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EDDY CURRENT TEST FOR BOLTS

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Syed Ali
Robert Maiello

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EDDY CURRENT TEST FOR BOLTS

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he abstract of this report was presented by Syed Ali at the 37th Defense Conference on Nondestructive Testing eld at the Naval Aviation Depot, Jacksonville, FL on 1-3 November 1988.

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ABSTRACT (CONTINUE ON REVERSE IF NECESSARY AND IDENTIFY BY BLOCK NUMBER)

The signal strength and the phase angle of the eddy current indication is a function of metal integrity, stand off yield strength, hardness, grain structure, and electrical conductivity.

This concept was used to differentiate between grade 5, 8, and 8.2 bolts. The statistical analysis of the data obtained from this study shows a high degree of correlation between bolt grade and eddy current indications. Tests were also conducted to detect 5% surface cracks of various orientation and locations using the same eddy current setup. It is concluded that eddy current technique can be used as a reliable inspection method to detect cracks and to differentiate between different grades of bolts.

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PREFACE

In recent years the United States fastener industry has identified the problem of mismarked bolts and screws. These bolts have permeated the entire United States stock of fasteners including the Department of Defense (DOD). The problem of substituting grade 8.2 for grade 8.0 in temperature applications less than $500°F$ is not serious. However, the fact that some foreign manufacturers have substituted cheaper materials raises the question of total fastener quality.

The U.S. Army Armament, Munitions and Chemical Command (AMCCOM) study in mid-1987 into fastener quality requirements identified several improvements to be made in the way the DOD purchases fasteners. One of these improvements was the suggestion that eddy current be investigated as a potential way of providing increased test accuracy at reduced costs.

Chemical composition and tensile testing are time consuming, destructive, and expensive. Prices for these tests range from $200 to $400 per fastener.* By augmenting these tests with eddy current inspection methods we can significantly increase our confidence of purchasing conforming product while reducing costs.

The DOD has spent millions of dollars to screen current field stocks of these mismarked fasteners. At AMCCOM it is believed that eddy current inspection is the one method which can be used to help ensure that this type of problem does not occur again.

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*This refers to 1987 money.

CONTENTS

FIGURES

INTRODUCTION

Theory and Principle of Eddy Current Test (app A)

When a metal part is placed inside or near a coil which is excited by an alternating current, the voltage output from the coil will be affected. This is the basic principle employed by all electromagnetic comparators. The effect that the part has on the output of the coil is directly related to the permeability, conductivity, and physical dimensions of the part.

The voltage output of the coil may be affected in three different ways. The first is amplitude which is a change in the magnitude of the voltage output. The second is a change in the phase which is a change in the time relation of the output voltage. The third is harmonic distortion which occurs when the high power is used on ferrous material to nearly saturate the part. This is usually an excellent way to indicate differences in core hardness. On a linear oscilloscope presentation, the type of wave forms for these various types of changes are shown in figure 1.

The amount of change produced will be affected by the excitation frequency of the coil, the conductivity and permeability of the material, and the sensitivity of the instrument. Nonferrous materials, have differences in electrical conductivity. Magnetic (ferrous) materials have differences in both electrical conductivity and magnetic permeability. The permeability differences generally have a greater effect.

When sorting for differences in dimension, the entire part must be within the field of the coil, except where the differences are those of inside or outside diameter. Dimensional changes will usually produce a difference in amplitude. In some cases of non-magnetic material, they will produce a phase change. Also the phase angle difference between two materials will be greatly affected by the excitation frequency.

Two different ways of looking at signal differences, i.e., linear and vector are shown in figures 1 and 2. Depending on the type of test and equipment used, one will obtain one or the other type of reading.

DISCUSSION

Three hundred bolts were tested in this experiment. Three eddy current instruments were used to observe the repeatability of data: A Nortec NDT-18, Magnetic Analysis PC5, and a Nortec NGT-6D. Both encircling coils and surface probes were used.

Operating procedures depends upon the equipment being used. Procedures must be submitted and approved by the appropriate government agency.

1

In general MIL-STD-410 applies to all NDT system operations. An operator must be at least level I and calibration person shall be at least level II. Procedures are to be written by level III.

The following points must be considered and detailed in operating procedure and followed for setup and operation:

1. Frequency

2. Size of probe/coil

3. Lift off for probe/fill factor for coil

4. Type/style of probe i.e., absolute, differential, etc.

5. Complete coverage of bolt for crack detection

6. Crack (reject) standard for crack detection

7. Reference standard for guide inspection

8. X-Y axis adjustment

9. Orientation of scope to obtain crack signal on x axis and noise/irrelevant signals on y axis

11. Gain control and optimization for the repaired setup

12. Automatic null and/or reset

13. Adjustment of reject level (both audio and visual alarms)

14. Suppression of noise level if applicable

In the first part of this experiment crack simulation and detection was studied. A v-block (fig. 3) was used to hold the bolt and surface probe. The left off was then adjusted to obtain the maximum signal for crack detection. Standard 1/2 - 13 x 14 inch long bolts were used. These standards were designed for worst condition defects and can be used for determining test machine sensitivity and also to calibrate the test machine.

The eddy current signal for three different kinds of defects is shown in figure 4. The large amplitude pluses represent defects while the smaller ripple signal is noise. By choosing a reference amplitude one can distinguish between a bolt with a crack and one without a crack. Note that the signals here are dynamic and depending on the rate of scan one will get multiple pluses at a defect.

During the second part of this experiment eddy current was used to separate bolts by grade. Since one of the variables effecting the eddy current in a material is its electrical conductivity, the eddy current signal can give an indication of this parameter. Using the electrical conductivity of copper as a reference the eddy current signal from grade 5 and grade 8 bolts was compared to the eddy current signal from copper [International Annealed Conductivity Standards (IACS) 100 - 101%]. A representation of grade 5 and grade 8 bolts referenced to copper and titanium is shown in figure 5. In figure 6, one can see two different orientations of the eddy current signal obtained from a sample of copper, titanium and grade 5 bolt and grade 8 bolt. (Note, there are two orientations but it is the relative position that is of importance.)

To measure eddy current signals a Nortec Protable Eddyscope was used (Model NDT-18). The surface probe was held in the apparatus at a constant 0.005 inch lift off. The eddy current signal was measured at two different times during the day and the results were averaged.

Eddy current readings taken on the Nortec -18 (fig. 7) were measured by their horizontal distance from the null value (origin of trace in fig. 7). The horizontal axis of the CRT displays the impedance of the material while the vertical axis displays the reactance of the test material. Eddy current readings in this experiment were relative impedance measurements (unitless) since only CRT divisions were taken as measurements. In figure 7 it can be seen that the grade 8 signal is stronger on the horizontal scale.

Using a Rockwell hardness apparatus hardness readings were taken on the end of each bolt and on the heads. All hardness measurements used SAE standards. The Rockwell hardness plotted for grade 5 and grade 8 bolts is shown in figure 8. The eddy current signal plotted for both grade bolts is shown in figure 9. Note the similarities between the two graphs. Each grade of bolts being separated from the other on the hardness and eddy current scale. A threshold value can be chosen to distinguish between the two grades. The Rockwell hardness as a function of eddy current is shown in figure 10. A linear relationship was assumed between the two and a statistical analysis (app B) shows a high correlation between eddy current and Rockwell hardness for both bolts. It is important to note that the eddy current readings gave an indication of the bolt hardness and were not a measurement of the hardness itself.

Additional tests were done on grade 5 and grade 8 bolts, one using an IBM PC to compare the distorted test signal from a Grade 5 bolt to the signal from a grade 8 bolt. A signal from each bolt using harmonic distortion as an indication of which grade is in the coil is shown in figure 11. Encircling coils were used at a test frequency of 60 cycles. The two grades and the voltage that each distorts the coil is shown in figure 12; grade 8 causes more distortion than grade 5.

The data was statistically analyzed to determine confidence levels although it should be obvious that there was a major difference. As mentioned before, the two tests were averaged and used as a single set of data. Equations were obtained for relationships between eddy current and Rockwell hardness, voltage deflection and eddy current, Rockwell hardness and voltage deflection. As a final test, measurements were graphed against pull test measurements.

The statistical analysis (app B) starts with the comparison of eddy current readings. The eddy current readings (relative impedance) for all 50 samples from tests taken at two different times during the day are shown in appendix B (fig. 1). The results of each test for a particular grade: the mean, standard deviation, and variance (standard deviation squared) is shown in part I (app A). An F test was done on these values. The F test corresponded to a p value in tables that indicated a difference between the two normal distributions of test data. For example, if the two sets of data, taken at different times during the day, gave identical means and distributions for grade 5 bolts, then the F ratio would be one (the variances are equal) and the p value would be expected to be approximately 0.50 for two normal curves that have a fairly even chance of occurrence (50%).

In part 1 (app B), a second test was done called the sign test. This test compares the values in each set of data, in this case measurements made at 1000 and 1300. This test subtracts each set of data , point per point, and notes the sign of the subtraction. For two identical sets of data the number of negative signs should equal the number of positive signs, if not then the data is skewed and not identical. The p value here reflects the distribution of positive and negative signs. These tests indicated the need for recalibration from one test to another but did not visciate the conclusions that grade 5 and grade 8 were differentiated by eddy current signal.

In part 6 of the statistical analysis (app B), the risks were calculated in deciding between grade 5 and grade 8 bolts. The decision e1 represents the chance that it was decided that a bolt was grade 8 when it was actually grade 5. The decision e2 represents the opposite case, when the decision was made that a bolt was grade 8 when it was actually grade 5. Where a decision may be made is illustrated in appendix B (fig. B-11). This illustrates that the data for each grade of bolt is distributed normally but the distributions may overlap at point Z.

The next step in deciding between grades is to establish a decision rule as stated in part 6 (app B). Point Z was chosen as the value to distinguish between grades. If the eddy current reading, Rockwell hardness or voltage deflection is greater than Z, decide the bolt is grade 5 (region e1 in app B, fig. B-11). If the response is less than Z, then decide the bolt is grade 8. The next statement in part 6 (app B) reiterates this by stating that X is the normal curve of grade 5 and Y is the normal curve of grade 8.

The next step in part 6 (app B) is to state that out test measurement, represented by z, falls between the two means. Two assumptions can be made. The first, eq 1 (app B), states that one wants the minimum of the sum of the two errors (e2 + e1) here e2 equals $P(z < Y)$. Again, z is an eddy current, Rockwell hardness or peak voltage reading, and should not be confused with z, the point of intersection.

The second assumption is given in part 6, appendix b, equation 2. This equation states that one wants to minimize the worst of two mistakes in deciding between bolts. Here e2 or e1, whichever is larger, is taken and minimized. Computer programs performed the analysis of these equations to find the point z where the errors e1 and e2 are a minimum. The results are listed in appendix B, part 6. Eddy current, for example shows a mean of 7.1077 for the first equation and an error type e1 of 0.18%. This says that given 10 thousand grade 5 bolts, the eddy current test would mistake 18 of them as grade 8 bolts. Likewise, from equation 1 (app B), the eddy current test would mistake nine out of 10 thousand grade 8 bolts as grade 5 bolts. In a mixture of grade 5 and grade 8 bolts, one can expect approximately 12 out of 10 thousand decisions to be erroneous.

Part 2 of appendix B shows the mean eddy current (relation impedance), and the separated measurements and their distribution are shown in appendix B (figs. B-2 and B-3). Similar graphs (figs. B-4 through B-7) show the test data and how it was distributed for test measurements. A linear regression done on the measured values is shown in appendix B (figs. B-8, B-9, and B-10). Correlation coefficients were found relating eddy current to Rockwell hardness, eddy current to peak voltage, and peak voltage to Rockwell hardness. Shown in parts 3, 4, and 5 (app B) are the coefficient of the fitted line and an F test done on the points.

Another set of eddy current tests was done on a set of 43 grade 5 bolts and 139 grade 8 bolts. Again measurements were taken at two different times during the day to give two test sets. The mean and standard deviation for this set of bolts is shown in part 7 of appendix B. An F test was done on this data and also a T test. Again a p value was obtained that indicated a rare probability of the measurements occurring.

The distribution of pull test measurements is shown in appendix B (fig. B-13). A linear regression was done on the measurements plotted against eddy current, Rockwell hardness, and voltage deflection. The fitted line is shown in appendix B (figs. B-14, B-15, and B-16). Correlation coefficients were computed again for each grade individually and both grades together.

CONCLUSIONS

Eddy current can be used to detect surface cracks at all locations and orientations. Simply receiving a large distortion in the eddy current signal will reveal a defect and a bolt can be rejected by a system on this signal alone. Probes at different positions can give an indication of a crack location but a crack position need not be known for a pass/fail test.

Different grades of bolts can be segregated using an eddy current test system. One can see different eddy current signals for different grade bolts which indicate properties of the bolt such as its Rockwell hardness. Referring to figure 7 one can see that a threshold for eddy current level can be chosen between 6.9 to 7.2, above which a bolt is considered grade 8. Below this level, a bolt is regarded as grade 5.

The results of the statistical analysis test such as the F test and T test show that one cannot assume that two sets of data, taken from one sample of bolts, will be the same. The p values obtained show the probability that one could expect to see the data if measurements were taken again. The low values obtained here, again, suggest that the same sample will give a slightly different measurement each time it is tested.

The results of the decision risk (app A, part 6) shows that the least amount of error was obtained with voltage deflection measurements. This was because the encircling coils used for these measurements gave an average reading as opposed to a surface probe used for the other measurement which gave a more localized reading.

High correlation coefficients from the linear regression accounted for 94% of the errors in eddy current measurements (app B, part 2A). A correlation of 92.8% was obtained relating eddy current and Rockwell hardness (app B, part 2). This leaves 7.2% of experimental errors unaccounted for. Eddy current measurements therefore indicate Rockwell hardness.

