ABSTRACT

AN INVESTIGATION TO DETERMINE THE RELIABILITY
OF THE BRINELL TEST AND SOME NONDESTRUCTIVE TESTS
IN QUALITY TESTING GRAY IRON CASTINGS

by James T. Webster

Demands by the customers of foundries for tighter quality standards due to increased warranty periods coupled with typical problems associated with producing gray iron castings often results in Brinell testing 100 percent of the castings. For present production line operations, 100 percent Brinell testing is a rather inefficient process. These problems prompted an effort to find a more efficient quality testing process. The first step was an investigation to determine the reliability of the Brinell test and some nondestructive tests in quality testing gray iron castings. The nondestructive tests investigated were the resonance test, static magnetic tests, and eddy current tests.

First, the theoretical aspects of each test were investigated. No fundamental law which can be expressed mathematically independently of the measuring process has been developed for hardness. A theoretical relationship does exist which relates resonant frequency to modulus of elasticity. The modulus depends upon the graphite phase in gray iron. Static magnetic properties, magnetic retentivity and coercive force, are definite points on the cyclic, direct current, hysteresis curve obtained by saturating a ferromagnetic sample. Coercive force is independent of mass and shape. Eddy current distributions and alternating magnetic field distributions

can be predicted from mathematical considerations for test samples of simple geometrical shape.

A number of test bars and as cast parts of the same type were furnished by Central Foundry for conducting nondestructive tests. Several Brinell impressions were taken over the surface of the test bars and cast parts and averaged. In order to evaluate each nondestructive test, tensile strength, carbon equivalent, and microstructures were determined for the test bars. Only Brinell impressions were taken for evaluation of the nondestructive tests on the as cast parts.

The nondestructive tests were classified as resonant frequency tests, static magnetic tests, and eddy current tests. Resonant frequency tests were conducted with Magnaflux's SR-100 tester. Static magnetic field tests were conducted with a Foerster Coercive Force Meter. Eddy current tests were conducted with Magnaflux's ED-300 Eddy Current Probe Tester and Foerster-Hoover's QC-1000 Comparator. The Retentivity test and the ED-300 Eddy Current tests were eliminated from consideration due to inaccuracies and duplication of the other tests. Thus the magnetic test considered was the coercive force test, and the eddy current test considered was the QC-1000 Comparator test.

It was concluded that the Brinell test is not a sufficient quality test for gray iron. The resonant frequency test evaluates the graphite phase in gray iron independently of the matrix. The coercive force test indicates the amount of ferrite in the matrix independently of the graphite phase, mass, and shape of a test sample. The QC-1000 Comparator evaluates tensile strength which is dependent upon both the graphite phase and the metallic matrix of a test sample.

It is recommended that further laboratory investigation be performed, that application be made to foundry production, and that establishment of new standards be initiated. Further laboratory investigation should include investigation to determine the affect of a range of ferrite contents, a range of pearlite coarseness,and a range of temperature upon coercive force. The affect of temperature, mass, and shape variations on QC-1000 test indications should be investigated. For the resonance test, methods of support, methods of inducing resonance, and the affect of mass and shape variations should be investigated.

Additional work is required for the design of test systems for particular applications in production testing. Production applications include test set-ups for annealing control and foundry control, and a test set-up for final inspection of the quality of castings before being shipped to customers.

Finally, new standards must be set in terms of the improved quality test both in the foundry and at the customer.

AN INVESTIGATION TO DETERMINE THE RELIABILITY OF THE BRINELL TEST AND SOME NONDESTRUCTIVE TESTS IN QUALITY TESTING GRAY IRON CASTINGS

By

James Thomas Webster

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

1964

PREFACE AND ACKNOWLEDGEMENTS

This thesis is being submitted in partial fulfillment of the requirements for a Master of Science degree in Mechanical Engineering at Michigan State University and for a Bachelor of Mechanical Engineering degree at General Motors Institute. Under the Bachelor-Master Plan of General Motors Institute, I spent the fifth year working towards a Master of Science degree. The thesis I wrote will serve to complete the requirements of my graduate work, as well as my undergraduate work.

My sponsoring unit, Central Foundry Division, Danville Plant, assigned me the problem to design a mechanized hardness test for gray iron castings. This problem was broken down into two parts: investigation of the Brinell test and some nondestructive tests; and the design of test set-ups for specific applications in the foundry. My thesis involves mostly the first part of the problem, since I felt that this part necessarily had to be done first and its scope was sufficient for a thesis.

Because of the specialized equipment required for my investigation, I had to borrow several pieces of equipment from several companies. In practically all the cases, I transported my test samples to the companies, since the equipment involved was in almost continuous use. I am greatly appreciative to the following people and companies:

Senior Metallurgical Engineer C. L. Langenberg
and Experimental Metallurgist L. D. Tankersley
of Oldsmobile Division, Plant #1, General Motors
Corporation.

Mr. Art Lindgren, Mr. James Priore, and Mr. J. Baranowski
of Magnaflux Corporation.

Research Engineers M. J. Diamond and Bob Lutch of Central
Foundry Division, General Motors Corporation.

Mr. W. L. Welsh of Foerster-Hoover Electronics, Inc.

I am also greatly appreciative to Central Foundry, Danville Plant, for supplying me with the test bars and cast parts necessary for this investigation.

Finally, I am deeply indebted to Dr. H. L. Womochel, Professor of Metallurgy, in the Metallurgy, Mechanics, and Materials Science Department at Michigan State University for his guidance.

TABLE OF CONTENTS

CHA

CON

REC

BIB

APP

APP

TABLE OF CONTENTS (Con't.)

LIST OF ILLUSTRATIONS

LIST OF APPENDICES

INTRODUCTION

As a result of increasing the warranty periods on General Motors automobiles, quality standards are being tightened in all phases of automobile production. This thesis concerns only the narrow aspect of testing gray cast iron parts for quality. Tensile strength, wear resistance, damping capacity, and machinability of parts must be uniform and within specifications to insure a high degree of reliability and low production costs.

These properties of gray iron are a function of the amount and nature of the graphite phase and the nature of the metallic matrix. In high production founding besides the temperature and chemistry controls, the inoculation of the molten iron before it is poured and the cooling rate of the casting after it is poured are critical. The degree of inoculation and rate of solidification affect the nature and amount of the graphite phase. Since castings are "shaken out" of their molds above 1330 degrees F., the lower austenite transformation range, the rate of cooling through this transformation range governs the nature of the metallic matrix. Central Foundry Division, Danville Plant, at present has no positive control over the rate of cooling of its castings through this very critical transformation range. As a result of these and other variables, the structure of gray iron can fluctuate widely.

With these existing production problems and requirements of increased reliability, some parts must be 100 percent quality tested. The most widely used test for quality of gray iron parts is the Brinell Hardness test. With conventional Brinell machines, a considerable amount of labor is expended when testing production castings 100 percent. In addition, only a small local area is tested and the area tested is very close to the surface of the casting. Since the "skin condition"[1] from casting to casting is variable and since the customer sometimes machines this "skin" completely off, Brinell hardness readings can be misleading as to the quality of the part. Furthermore, very small parts which must remain unstressed or which may be damaged by the Brinell impression, cannot be advantageously tested with the Brinell method.

These factors led to the current problem of investigating the Brinell test and other nondestructive tests for gray iron. A survey of the field of nondestructive testing has shown that at present magnetic and sonic methods offer a good potential for development. Mr. Charles Walton has said that "the damping of sonic vibration is closely related to the graphitic phase in iron as is the resonant frequency (modulus of elasticity at low stress)" and that "magnetic properties are more closely related to the silicon content and the matrix structure whereas Brinell hardness is influenced by both the matrix structure and the graphite phase."[2]

---

[1]"Skin condition" is the existence of a different matrix structure and graphite type and distribution found at or near the surface than is representative of the casting as a whole.

[2]From a letter from Mr. Charles Walton, Technical Director of the Gray Iron Founder's Society, dated July 6, 1964.

Other methods considered were x-ray and nuclear techniques, infrared analysis, and dynamic hardness tests, such as Shore Scleroscope tests. Jones and Laughlin of Aliquippa, Pennsylvania have developed a device using Beta rays to detect underannealing of a continuous low carbon steel strip.[3] At Hennecott Research Center in Salt Lake City, Utah, infared analysis has proven to be "quick and easy," but instrumentation is expensive.[4] Since vibrations within a molecule are related to the frequencies absorbed, no two compounds give exactly the same pattern when transmission of radiation is plotted against wave length. Also "the depth of an individual absorption band can be related to the concentration of material responsible for it."[5] These methods should be further investigated to determine whether they can be applied to cast metals containing the graphitic phase.

In order to investigate the sonic and magnetic properties of gray iron, thirty transverse test bars and twenty-six cast parts, Part No. 5692885 pump housings, were obtained from Central Foundry Division, Danville Plant. The cast parts were castings which had to be 100 percent quality tested before shipping them to the customer. Six of the test bars were annealed. For the test bars, Brinell hardnesses, resonant frequencies, residual induction values, coercive force values, eddy current indications with both a coil and a probe, and tensile strengths were determined. Only Brinell hardnesses,

---

[3]"Hardness Gaged 'On The Fly'," The Iron Age, (CXCII, Sept. 19, 1963), 108-9.

[4]Tuddenham, W., and Yimmerly, S. R., "Infared Analysis is Quick and Easy," Engineering and Mining Journal, (July 1960), pp.92-4.

[5]Ibid.

resonant frequencies, and eddy current indications were obtained for the cast parts. Finally, a thorough microstructural analysis was made on eleven of the test bars. With this information, an extensive analysis of the Brinell test and other nondestructive tests was made.

The investigation of this problem will be reported in the chapters to come as follows: the Brinell test, the resonance test, static magnetic tests and eddy current tests, conclusions and recommendations.

CHAPTER I

THE BRINELL TEST

Brinell hardness testing was developed around 1900 by Dr. J. A. Brinell. Essentially the method has remained unchanged since then. As mentioned previously, this method of determining the quality of gray iron parts is standard in General Motors Corporation. This Chapter discusses theory and factors concerning Brinell testing, preliminary testing procedure, and the relationship of Brinell hardness to physical properties and microstructure.

Theory and Factors Concerning Brinell Testing

For Brinell testing of gray iron, a ten mm. steel ball and 3000 kg. load must be used because of the inherent inhomogeneity of the material. Brinell Hardness number is expressed by the formula $BHN = \frac{P}{\frac{\pi D}{2}(D - \sqrt{D^2 - d^2})}$ where P is the load in kilograms, D the diameter of the ball, and d the diameter of the impression in millimeters. The Brinell Hardness Number is then equal to the applied load divided by the contact area of recovered indentation.[6] The permanent impression produced is dependent upon several factors including yield strength,

[6]Samuel R. Williams, Hardness and Hardness Measurements, (Cleveland: American Society for Metals, 1942), pp. 153-7.

ability of the material to flow, the amcunt and distribution of the graphite near the impression, and the ability of the material to work-harden upon deformation.

It should be noted that the word "hardness" by itself has no concise physical meaning. As S. R. Williams[7] points out there are no reliable conversion tables connecting even 500-kilogram Brinell hardness with 3000-kilogram Brinell hardness. This means that the Brinell hardness number is also dependent upon the size of the penetrating ball and upon the load when testing the same material which is uniform in its physical properties. This combination of applied load and ball diameter have a different effect upon the material in question, such as its effect upon the degree of cold-working. This is also true when trying to correlate say Vickers or Rockwell hardness with Brinell hardness. Different shaped penetrators thus have an effect upon the hardness value, given the same homogeneous material. Therefore, the "hardness" of a material must be qualified by the method used.

As of yet, no fundamental mathematical relationship has been developed for hardness. In Brinell testing and other static indentation tests, the elastic limit of the material is exceeded. In dynamic tests if the elastic limit is exceeded, the rate of deformation plays an important part. If the elastic limit is not exceeded, the hardness number is dependent upon the elastic modulus. Is then hardness a fundamental physical property? If so a fundamental mathematical relationship

---

[7] Ibid., 8.

applicable to all materials, could be developed.

Another factor in Brinell testing is reading of the Brinell scope. It has been found that human error can be an important factor in Brinell scope reading. At best in high production an accuracy of $\pm$ .05 mm. diameter is obtainable with the conventional scope, which corresponds to a nominal accuracy of $\pm$ 5 in Brinell Hardness Number. In the laboratory, however, better accuracy can be obtained when taking several readings (interpolating to the second decimal place) and averaging these values.

Finally, still another factor in Brinell testing is section size. Usually in production Brinell testing, only one Brinell reading is made on a casting to determine if it is acceptable. In order to investigate the hardness variation over the surface of a complex cast part with variations in section size, Brinell hardnesses were made at five different locations on the cast parts obtained from Central Foundry. In Figure 2 in the Appendix, position (1) represents the single position where the part is production Brinell tested, and positions (2) through (6) represent the locations where Brinell hardnesses were taken for laboratory investigation. The Brinell diameters at these different locations for six of these cast parts were plotted in Figure 4 in the Appendix. It can be seen in Figure 4 that quite a variation in Brinell hardness can be obtained over the casting surface. Thus it is not sufficient to represent the hardness of the whole casting by the hardness at one location.

Preliminary Testing Procedure

In order to insure varying microstructures among the thirty test bars which were made from a standard transverse test bar pattern, three carbon equivalent[8] ranges were specified: 3.70 to 4.12 percent, 4.13 to 4.22 percent, and 4.23 to 4.60 percent. A group of ten castings were poured in each carbon equivalent range. The first group with the lowest carbon equivalent range had no inoculant added before pouring. The other two groups had one pound of SMZ (Silicon-Manganese-Zirconium) inoculant added to 800 pounds of iron just before pouring. Also, two castings from each group were cooled for forty minutes in their green sand molds. The rest of the castings cooled eleven minutes in their molds and cooled to room temperature on a steel bench. Two castings from each group were annealed at a temperature of 1300 degrees F. in air for three hours and then allowed to cool in the furnace with the door partially open for twelve hours.

