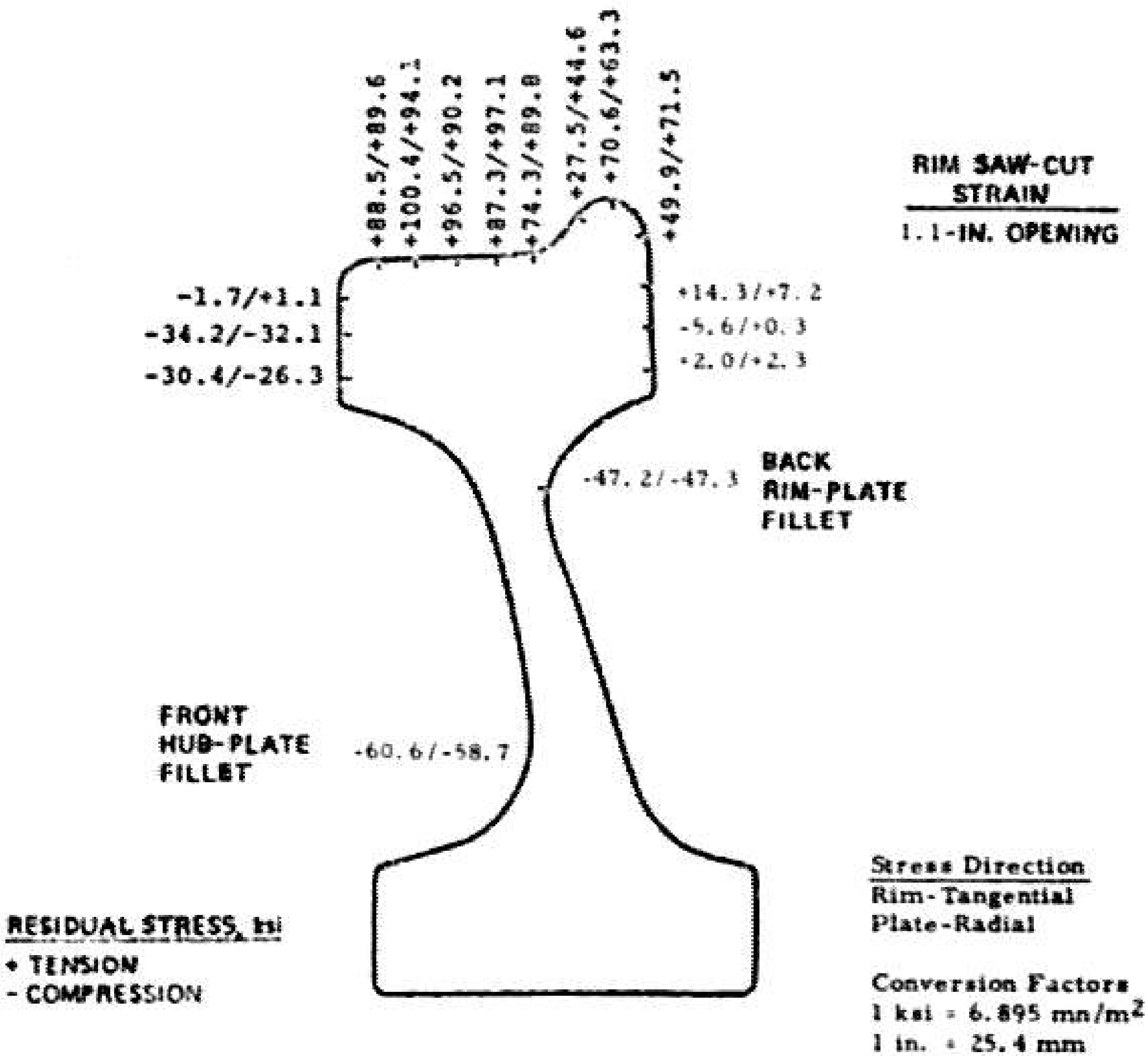