Graphically or statistically, this experiment shows that the eddy current test can detect cracks and defects in fasteners. Eddy current methods can also be used to discriminate between grades of bolts as these methods give indications of Rockwell hardness and yield strength.
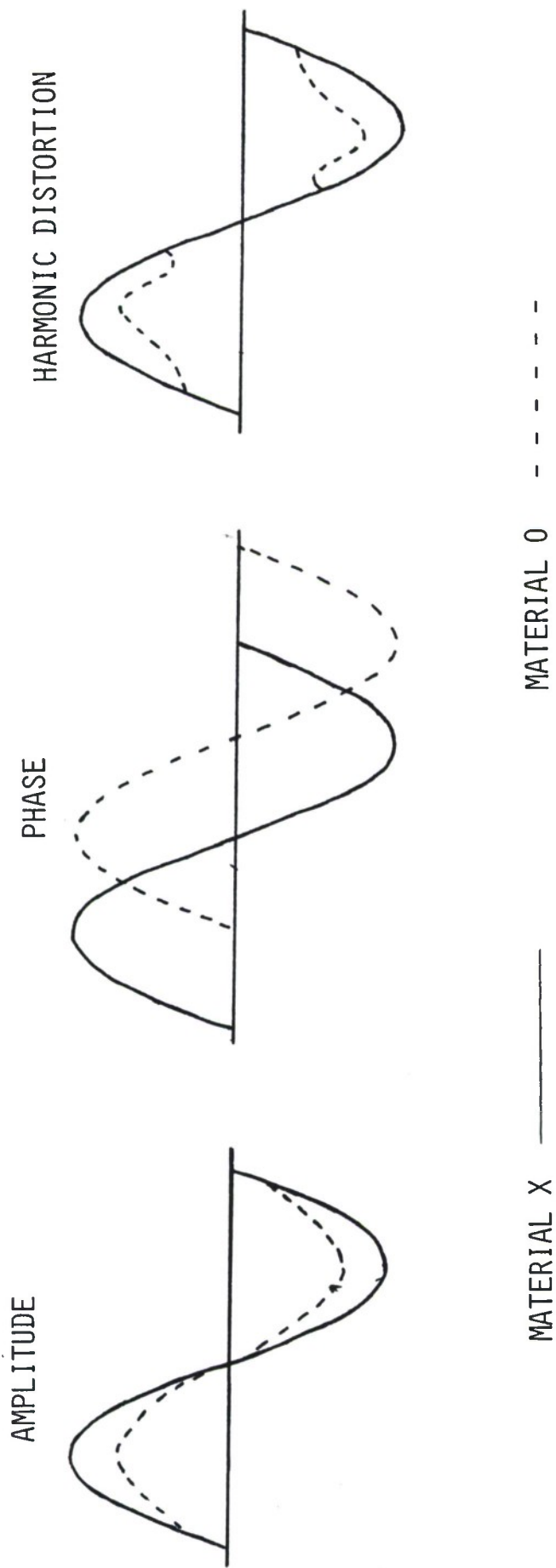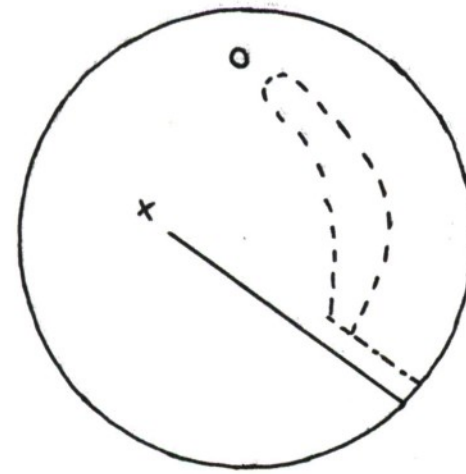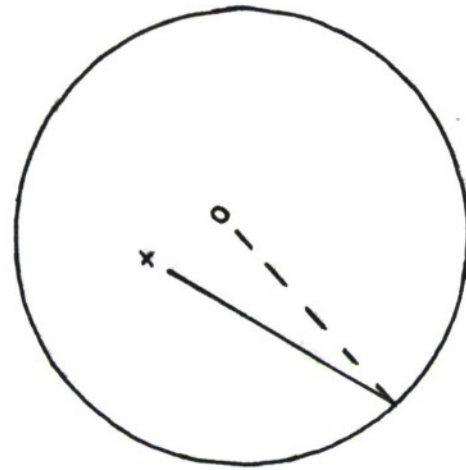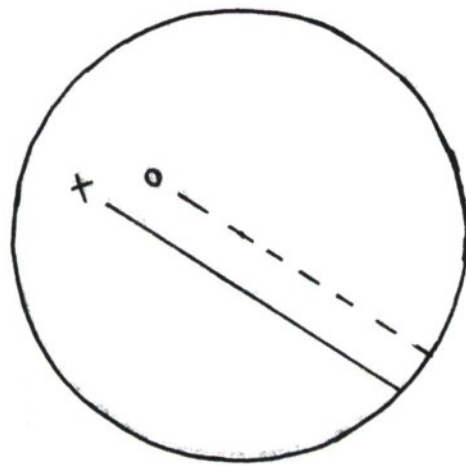
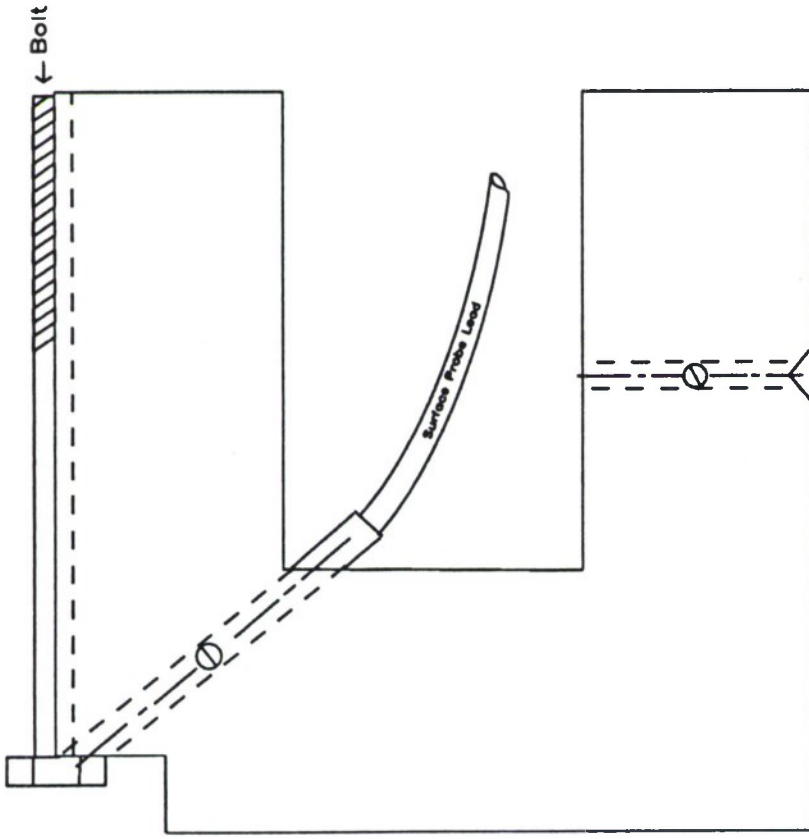Figure 1. Linear presentation

AMPLITUDE

PHASE

HARMONIC DISTORTION

MATERIAL X ——————

MATERIAL O — — — — —

7

AMPLITUDE   PHASE   HARMONIC DISTORTION

MATERIAL X   ———   MATERIAL O   – – – – –

Figure 2. Vector presentation

8

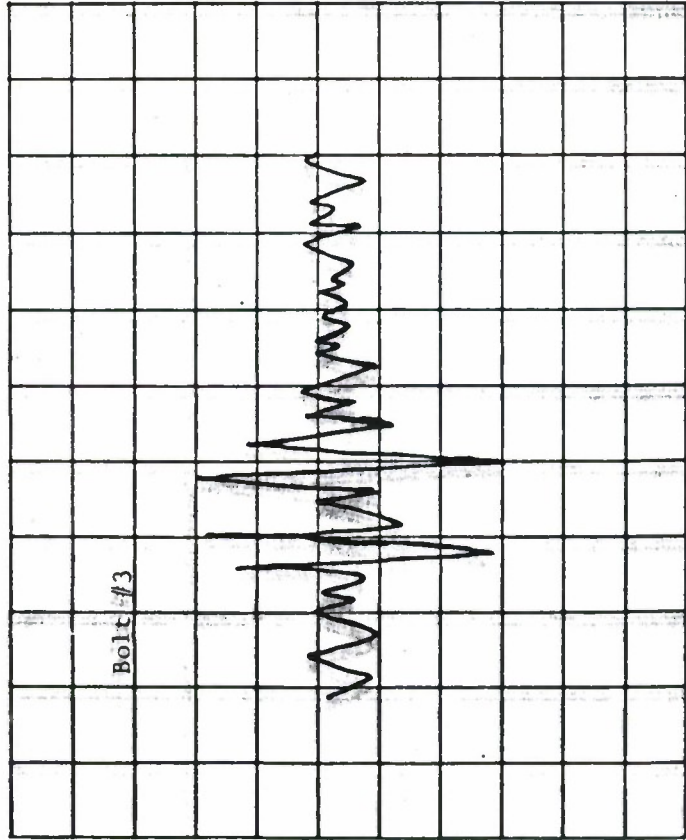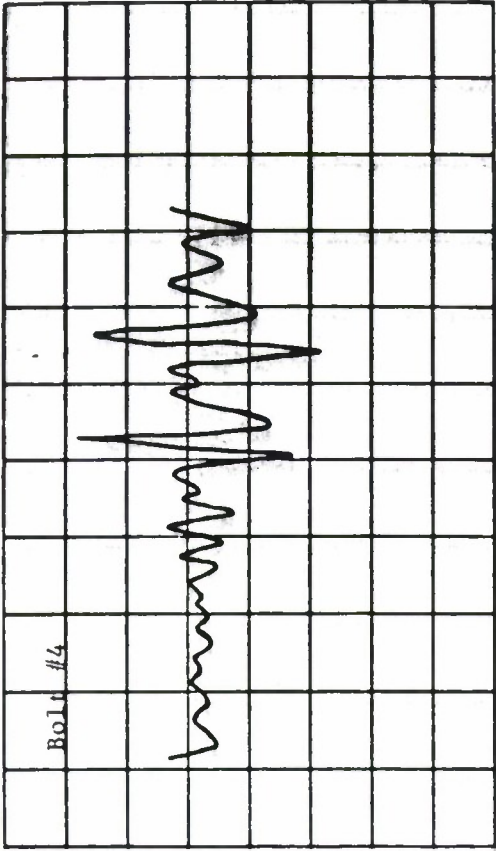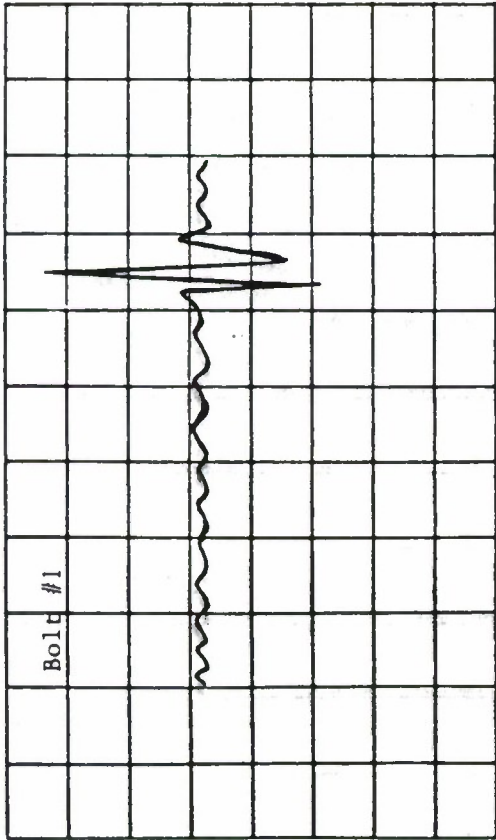side view

← Bolt

Surface Probe Lead

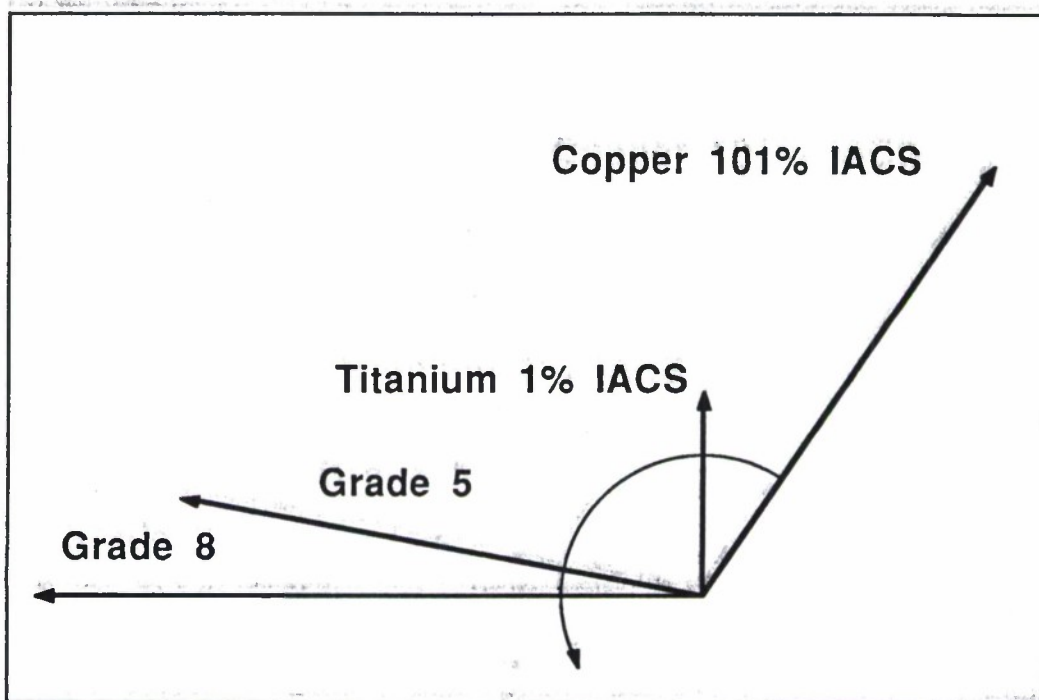top view

Figure 3. V-block

9
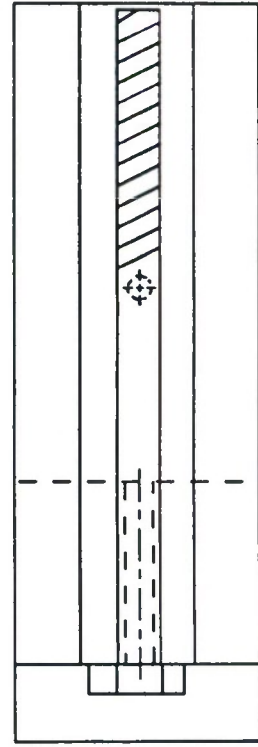
Eddy current   Crack signal
0.025 deep x 0.006 wide x 0.25 long
EDM notch in 0.5 inch bolt

Bolt 1: Longitudinal defect in shank
Bolt 3: 45-deg defect in head and shank joint
Bolt 4: Circumferential defect in Threads
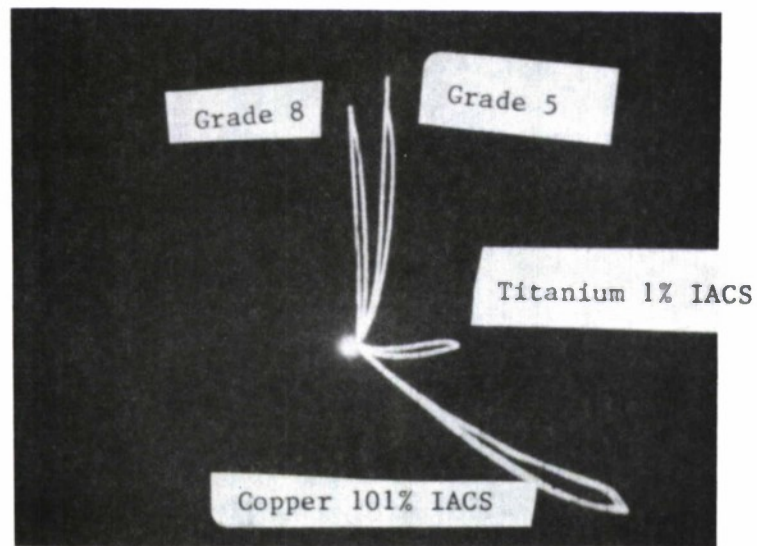
Dynamic signal

Helitester differential probe

Figure 4. Scope display for cracks

10

Using IACS conductivity standard, regardless of the scope orientation or signal configuration,

Grade 5 will always appear at a lesser angle than Grade 8.

Figure 5. Comparison of materials using eddy current techniques
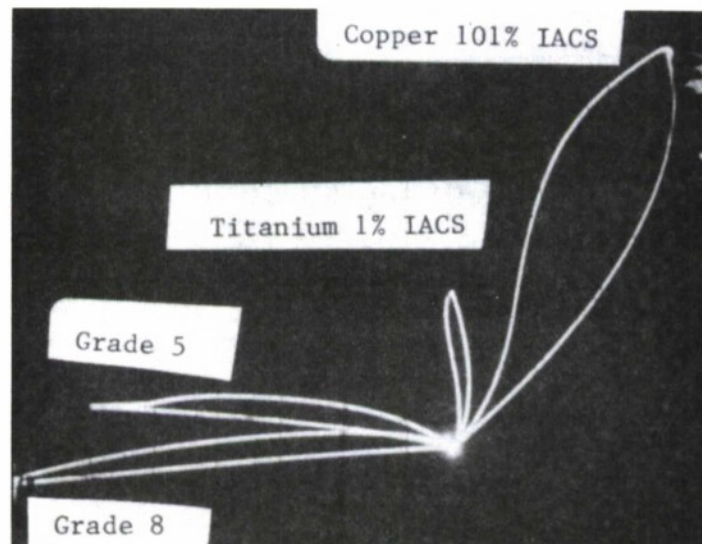
Figure 6. Eddy current signal using Nortec NDT-18 and a 100 kHz pencil probe
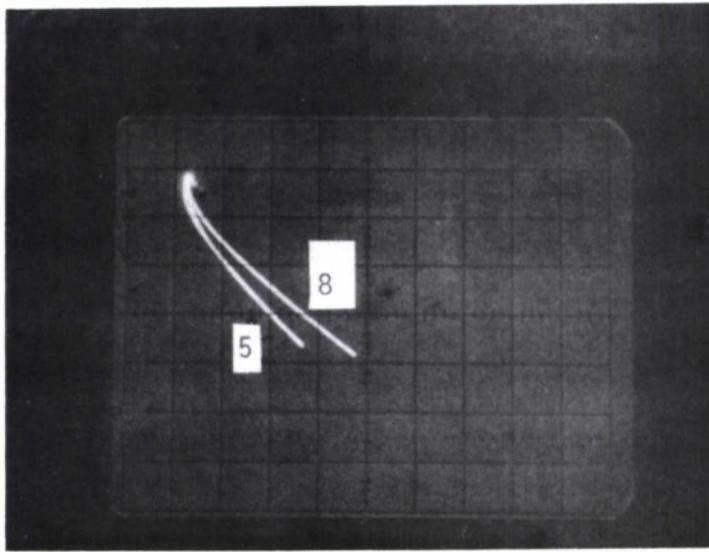
GR5 #17   GR8 #48
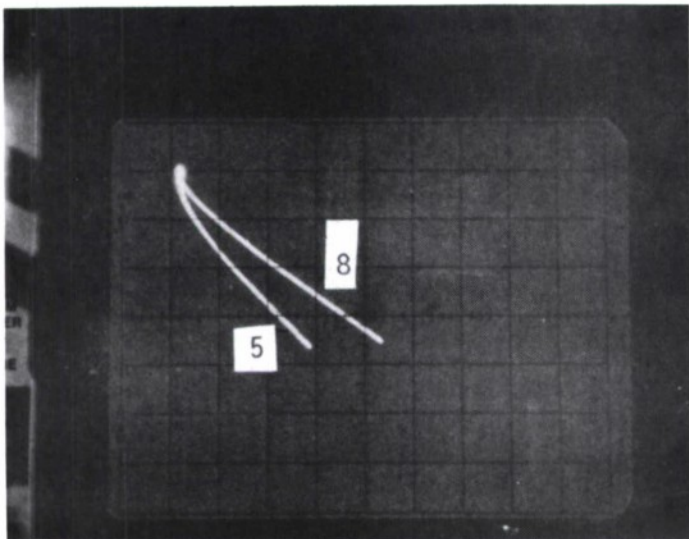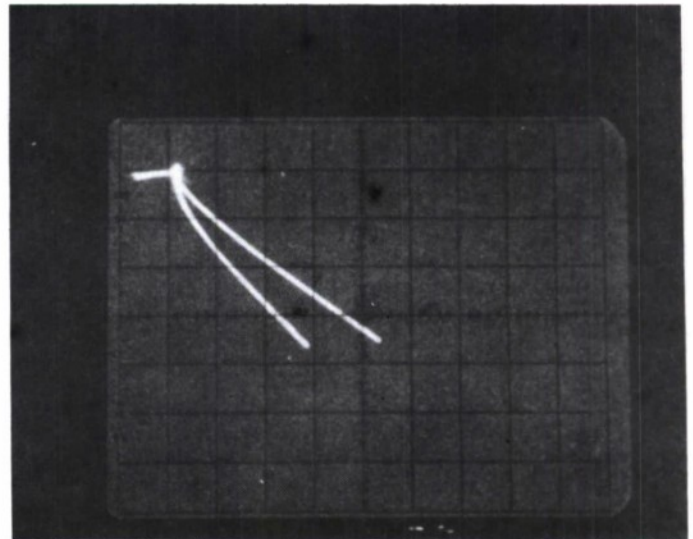
GR5 #24   GR8#32   GR5 #10   GR8 #39

NOTE: Consistent orientation of signal from each grade bolt.