Carbon equivalent was determined initially with a thermal arrest unit,[9] a device that detects the freezing temperature of the iron which is related to carbon equivalent. Pouring temperature and chill depth were taken at the time of pouring. Later carbon, silicon,

---

[8]Carbon equivalent is given by the following formula: CE = C + 1/3 (Si + P). In this study, phosphorous content was not considered.

[9]Milton J. Diamond, "A Summary of Some New Processing and Quality Control Developments in Foundry Technology," General Motors Engineering Journal, (XI, Second Quarter, 1964), p. 26.

manganese, and chromium content were determined by conventional chemical methods. It was thought that differences in inoculation would give the largest possible graphite variation and that longer cooling in the mold and annealing would produce more ferrite in the matrix structure.

Four Brinell tests were taken on each test bar. The resulting average Brinell diameters varied from 4.0 to 4.55 mm. (229 to 174)[10] for the as cast bars and 5.34 to 5.57 mm. (124 to 112) for the annealed bars. (See Figure 1 in the Appendix for location of Brinell tests) It would have been desirable to have more test bars in the range of 4.55 to 5.34 mm. diameter (174 to 124) but the time required to select and to anneal these test bars would have been too great.

As described earlier, the twenty-six cast production parts from Central Foundry were Brinell tested here in the laboratory at locations (2) through (6) in Figure 2 in the Appendix. The average Brinell diameter of these cast parts varied from 3.88 to 4.83 mm. (244 to 154). The range acceptable to the customer was 4.0 to 4.7 mm. diameter in position (1) on the casting (See Figure 2). Since Central Foundry's customers normally specify Brinell diameter rather than Brinell Hardness Number, Brinell diameter has been referred to in this paper more than to Brinell Hardness Number. There is a possibility of conversion errors when converting from Brinell diameter to Brinell Hardness Number to Brinell diameter. Figure 3 shows the relationship

---

[10]Brinell Hardness Numbers are contained in parenthesis after the Brinell diameter.

between Brinell Hardness Number and Brinell diameter.

Brinell Hardness as Related to Physical Properties and Microstructure

This section will discuss how Brinell hardness is related to tensile strength, some foundry variables, machinability, and microstructure.

Tensile Tests. Tensile strength is influenced by both the amount and nature of the graphite and by the nature of the matrix, as is Brinell hardness. Accuracy of tensile testing gray iron is quite dependent upon the variation in physical factors of the test specimen since gray iron is in fact a brittle material. Such factors as stress raisers produced by machining, geometry, and any bending during the test will affect the accuracy of the test. Figure 5 shows the standard speciman used. Because of various factors in testing and machining, it was felt that at most only seven out of the eleven desired tests gave accurate results.

Figure 6 shows a plot of Brinell diameter versus tensile strength for seven specimen. This Figure shows a general correlation of Brinell diameter and tensile strength.

Figure 7 which shows tensile strength versus Brinell Hardness Number for 1495 samples[11] shows a considerable spread particularly at higher values of Brinell Hardness. The converging of the upper and lower limits seems significant. Since the spread of this curve is so

---

[11] Metals Handbook, ed. Taylor Lyman (Metals Park, Ohio: American Society for Metals, 1961), I, p. 354.

great, the Brinell test is not a reliable indication of tensile strength.

Some Foundry Variables. Often Brinell hardness is used as a control in the foundry operation. Chemistry, pouring temperature, inoculation, cooling rate in the mold, and cooling rate after shake-out, all affect Brinell hardness. All of these variables must be controlled in order to control Brinell Hardness.

Among the variables examined here are pouring temperature, carbon equivalent, and cooling time in the mold. No correlation could be established concerning the relationship of Brinell hardness and pouring temperature, but all other variables being constant an increase in pouring temperature up to 2725 F. should result in a decrease in Brinell hardness.[12]

Comparing as cast parts, a much better correlation was obtained between Brinell diameter and carbon equivalent determined by the Thermal arrest unit than with the carbon equivalent determined by the wet chemical method (see Figure 8). No appreciable hardness change resulted when leaving the castings in their molds for forty minutes over the castings cooled for eleven minutes in their molds.

Machinability and Microstructure. Machinability and microstructure were examined to determine how they are related to Brinell Hardness. Since microstructure tends to vary from normal to abnormal from the center to the surface and tends to vary somewhat from point to point, microstructures that were compared were taken at the same distance

---

[12]Dr. Dimitri Kececioglu, "Factors Affecting Gray Iron Machinability," Foundry (XCI, October 1963), p. 115.

from the surface and were representative of the structure as a whole at a given depth.

Machinability is not an absolute property but a relative one. It is difficult to measure and, like the Brinell test, depends upon the method of measurement and has no fundamental mathematical derivation.

Brinell Hardness was related to a machinability index in a series of tests conducted by Dario Fortino of Fiat.[13] In these tests a constant-pressure drilling machine was used. The machinability index was determined from a correlation of the time required to drill through a certain thickness of UNI AB 40P steel with that required to drill through the same thickness of cast iron. A machinability index of 100 was assigned to the steel. It was concluded by the Italian investigator that Brinell hardness permits only an approximate estimate of machinability: the lower the Brinell hardness the better the machinability. Upon examining why two castings having the same Brinell Hardness Number had different machinability indexes, Mr. Fortino found that graphite in the first casting was mostly of type 5A with six to twelve mm. flake length, whereas that in the second casting was of type 4A with twelve to twenty-four mm. flake length.

To determine what change in graphite form and structure results in a change in hardness, six of the thirty test bars were annealed to such an extent that all the pearlite was converted to ferrite. This

---

[13]"Machinability of Iron Castings," Foundry Trade Journal, (CXII, December 13, 1962), pp. 729-35.

eliminated the matrix as a variable.* (This heat treatment was explained under "Preliminary Testing Procedure" in this Chapter.) Comparing Figures 9 and 10, it can be seen that the shorter and abnormal graphite results in a higher Brinell hardness than does the longer randomly oriented flakes. The Brinell varied from 5.46 to 5.80 mm. (118 to approx. 100). The direct influence of the matrix could not be determined in the as cast samples because pearlite was about the same from sample to sample. When ferrite was observed it was always associated with a difference in graphite.

Evaluation of the Brinell Test

The following conclusions were arrived at from this study of the Brinell Test:

1. Brinell hardness has not yet been shown mathematically to be a fundamental physical property of metal alloys.
2. Brinell hardness represents only the quality of the material immediately surrounding the test location. A change in section size results in a change in Brinell hardness.
3. The Brinell scope can be source of error.
4. Some small parts would be destroyed by the Brinell test.
5. Tensile strength cannot be accurately predicted from the Brinell test.
6. A general correlation exists between Thermal arrest carbon equivalent and Brinell hardness.
7. Changes in machinability index due to small changes in graphite could not be detected with the Brinell test. Brinell hardness is only an approximate estimate of machinability.

*The effects that small differences in silicon, manganese, and chromium contents had on matrix hardness among the six castings were neglected. In order to completely eliminate the matrix as a variable, the alloy contents should be held constant.

8. By examining the microstructures of samples where the matrix was eliminated as a variable, it was shown that larger changes in graphite could be detected with the Brinell test.

The above conclusions indicate that a more sufficient quality test than the Brinell test needs to be developed. A sufficient test should be able to measure both the matrix and the graphite independently, which is not possible with the Brinell test.

CHAPTER II

THE RESONANCE TEST

Resonance testing, like indentation hardness testing, is not new to the foundry industry. For years resonance testing has been used to test Arma Steel parts.[14] Arma Steel (pearlitic-malleable iron) is resonance tested by first striking the part with a hammer and then using a sensitive microphone to pick up the vibrations. This Chapter will analyze the resonant frequency test in order to determine what application it has in quality testing gray iron. Theory and factors in resonance testing and resonant frequency as related to microstructure and physical properties will be discussed.

Theory and Factors in Resonance Testing

Resonance occurrs when the frequency of a periodic exciting force approaches the natural frequency of vibration of a body.[15] This natural frequency of mechanical vibration may be expressed generally as

Frequency = (shape factor) x (physical - constants factor) (1)

Shape factor is a function of the geometrical design and the dimensions

---

[14]Milton J. Diamond, "The Utilization of Sonic Principles for Application to an Automatic Method of Casting Inspection," General Motors Engineering Journal, (March-April 1956), pp. 38-42.

[15]Nondestructive Testing Handbook, ed. Robert C. McMaster (2 Vols.; New York: The Ronald Press Company, 1959), II, Sec. 51, 1.

of a body. The physical-constants factor includes modulus of elasticity, density, and Poisson's ratio of the material.

An important factor which determines resonant frequency is the mode of vibration of a given body. For a body of simple shape, the modes of vibration can be induced independently of each other. The fundamental modes of vibration include flexural, longitudinal, torsional, diametral, radial, and annular modes of vibration (see Figures 15 thru 20). The nodes as shown are points which remain stationary. Multiples of the fundamental frequency can also occurr which results in adding and shifting nodal points. Complex shapes often vibrate with several of the modes cited above.

The cylindrical test bar used in this study was vibrated in the longitudinal mode as shown in Figure 16 and supported at the nodal point in the center. The relation for a long cylindrical bar in the longitudinal mode of vibration is

$$f = \frac{1}{2L}\left(\frac{Eg}{d}\right)^{\frac{1}{2}} \qquad (2)$$

where E is modulus of elasticity, f is fundamental resonant frequency, d is density, g is acceleration due to gravity, and L is the length of the cylindrical bar.

It is generally known that the modulus of elasticity of gray iron is closely related to the tensile strength providing the matrix structure remains constant. The curved nature of the stress-strain curve of gray iron in tension is also well known, so the modulus referred to above, of course, is the modulus determined at a specific point on the stress-strain diagram. Some investigators measure the

tangent elastic modulus at a point on the stress-strain curve that is one-fourth the value of the tensile strength. However, others such as Dr. E. Plénard[16] of the Centre Technique des Industries de la Fonderie, Paris, France insist that the modulus of elasticity of gray iron should be measured at the origin of the stress-strain curve after accomodation has occurred since this value is truly a constant for a particular iron. Accomodation is the process of arriving at a stable stress-strain curve which is cyclic when applying cyclic stresses which do not cause yielding of the material. (See Figure 21)

Resonant frequency was determined at low stress levels in this investigation. So the modulus at the origin of the stress-strain curve would apply here.

Resonant Frequency as Related to Physical Properties and Microstructure

Before examining physical properties and microstructure the testing procedure will be discussed. As can be seen in equation (2), the important variables are length, density, and elastic modulus. The density of gray iron was assumed to be constant in this investigation. However, the higher the carbon equivalent resulting in a higher free graphite content, the lower would be the average density, and a

---

[16] Elizabeth Plénard, "The Elastic Behavior of Cast Iron," (unpublished paper presented at the A. S. M. Cast Iron Seminar, June 1964), p. 8.

corresponding tendency to increase the resonant frequency would result. Length was very closely controlled. The castings were machined to a length of 7.958 inches in a lathe. The maximum deviation from this value did not affect the resonant frequency significantly.

Resonant frequencies of the thirty test bars and twenty-six castings were measured with Magnaflux's SR-100, an instrument developed by the British Cast Iron Research Association. Figure 22 shows a schematic diagram of the instrument. The bars were supported on three pins near the nodal point and vibrated longitudinally with an electromagnetic transducer. (The detecting and exciting transducers were of the same type.) A piece of styrofoam was also used. This worked well as a support near the center, when the parts were grounded. Styrofoam was used to support the cast part as well. Several trial and error positions were tried before a position could be found in which the casting would resonate. The fundamental frequency was found by means of a lissojous figure on a cathode ray oscilloscope. Repeatibility was within $\pm$ 1 CPS even with different transducers, including a mechanical transducer and a small transducer of the type used to measure angular speed of a gear. When the two SR-100 transducers were within about three inches of each other and the air-gap was from one-eighth to one-fourth of an inch, interference of the scope pattern resulted from direct interaction of the two transducers.

It was also found that a temperature increase of 26 F. degrees in the test bar resulted in a decrease of twenty-seven CPS in the resonant frequency of the test bar.

In the following discussion the relationship of resonant frequency to tensile strength, Brinell hardness, carbon equivalent, and microstructure will be established. But first the procedure used to determine static modulus will be discussed. Since Resonant frequency is theoretically related to the modulus by equation (2) and modulus (E) determined in the tensile test has been found to correlate with tensile strength, it would be desirable to compare the modulus found by equation (2) and that determined with the tensile test. The former modulus is referred to as dynamic modulus, and the latter is referred to as static modulus.

Elastic Modulus. Static modulus is determined in the tensile test from a stress-strain curve. In the conventional method a drum with graph paper rotates through an angle that is directly proportional to the load applied to the tensile speciman. A recording pen which moves along the axis of the drum is displaced parallel to the axis of the drum with a movement directly proportional to the strain in the sample as determined by an extensometer. This method is good for observing the entire stress-strain curve up to fracture. But at low loads (and low values of tensile stress) this method has proven to be inaccurate.

This and other factors prompted the use of a more sensitive stress detecting method at low stress levels. It was decided to use some SR-4 strain gages to detect both stress and strain. Because Duco cement pulled graphite from the pores of the metal, Eastman 910 cement was used to attach the gages. See Figure 23 for a description of the test set-up. To measure strain two gages were attached to the

tensile speciman as shown. In order to compensate for bending, the gages were placed in opposite arms of a bridge. Temperature compensation was accomplished by placing "dummy" gages in adjacent arms of the bridge. (See Figure 23) To record stress, two SR-4 gages were cemented to a steel swivel shaft and fed into a bridge in the same manner as for recording strain of the gray iron speciman. Strain in the steel shaft theoretically is proportional to the stress in the shaft. Neglecting reduction of area in the steel shaft and in the gray iron speciman, the tensile stress in the gray iron sample is found to be:

$$S = \tfrac{1}{2} \frac{A_s}{A_g} e_s E_s \tag{3}$$

and the strain is

$$e = \frac{e_g}{2} \tag{4}$$

where e_s is the sum of the strains from the gages on the steel swivel shaft, E_s is the elastic modulus for steel in tension which is a constant, A_s and A_g are the cross-sectional areas of the steel shaft and gray iron speciman, e_g is the sum of the strains from the two gages on the gray iron sample, and e is the average tensile strain in the gray iron sample.