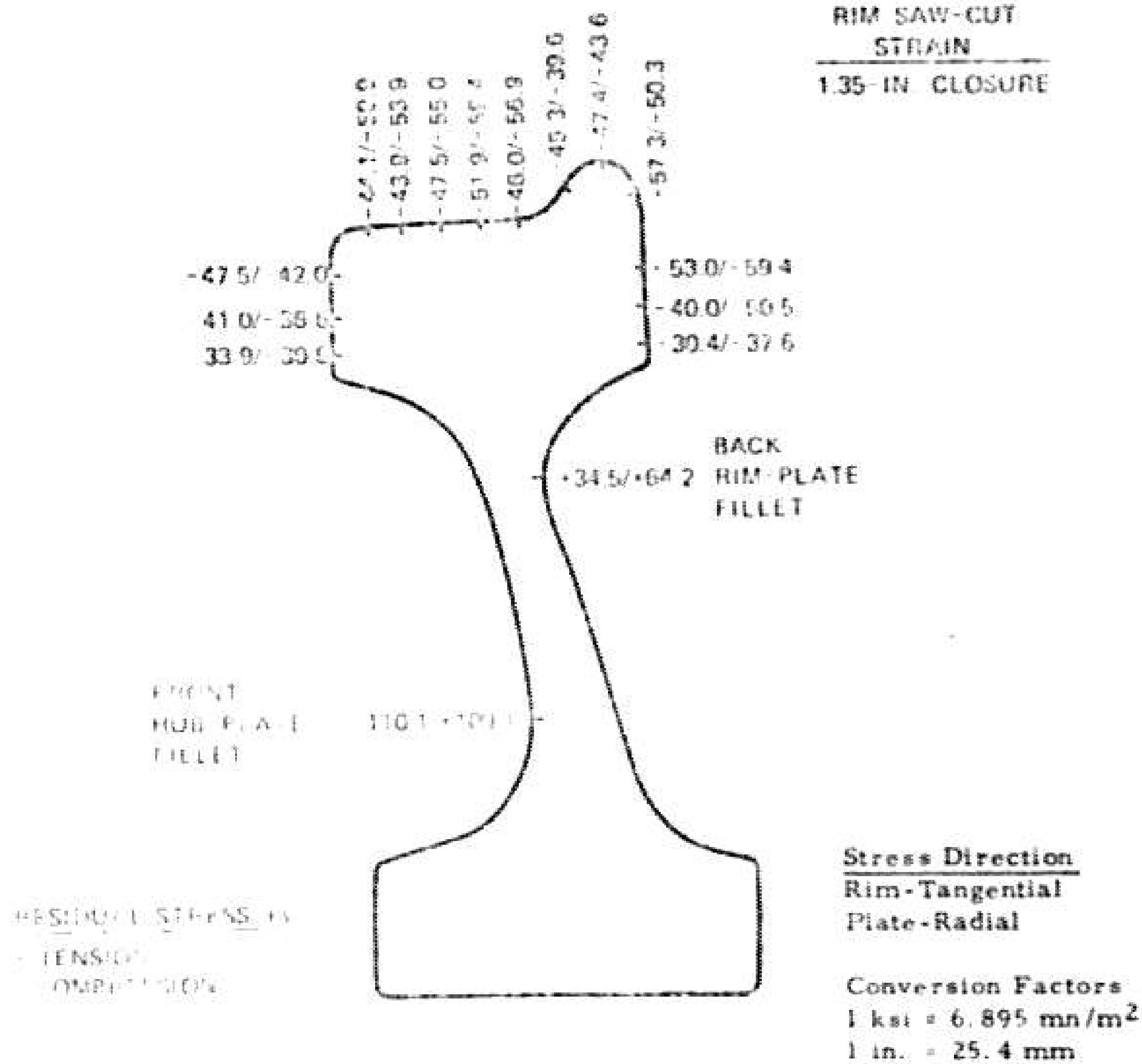