Figure 7. Eddy current signals on the Nortec NDT-18
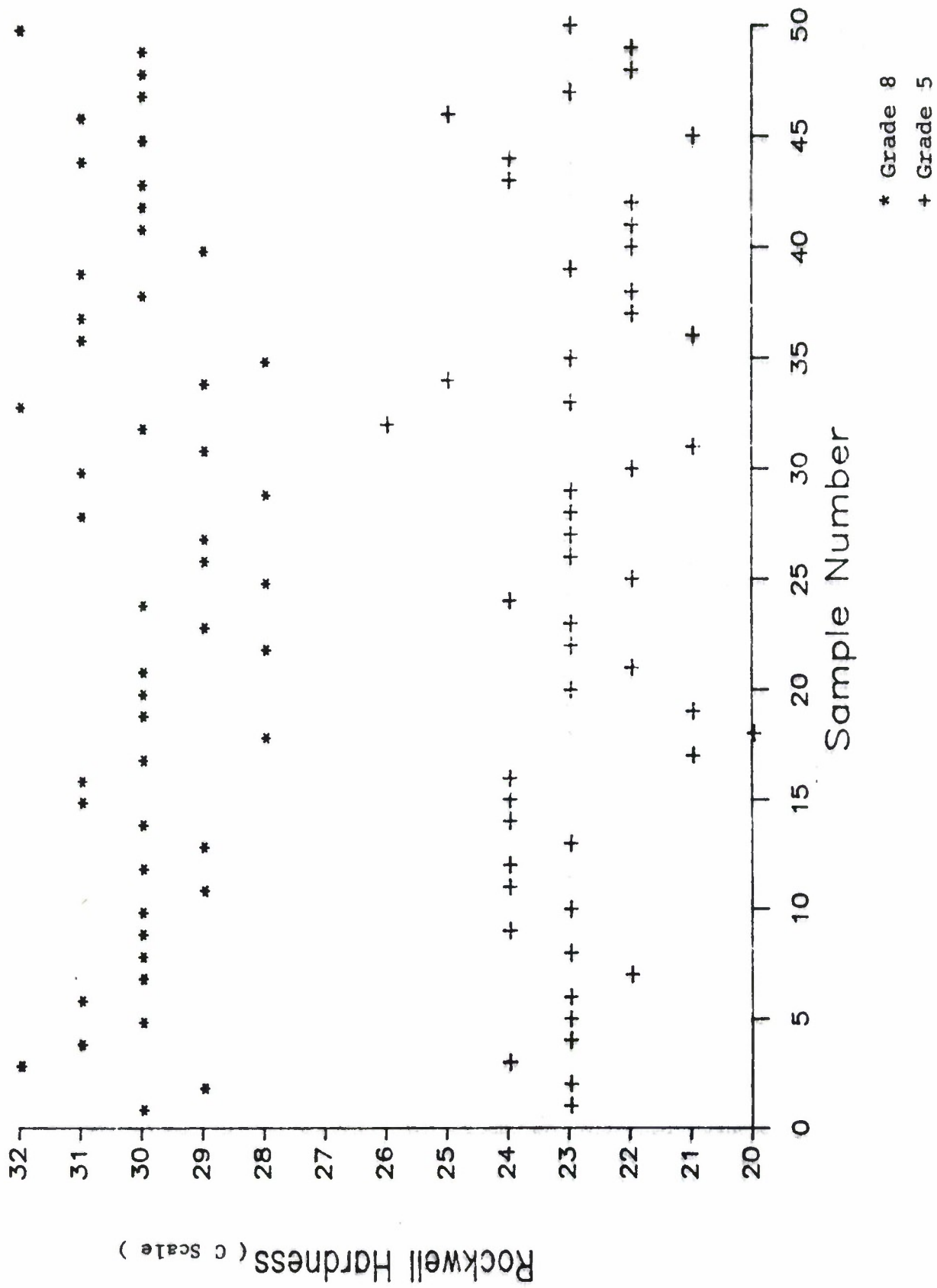
Figure 8. Hardness test for grade 5 versus grade 8

* Grade 8
+ Grade 5

Rockwell Hardness (c scale)

Sample Number

14
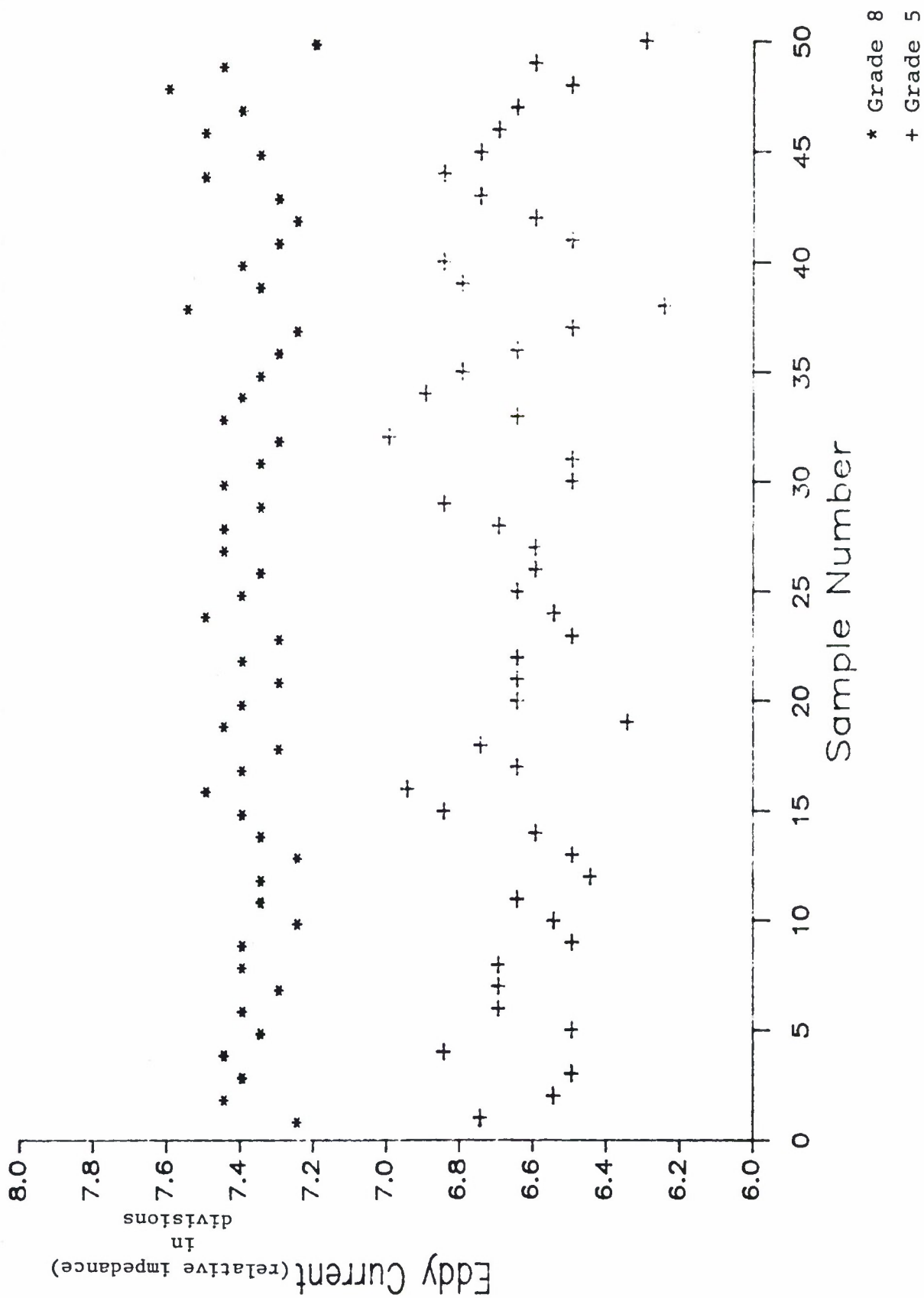
Figure 9. Eddy current tests for grade 5 versus grade 8 using 100 kHz

* Grade 8
+ Grade 5

15
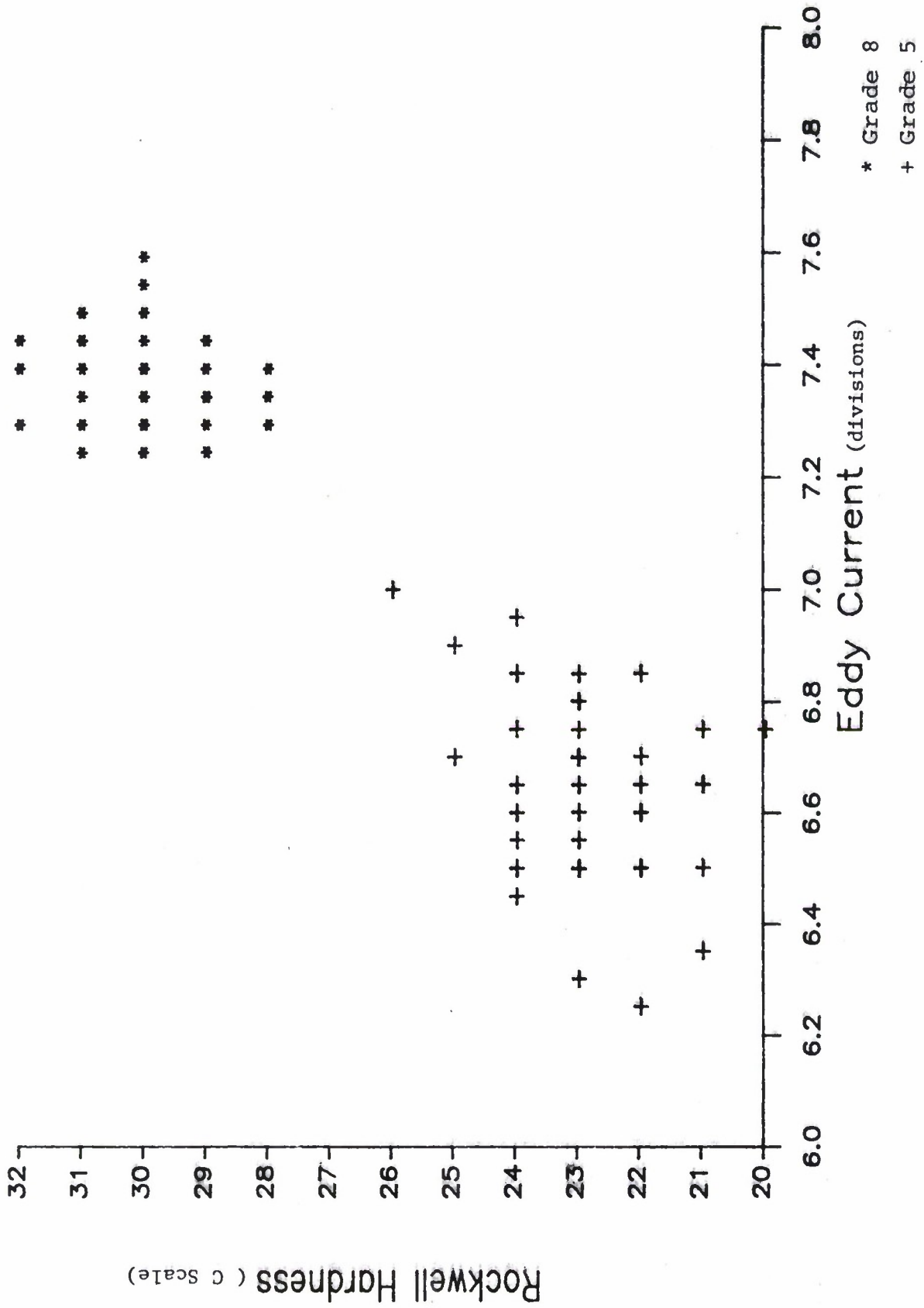
Figure 10. Hardness versus eddy current

* Grade 8
+ Grade 5

Rockwell Hardness (c scale)

Eddy Current (divisions)

16
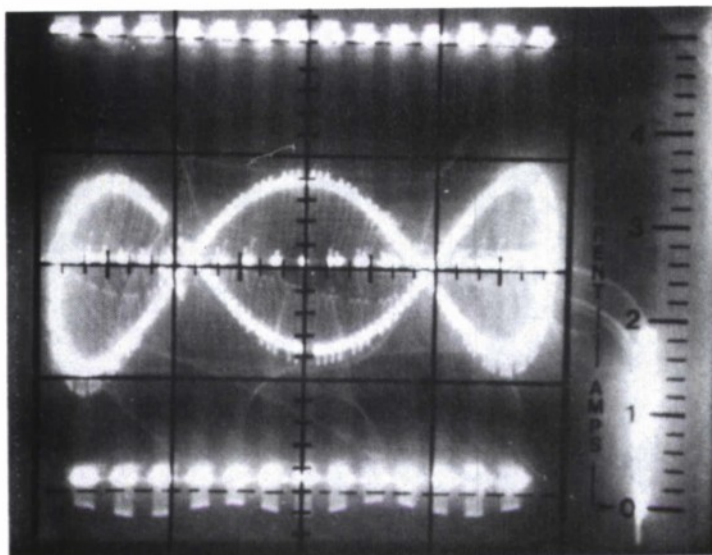
Grade 8 in reference coil
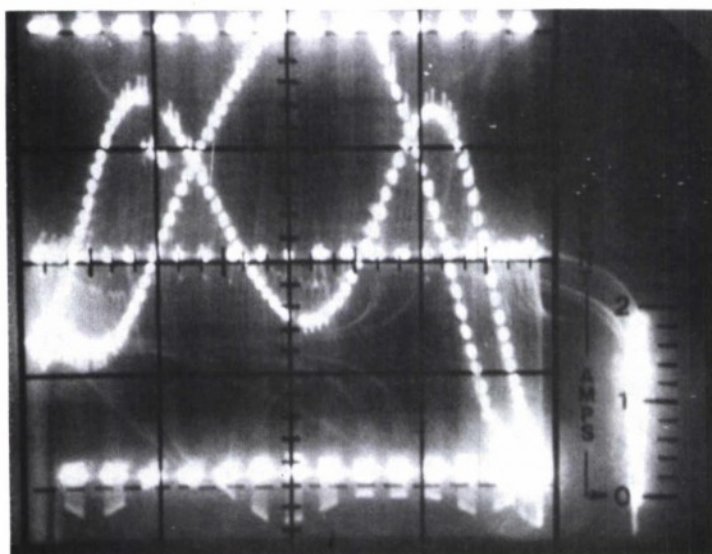
Harmonic distortion due to grade 5 in test coil