Next, the two bridge output voltages, one for stress and one for strain in the gray iron tensile sample, were each fed into a Brush carrier amplifier whose outputs were each fed into a preamplifier of a Sanborn optical X-Y recorder. The stress was recorded on the Y-axis

and the strain on the X-axis. The X-Y recorder recorded the stress-strain curve by means of a sharply focused highly intense light beam and a photographic paper. The X and Y axes were calibrated in terms of microinches per inch of strain.

Stress-strain curves were obtained with this method. But because of a faulty amplifier discovered in the circuit too late, the stress-strain curves were not accurate. Since available samples for tensile testing were exhausted, no results could be reported here. However, if the method were perfected, it would be ideal for analysis of the stress-strain curve of cast irons at any stress level below the stress at which plastic deformations begin because of the high sensitivity which is possible.

Tensile Strength. The relationship between tensile strength and resonant frequency for s i x as cast bars is shown in Figure 24. It was felt that sample 2A 3, the sample which did not fall close to the straight line in Figure 24 had an erronous resonant frequency due to unknown factors. These bars were poured in groups of two per mold and the resonant frequencies of the two bars per mold were found to be within 100 CPS of each other in every case except this bar which had a resonant frequency of 9654 CPS while its mate had a resonant frequency of 9908 CPS.

Previous studies have been made in which many more samples have been tensile tested and the results plotted against resonant

frequency. In an article by A. G. Fuller[18] and others, a similar correlation was found as in Figure 24. Mr. Fuller's data showed that the tensile strength did not exceed ± 2000 Psi about the mean line.

Brinell Hardness. When plotting average Brinell diameter against resonant frequency, data for the as cast test bars were considered separately from data for the annealed test bars. In Figure 25, the upper curve represents six annealed test bars and the lower curve represents twenty-four as cast test bars. As was cited earlier, the matrix structure of each of the annealed bars were found to be all ferrite. This was discovered by etching the sample in a two percent nital solution. The lower curve shows another relation, but all of the points except one are grouped within ± 1.5 mm. of the mean line. In comparing average Brinell diameter to resonant frequency of the twenty-six as cast parts shown in Figure 2, a considerable spread is found above a Brinell diameter of 4.3 mm. (197) (See Figure 26). When observing the non-uniformity of castings in Brinell hardness, it is evident in Figure 4 that at 4.3 mm. diameter and lower the Brinell diameter is much more uniform.

Carbon Equivalent. As shown in Figures 27 and 28, a good correlation between carbon equivalent and resonant frequency is not

---

[18]A. G. Fuller, et al, "Sonic Testing: A simple Non-Destructive Test for Verifying Casting Quality," BCIRA Journal, (VII, May 1963), p. 372.

obtained. But the correlation between Thermal arrest carbon equivalent and resonant frequency is better than the correlation between wet carbon equivalent and resonant frequency.

Microstructure. Modulus of elasticity has been found to be related to the average flake length of the graphite in the microstructure which is in turn a function of the cooling rate and graphite content. It has been found also that the coarser the graphite, the greater the systematic deviation between the dynamic modulus determined by equation (2) and the static modulus.[19] It is suggested by Dr. Plénard that this systematic deviation might be a result of the heterogeneous nature of the structure of gray iron since there should be no distinction between static and dynamic modulus. Equation (2), then, might also need to consider a factor of graphite flake size for coarser structure.

These considerations indicate a relationship between graphite quantity and length of flakes and resonant frequency.

A photomicrograph toward the center of sample 1A1 (Figure 9) which shows a relatively short graphite length and some abnormal graphite has a resonant frequency of 10052 CPS, while sample 3A1 which has a much greater average graphite length has a resonant frequency of 9202 CPS. Upon examining the microstructures of samples 2A1 and 2A2 (Figure 25) which had resonant frequencies in between samples 1A1 and

---

[19] Plénard, pp. 15 and 16.

3A1, it was found that the average flake length was between that of samples 1A1 and 3A1. Also some abnormal graphite was found in samples 2A1 and 2A2. This suggests a relationship between flake size and resonant frequency.

A further investigation was made with samples 1A5, 3A7, and 3A3 (see Figure 25). Again sample 1A5 having a high resonant frequency had a shorter flake length and abnormal graphite. Sample 3A3 having a low resonant frequency had coarser graphite flakes. And sample 3A7 having an intermediate resonant frequency had graphite intermediate in size. This effect can be observed in the photomicrographs in Figures 9 and 10. Figure 9 showing the fine graphite flakes was associated with a high resonant frequency, and Figure 10 showing the coarse graphite flakes was associated with a low resonant frequency. Graphite flake size, then, determines resonant frequency.

Another significance concerning resonant frequency is the pronounced shift of the resonant frequency of the annealed samples toward the lower frequencies in Figure 25. The carbon equivalents and chill depths of the samples 3A1, 3A3, and 3A4 are the same, and the carbon equivalents and chill depths of samples 2A1, 2A2, and 3A7 are nearly the same. Since it was determined that the matrix was nearly the same from sample to sample, then the above grouped samples would have all been similar in Brinell hardness, microstructure, and resonant frequency in the as cast condition. The pronounced shift which is about 300 CPS to the left, could be a result of both matrix change and a result of secondary graphitization occurring upon annealing.

It should be noted that pearlite and ferrite have slightly different elastic moduli which might affect resonant frequency.

At the surface, all the samples had the rozette pattern of graphite as shown in Figure 11 but again varying in fineness. The finer surface graphite was associated with a finer graphite at the center and the coarser surface graphite was associated with the coarser graphite at the center. In addition some ferrite which varied in quantity from sample to sample was associated with the finer surface graphite (see Figure 11). Again the greater quantities of ferrite at both the surface and interior seemed to be associated with the larger graphite flakes as represented by Figure 10 and, therefore, with lower resonant frequencies. Figure 12 shows the ferrite patterns associated with the coarser graphite flakes represented by Figure 10. This could mean that at lower resonant frequencies (coarser graphite flakes) one would expect to find some ferrite.

Figure 13 shows a photomicrograph of the typical pearlite found in all the as cast samples examined. No pronounced variation in pearlite was found. This means that the pearlite was eliminated as a variable. Finally, Figure 14 shows evidence of still another constituent found in all the samples examined in slightly varying amounts. Since this material was located in between eutectic cells and was not continuous when examined at higher magnifications, it was concluded to be steadite. Steadite is a hard brittle constituent that consists of a binary eutectic of ferrite (containing some phosphorous in solution) and iron phosphide (Fe_3P). Steadite becomes visible when the phosphorous content

exceeds 0.1 percent. Unfortunately, the phosphorous content was not analyzed for these samples, and no definite decision could be arrived at as to effects of phosphorous. It was thought, though, that the amount of steadite was too small to affect the test indications.

Evaluation of the Resonance Test

The conclusions arrived at in the analysis of the resonance test are as follows:

1. A theoretical relationship exists between resonant frequency and modulus of elasticity of gray iron at low stress levels. Since modulus has been found to be related to the amount and nature of the graphite (if modulus is defined properly) and nearly independent of the nature of the matrix, resonant frequency should also be related to the amount and nature of the graphite.

2. Elastic modulus was not accurately determined. However, a promising method using strain gages for analysis of the stress-strain curve at low stress levels was found, but the method needs perfecting.

3. Relationship between resonant frequency and tensile strength among six as-cast test bars was good but not enough tensile tests could be obtained. Others have found similar relationships with an accuracy of $\pm$ 2000 Psi about the mean curve through the points. The matrix must be the same from sample to sample when comparing tensile strength since resonant frequency is a function of E which is a function only of the graphite.

4. Average Brinell hardness and resonant frequency seem to have a good correlation when the variation of Brinell hardness does not vary significantly from point to point within a cast part.

5. A general correlation was found to exist between Thermal arrest carbon equivalent and resonant frequency, but was not significant enough to use as a melting control.

6. Examination of microstructures of eleven selected samples revealed a relationship between resonant frequency and graphite size and type. The coarser flakes structure having

very little type D graphite was associated with a lower resonant frequency. The finer flake structure with much more type D and E graphite was associated with a higher resonant frequency. Greater quantities of free ferrite seemed to be associated with the coarser structured graphite and with the lower resonant frequencies.

The resonance test, then, offers a precise means of analyzing the influence of the graphite phase nearly independent of the type of matrix structure. The next step would be to find a method which would analyze the matrix structure independently of the amount and nature of the graphite. This attempt is made in the next chapter.

CHAPTER III

STATIC MAGNETIC TESTS AND EDDY CURRENT TESTS

Magnetic properties were known to be associated with hardness of steel for many years. A magnetically "hard" material is usually "hard" physically. Hard steels will, in general, give hysteresis curves of large areas and soft steels, small areas.[20] M. J. Diamond has applied magnetic retentivity to sort Arma Steel rocker arms according to hardness.[21] Thus, a relationship of mechanical hardness to magnetic properties of ferromagnetic materials is indicated.

The tests analyzed in this investigation may be classified into two groups: static magnetic tests and eddy current tests. The static magnetic tests include the magnetic retentivity test and the coercive force test. These tests were conducted with a Foerster Coercive Force Meter. The eddy current tests include a comparative test and a probe coil test. The comparative test was conducted with a Foerster-Hoover Model QC-1000 comparator which used two transformer coils. A standard of the same kind as the part to be tested was placed in one coil, and the part to be tested was placed in the other coil. The probe coil test where the axis of the coil was placed perpendicular

---

[20] Williams, p. 383.

[21] Diamond, "A Summary ...," p. 26.

to the test surface was conducted with Magnaflux's model ED-300 Eddy Current Tester.

These static magnetic tests and eddy current tests will be discussed as follows: principles in static magnetic testing and eddy current testing, testing procedure, microstructure and physical properties, and evaluation of these tests.

Principles in Static Magnetic Testing and Eddy Current Testing[22]

Both static magnetic tests and eddy current tests have been employed in industry to nondestructively test ferrous parts. The principles upon which these tests are based will be discussed below.

Static Magnetic Tests. The advantage of static magnetic tests is that test indications are representative of the whole cross-section rather than mainly the surface of the part. Retentivity is that value of residual induction on the direct-current magnetization curve which is obtained by saturating a ferromagnetic sample and then reducing the magnetizing force to zero. Coercive force is the amount of magnetizing force required to reduce the residual induction to zero after saturation of the material. (See Figure 29.) An advantage of the coercive force method is that it represents a factor which can be measured independently of the shape and mass of the material. This means that the coercive force of two different parts could be compared, if desired. Coercive

---

[22]NDT Handbook, II, 34.1 to 42.74.

force has been related to such properties as hardness, tensile strength, depth of case, alloy content, and aging conditions. When correlating these properties to coercive force, two other factors must be considered. It is important that no reversal appear in the function relating coercive force to material properties. It is stated in the Nondestructive Testing Handbook, Vol. II, that such reversals may appear with several alloys, particularly after repeated heat treatment. This reference also states that coercive force is dependent upon the temperature of the material being tested.

Eddy Current Tests. Eddy current testing was developed by Dr. Foerster in Germany around the end of World War II. The principles developed then form the basis of present-day eddy current testers. A schematic representation of the two types of probes used in this study are presented in Figure 30. The QC-1000 Comparator uses the transformer coil where a part to be tested is the core (Figure 30A), and the ED-300 Eddy Current Tester uses the single inductor coil (Figure 30B). An induced magnetic field in either probe produces eddy currents which in turn produce an opposing alternating field in the sample. The change in impedance due to the presence of the part in both eddy current methods is dependent upon electrical conductivity, dimensions of the part, magnetic permeability, presence of discontinuities, frequency of the test coil, the size and shape of the coil, and the coupling between the coil and the sample.

A factor in eddy current testing which must be considered is that the alternating fields are stronger at the surface than at the center of the part. The penetration depth, P, is defined as the depth

below the surface at which the field has decreased to 36.8 percent of the field strength. In order to determine the effective depth, the mathematical solution of the general case of a cylindrical test object had to be obtained.[23] In this solution the cylinder was assumed to have a uniform permeability over its cross-section designated as effective permeability (U_{eff}) which is related to electrical conductivity, relative permeability, diameter of the test object, and test frequency. From this solution which occurred as the argument A of the Bessel function, the values of frequency defined as the limit frequency, f_g, was obtained by setting A equal to unity. The value for f_g is:

$$f_g = \frac{5066}{U_{rel}\ C\ D^2} \qquad (1)$$

where U_{rel} is the relative permeability of the test material, C is the electrical conductivity of the test material in meter/ohm-mm^2, and D is the diameter of the test sample. The ratio of f/f_g determines the value and phase angle of the field strength at a given point below the surface of the test sample, f being the test frequency. The effective depth for a particular f/f_g ratio is then determinable.[24] For a homogeneous iron sample of the same nominal diameter as the test bars used in this study, 1.2 inches diameter, the effective depth was computed to be approximately 0.15 inches for a coil frequency of 60 CPS and roughly 0.04 inches for a coil frequency of 360 CPS. These

---

[23] Ibid., II, 36.13.

[24] NDT Handbook, II, 37.9.

calculations were made assuming that the coil axis was coincident with the axis of the cylindrical test bar. The main significance of the general mathematical solution is that effective depth is predictable knowing test frequency (f), limit frequency (f_g), and the diameter of a cylindrical test bar.

Another significant principle worthy of mention is the law of similarity in eddy current testing. This fundamental law is stated as follows:

> "The effective permeability, as well as the geometrical distributions of the field strength and eddy current densities, is the same for two different test objects, if the ratio f/f_g, is the same for each test object."[25]

This law is significant in comparative testing, as with the QC-1000 Comparator. Since f_g is a function of U_{rel}, C, and D, a comparative test would indicate a difference in relative permeability, electrical conductivity, and size. Size was considered as a constant in this investigation. So a difference in test indications with the QC-1000 Comparator was a measure of the relative permeability and electrical conductivity with respect to a standard.