FIGURE B-4. INDICATED RESIDUAL STRESSES IN NEW WHEEL NO. 3 (1-72-S-2472-A) AFTER A COMBINATION OF DRAG BRAKING, EMERGENCY-STOP BRAKING, AND EMERGENCY-STOP BRAKING WITH A WORNOUT BRAKESHOE



INDICATED RESIDUAL STRESSES IN NEW WHEEL NO. 4
(1-72 S-2466-A)

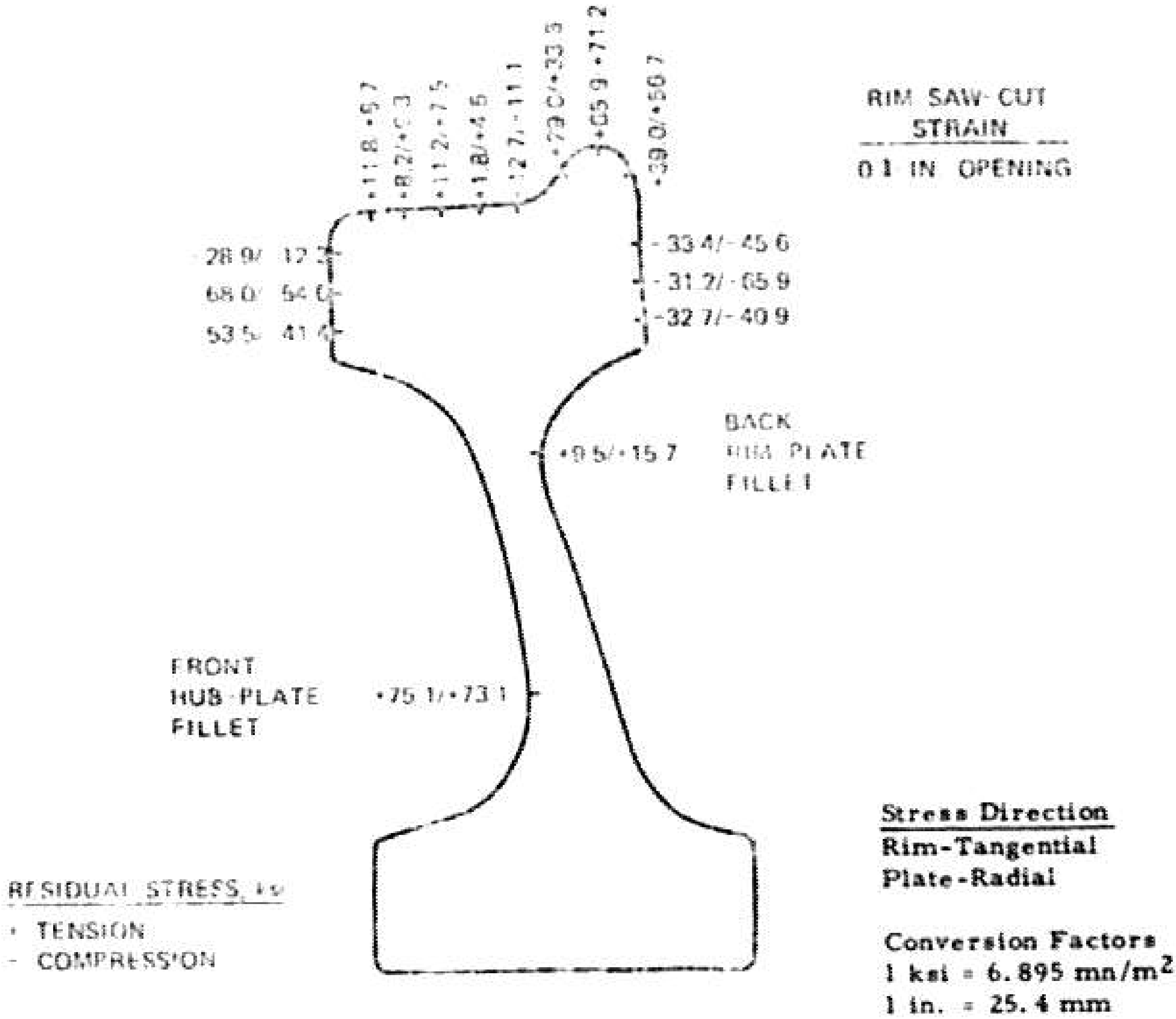


FIGURE B-6. INDICATED RESIDUAL STRESSES IN USED WHEEL NO. 5 (1-71-S-10191-A) WHICH CONTAINED A FATIGUE-TYPE THERMAL CRACK