Figure 11. Scope display for harmonic distortion
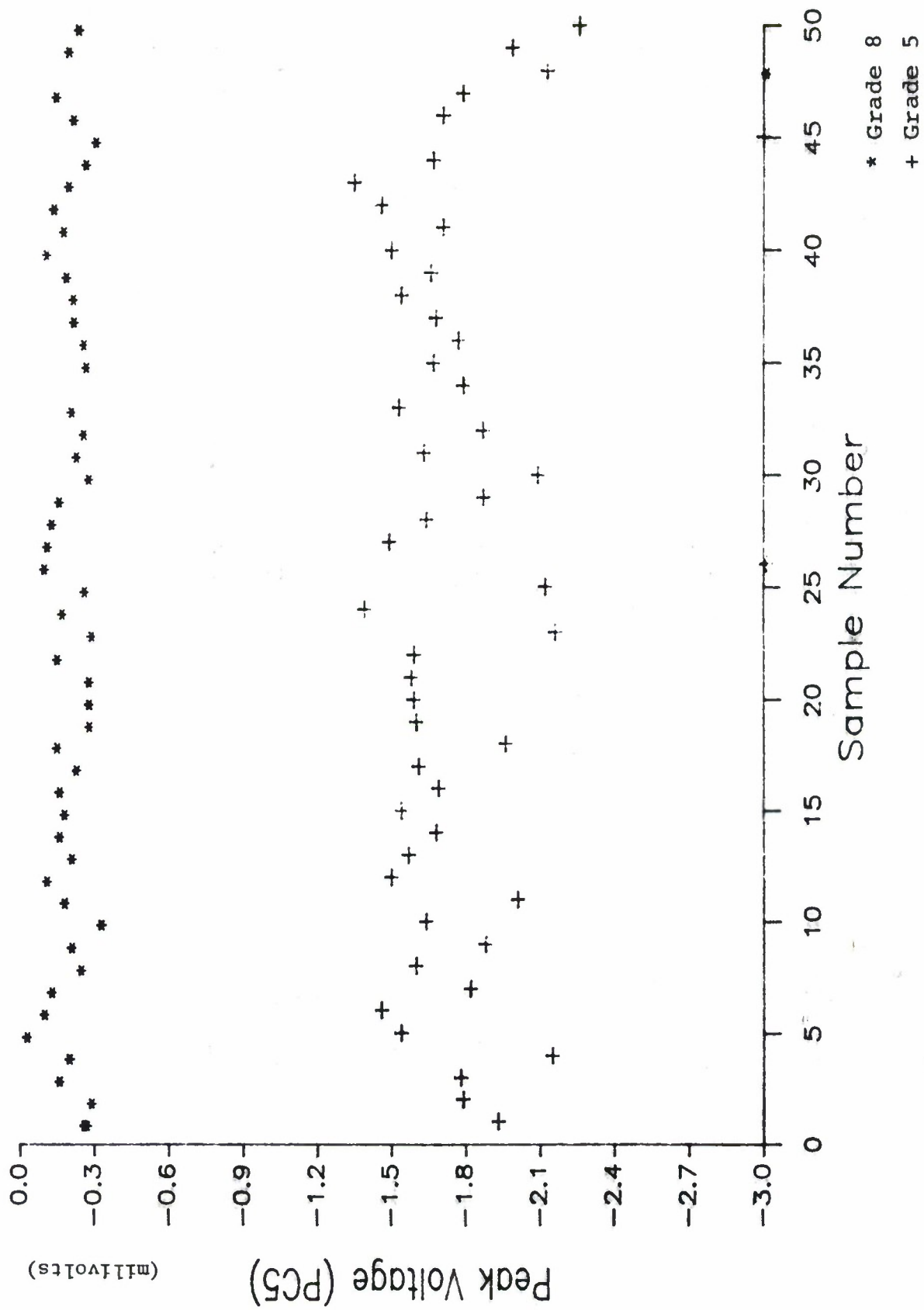
Figure 12. Eddy current for grade 5 versus grade 8 using 60 cycles

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BIBLIOGRAPHY

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2. <u>American Society for Test and Materials</u>, ASTM-E566, 1982.

3. <u>Society for Automotive Engineering</u>, SAE J429, Aug 83

APPENDIX A

ENVELOPE DRAWING

1. PURPOSE:

1.1 These instructions are provided as guidance in the design fabrication and operation of a nondestructive eddy current test system for segregation of (1) defective (cracked) bolts as defined in the standard designs (2) segregation with reference to various grades.

1.2 - Two commercially available testers may be used for this purpose.

2. SYSTEM REQUIREMENTS:

2.1 The inspection system shall be designed to perform automatic inspection for detection of flaws in the areas shown in the standard design and segregation with reference to various grades.

2.2 The System shall be capable of automatically:

    a. Receiving upon demand the bolts.

    b. Securing, manipulating or rotating the bolt as required to accomplish the defect and grade inspection.

    c. Inspect the bolt for defects identified in the standard design and test for grades.

   d. Making an Accept/Reject decision on each item inspected. This decision will be based on the calibration of the system against approved standards, such as comparison with known grades or international conductivity standard and with machined EDM notched standard.

    e. Releasing the items back into the system (or accept bin), with the rejects being removed to the reject station.

2.3 Eddy current transducers fixed and/or moveable as required, shall be chosen to optimize detection of natural discontinuites as represented by notches contained in the standard. Eddy current coils may be used for the identification of grades.

2.4 The sensor or the bolt shall be rotated a minimum of 370° during the inspection for defects.

2.5 The system shall differentiate between lift off or edge effect and defect signals. The system shall clearly distinguish different grades of bolts based on conductivity test.

2.6 The system shall be equipped with an automatic calibration cycle i.e. a mechanism that holds the reject standards, feeds the reject standards thru the system periodically, observes that the standards are rejected and collects the standards back into the standard storage mechanism. If any step of the above cycle is improper the system shall shut off automatically until any malfunction in the calibration cycle is corrected. The intervals of this calibration cycle shall be such that the bolts inspected between two intervals are within a traceable area. If at any time the system is found out of calibration, all bolts inspected since the last successful calibration shall be reinspected after equipment is recalibrated. (Optional)

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2.7   The inspection system shall have the capability of operating in either an automatic or manual mode.   In the automatic mode the system shall repetition sequence through the complete inspection cycle which consists of loading the item into the test position, performing the inspection, unloading the test item and segregating acceptable and unacceptable items in a fail-safe manner. The accept/reject shall normally be in a reject position.   To move the mechanism to the accept position an accept signal will be required at the end of the inspection cycle.   In the automatic mode the system design will be such that once the inspection cycle is started, the operator will have no influence over the system operation.   The emergency stop switch will be the only means of stopping the system immediately while the system is set in the automatic mode.   A normal stop switch will be provided that will allow stoppage while in the automatic mode but only at the end of the inspection cycle regardless of when the switch is actuated.   If during the inspection cycle the emergency stop switch is actuated, the part being inspected will be reinspected after the reason for stoppage in corrected.   The system design shall provide for continuous operation while set in the automatic mode.   That is, the system will continue to sequence through the inspection cycle provided that the next test item is in the feed position.   If while in the automatic mode the next test item is not in the feed position, the system will hold until the next item is in position.   When it is positioned for inspection the sequencing shall automatically start again unless the stop switch has been actuated. When the system is set in the manual mode, sequencing through the inspection cycle will require switch actuation to load, inspect, unload and segregate. While in the manual mode the capability to stop the system anywhere in the inspection cycle shall be provided.

2.8   The system shall reduce the edge effects and lift offs as much as possible.

2.9   The system shall be capable of inspecting various sizes of bolts.

2.10   The system will display a visual & audible reject signal each time a reject decision is made.   The signal will be automatically reset when the item is received into the reject area.

2.11   The systems controls, counters and visual displays shall be located at the Central Control Console.

2.12   The system shall be capable of inspecting the required production rate. Either a multi station system or more than one system may be used.

2.13   The eddy current inspection system shall conform to all plant, municipal, state and national safety regulations.

2.14   The system shall operate with specified performance in a temperature range of +60 to +125 F.

2.15 Precautions shall be taken to eliminate conditions that may contribute to the generation of false reject signals. This would include such features as electrical filtering to suppress spurious electrical signals, shielding and to eliminate picking up radio frequency signals.

2.16 All electrical panels used in the system shall be provided with a means to control the temperature so that the maximum rated temperature of the equipment is never exceeded. The air circulation system used in the cooling shall be equipped with a filter to remove any contaminants which may have an adverse effect on system reliability.

3. STANDARDS:

3.1 Calibration standard for cracks is shown in para 10. Grades are indicated in SAE standard.

3.2 Standards shall be made from defect free bolts. All slots are to be EDM machined.

3.3 Known (certified) SAE graded bolts of same size and configuration shall be used as a standard for grade.

3.4 The international conductivity standard may also be used for initializing the system.

4.0 Eddy current flaw detector - The following characteristics are recommended as a minimum for each required channel:

4.1 The detector shall provide a visual display on an oscilloscope for each sensor/channel response when the system is in the manual mode.

4.2 The oscilloscope shall have sufficient illumination at all detector setting to be viewed under normal industrial conditions.

4.3 Manual horizontal and vertical position controls shall be provided to center the oscilloscope screen display in addition to an automatic compensating null balance circuit.

4.4 The detector operational frequency shall be adjustable and compatible with the sensor used. Sixty (60) cycles is recommended for the coils used for grade inspection and not more than 100 KHz for crack inspection.

4.5 Signal to noise ratio shall be 4 to 1 minimum between the reject signal and extraneous generated noise levels from the eddy current sensor, utilizing the eddy current standard as the reference. Verification of the signal to noise ratio shall be established when calibrating the system with standard.

4.6 If the system design is such that the signal strength is also proportioned to the time interval the flux is being intercepted, the system design shall include a means of maintaining constant RPM of bolts. Indicator(s) shall be provided to detect any deviations from preset RPM. (Optional)

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4.7 The detector shall be housed in a cabinet that meets the electrical Hazardous Designation for the operating area.

4.8 Solid state circuitry shall be utilized throughout the system.

4.9 Spare parts and circuits including sensors shall be provided in quantities necessary to accomplish normal maintenance in order to assure proper equipment availability. Various coils may be required to accommodate different diameter bolts.

4.10 Provisions shall be made to lock a cover panel over the instrumentation controls.

5.0 <u>Sensor</u> The sensor holding mechanism shall have the following features:

5.1 The sensor holding mechanism shall provide stability to insure sensor alignment, and minimize vibration throughout the range of system operational speed.

5.2 Direct contact of sensor with the bolt body shall be avoided. The signal amplitude shall remain constant within 15% in the normal lift off operating range.

5.3 The frequency of sensor shall be compatible with the detector. See para 4.4

6.0 Test:

A dynamic test will be conducted after the system has been set up in accordance with the operating instructions. The test will be conducted to demonstrate the adequacy of the detection capabilities of the inspection system. A plan defining details of the test will be prepared and submitted to Commander, AMCCOM, Picatinny Arsenal, NJ 07806-5000, ATTN: AMSMC-QAH-T(D) for approval.

7.0 Approval (AMSMC-QAH-T(D)) of the following is required prior to fabrication of the equipment.

    a. Inspection System Designs.

    b. Specifications for Commercial Items.

    c. Set Up Procedures.

    d. Calibration Procedures.

    e. Operating Instructions.

8.0 <u>USE OF INSPECTION SYSTEM</u>:

As a minimum the adequacy of the inspection system shall be checked by the use of standards at the start and finish of each inspection shift or change of operator, as well as at one hour intervals during inspections. All (coils & probes) shall properly indicate a reject signal when a defect is encountered. If the inspection process is determined to be inadequate, the condition shall be corrected and all items inspected since the last acceptable inspection check shall be reinspected. Equipment used shall provide for a positive activation of a buzzer or alarm and a reject light for each channel to alert the operator of signal indications exceeding the reject amplitude. A log book shall be maintained by the operator of each system which as a minimum will document the use of standards, number of items inspected, number of suspects and rejects by grades and cracks, changing of sensors, instrumentation repairs, reasons for malfunctions, if any, and changes of qualified operators. This log book shall be made available when requested for government review.

9. Suggested Sources.

   Intricate Machine and Engineering, Inc.
   16 Extension St.
   P.O. Box 505
   Attleboro, MA   02703

   Rompas N.D.E.
   1001 W. 17 St.
   Suite U
   Costa Mesa, CA   92627

   Magnetic Analysis Corp.
   535 South 4th Ave.
   Mount Vernon, NY   10550

   Nortec Instruments Inc.
   421 N. Quay Street
   Kennewick, WA   99336

   Magnaflux Corporation
   1600 Harrison Ave.
   Mamaroneck, NY   10543

   K. J. Law
   23660 Research Ave.
   Farmington Hills, Michigan   48024

   Balteau Electric Corp.
   63 Jafferson St.
   Stamford, CT   06902

Forester Instrumentation, Inc.
202 Rosemont Dr.
Cerapolis, PA 15108

Shurtronics Corp.
2541 White Road
Irvine, CA 29724

Hentschel Instrument, Inc.
2505 S. Industrial Highway
Ann Arbor, MI 48104

10 Defect (crack) Standards

Longitudinal crack is the shank .025 deep x .25 long x .004 wide.
Circumferential crack is the minor diameter of threads .025 deep x .25 long
x .004 wide. 45° crack is the joint of head and shank .025 deep x .25 long
x .004 wide. 45° orientation is from the longitudinal axis of the bolt with
the notch in the head of the bolt.

11. For clarification & details please contact Mr. Syed M. Ali,
AMSMC-QAH-T(D), AMCCOM, Picatinny Arsenal, NJ 07806-5000

APPENDIX B

STATISTICAL ANALYSIS FOR GRADE 5 AND GRADE 8

Eddy Current
Hardness Test Data

Rockwell Machine Tolerance ±1 number
Human error in readout ±1 number

Eddy Current Scope Readout
Human error +.2

Temperature Variation is to be applied

Instrument: NORTER NDT-18
Setting:
Horizontal Position 1-1
Vertical Position   1-5
Gain   35
Frequency   100 KHz
Probe - Pencil

Statistical Analysis of Grade 5 and Grade 8 bolts

This Appendix is divided into 7 parts, each labeled numerically.

The first part below shows the mean for the two test, test 1 and test 2.

Part -

1. Comparison of Repeat Eddy Current Readings. See Figure B-1

   Bolts Grade 5:

   Eddy Current Data- $\bar{X}_1 = 6.566$ $s_1 = 0.1975$ $s_1^2 = 0.0390$

   $\bar{X}_2 = 6.716$ $s_2 = 0.1503$ $s_2^2 = 0.0226$

   $F = 0.0390/0.0226 = 1.73$ ==> $p = 0.0295$ ==> significant difference in variability of first reading and second reading.
   Based on Sign Test mean of first readings significantly less than mean of second readings , $p = 0.00015$

   Bolts Grade 8:

   Eddy Current Data- $\bar{X}_1 = 7.340$ $s_1 = 0.1125$ $s_1^2 = 0.0127$

   $\bar{X}_2 = 7.418$ $s_2 = 0.0825$ $s_2^2 = 0.0068$

   $F = 0.0127/0.0068 = 1.86$ ==> $p = 0.0162$ ==> significant difference in variability of first reading and second reading.
   Based on Sign Test mean of first readings significantly less than mean of second readings , $p = 0.05946$

In what follows the average of the two readings for Eddy Current was used.

- -

2. Statistics for Test Results.

	Bolts 5	Bolts 8	
Mean Eddy Current	6.641	7.379	Figs B-2 & B-3
SD Eddy Current	0.160	0.087	
Mean Rockwell Hardness	22.86	29.96	Figs B-4 & B-5
SD Rockwell Hardness	1.16	1.03	
Mean Peak Voltage (PC5)	-1.770	-0.250	Figs B-6 & B-7
SD Peak Voltage	0.333	0.402	
Mean Peak Voltage (PC5) w/o	-1.719	-0.194	Fig B-7
SD Peak Voltage w/o	0.222	0.066	
Corr Between EC & RH	0.329	0.127	Fig B-8
Combined Corr Betw EC & RH	0.928		Fig B-8
Corr Between PV & RH	0.081	-0.020	Fig B-9
Combined Corr Betw PV & RH	0.938		Fig B-9

2A. Statistics for Test Results.