Testing Procedure

The static magnetic test instrument investigated was the Foerster

---

[25]NDT Handbook, II, 37.10.

coercive force meter which measures magnetic retentivity and coercive force. The eddy current instruments investigated were the QC-1000 Comparator and the ED-300 Eddy Current Tester.

The thirty test bars that were resonance tested were first tested with the QC-1000 Comparator. Then three-inch bars from the longer bars tested above were machined to length in order to measure coercive force and retentivity. The ED-300 tests were also made on the three-inch test bars. (See Figure 1.) Only QC-1000 and ED-300 indications were taken on the cast parts from Central Foundry since their physical size would not allow them to be placed in the Coercive Force Meter Test Coil.

The testing procedure for static magnetic tests and eddy current tests will be presented.

Static Magnetic Tests. A diagram of the Coercive Force Meter is shown in Figure 31. The high-sensitivity field probes are aligned so that the tangential field from the test coil does not affect the probes when reversing the field to measure coercive force. This unit must also be compensated for the earth's magnetic field. Testing procedure involved these steps:

(1) Making preliminary adjustments and compensating for the earth's magnetic field.

(2) Slowly and steadily, without stopping, increasing the magnetizing force until the sample was saturated.

(3) Slowly and steadily, without stopping, decreasing the magnetizing force to zero.

(4) Reading the relative magnetic retentivity.

(5) Reversing the current and thus the direction of the magnetizing force; and increasing the magnetizing force until the value of relative magnetic induction is zero.

The value of magnetizing force required to perform step (5), then, is the coercive force of the material tested.

Eddy Current Tests. With the QC-1000 Comparator, magnetization variations, permeability variations, or the variations of the curvature of the hysteresis loop of a sample with respect to a standard are measured. The above instrument is similar to the Magnatest Q instrument[26] which is a linear time-base instrument. The variation in magnetic properties between two parts is represented by the relative change in the vertical position of a trace displayed on a cathode ray oscilloscope. The linear time-base is applied to the horizontal plates of the oscilloscope. (Figure 32)

The QC-1000 unit uses only one test frequency, 60 CPS. It would be desirable at times to measure magnetic properties at even lower frequencies, for two reasons: a greater penetration depth can be obtained, and the effects of inhomogeneous internal stresses[27] can be eliminated. Inhomogeneous internal stresses tend to result in an inseparable pattern on the oscilloscope screen.

Testing procedure with the QC-1000 Comparator was as follows:

(1) Making preliminary adjustments according to the instruction manual.

---

[26]NDT Handbook, II, 40.29.

[27]NDT Handbook, II, 42.43.

(2) Choosing a standard sample and placing it into one of the two coils (see Figure 32), the standard being midway between the extremes of Brinell hardness.

(3) Adjusting the scope display to obtain a horizontal line when properly placing other samples of identical Brinell hardness into the second coil one at a time.

(4) Adjusting vertical sensitivity, such that a full scale difference in scope display results, when examining a number of samples on the "hard" side of the hardness range and on the "soft" side of the hardness range.

(5) Making a "phase" adjustment in order to locate the maximum deflection of the trace at the center of the screen.

(6) Placing a grid over the oscilloscope screen and taking readings of the trace position near the center of the screen, considering any phase shift.

Next, testing considerations for the ED-300 tester will be examined and the test procedure presented. Essentially, the ED-300 tester which operates at a frequency of 360 CPS, is a power-loss measuring device for ferromagnetic materials. The power-loss is due to hysteresis losses and eddy current losses in the material. The following excerpt serves to explain how the ED-300 operates:

> "When an alternating current is made to flow through a coil held in close proximity to a ferromagnetic metal, alternating magnetic fields are induced in the metal. These fields, in turn, will induce circular counter-currents (eddy currents) within the metal. The respective counter field developed by the eddy currents will oppose the applied field with a magnitude and phase dependent on the resistivity and permeability of the metal. Both of these characteristics vary with analysis and structure, permeability being by far the greatest affected. The losses associated with each cannot be measured independently of each other using alternating magnetic field techniques, but their sum can be indicated on the ED-300 meter as Mx numbers or power-loss probe measurements."[28]

---

[28] Operating Manual for Magnatest ED-300 Low Frequency Measuring Instrument, (Magnaflux Corporation), 5-1.

The ED-300, like the QC-1000, is a special application of general eddy current principles. The QC-1000 compares a standard with an unknown test speciman, while the ED-300 reads directly the power losses in different parts. The methods would be comparable providing the effective penetration of both were the same. (Figure 33)

Preparation of the ED-300 for use after initial warm-up was found to be very simple and rapid. Initial warm-up requiring about an hour takes the most time. After the instrument had warmed up, the sensitivity was set at maximum and the probe was compensated for lift-off with a test bar intermediate in Brinell hardness. Lift-off is a term used to designate adjustment of the instrument so that no difference in reading is obtained when the probe is lifted a few thousandths of an inch off the surface of a test sample. When compensated for lift-off, oxide scale or burnt-in sand on a casting a few thousandths thick will not affect the reading. To compensate for lift-off, a piece of ordinary writing paper was placed between the probe and the test sample and adjustments were made until the presence of the paper did not affect the results. Then the samples were tested. First, the two ends of the cylindrical test speciman which were machined surfaces were tested at the center. Then lift-off was readjusted so the contour of the as cast cylindrical surface could be measured. Since the as cast surface was of different geometry, an overall average value could not be obtained. When conducting tests on the thirty test bars and twenty-six cast parts, the following observations were made:

(1) Geometry of the test surface affects the results.

(2) Mass affects the results.

(3) A maximum down-scale jump of ten percent of the total scale occurred while taking measurements. Readings at maximum scale reading were taken after observing scale indications for approximately one minute.

The first two observations could, of course, be predicted from the earlier theoretical considerations.

Physical Properties and Microstructure

Before, considering each test separately, a comparison will be made between the test indications. The coercive force test and the magnetic retentivity test should be related since they are both static tests; and the QC-1000 and the ED-300 eddy current tests should be related.

The comparison of static magnetic tests should indicate whether to eliminate one of the tests from consideration. Neglecting sample 2A7 in Figure 34 a maximum deviation about the mean line of the plot of residual magnetism against coercive force was $\pm$ 12 units of residual magnetism. This deviation was probably due to errors in determining residual magnetism. This was concluded after considering the following. In the Nondestructive Testing Handbook, Vol. II, it was reported that "a rod or small grindings of a given material will give, without re-calculation, the same measured values" of coercive force regardless of weight. Retentivity, however, would change since the orientation of the material to the detecting probe would change (see Figure 31). Thus, errors in retentivity might result due to positioning of the sample. It would seem, then, that coercive force as measured by a Coercive Force Meter would be less subject to variations due to

extraneous factors. Thus, one of the static magnetic tests, the retentivity test, was eliminated.

Next, when plotting surface indications against center indications per sample for the ED-300, a considerable spread was obtained (see Figure 35). This is not surprising since the effective penetration depth for a steel cylinder of the same diameter as the test bars was only 0.04 inches. When plotting QC-1000 Comparator test indications against ED-300 center indications, a rather narrow relative deviation about the mean line resulted (see Figure 36). Surface conditions appeared to have a more pronounced effect upon the results of the ED-300 test than upon the results of the QC-1000 test due to the higher frequency involved with the ED-300. Also the relationship between ED-300 (center indications) and QC-1000 tests has the correlation expected, since both are eddy current tests.

As a result, then, the less accurate tests were eliminated and the magnetic tests under consideration were reduced to a static field measurement, coercive force; and an eddy current comparison of two samples, the QC-1000 Comparator indications. The relationship of coercive force and QC-1000 indications to tensile strength, Brinell hardness and carbon equivalent, and microstructure are reported here.

Tensile Strength. As can be seen in Figure 37, the correlation between tensile strength and the QC-1000 indications for seven tensile tests is good. However, more tensile tests should be made in order to establish the standard deviation. It is not surprising to find a correlation between eddy current indications and tensile strength since tensile strength is a function of the two variables matrix + graphite, and the eddy current indications are a function of the permeability

and conductivity, which in turn are functions of the matrix material and graphite.

Next examining coercive force (Figure 38), one finds a much poorer correlation of tensile strength with coercive force. This might be expected when considering the following factors:

(1) The coercive force is a property of the material and not dependent upon mass or shape.

(2) Graphite size should not affect the coercive force of the material appreciably since it is nonmagnetic and would have nearly the same permeability as air.

(3) Coercive force is dependent upon the amount of combined carbon, silicon content, and other alloys in solid solution with the iron.

Brinell Hardness. Average Brinell diameter was plotted against the QC-1000 test indications for both the test bar and the as cast parts. An average deviation of less than $\pm$ 0.20 mm. Brinell diameter is indicated for both the test bar and the as cast part (see Figures 39 and 40, respectively). When comparing Figures 6 and 37, it can be seen that a much better correlation exists between QC-1000 comparator indications and tensile strength than between Brinell hardness diameter and tensile strength. Thus a deviation is expected when comparing average Brinell diameter with QC-1000 test indications. Therefore, if tensile strength is the property important to the customer,the QC-1000 comparator test would be much more reliable than the Brinell test.

Coercive force and Brinell hardness seemed to be better related than coercive force and tensile strength. (See Figures 38 and 41) A deviation of $\pm$ 0.20 mm. resulted about the mean line connecting the two sets of points. Again, more points between these two groups of points would have been desirable.

Carbon Equivalent. The correlation between QC-1000 test indications and carbon equivalent was not good. There was even poorer correlation between coercive force and carbon equivalent.

It must be remembered that carbon equivalent is determined before a casting is poured. The important variables, ladle inoculation which affects the graphite phase, and cooling rate, which affects both the graphite phase and the matrix, are not taken into account when trying to correlate these test indications with carbon equivalent.

A test which does adequately evaluate the properties of gray iron, however, can be used in Foundry control. By observing the changes in carbon equivalent before the iron is poured and by observing changes in test indications after gray iron parts are poured and have cooled, changes in the intermediate variables, inoculation and cooling rate, can be observed.

Microstructure. Coercive force and QC-1000 comparator indications of some of the test bars were compared with microstructures to determine if a relationship exists between these test indications and microstructure. Also, tensile strength, resonant frequency, and Brinell hardness were used to supplement microstructural observations.

In the comparing coercive force with tensile strength which is a function of both matrix and graphite and considering resonant frequency which is a function of graphite only, the relationship between coercive force and microstructure can be deduced. In closely examining Figure 42, it can be seen that the effect of ferritising treatment (annealing) is to reduce both the coercive force and the tensile strength. It can be seen that a reduction in resonant frequency

(and therefore a coarsening of the graphite) also causes a reduction in tensile strength (considering either the as cast group or the annealed group), but does not affect coercive force. Thus, it can be deduced that the change in graphite flake size does not affect coercive force.

Can coercive force detect smaller changes in the matrix than was brought about by the ferritising treatment? To answer this question, Figure 41 was examined. The lower coercive force of samples 3A3 and 3A4 may be attributable to the presence of some ferrite around the graphite flakes as shown in Figure 12. Other small changes in coercive force were not explainable on the basis of microstructures, since any changes in pearlite coarseness were not observed. It was found from this investigation, then, that coercive force is related to the amount of ferrite in the matrix, but is independent of the graphite size.

The eddy current test, the QC-1000 comparative test, seems to be a good indicator of tensile strength (see Figure 37). Tensile strength, of course, is related to both the graphitic phase and the matrix. When analyzing Figure 39 and picking out samples whose microstructures were examined, it can be seen that the QC-1000 indications are influenced by both the matrix and the graphite. Samples 1A1 and 3A1 have the same type of matrix (ferrite), but sample 1A1 has flakes of shorter length than sample 3A1 (see Figures 9 and 10, respectively). The differences between samples 3A1 and 1A5 in QC-1000 comparator test indications are primarily a result of changes in matrix. Sample 3A1 has an all-ferrite matrix, and sample 1A5 has an all-pearlite matrix.

Evaluation of Static Magnetic Tests and Eddy Current Tests

The static magnetic tests considered were magnetic retentivity test and coercive force test which were conducted with a Foerster Coercive Force Meter. The magnetic retentivity test was eliminated from consideration because it depended upon orientation with respect to the measuring probe and upon the geometry and mass of the test sample. Coercive force depended upon neither geometry nor mass of the test sample. The following conclusions were reached in the investigation of the coercive force test:

1. Coercive force, being a static magnetic field test, is representative of the entire cross-section.
2. The coercive forces of two different parts with different masses and shapes can be compared because coercive force is independent of mass and geometry of the test sample.
3. It is significant that no reversals appear in the function relating physical properties to coercive force.
4. Coercive force is dependent upon temperature.
5. The coercive force test is not a sufficient test by itself to predict tensile strength or Brinell hardness.
6. Carbon equivalent of gray iron could not be significantly correlated with coercive force.
7. Coercive force seemed to be related to the amount of ferrite and pearlite in the matrix independent of graphite size. In the samples examined for microstructure, the coarseness of pearlite did not vary. Thus the affect that changes in coarseness of pearlite has on coercive force was not investigated.

The coercive force test would be the solution to the problem of finding a test which examines the metallic matrix of a casting independently of the graphite size, if differences in pearlite coarseness could be

detected with the coercive force test.

The eddy current tests considered were the QC-1000 Comparator test and the ED-300 Eddy Current test. The ED-300 test, nearly the same as the QC-1000 test in principle, was eliminated from consideration because it depended more upon the abnormal surface conditions than did the QC-1000 Comparator test. The conclusions reached concerning the QC-1000 Comparator test were as follows:

1. The penetration depth (or effective depth), which is defined as the depth below the surface of the test sample for which the field strength drops to 36.8 percent of the surface field strength, can be predicted accurately for simple geometrical shapes adaptable to mathematical solution.