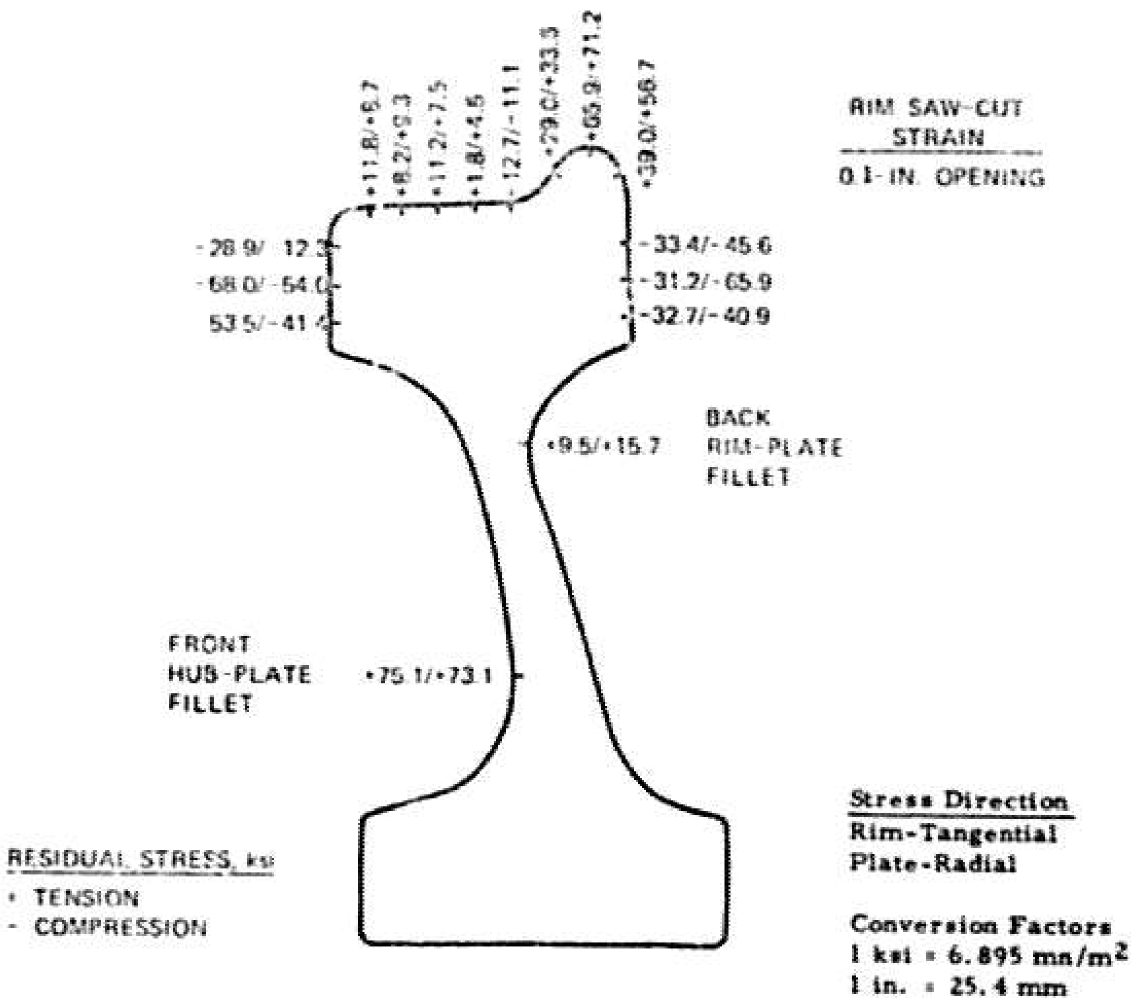


FIGURE B-7. INDICATED RESIDUAL STRESSES IN USED WHEEL NO. 6 (1-71-S-10190-A)

If one assumes that the shot-peened surface of SS-1f had a residual compressive stress of 45 ksi, then the data for that specimen conform to the usual "S" shape calibration curve obtained for steels. The 45 ksi shift is reasonable since that stress value is bracketed by the residual stress determinations shown in Table C-2 (-27 ksi to 39 ksi) and half the yield strength for the railroad material (-60 ksi) which has a hardness of approximately BHN 262 and therefore a yield strength on the order of 120 ksi.[15] It should be emphasized, however, that the calibration curve shown in Figure 11 is for a thin specimen of railroad wheel material. For application to the railroad wheels which are thick relative to the 1/4" specimen, the curve should be adjusted slightly downward to reflect the dispersion of the magnetic flux in thicker specimens.

APPENDIX C

CALIBRATION EXPERIMENTS

The following discussion details the calibration experiment previously outlined in Section 4.2 of this report. Table C-1 summarizes the calibration experiment by tabulating the specimens utilized, the kind of data acquired for each specimen, and the location of the respective data presentations.

In previous Barkhausen noise measurement programs, it has been a practice to obtain calibration data from cantilever beams which are generally 1/8" or 1/4" thick and ground on both sides. A specially designed bending fixture is available into which such specimens can be inserted and subjected to controlled deflections. A dial indicator on the fixture is utilized to measure the deflection of the beam from which the corresponding stress can be calculated. It is also known from past experience that the Barkhausen noise measurement is influenced to a limited extent by the geometry of the test specimen. The magnetic flux used to excite the Barkhausen activity is more concentrated in a thin specimen than in a thick specimen. Since the Barkhausen activity increases with greater rates of change in magnetic flux, a somewhat greater Barkhausen signal is obtained from a thin specimen than from a thick specimen in the same stress condition. Accordingly, the first calibration experiment was designed to address the problem of obtaining a valid calibration curve for the thick railroad wheels from specimens thin enough to be deflected in the existing fixture.