	Bolts 5	Bolts 8	
Mean Pull Test	11019.4	13158.5	Fig B-13
SD Pull Test	198.4	94.7	
Corr Between EC & PT	0.265	-0.312	Fig B-14
Combined Corr Betw EC & PT	0.942		Fig B-14
Corr Between RH & PT	0.213	-0.137	Fig B-15
Combined Corr Betw RH & PT	0.951		Fig B-15
Corr Between PV & PT	-0.083	-0.019	Fig B-16
Combined Corr Betw PV & PT	0.888		Fig B-16

----

3. Regression of Hardness on Eddy Current: See Figure B-8

	Coef	Std Err	t Value
Intercept	-35.49517	2.505027	-14.16958
Eddy Current	8.83098	0.356798	24.75065

Residual Standard Error = 1.392655   Multiple R-Square = 0.862087
N = 100   F Value = 612.595 on 1, 98 df

Covariance matrix of coefficients:

	Intercept	Eddy Current
Intercept	6.275161	
Eddy Current	-0.892406	0.1273047

----

4. Regression of Hardness on Peak Voltage: See Figure B-9

	Coef	Std Err	t Value
Intercept	30.68327	0.2062292	148.7823
Peak Voltage	4.44914	0.1680104	26.48134

Residual Standard Error = 1.289545   Multiple R-Square = 0.880692
N = 97   F Value = 701.261 on 1, 95 df

Covariance matrix of coefficients:

	Intercept	Peak Voltage
Intercept	0.04253050	
Peak Voltage	0.02676957	0.0282275

----

5. Regression of Eddy Current on Peak Voltage: See Figure B-10

	Coef	Std Err	t Value
Intercept	7.44979	0.0233722	318.7460
Peak Voltage	0.46288	0.0190408	24.3097

Residual Standard Error = 0.146146   Multiple R-Square = 0.861508
N = 97   F Value = 590.962 on 1, 95 df

Covariance matrix of coefficients:

	Intercept	Peak Voltage
Intercept	5.462596e-4	
Peak Voltage	3.438270e-4	3.625527e-4

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6.Decision Risks

	Actual	
	Grade 5	Grade 8
Grade 5	$1 - e_1$	e_2

Decide

Grade 8	e_1	$1 - e_2$

Decision Rule: Decide Grade 5 if response (i.e. RH, EC, PV) is greater than Z, Grade 8 otherwise. (Note: this assumes that the average response for Grade 5 bolts is less th Grade 8 bolts. If this is not the case, then simply reverse the roles of the 5's and 8's.) Z is the solution of the following:

With , $e_1 = P(X > Z)$ and $e_2 = P(Y < Z)$,

given $X \sim N(m_5, s_5^2)$, $Y \sim N(m_8, s_8^2)$, want to minimize G over z,

$m_5 < z < m_8$, where:

   (1) $G = P(X > z) + P(Y < z)$

   (2) $G = \max[P(X > z) , P(Y < z)]$

Solutions to above problem for:

   A. EDDY CURRENT

(1)	7.1077	$e_1 = 0.18\%$	$e_2 = 0.09\%$
(2)	7.1191	$e_1 = 0.14\%$	$e_2 = 0.14\%$

   B. ROCKWELL HARDNESS

(1)	26.60	$e_1 = 0.06\%$	$e_2 = 0.06\%$
(2)	26.62	$e_1 = 0.06\%$	$e_2 = 0.06\%$

   C. PEAK VOLTAGE

(1)	-0.5556	$e_1 = 0.00\%$	$e_2 = 0.00\%$
(2)	-0.5435	$e_1 = 0.00\%$	$e_2 = 0.00\%$

7. Comparison of Test 1 and Test 2 Results for Eddy Current:

See Figure B-12

. Grade 5 Bolts:

	Test 1	Test 2
Mean of Eddy Current	6.641	6.705
SD of Eddy Current	0.160	0.204

$F = 0.204/0.160 = 1.275 \implies p = .21 \implies$ Variances not sig. diff.

Therefore pooled SD for Eddy Current = 0.180

$t = (6.705-6.641)/[0.180(1/50 + 1/43)^{1/2}] = 1.7016$

$\implies p = 0.046 \implies$ Means are significantly different.

Grade 8 Bolts:

	Test 1	Test 2
Mean of Eddy Current	7.379	7.580
SD of Eddy Current	0.087	0.111

$F = 0.111/0.087 = 1.270 \implies p = .17 \implies$ Variances not sig. diff.

Therefore pooled SD for Eddy Current = 0.104

$t = (7.580-7.379)/[0.104(1/50 + 1/139)^{1/2}] = 11.68$

$\implies p = 0.000 \implies$ Means are significantly different.

Based on these results it is recommended that additional eddy current tests be conducted on test 1 and test 2 bolts using a standard on two different occasions so that readings can be properly zeroed.
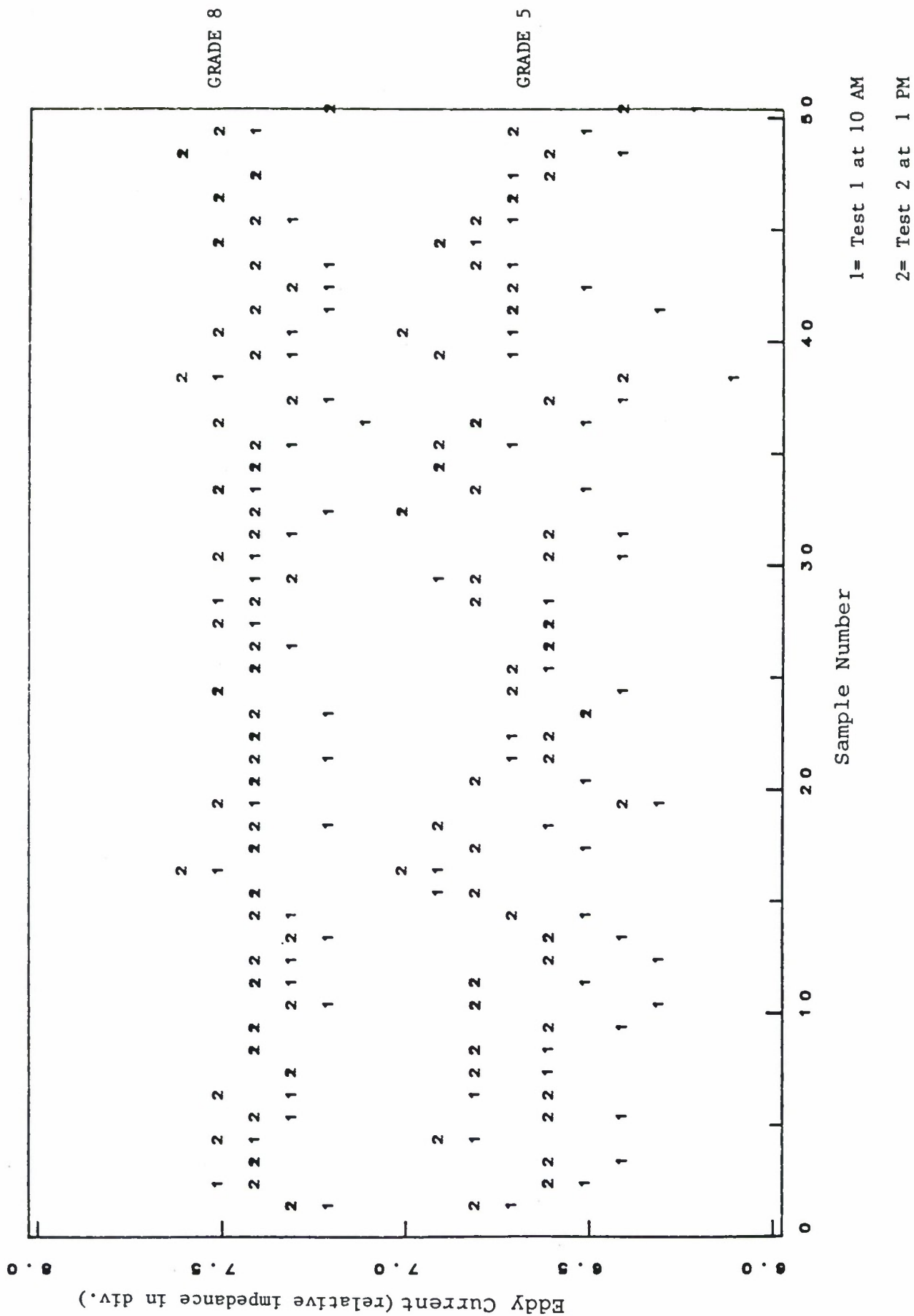
Figure B-1. Statistical analysis

1= Test 1 at 10 AM

2= Test 2 at 1 PM

GRADE 8

GRADE 5

Eddy Current (relative impedance in div.)

Sample Number

37
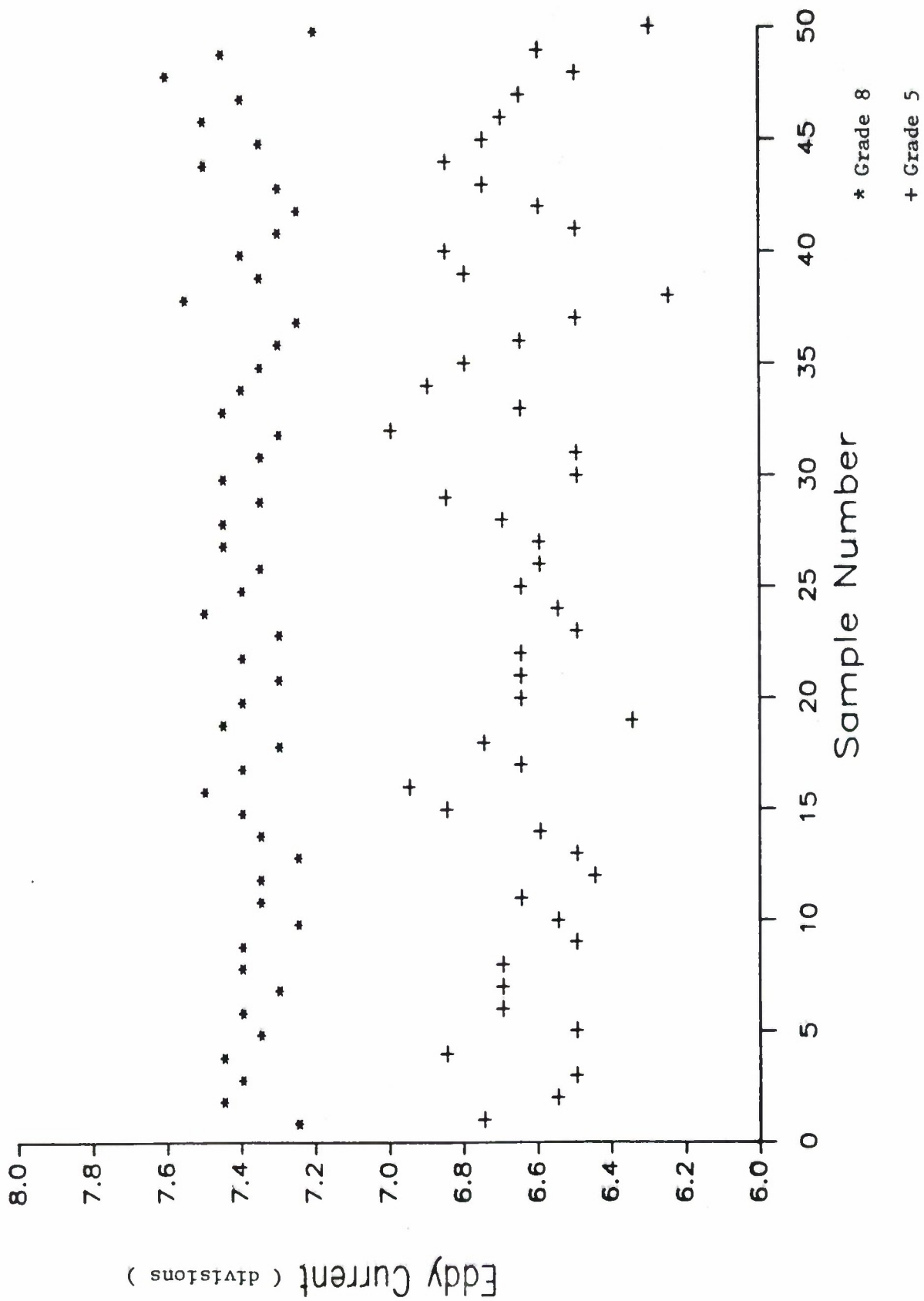
Figure B-2. Grade 5 versus grade 8 (eddy current)
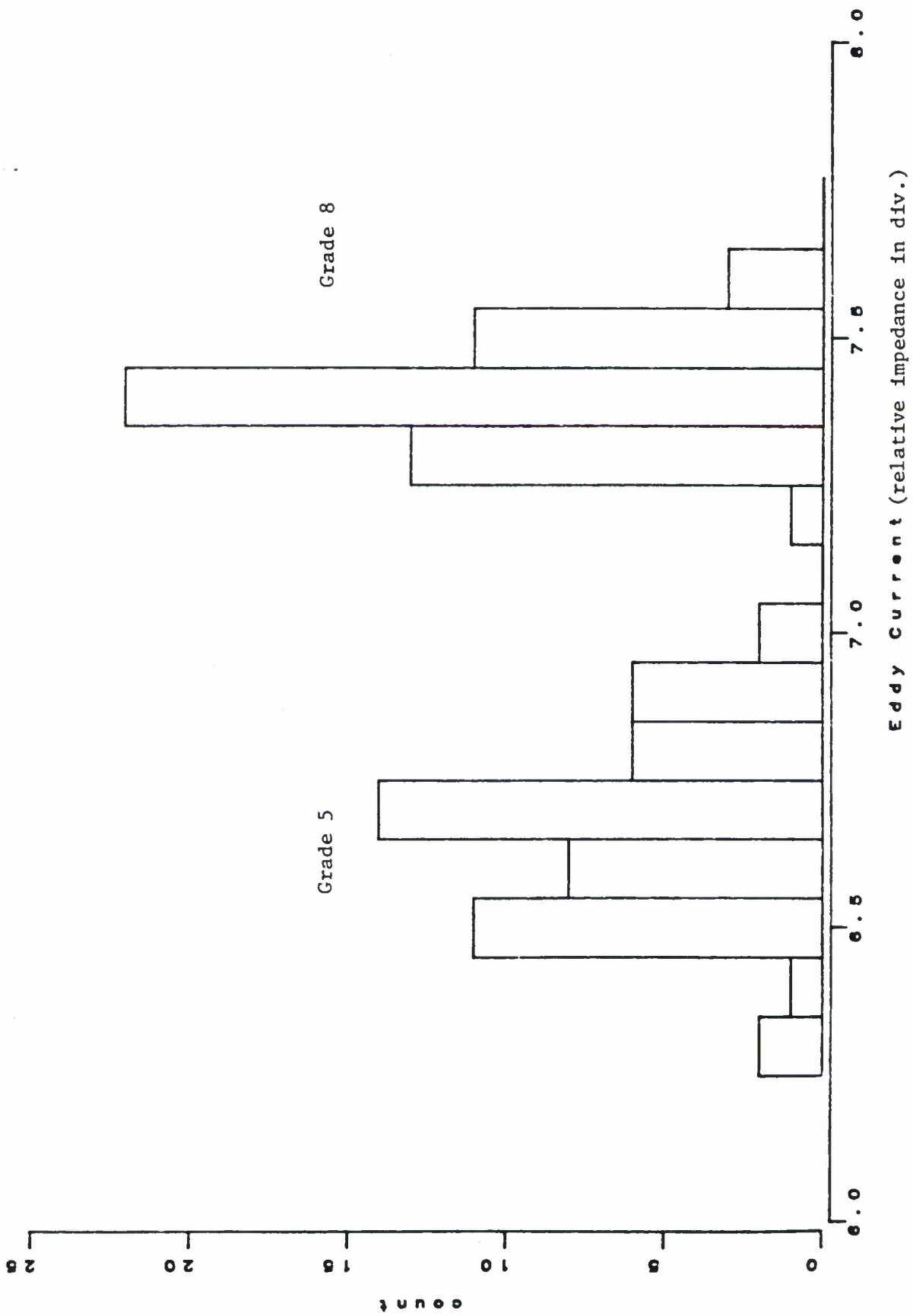
Figure B-3. Eddy current (5 versus 8)
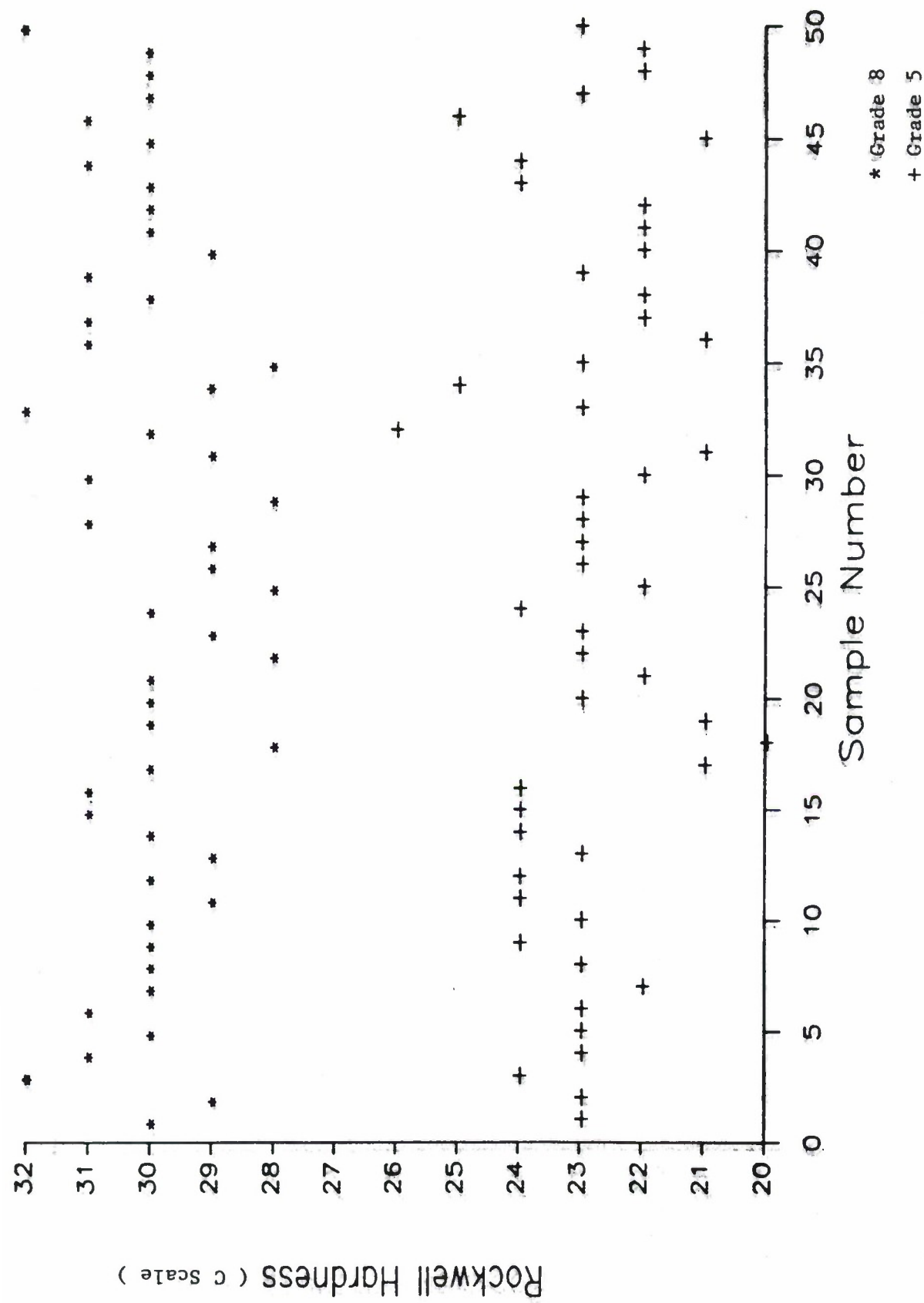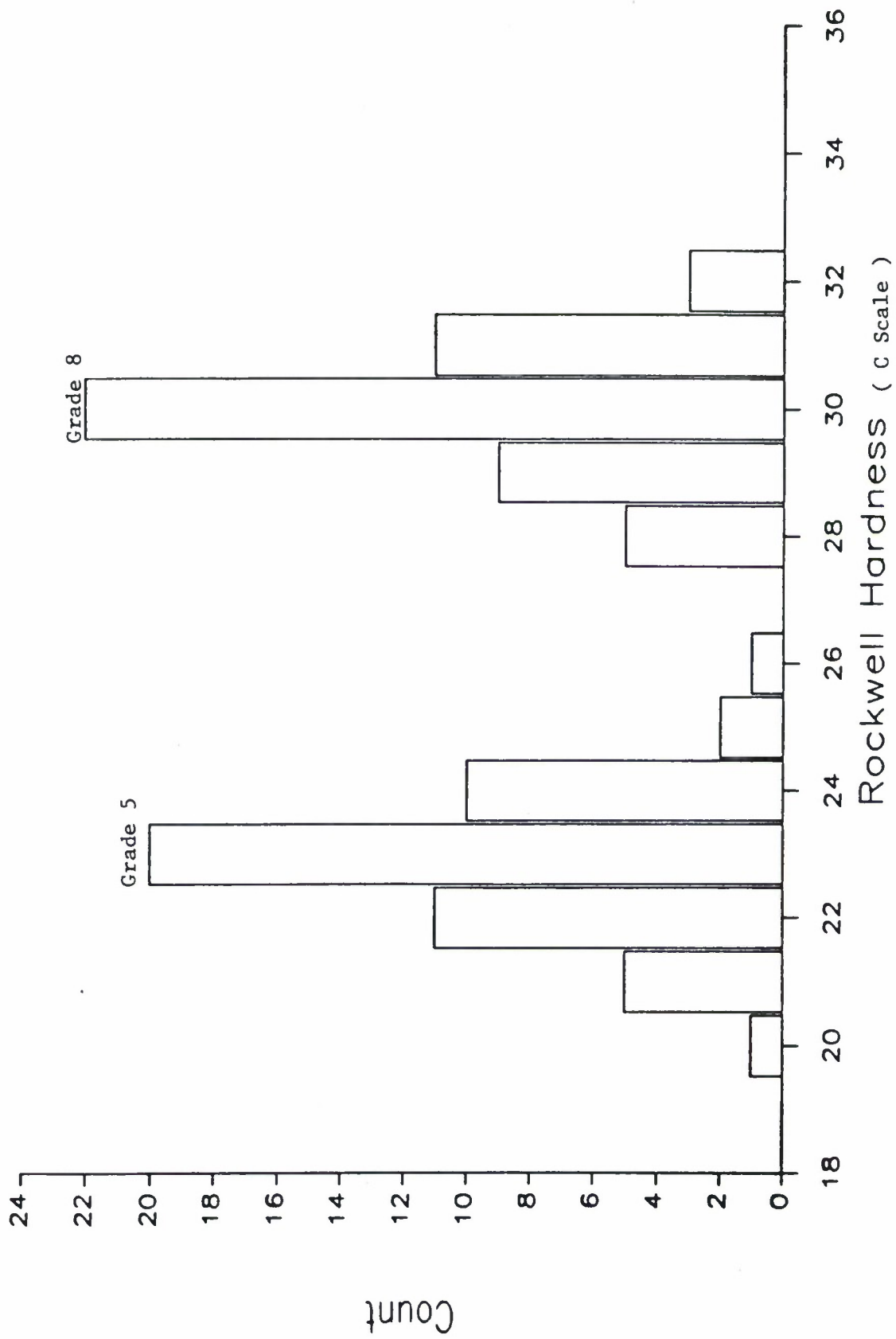
Figure B-4. Grade 5 versus grade 8 (Rockwell hardness)
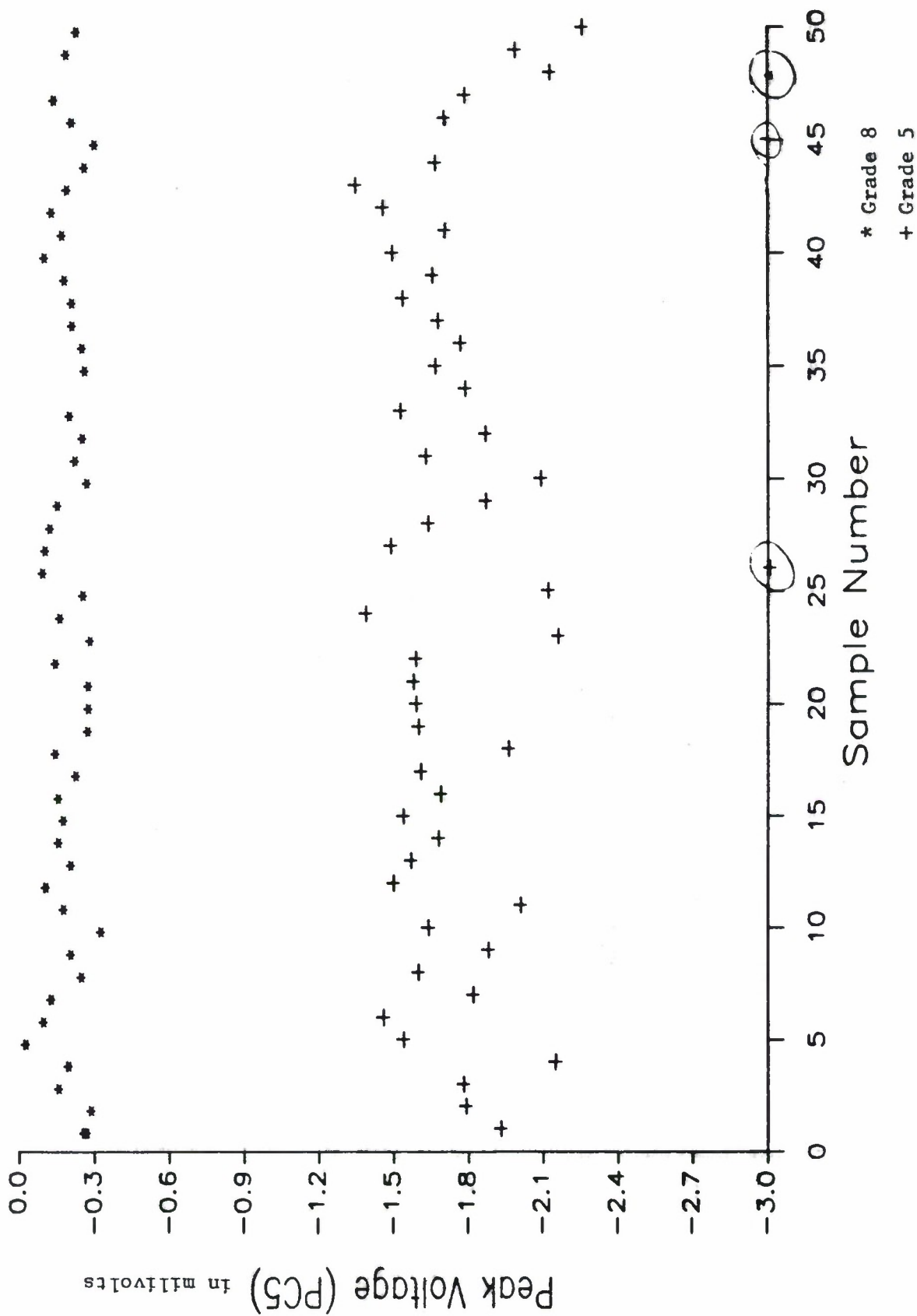
Figure B-5. Bolt hardness (5 versus 8)