2. The Law of Similarity, in essence, states that if relative permeability, mass, geometry, and test frequency of two parts are the same the eddy current distribution and effective permeability in one part will be identical to the eddy current distribution and effective permeability in the other. This law forms the basis of comparative testing.

3. Tensile strength and QC-1000 test indications have a much better correlation than tensile strength and Brinell hardness.

4. A correlation exists between Brinell diameter and QC-1000 Comparator test indications which has an average deviation less than $\pm$ 0.20 Brinell diameter about a mean line drawn through the test points.

5. No significant correlation was found between carbon equivalent and QC-1000 Comparator indications.

6. Analysis of microstructures showed that QC-1000 test indications are a function of both the matrix and the graphite.

The QC-1000 Comparator test indication, like Brinell hardness, is a function of both matrix and graphite. But the QC-1000 Comparator test is a more reliable test than the Brinell test in predicting tensile strength.

CONCLUSIONS

The goal of this investigation was to examine the Brinell test, the resonance test, static magnetic tests, and eddy current tests in order to find a sufficient test or a combination of tests which are capable of examining the quality of gray iron. The conclusions resulting from this investigation are as follows:

1. The Brinell test is not a sufficient quality test to predict the physical properties and microstructure of gray iron.

2. The resonant frequency test evaluates the graphite phase in gray iron independently of the matrix. A larger graphite flake size results in a lower resonant frequency. Resonant frequency depends upon the graphite phase, dimensions, density, and temperature of the sample being tested.

3. The coercive force test evaluates the amount of ferrite in the matrix independently of the graphite flake size. Coercive force is dependent upon the amount of carbon and other alloying elements in solution and upon temperature.

4. The QC-1000 Comparative test, like the Brinell test, evaluates both the metallic matrix and the graphite phase; however, the QC-1000 test is more reliable than the Brinell test in predicting tensile strength.

In summary, the Brinell test is not a sufficient quality test for gray iron. The resonance test evaluates the graphite phase independently of the matrix. The coercive force test evaluates the amount of ferrite in the matrix independently of the graphite phase. Finally, the QC-1000 test depends upon both the matrix and the graphite phase, but test indications are more closely related to tensile strength than to Brinell hardness.

RECOMMENDATIONS

Recommendations are made as follows: further investigation, production line application, and establishment of standards.

Further Investigation

Further laboratory investigation should include:

1. Correlation of coercive force and ferrite content over a range of ferrite content: In this investigation the matrix had no ferrite, two percent ferrite, or 100 percent ferrite. Ferrite contents of ten, twenty-five, and fifty percent should be investigated in addition.

2. Observation of the affect that differences in pearlite have on coercive force: In this investigation the differences in pearlite coarseness were not detectable under the microscope. As large a range of pearlite as is possible should be examined.

3. The affect of temperature on coercive force: The temperature of a single gray iron sample could be varied, and successive readings of coercive force could be taken in order to establish an experimental relationship between coercive force and temperature. Temperature of castings varies considerably in various stages of foundry production.

4. The affect of temperature on QC-1000 test indications: It was not determined in this investigation how QC-1000 test indications vary with the temperature of the test sample. The affect of temperature on QC-1000 comparator indications could be investigated as proposed in (3) above.

5. Methods of supporting samples to be resonance tested: Pins and styrofoam were used to support parts at nodal points when they were resonance tested. Pins will likely break-off and styrofoam may not be durable enough in production foundry testing. Thus, better methods of support should be investigated.

6. Methods of inducing resonance in small parts: In this investigation, when the SR-100 electromagnetic transducers were within about three inches of one another and loosely coupled with the sample being tested, "cross-talk" or

interference between the two transducers resulted. First, shielding of one transducer from the other should be tried. If this does not work, different transducers should be tried.

7. Theoretical and experimental investigation of the resonant frequencies of complex parts: A complex part often has many frequencies at which it resonates. These frequencies must be far enough apart so that no more than one frequency falls in the testing range.

8. The affect of mass and shape variations in production castings upon resonant frequency.

9. The affect of mass and shape variations in production castings upon QC-1000 comparator test indications.

Production Line Application

After investigation of the nine items above, test set-ups for production line testing in the foundry must be designed. A quality test could be used for two different purposes in a production foundry: as a control device or as a final inspection device. Figure 43 shows the possible test locations in the production routing and Appendix B shows an example of a specific test set-up.

Control Device. Used as a control device, the quality test could be used either as a test evaluating heat treatment or as a test evaluating iron pouring and mold line performance.

In the heat treatment of gray iron castings at Central Foundry, Danville Plant, the castings are heated to temperature uniformly, held at temperature for a period of time, and then cooled uniformly in a cooling zone in the furnace and in air. The heat-treatment could be either for stress relief or for various degrees of ferritising (annealing). When cooled to a certain temperature, (the temperature must be below the Curie temperature) the coercive forces and resonant frequencies of several castings could be obtained. The amount of free ferrite

(coercive force) and the size of the final graphite (resonant frequency) could be determined. This information could then be fed back into the annealing furnace as a control device. A similar control device might be set up to examine a certain percentage of castings prior to annealing. This device would indicate what adjustments on the annealing furnace are required to properly anneal the castings.

Used as a control on iron pouring and the mold line, the tests would be performed on uncleaned castings which had sufficiently cooled from their shake-out temperature. The castings could be standard test bars. The coercive force test would evaluate the variables affecting the matrix, namely chemistry and cooling rate. Soon chemistry will be determined rapidly enough so that cooling rate will be the only unknown at the time a casting is shaken-out of its mold. If chemistry is known, mold line speed can be adjusted in order to control the cooling rate of the matrix. At the same time, the resonant frequency test would evaluate the variables affecting the graphite phase which are inoculation, rate of solidification, and chemistry. The rate of solidification is controlled by chemistry, pouring temperature, and heat transfer. The variables which can be easily adjusted are inoculation, chemistry, and pouring temperature. Thus, a resonant frequency indication might require adjustment of one or more of these variables in order to hold the graphite phase within a specified range.

Final Inspection Device. When used as a final inspection device, a quality test should segregate the acceptable castings from the unacceptable ones.

Suppose, for example, that strength and machinability were the important factors to a customer. A test would have to be devised which would indicate strength and machinability.

One approach might be to use the QC-1000 comparator to directly evaluate strength and the resonance test to evaluate the graphite phase. With the combination of these tests, the graphite phase and the matrix could be evaluated. The matrix would be evaluated indirectly since resonant frequency is a function of the graphite phase and the QC-1000 indication is a function of both the matrix and the graphite phase. A general indication of machinability would be determined since machinability is related to both the matrix and the graphite phase.

Another approach would be to use the coercive force test which determines the amount of ferrite in the matrix and the resonant frequency test which evaluates the graphite phase. Machinability which is a function of the microstructure would be generally indicated. Strength could be deduced from a combination of the above tests.

To summarize, a quality test might be used as a control or as a final inspection device. When used as a control device, separation of the matrix and graphite factors are important to simplify the controlling of both the annealing cycle and the casting process. When used as a final inspection device, separation of the matrix and the graphite phase are also important. For tensile strength the QC-1000 test which depends upon both the matrix and the graphite phase is adequate.

Establishing Standards

The establishment of standards at the foundry and with the customer are very important items in the application of a nondestructive test to final inspection.

In order to use the matrix and graphite tests separately as controls on final inspection, the customer must accept the new tests adopted and must be persuaded to give his specifications in terms of the nondestructive tests.

In summary, it is recommended that further laboratory investigation be conducted as indicated, that production line application be made, and that the proper standards be established in the foundry and with the customer.

BIBLIOGRAPHY

Diamond, Milton J. "A Summary of Some New Processing and Quality Control Developments in Foundry Technology," General Motors Engineering Journal, XI (Second Quarter, 1964).

Diamond, Milton J. "The Utilization of Sonic Principles for Application to An Automatic Method of Casting Inspection," General Motors Engineering Journal. (March-April, 1956).

Fuller, A. G., et al. "Sonic Testing: A Simple Nondestructive Test for Verifying Casting Quality," BCIRA Journal, VII (May, 1963).

Kececioglu, Dr. Dimitri. "Factors Affecting Gray Iron Machinability," Foundry, XCI (October, 1963).

Lyman, Taylor (ed.). Vol. I of Metals Handbook, Metals Park, Ohio: American Society for Metals, 1961.

"Machinability of Iron Castings," Foundry Trade Journal, CXII (Dec. 13, 1962).

McMaster, Robert C. (ed.). Vol. II of Nondestructive Testing Handbook, New York: The Ronald Press Company, 1959.

Operating Manual for Magnatest ED-300 Low Frequency Measuring Instrument, Magnaflux Corporation.

Plénard, Elizabeth. The Elastic Behavior of Cast Iron, (Unpublished paper presented at the A.S.M. Cast Iron Seminar, June, 1964).

Williams, Samuel R. Hardness and Hardness Measurements, Cleveland: American Society for Metals, 1942.

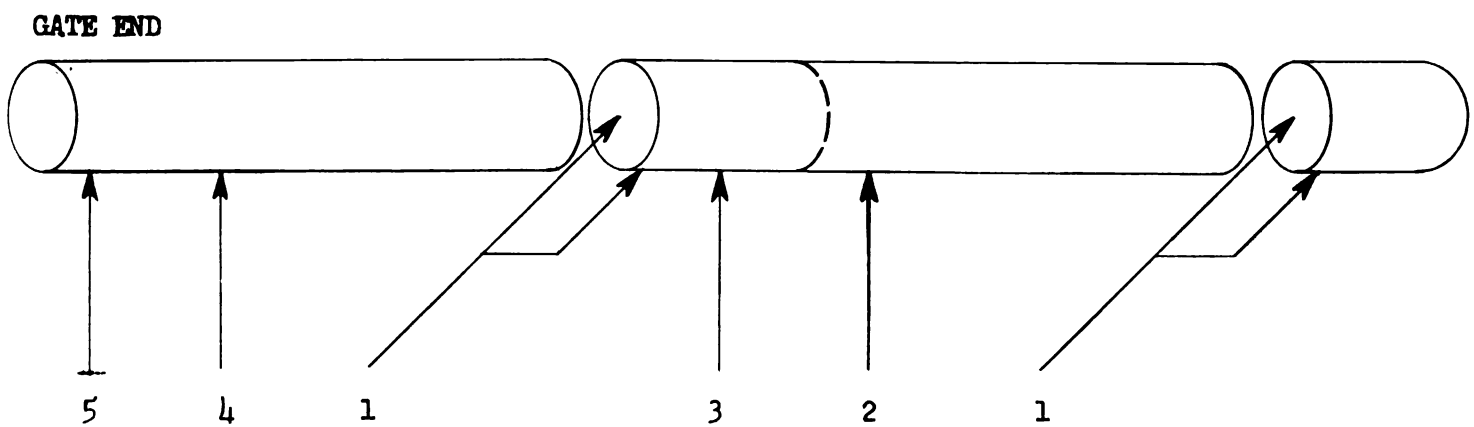
APPENDIX A

ILLUSTRATIONS AND GRAPHS

FIGURE 1

GRAY IRON TEST BARS

(STANDARD 1.2 INCH DIAMETER TRANSVERSE TEST BAR)



1. Brinell Test locations.
2. Test bar for Resonance Test: Length = 7.958 in.
3. Test bar for Coercive Force Test and ED-300 Eddy Current Test machined from 2 : Length = 3.000 in.
4. Portion from which tensile specimen were machined.
5. Location drilled for chemistry.