A section of railroad wheel nominally of the same type as the six railroad wheels in this program was obtained from the Standard Steel Corporation. Specimens (SS-1 and SS-4) were prepared from this material such that one surface of the specimen contained the shot-peened surface from the rim of the material sample and the opposite side of the specimen was carefully ground. Barkhausen noise measurements were made on each specimen prior to cutting it from the material sample and again after it was made into a 1" thick cantilever beam. One of the specimens (SS-1) was reduced in thickness in a series of steps and Barkhausen noise measurements were made on both sides at each thickness. When the beam finally became thin enough to be placed in the bending fixture, a calibration curve was obtained from each side of the specimen.

This experiment produced an interesting result when the specimens were finally reduced to 1/8" thickness. The Barkhausen noise data obtained from the shot-peened side of this thin specimen resulted in a calibration curve which had a negative slope for values of very high

TABLE C-1.

CALIBRATION EXPERIMENTS

Spec. I.D.	Size L x W x T	Description	Stress Application	Data Acquired	Data Presentation
SS-1a	See Note*	Peened as Rec'd.	None	Bark. Noise	Fig C1
SS-1b	6 x 3 x 1	Peened as Rec'd.	None	Bark. Noise	Fig C1
SS-1c	** 5.0 x 1.0 x 1.0	Peened as Rec'd., Opp. Side Ground(30u in)	None	Bark. Noise	Fig C1
SS-1d	** 5.0 x 1.0 x 0.5	Peened as Rec'd., Opp. Side Ground(30u in)	None	Bark. Noise	Fig C1
SS-1e	** 5.0 x 1.0 x 0.38	Peened as Rec'd., Opp. Side Ground(30u in)	Bending	Bark. Noise	Fig C1
SS-1f	** 5.0 x 1.0 x 0.25	Peened as Rec'd., Opp. Side Ground(30u in)	Bending	Bark. Noise	Fig C1
SS-1g	** 5.0 x 1.0 x 0.13	Peened as Rec'd., Opp. Side Ground(30u in)	Bending	Bark. Noise	Fig C1
SS-2	** 5.0 x 1.0 x 0.13	Both Sides Ground (30u in)	Bending	Bark. Noise	Fig C1
SS-3	** 5.0 x 1.0 x 0.13	Both Sides Ground (30u in), Stress Relieved	None	X-ray diffraction	Table C2
SS-4	** 5.0 x 1.0 x 1.0	Peened as Rec'd., Opp. Side Ground(30u in)	Bending	Bark. Noise	Table C2
SS-5	7.0 x 2.0 x 1.25	Peened as Rec'd., Opp. Side Ground(30u in)	Uniaxial Compression	Bark. Noise	Table C2
SS-5	7.0 x 2.0 x 1.25	Peened as Rec'd., Opp. Side Ground(30u in)	None	X-ray diffraction & hole technique	Table C2
SS-6	4 x 3 x 0.7	Peened to .004A2, 125u in finish	None	Bark. Noise	Fig C3
SS-7	4 x 3 x 0.7	Peened to .010A2, 250u in finish	None	Bark. Noise	Fig C3
SS-8	4 x 3 x 0.7	Peened to .006C2, 500u in finish	None	Bark. Noise	Fig C3
SS-9	4 x 3 x 0.6	Peened to .008C2, 500+u in finish	None	Bark. Noise	Fig C3
SS-10	4 x 3 x 0.6	Peened to .010C2, 750u in finish	None	Bark. Noise	Fig C3
SS-11	Complete Wheel	Penn Central Wheel as Rec'd., Used	None	Hole Technique	Table C2

* Before Specimen SS-1 was Cut From Sample of Wheel Material.

** Not Including Flanges for Mounting in Bending Fixture.

compression. The Barkhausen noise signature obtained from the shot-peened surfaces with high compressive stress application included a secondary peak which increased with compression, whereas the normal peak decreases with compression. As the secondary peak became more prominent, the electronic peak amplitude detector shifted to the secondary peak, resulting in the distorted calibration curve. Since the occurrence of the secondary peak was not seen in the data acquired from any of the wheels in the program, it was assumed that this anomaly was nonrelevant to the program effort and no further data were acquired from the 1/8" thick specimen.