Figure B-6.   Grade 5 versus grade 8 (peak voltage)
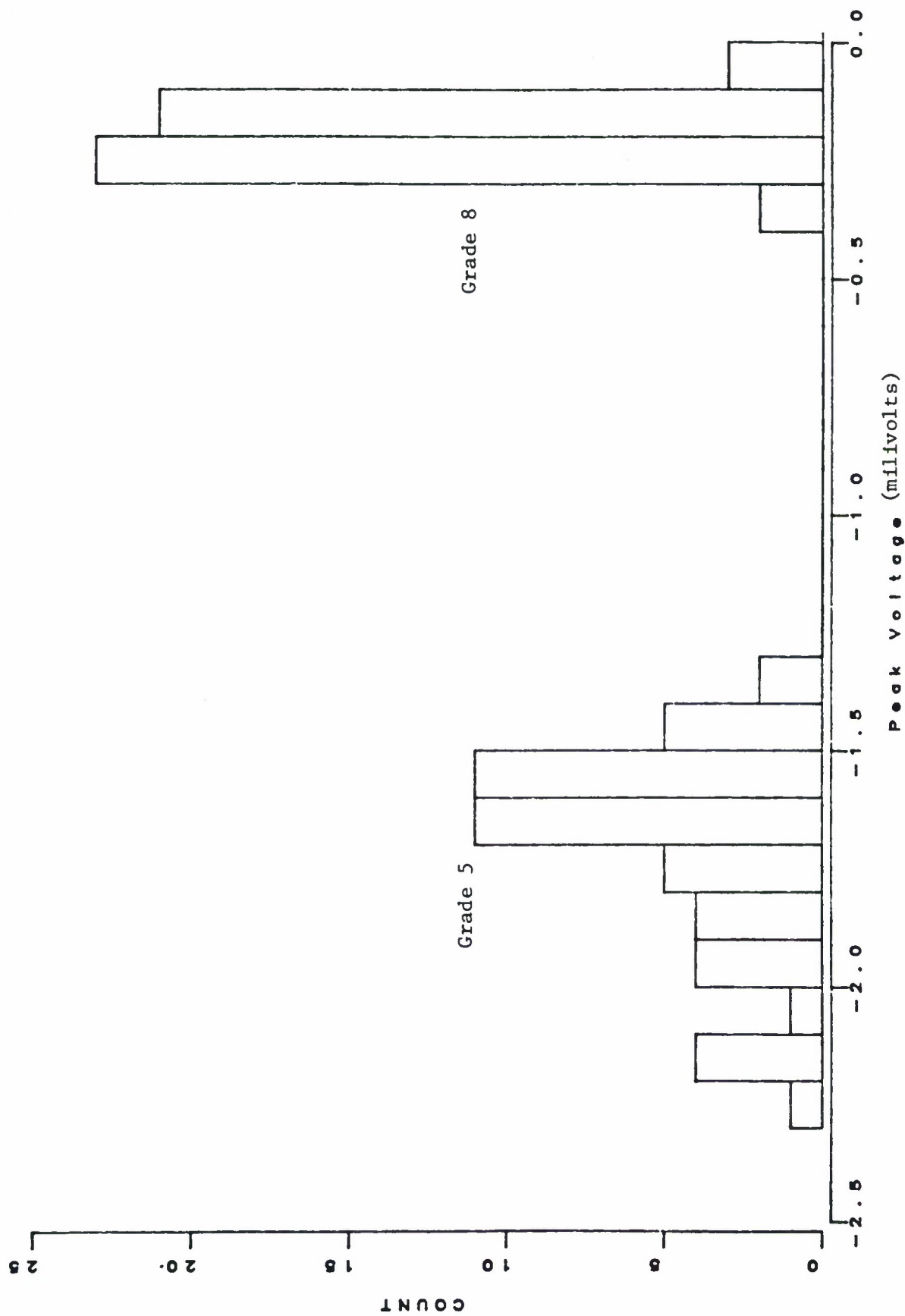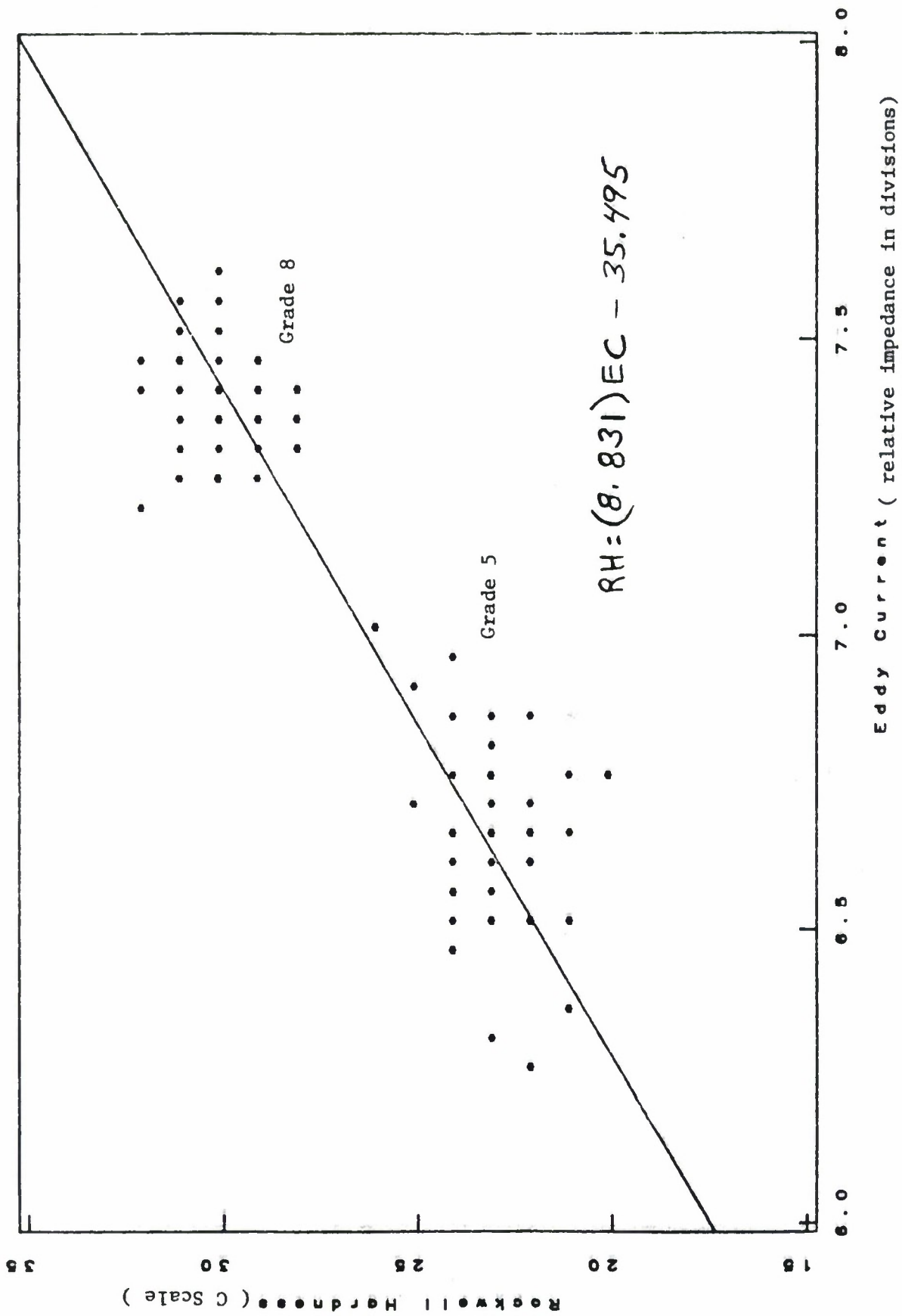
42