FIGURE 2

PART NO. 5692885 CAST PART

FROM CENTRAL FOUNDRY DIVISION

DANVILLE PLANT

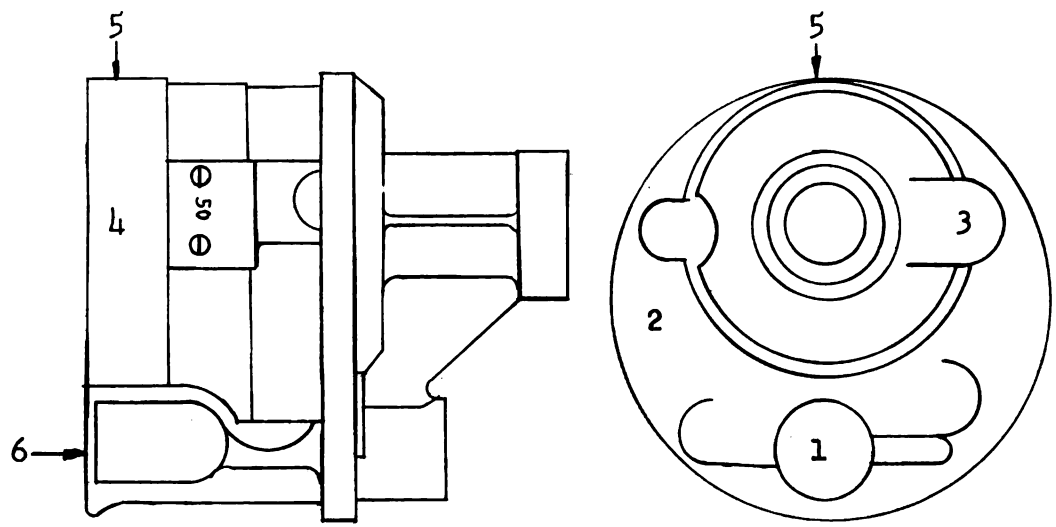


FIGURE 3

BRINELL HARDNESS NUMBER

VS. DIAMETER OF INDENTATION

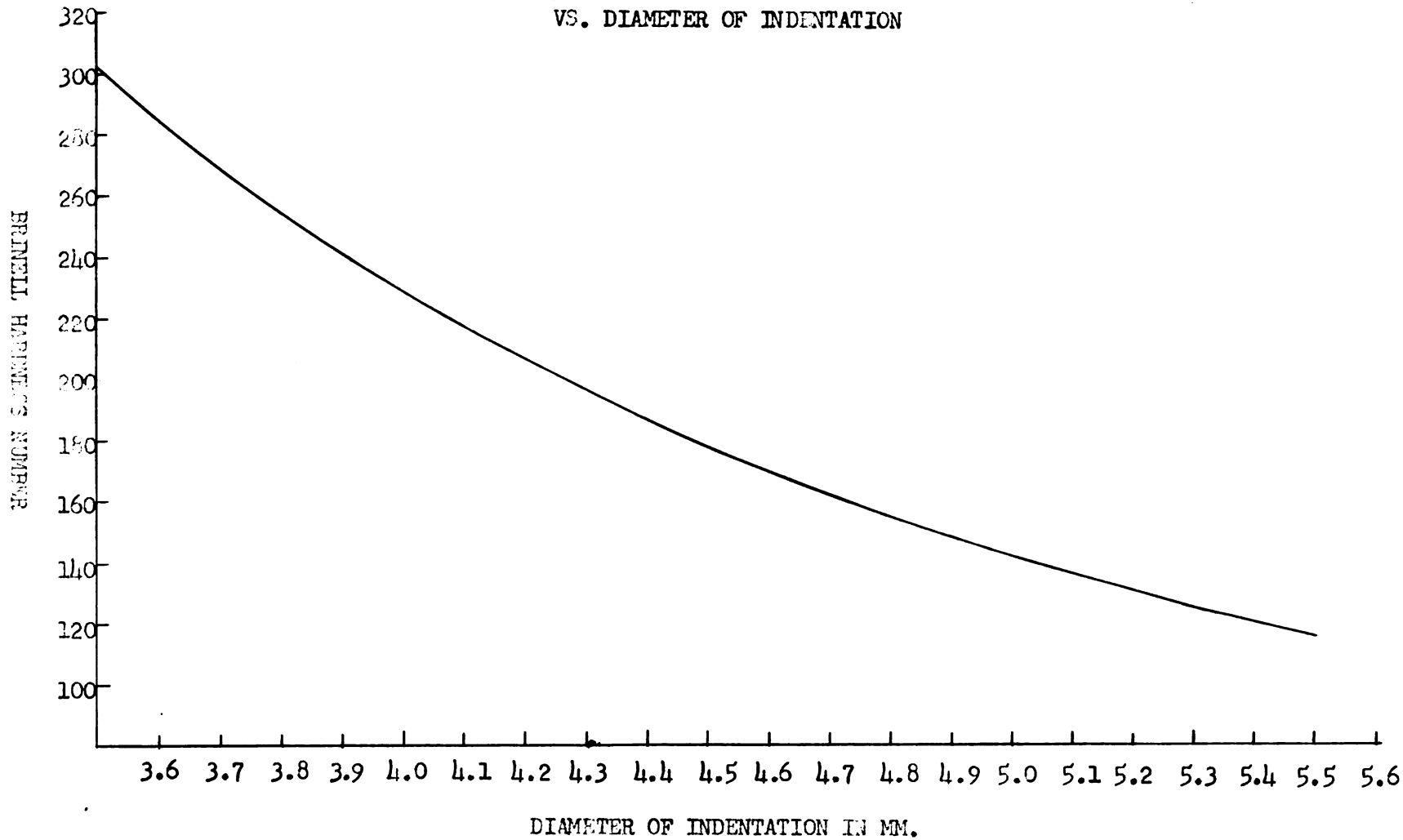
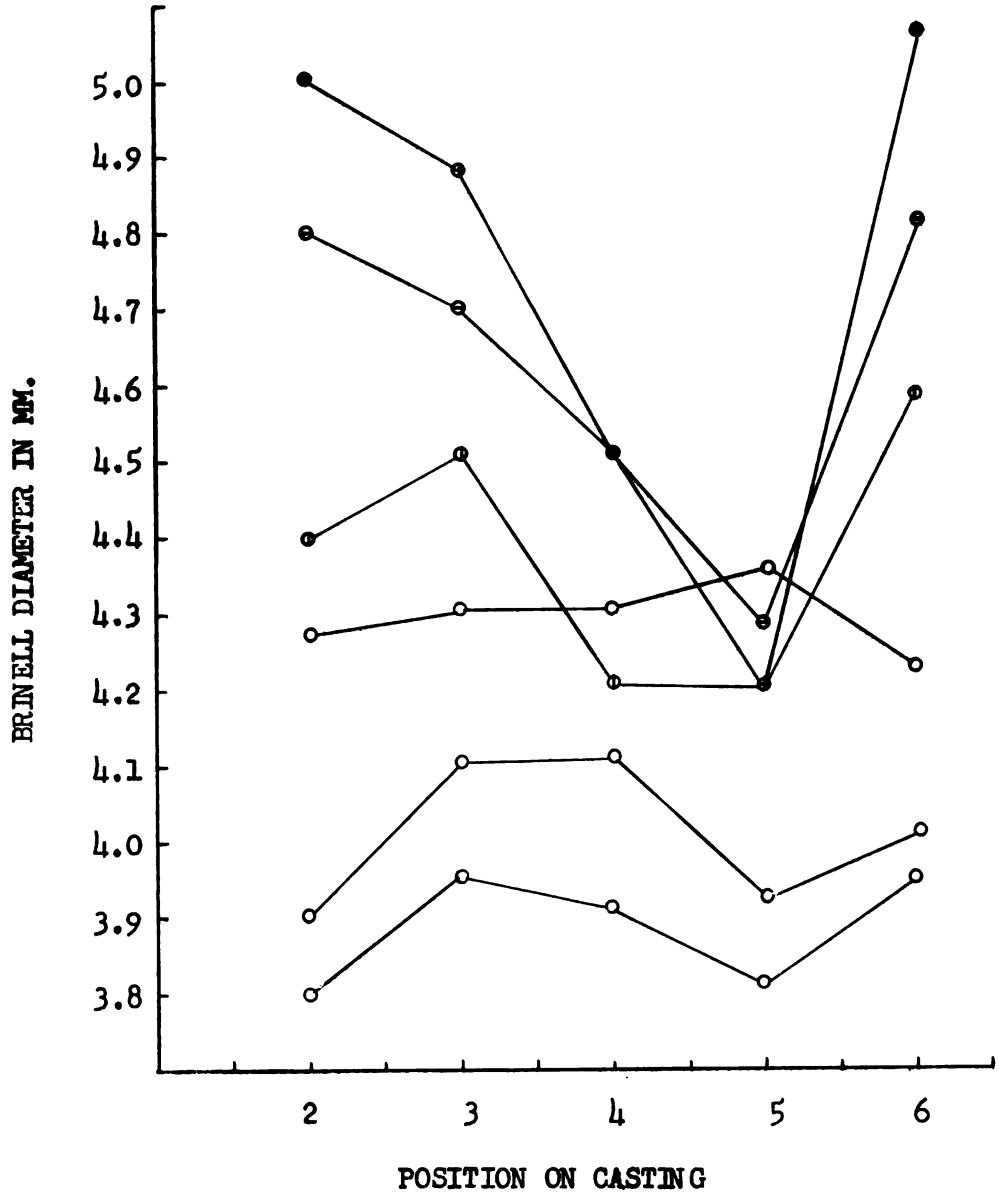