Since calibration curves had been obtained for specimen SS-1 only at 1/4" and 3/8" thicknesses, it was difficult to extrapolate the data for applications to thick specimens. Therefore, an additional 1" thick cantilever specimen (SS-4) was prepared as before and put into a fixture on a hydraulic press to be bent in a cantilever mode. No secondary peak occurred in the Barkhausen signature obtained from this specimen. However, the Barkhausen noise signature did tend to increase slightly when the shot-peened side had highly compressive stresses applied. To verify that this tendency was not a peculiarity of the method for stressing the material, another thick specimen (SS-5) was prepared with one 2" x 7" face shot-peened and the other ground. It was put in uniaxial compression along its longitudinal axis and Barkhausen noise data was acquired from both sides. The results from this experiment again confirmed the trend of the Barkhausen noise measurements to increase when the shot-peened surface was placed in high compression.

All the preceding calibration experiments related Barkhausen noise measurements to the magnitude of applied stress on material which had not been annealed in order to avoid changing the specimen metallurgically. Thus, to relate the Barkhausen noise measurements to residual stress levels, it was necessary to determine the actual residual stress at the specimen surface for at least one point on the calibration curve. This was also necessary in order to relate data from the shot-peened surfaces to that obtained from the ground surfaces. It was felt that this could best be done by making X-ray diffraction measurements on the shot-peened surface of specimen SS-5. X-ray diffraction measurements were made on both sides of that specimen. To obtain still more residual stress correlations from a shot-peened surface, a strain relaxation technique was employed on a B-36, Class A wheel purchased from the Penn Central Transportation Company. This industrial method for the determination of residual stresses (described in Reference 12) involved the installation of a strain gage rosette around the location at which a hole was drilled. Data from the strain gage rosette were accumulated as the hole depth was increased in increments of approximately 0.010 inch. Residual stress values obtained by the X-ray diffraction and strain relaxation techniques are tabulated in Table C-2. It should be stated that the personnel who made the X-ray diffraction measurements and the drilled hole strain relaxation measurements had only limited experience with either technique. However, upon examination, only the strain relaxation data obtained on specimen SS-5 appear to contain substantial error. Examination of the actual strain measurements made on that specimen reveal that the stress gradients normal to the surface were extremely high, a condition which very likely invalidates the technique as employed in this effort.

It is interesting to note that the X-ray diffraction stress determination made on both sides of specimen SS-5 are highly compressive and of nearly equal magnitudes. This may be explained by the fact that both sides of the specimen were cold worked in the regions of the X-ray diffraction measurements. The ground side was unaltered for the X-ray diffraction measurements while the shot-peened side was mechanically polished to smooth the surface at the location of measurements. Neither side was electropolished or chemically etched prior to the X-ray diffraction measurements. Thus, it is not unreasonable to assume that the very thin surface layers of both sides had experienced similar degrees of cold working resulting in the observed high level of residual compressive stress.

It is known that generally in materials that do not strain harden substantially, the maximum residual stress induced by shot-peening is around half the static yield strength for the material. Differences in the peening intensity do not substantially change this maximum residual stress level although greater peening intensity does cause the compressively stressed layer to increase in thickness.[13] To determine the significance of shot-peening intensity on the Barkhausen noise measurements, five specimens of wheel material were prepared and shot-peened to varying intensities. The peening intensity was verified by means of Almen test strips which were shot-peened along with the specimens. Figure C-2 shows the Barkhausen noise measurements obtained from these specimens and it is observed that the Barkhausen noise signatures vary only slightly with increased shot-peening intensity.

The conclusion of the calibration experiments is summarized in the calibration curve previously presented in Figure 11 of this report. That curve represents the Barkhausen noise data obtained from both sides of specimen SS-1f as presented in Figure C-1, but with the data from the shot-peened side shifted 45 ksi toward compression. It is probable that each pair of curves shown in Figure C-1 for the opposing sides of each specimen are really two different portions of a single calibration curve.

TABLE C-2.