Figure B-7. Peak voltage (5 versus 8)
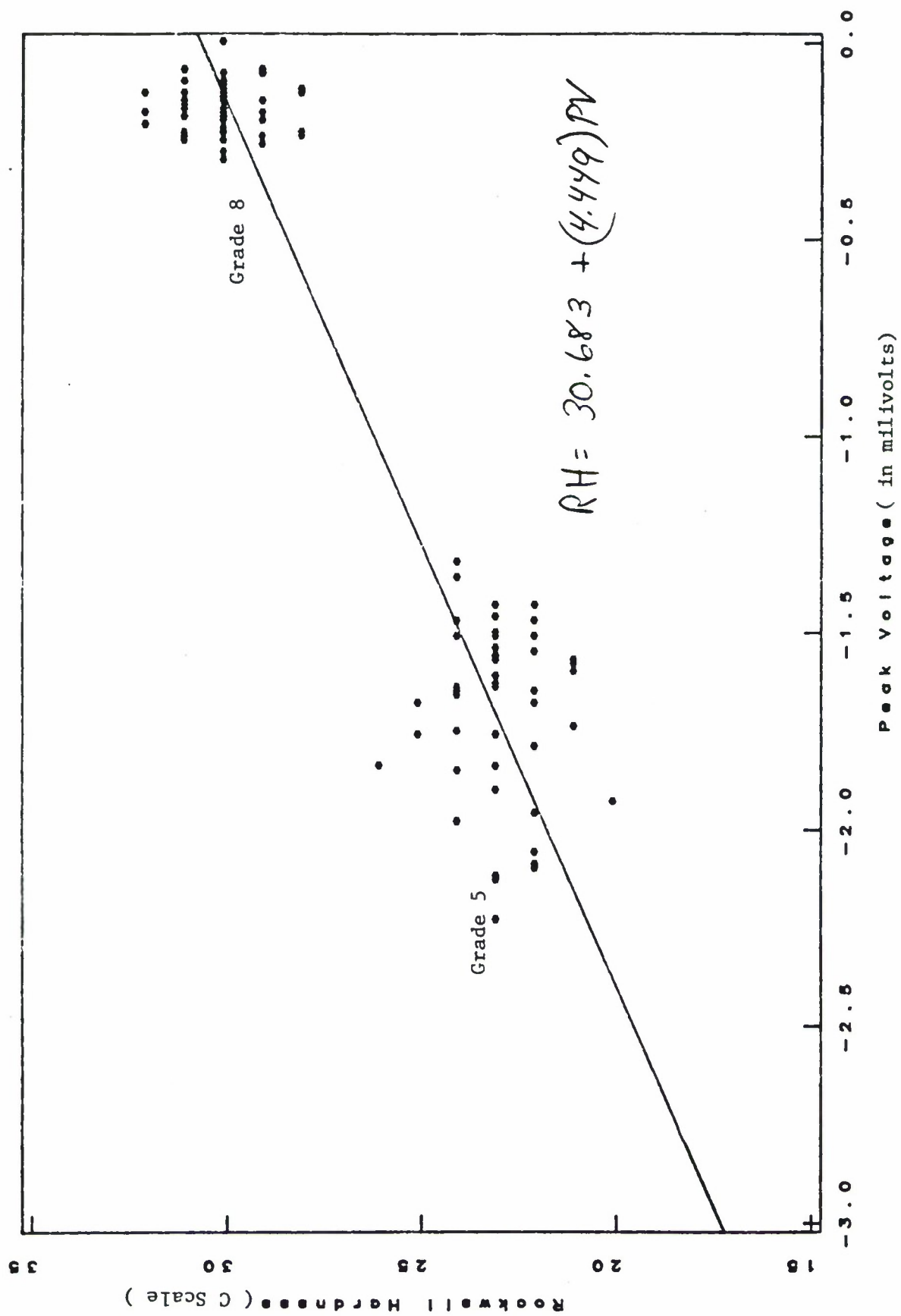
43

Figure B-8. Hardness versus eddy current

$$RH = (8.831)EC - 35.495$$

Figure B-9. Hardness versus peak voltage

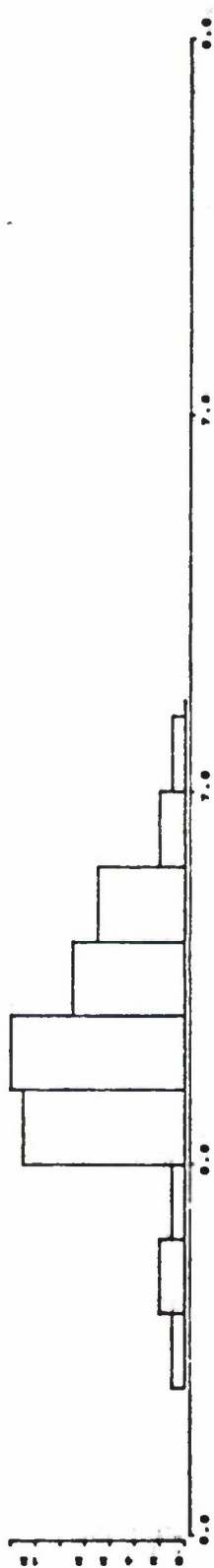$$RH = 30.683 + (4.449)PV$$
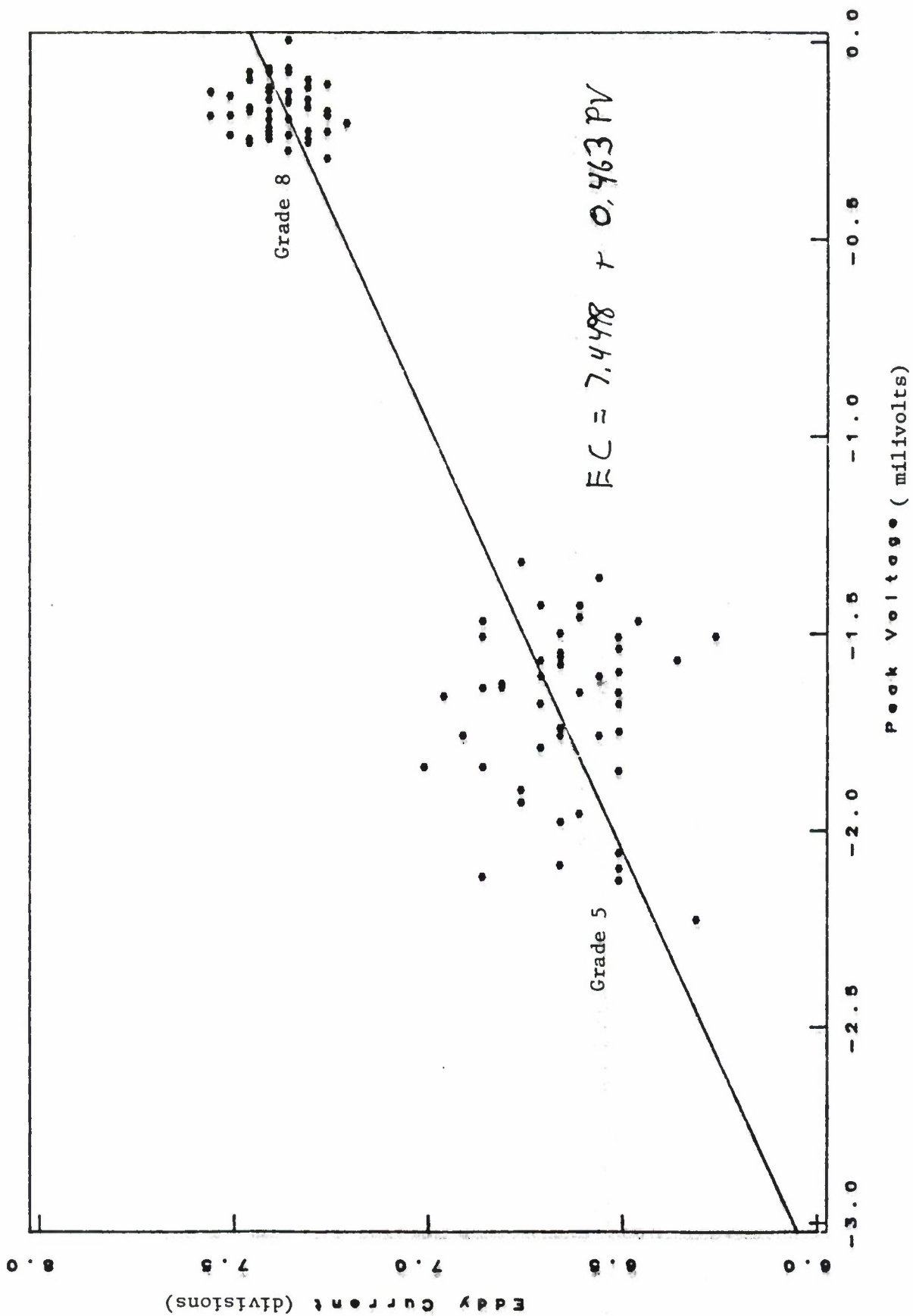
Figure B-10. Eddy Current versus peak voltage

$EC = 7.4498 + 0.463\,PV$
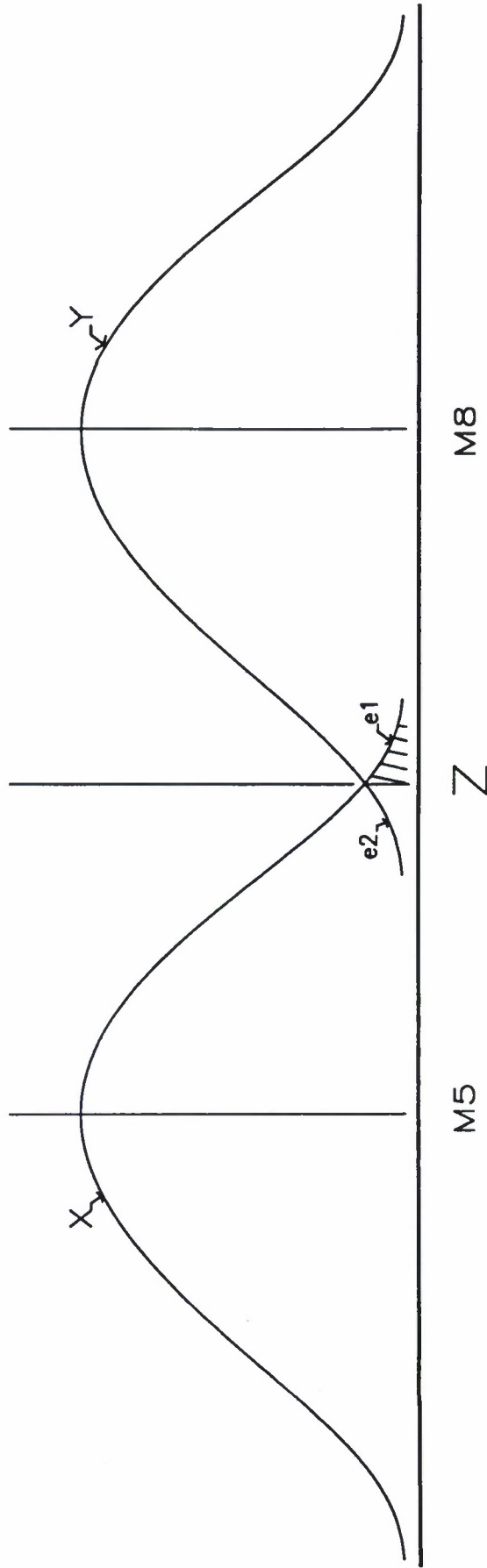
M5 = mean Grade 5 data
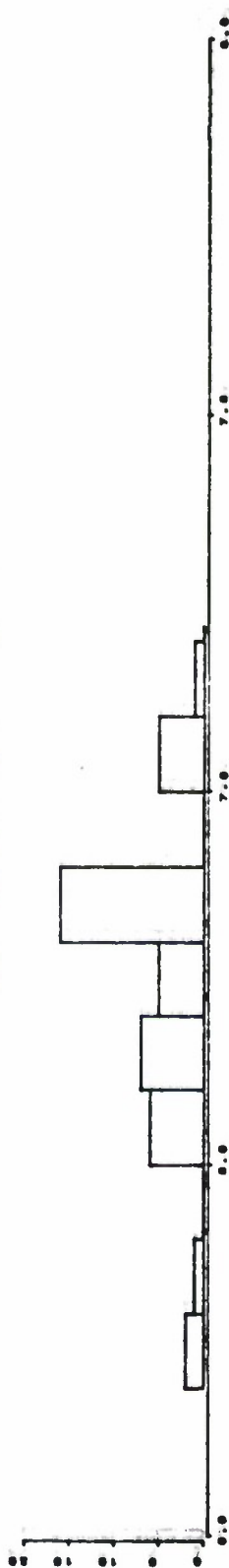
M8 = mean Grade 8 data

NOTE: X and Y are the two normal distributions from grade 5 and grade 8 bolts respectively. Region e1 is the area where a grade 5 bolt is mistaken for a grade 8. Region e2 shows the opposite case.

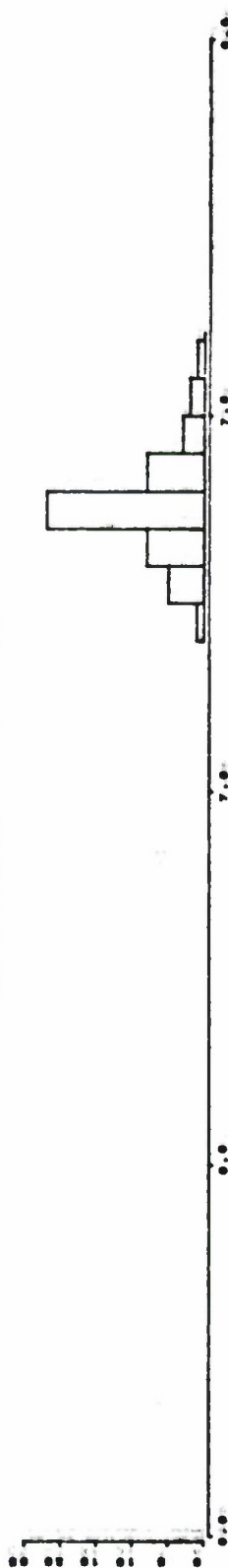Figure B-11. Decision risk for grades 5 and 8

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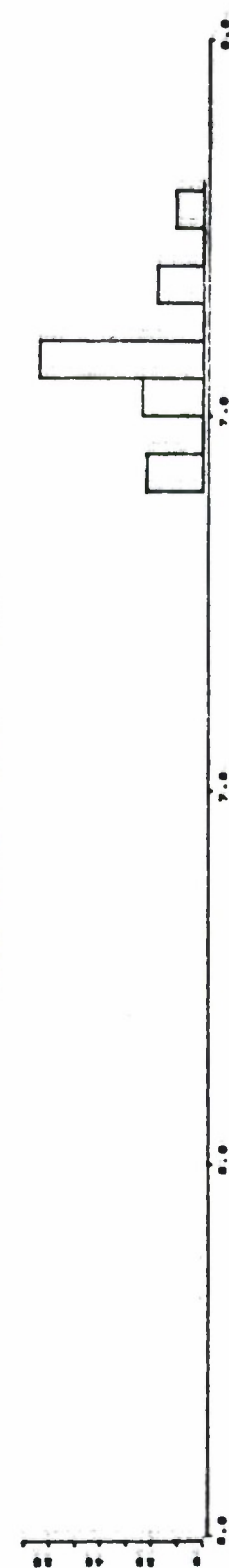All graphs are Count vs Eddy Current (in divisions).