FIGURE 4

BRINELL DIAMETER VS. POSITION ON CASTING

FOR SIX SAMPLE CASTINGS

PART NO. 5692885



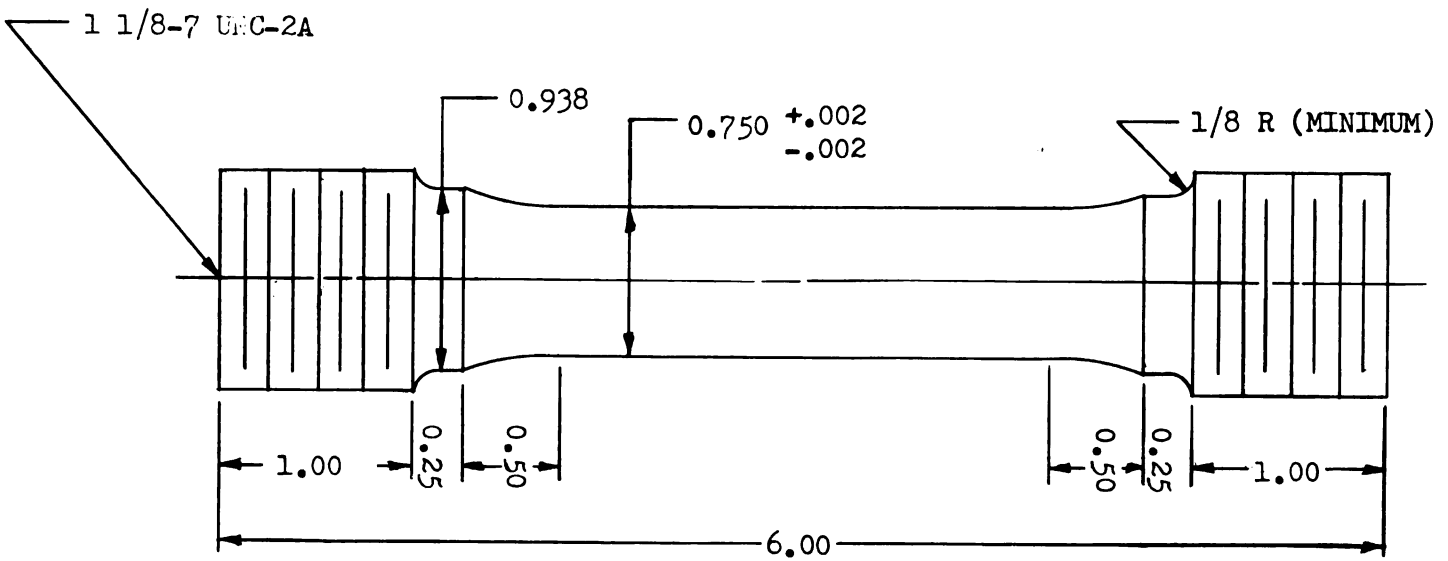


FIGURE 5

GRAY IRON TENSILE BAR

FIGURE 6

BRINELL DIAMETER VS. TENSILE STRENGTH

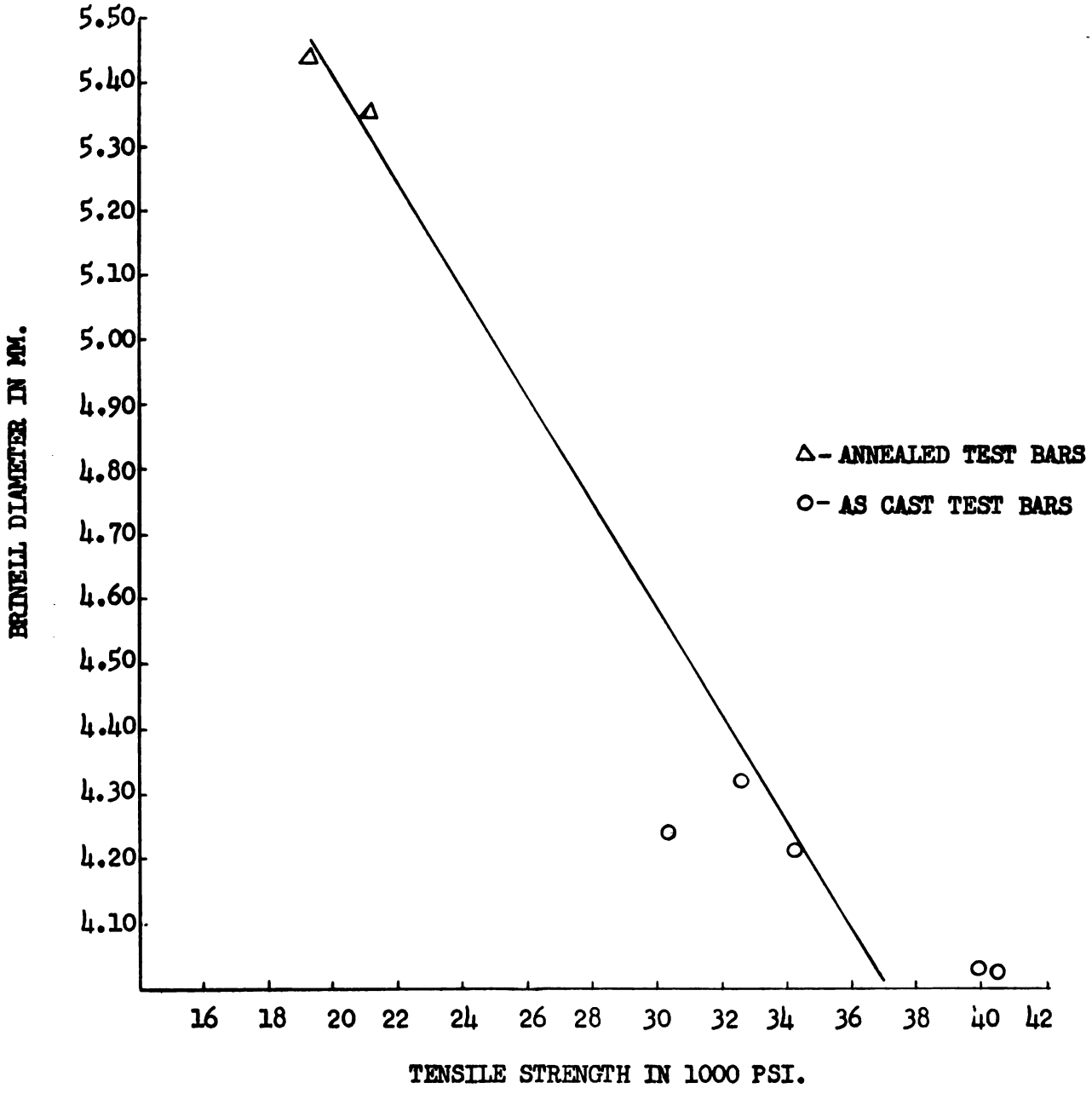


FIGURE 7

TENSILE STRENGTH VS. BRINELL HARDNESS NUMBER

FOR ABOUT 1500 GRAY IRON TENSILE BARS

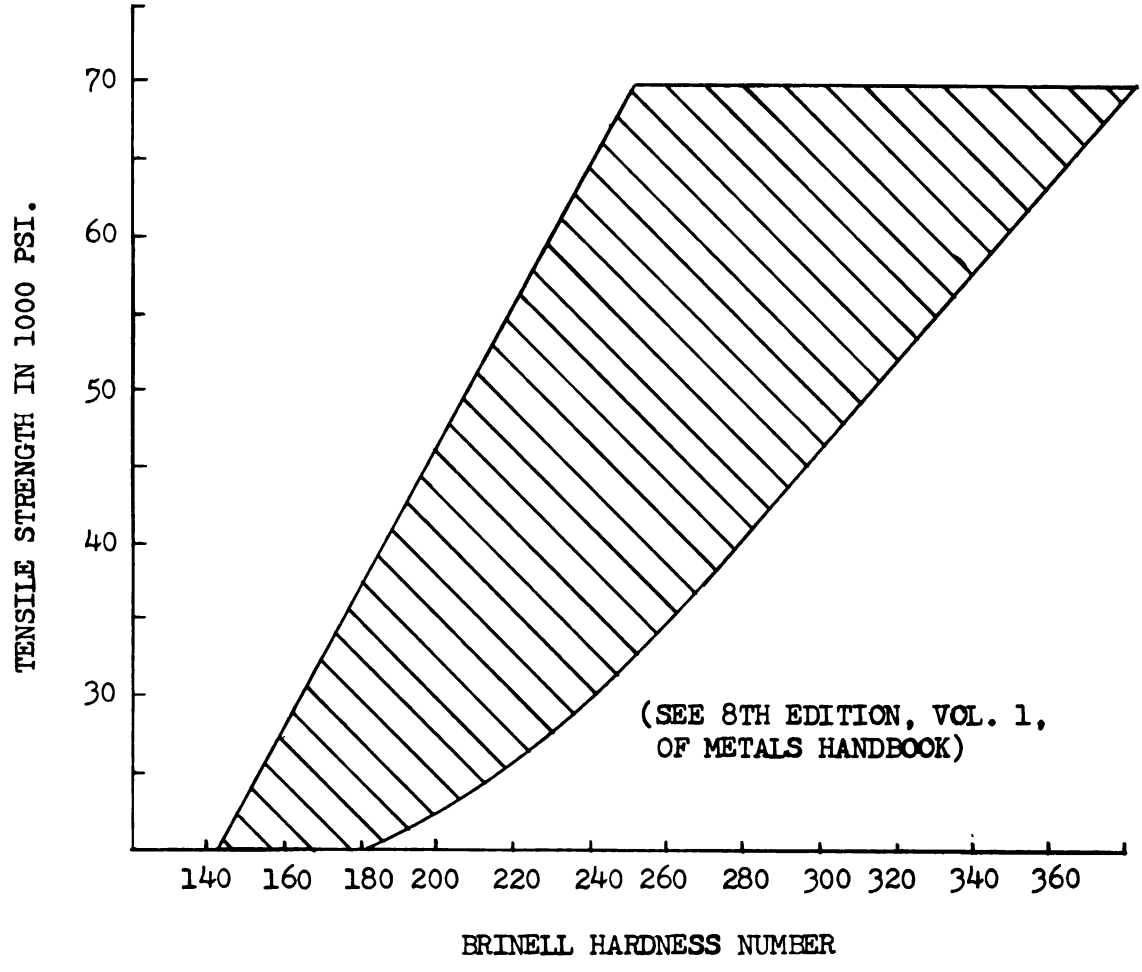


FIGURE 7

TENSILE STRENGTH VS. BRINELL HARDNESS NUMBER

FOR ABOUT 1500 GRAY IRON TENSILE BARS

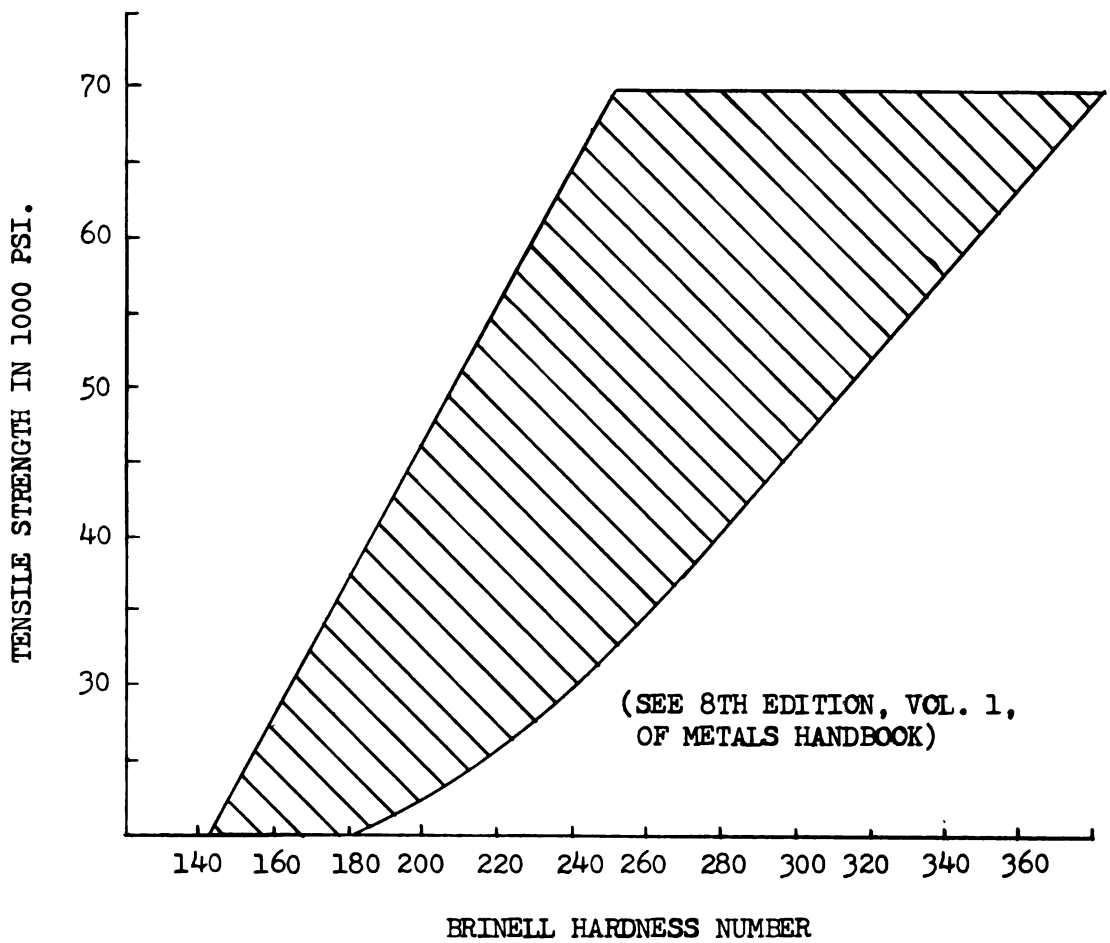
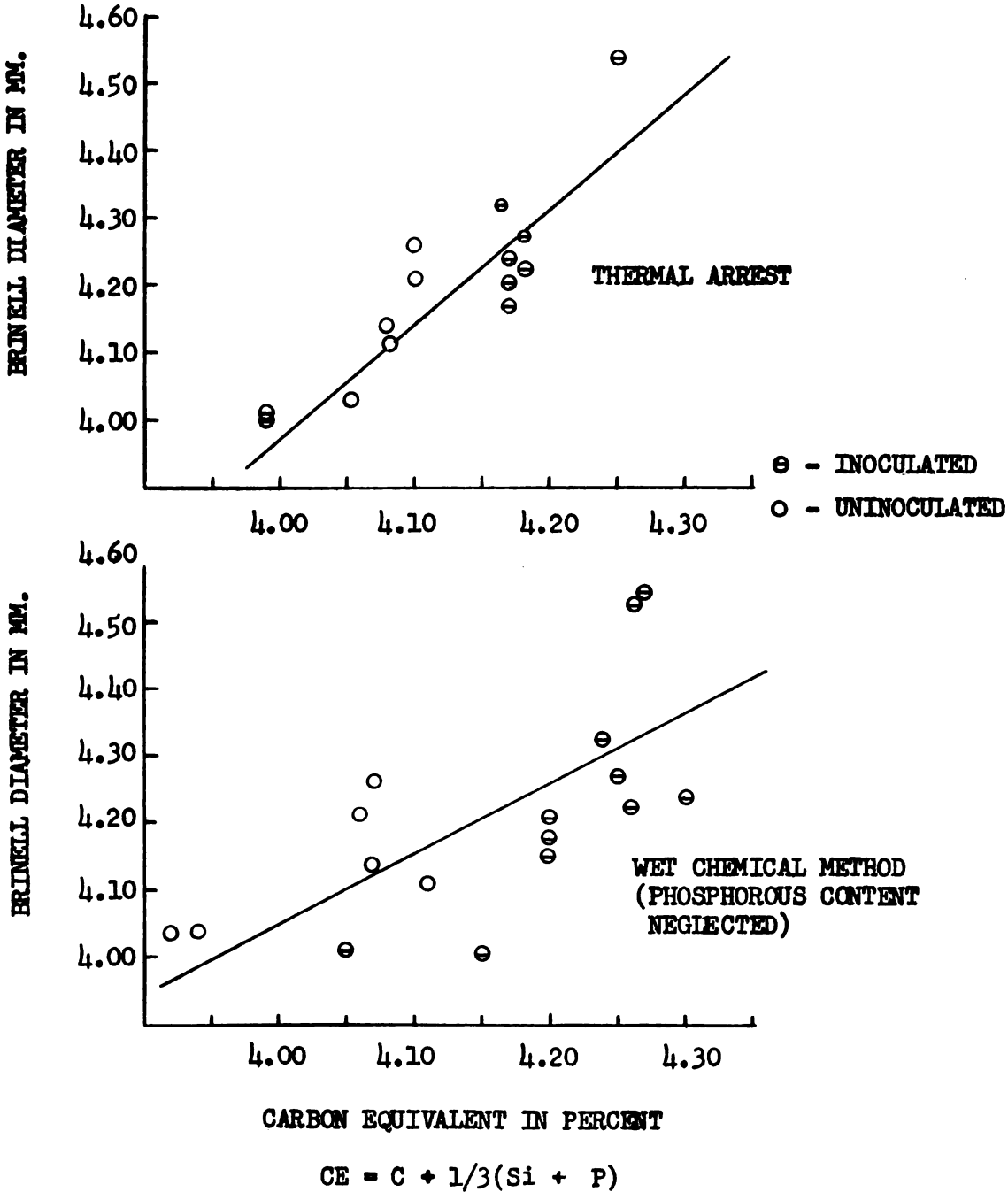


FIGURE 8

BRINELL DIAMETER VS. CARBON EQUIVALENT

FOR SOME AS CAST TEST BARS



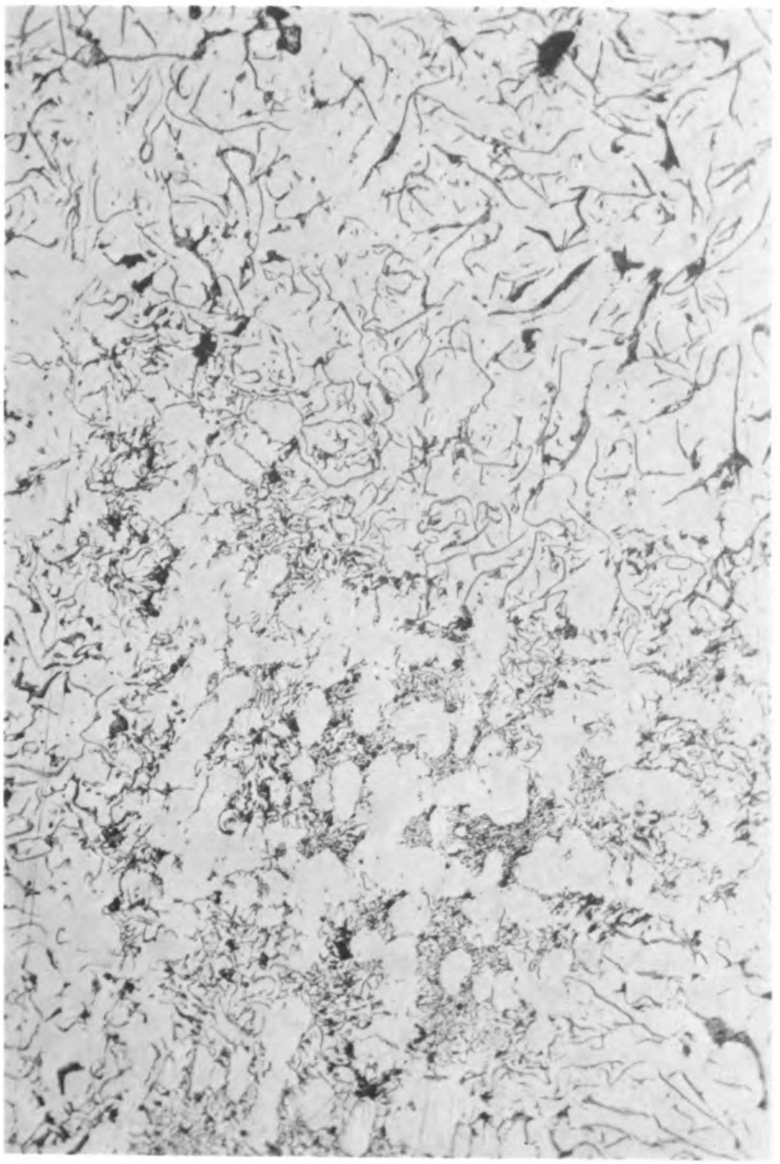


FIGURE 9

SAMPLE 1A1 AT CENTER

SHOWING GRAPHITE SIZE AND TYPE

Magnification--100x
Etch----------2 % Nital
Brinell-------5.46 mm. (118)
Resonant Freq.-10052 cps