RESIDUAL STRESS CALIBRATION DATA

Specimen I.D.	Comparison Technique	Residual Stress Determination	Barkhausen Noise Measurement
SS-3	X-Ray Diffraction	Data Invalid (See Note (1))	-
SS-5, Peened Side	X-Ray Diffraction (See Note (2))	-37.1 KSI	4.9
SS-5, Ground Side	X-Ray Diffraction (See Note (3))	-38.7 KSI	17.5
SS-5, Peened Side	Hole Technique	- 3.8 KSI (4)	4.9
SS-5, Ground Side	Hole Technique	+ 9.7 KSI (4)	17.5
SS-11, Front Plate	Hole Technique	-27.8 KSI	2.8
SS-11, Back Plate	Hole Technique	-27.0 KSI	0.97
SS-11, Front Rim	Hole Technique	-36.6 KSI	5.26
SS-11, Back Rim	Hole Technique	-26.9 KSI	7.66

NOTES:

(1) Data were invalid because the specimen holding fixture strained the specimen in the measurement region.

(2) Surface polished mechanically to remove rough peened surface finish.

(3) Surface as ground.

(4) These data are discounted for reasons explained in the text of Appendix C.

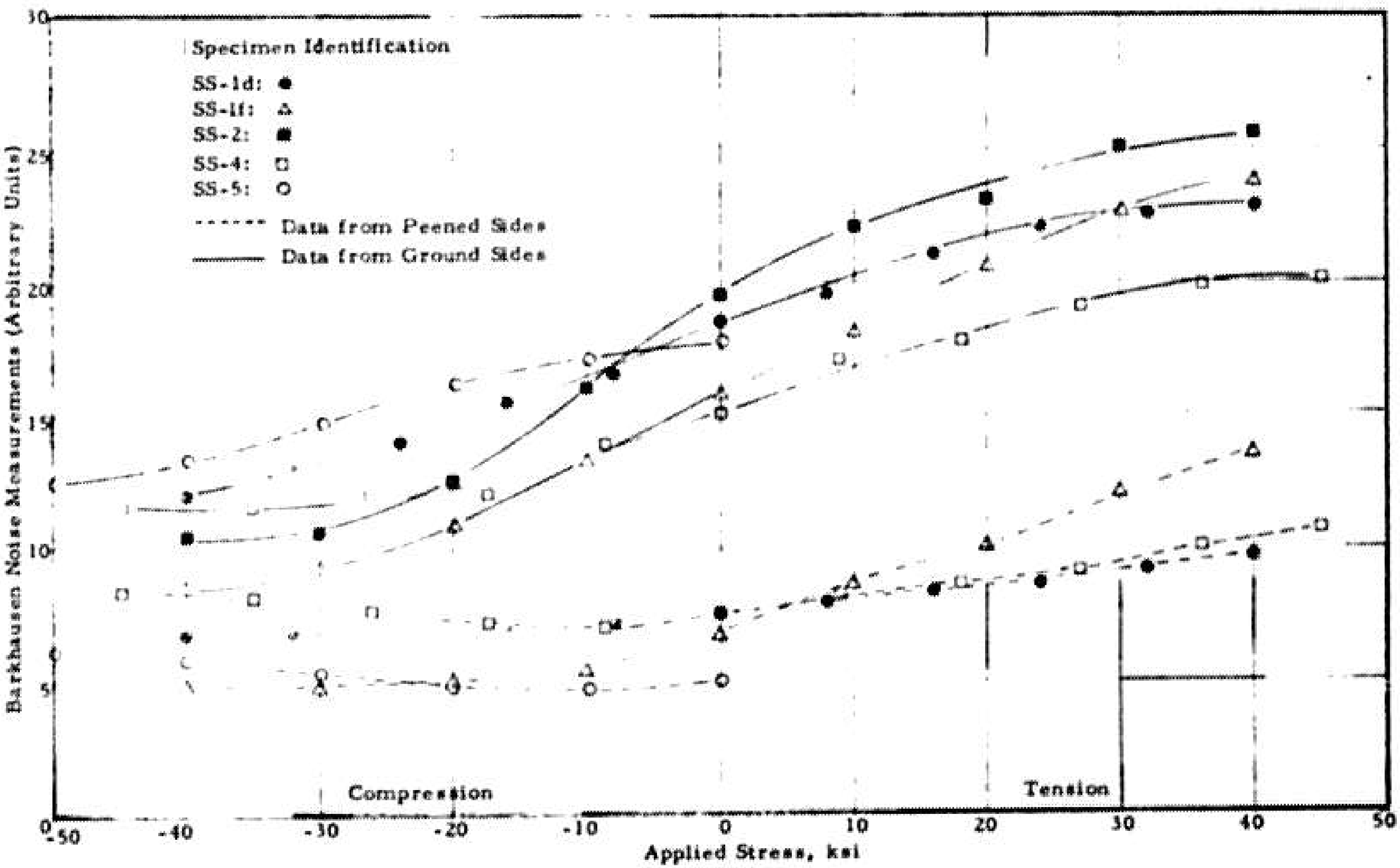


FIGURE C-1. BARKHAUSEN NOISE MEASUREMENTS ON SHOT-PEENED SPECIMENS — APPLIED STRESS

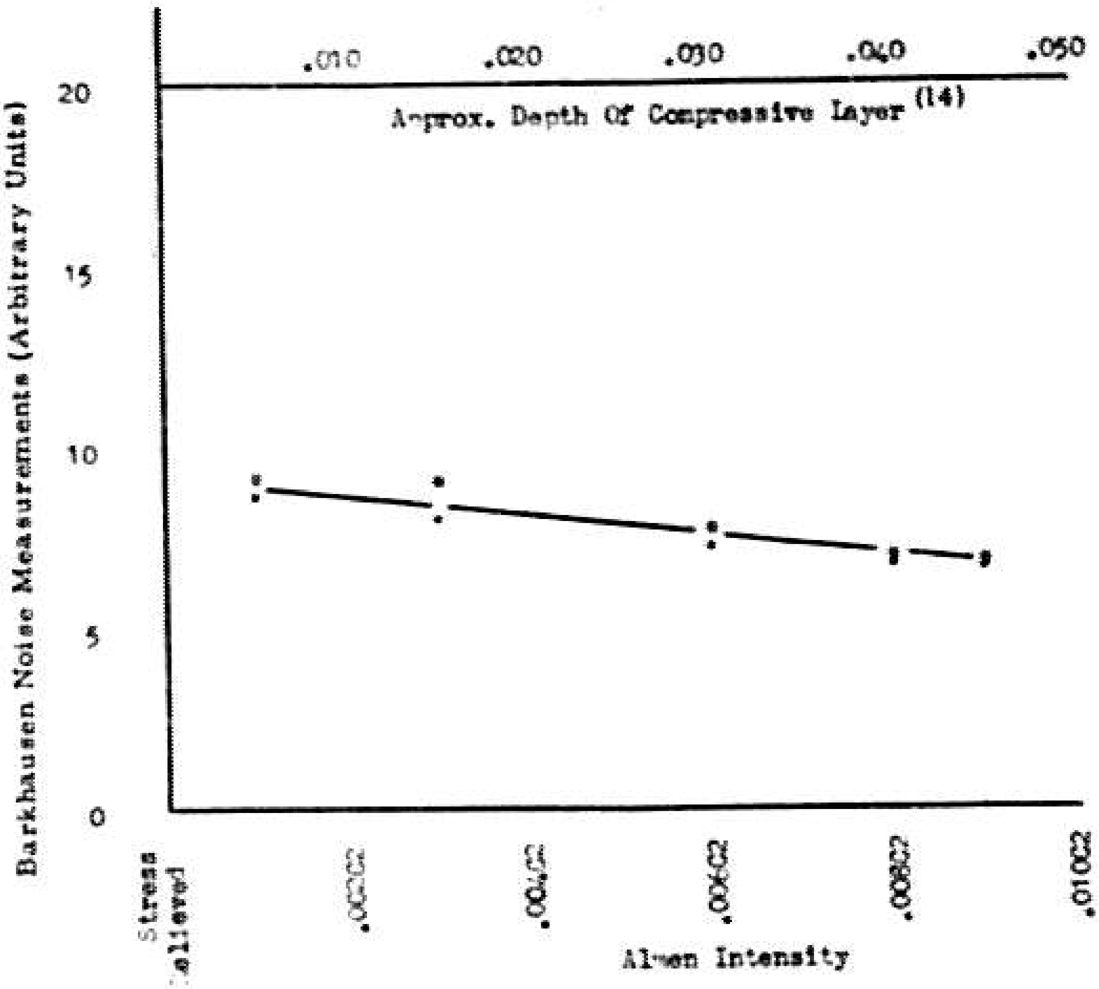


FIGURE C-2. BARKHAUSEN NOISE MEASUREMENTS ON SHOT-PEENED SPECIMENS — ALMEN INTENSITY

APPENDIX D
REPORT OF INVENTIONS

A diligent view of the work performed under this contract has revealed no innovation, discovery, improvement, or invention. However, this study demonstrated, for the railroad wheels evaluated, a qualitative consistency of detecting residual stresses for limited locations on the rim, between the Barkhausen results and the residual stresses determined destructively at USSC. Major changes from compressive to tensile stresses were located on the tread regions and sides of the rims.

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