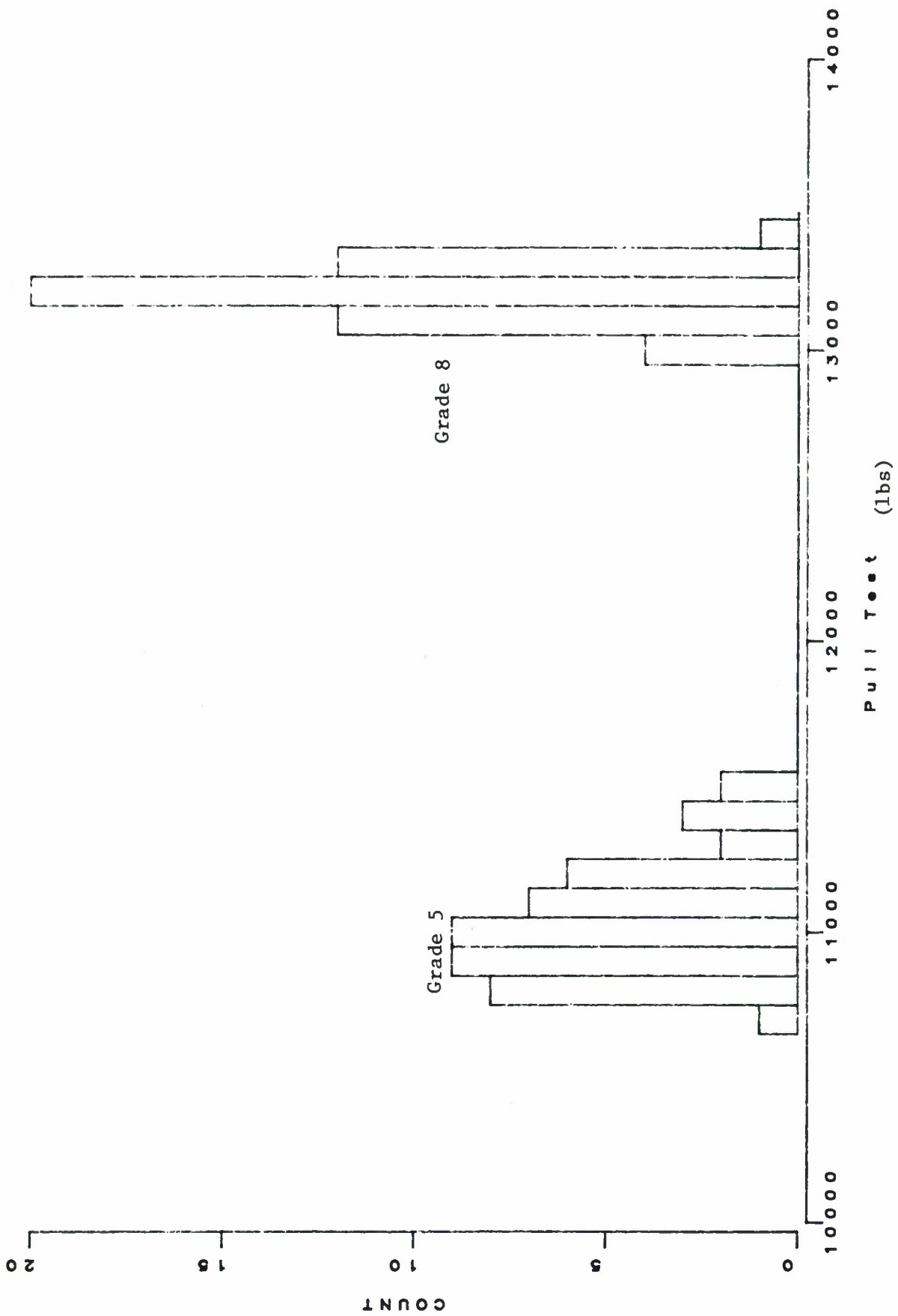Figure B-12. Distribution of eddy current signal readings
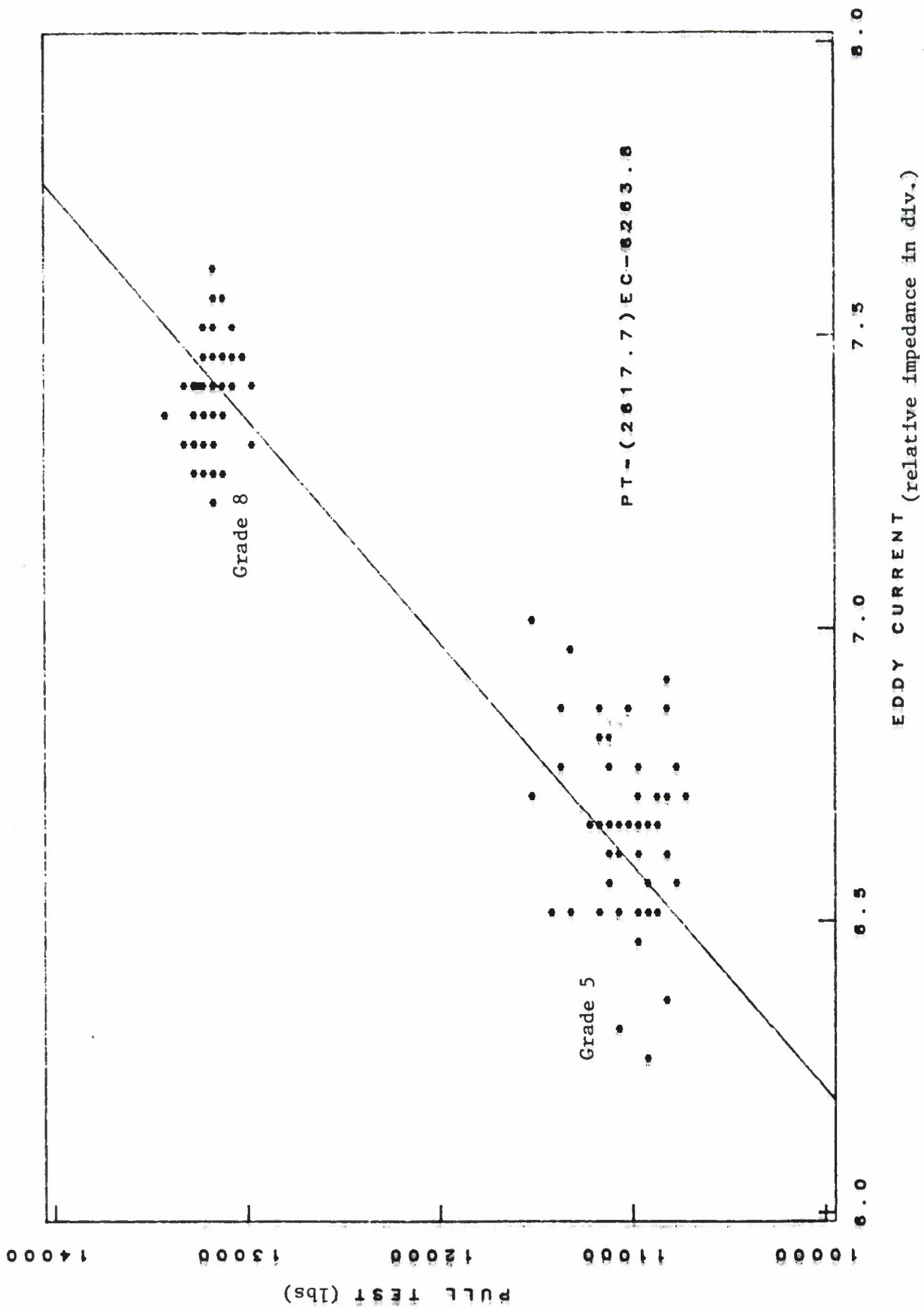
Figure B-13. Pull test (5 versus 8)

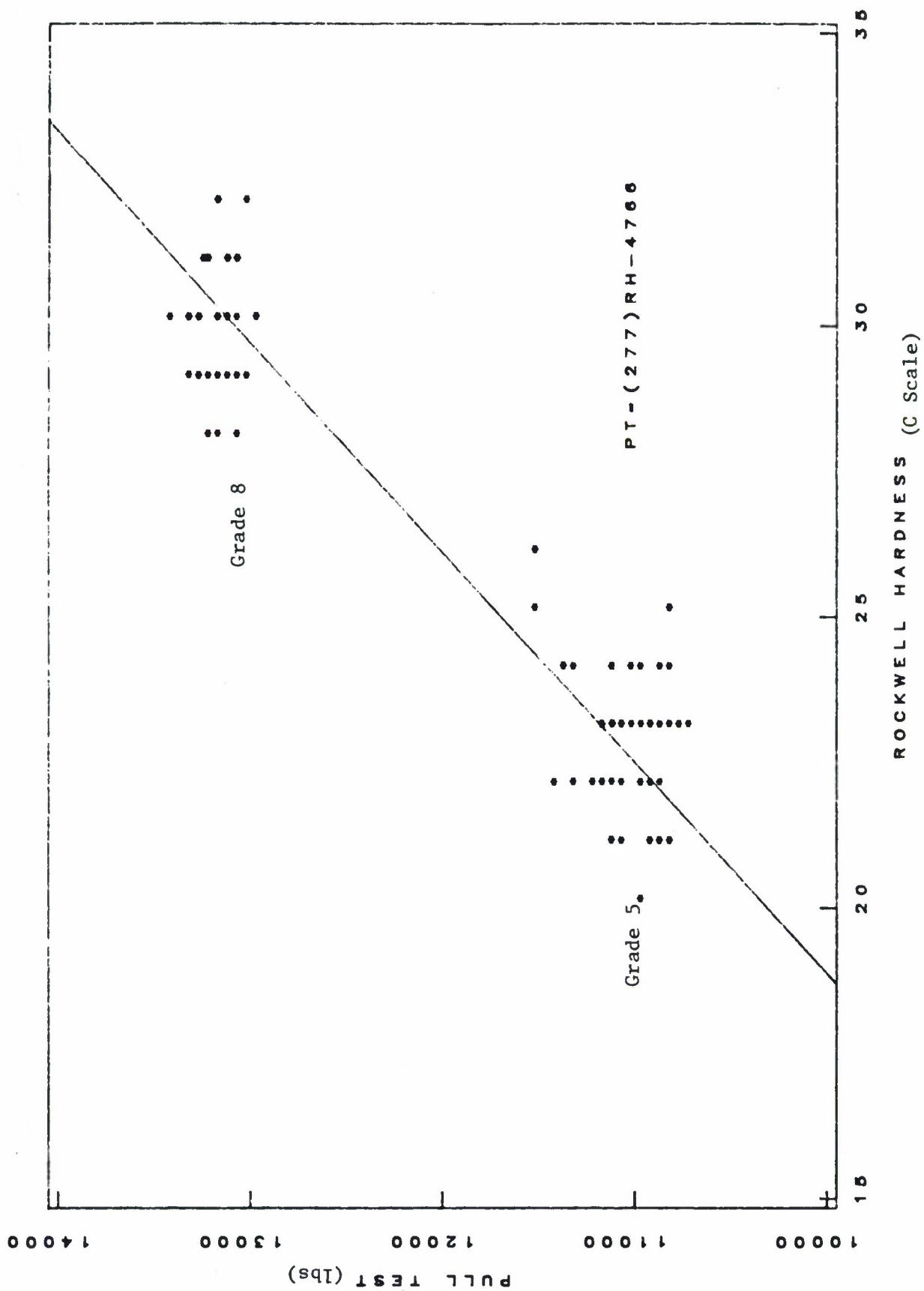Figure B-14. Pull test versus eddy current

Figure B-15. Pull test versus Rockwell hardness

51
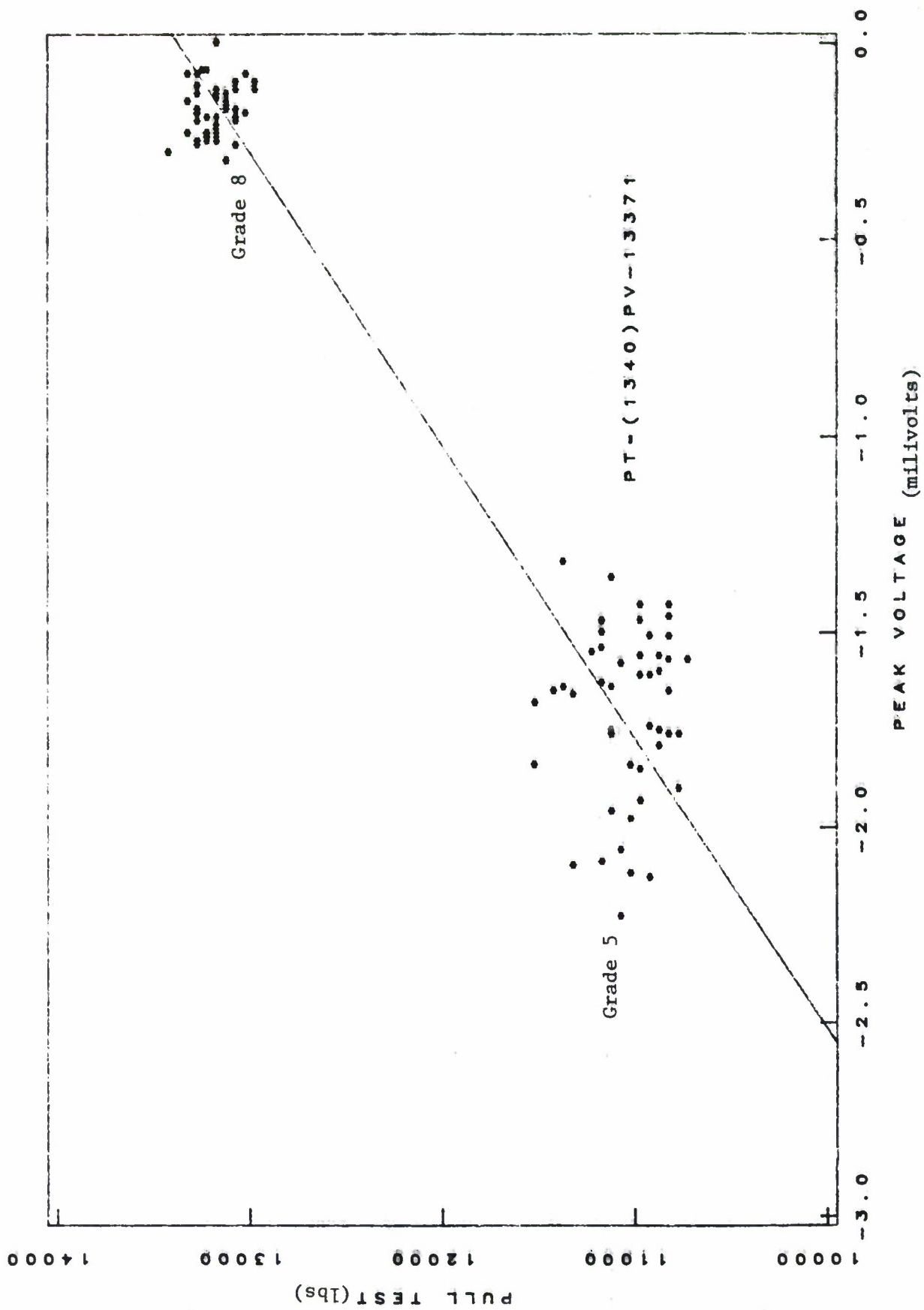
Figure B-16. Pull test versus peak voltage

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Armament Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCAR-IMI-I (5)
        SMCAR-TD
        SMCAR-TDC
        SMCAR-AE
        SMCAR-AEE
        SMCAR-AEE-WE
        SMCAR-AEE-WW (3)
        SMCAR-AEP
        SMCAR-AEP-R (6)
        SMCAR-AER-T
Picatinny Arsenal, NJ 07806-5000

Commander
U.S. Army Armament, Munitions and Chemical Command
ATTN: AMSMC-GCL(D)
Picatinny Arsenal, NJ 07806-5000

Administrator
Defense Technical Information Center
ATTN: Accessions Division (12)
Cameron Station
Alexandria, VA 22304-6145

Director
U.S. Army Materiel Systems Analysis Activity
ATTN: AMXSY-MP
Aberdeen Proving Ground, MD 21005-5066

Commander
Chemical Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCCR-MSI
Aberdeen Proving Ground, MD 21010-5423

Commander
Chemical Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCCR-RSP-A
Aberdeen Proving Ground, Md 21010-5423

Director
Ballistic Research Laboratory
ATTN: AMXBR-OD-ST
        SLCBR-IB
Aberdeen Proving Ground, MD 21005-5066

Chief
Benet Weapons Laboratory, CCAC
Armament Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCAR-CCB-TL
Watervliet, NY 12189-5000

Commander
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCAR-ESP-L
        SMCAR-ES, L. Artioli
        SMCAR-ES, R. Bowen
                C. Morton
                D. Cox
                J. Kolwey
                S. Stryjewski
                L. Randol
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        AMSMC-PC, A. Hale
                E. Maslanka
        AMSMC-PD, R. Stone
        AMSMC-QA, L. Griffin
        AMSMC-SF, D. Skogman
        MCLNO-LMA, Maj R. Frank
                CW02 Holewinski
Rock Island, IL 61299-6000

Director
U.S. Army TRADOC Systems Analysis Activity
ATTN: ATAA-SL
White Sands Missile Range, NM 88002

Director
Defense Advanced Research Projects Agency
ATTN: LTC C. Buck
1400 Wilson Boulevard
Arlington, VA 22209

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U.S. Army Materiel Command
ATTN: AMCDRA-ST
5001 Eisenhower Avenue
Alexandria, VA 22304

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Langley Research Center
ATTN: MS 168
Hampton, VA 23365

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Watervliet, NY 12189

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Moffett Field, CA 94035

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             Code 3891
China Lake, CA 93555

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             Code 6110
Washington, DC 20375

Superintendent
Naval Postgraduate School
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             Department of Aeronautics
Monterey, CA 93940

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Naval Ordnance Station
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Indian Head, MD 20640-5000

Air Force Armament Laboratory
ATTN: AFATL-DLODL
Eglin Air Force Base, FL 32542-5000

AFOSR
Bolling Air Force Base
Washington, DC 20332

AFRPL (DRSC
Edwards AFB, CA 93423-5000