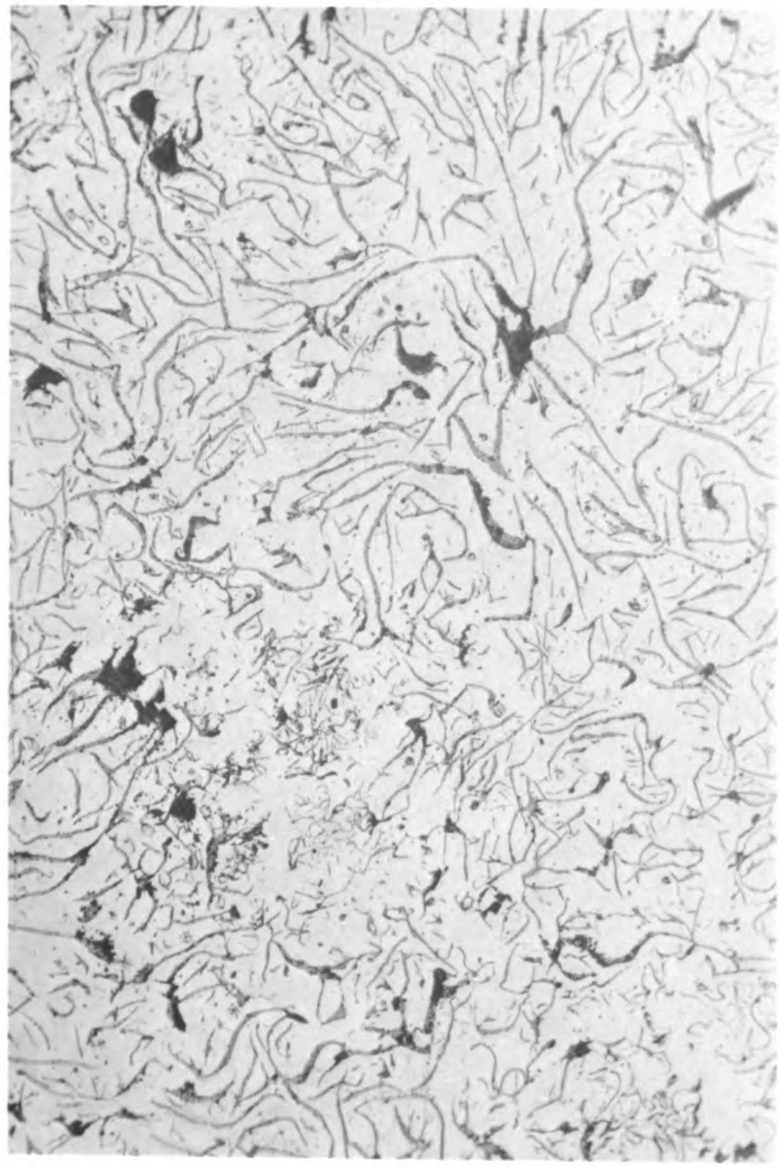


FIGURE 10

SAMPLE 3A1 AT CENTER

SHOWING GRAPHITE SIZE AND TYPE

Magnification--100x
Etch----------2 % Nital
Brinell--------5.80 mm. (approx. 100)
Resonant Freq.-9202 cps

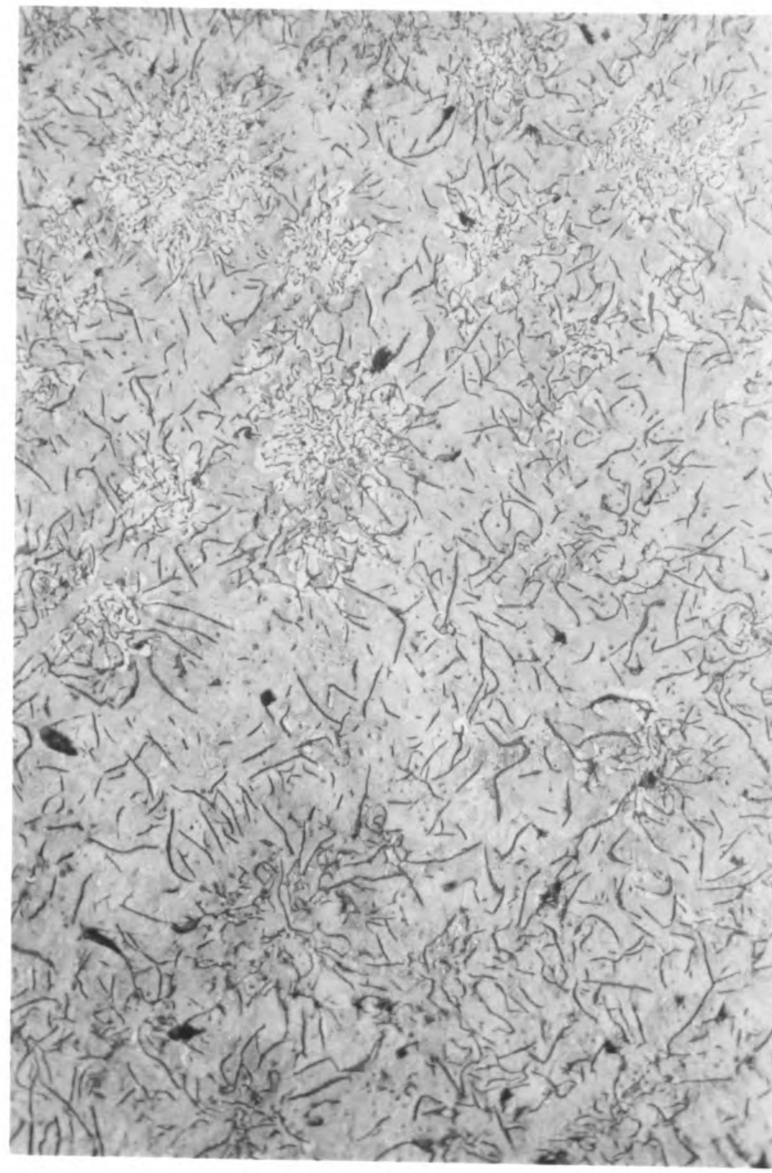


FIGURE 11

SAMPLE 2A3 SHOWING

SURFACE GRAPHITE AND FERRITE

Magnification--100x
Etch----------2 % Nital
Brinell--------4.18 mm. (209)

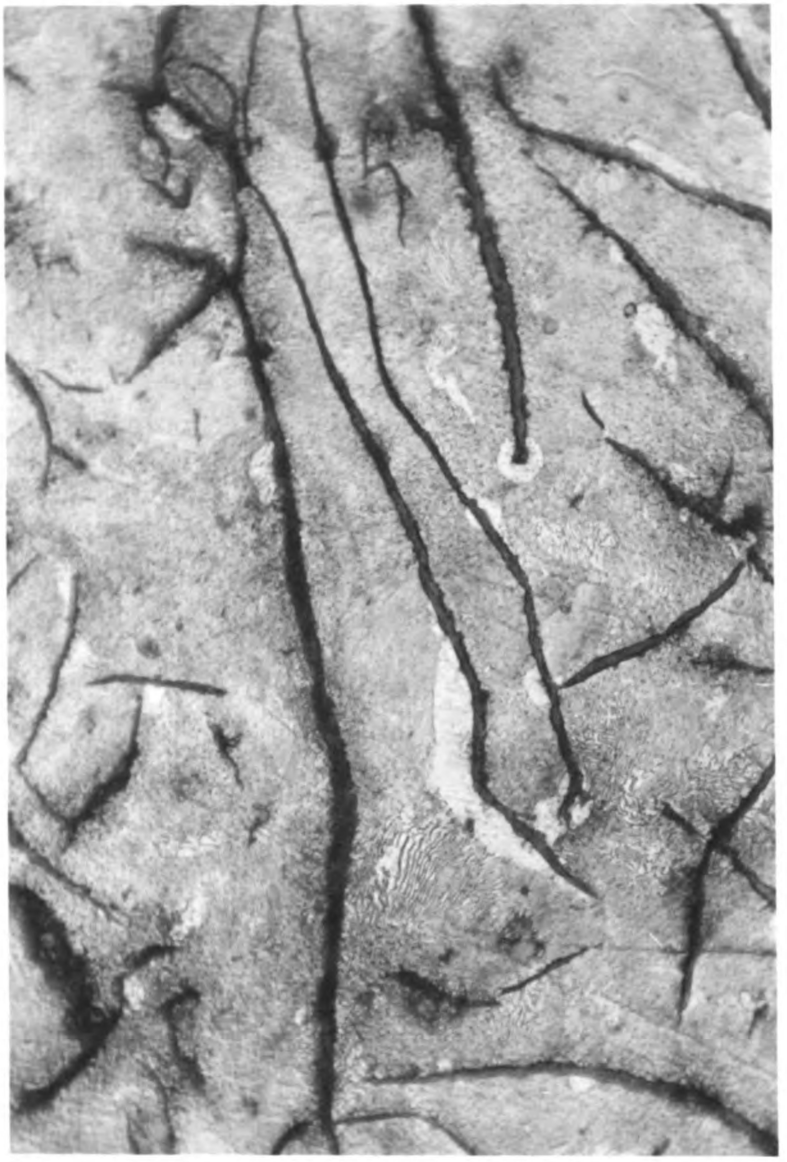


FIGURE 12

SAMPLE 3A3 AT CENTER

SHOWING FERRITE AND PEARLITE

Magnification--500x
Etch----------2 % Nital
Brinell--------4.60 mm. (170)
Resonant Freq.-9454 cps

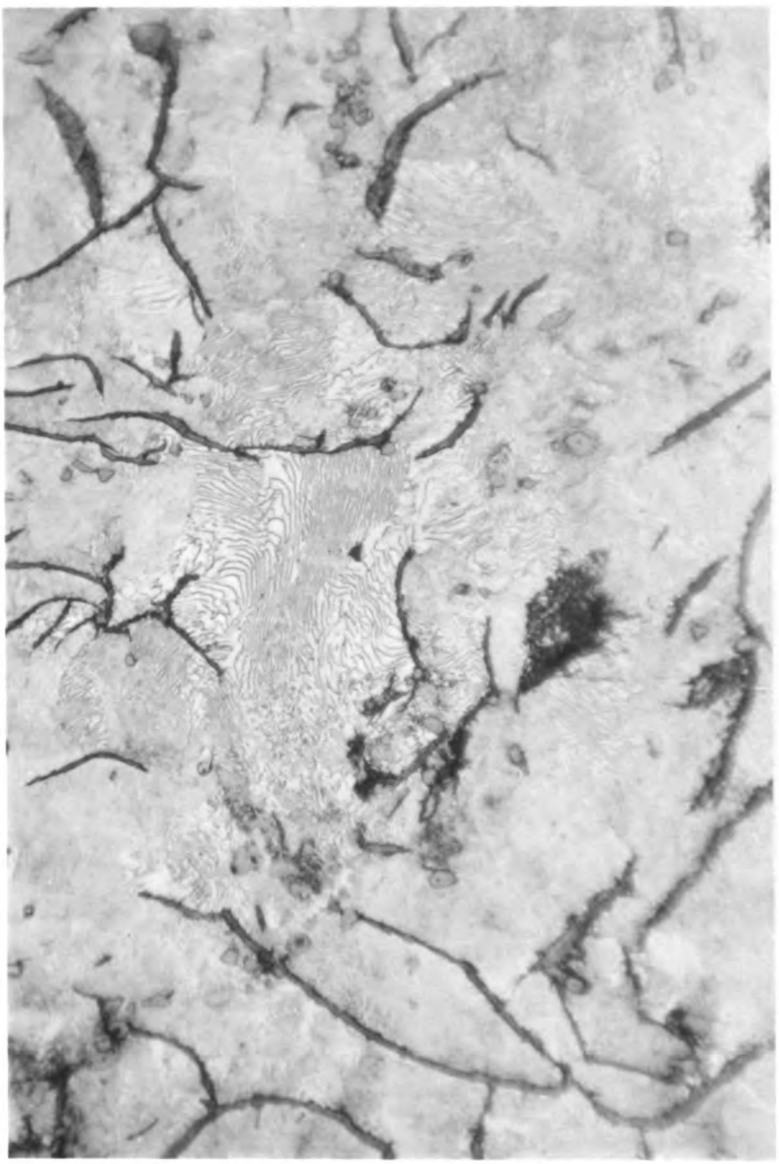


FIGURE 13

SAMPLE 2A3 SHOWING

PEARLITE AT CENTER

Magnification--500x
Etch----------2 % Nital
Brinell--------4.27 mm. (200)

FIGURE 14

TYPICAL PEARLITE AND

STEADITE NEAR CENTER

Magnification--500x
Etch----------2 % Nital

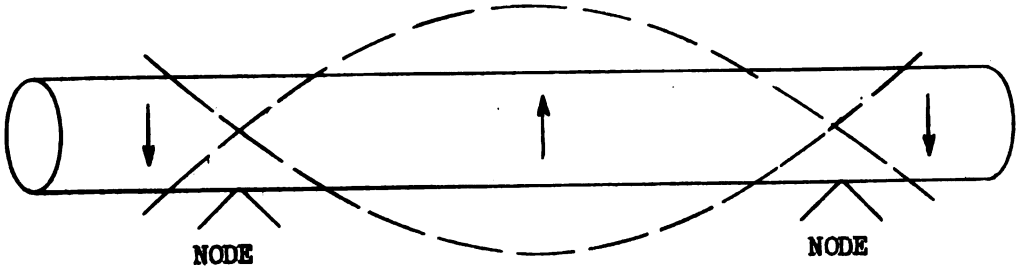


FIGURE 15

FUNDAMENTAL FLEXURE MODE

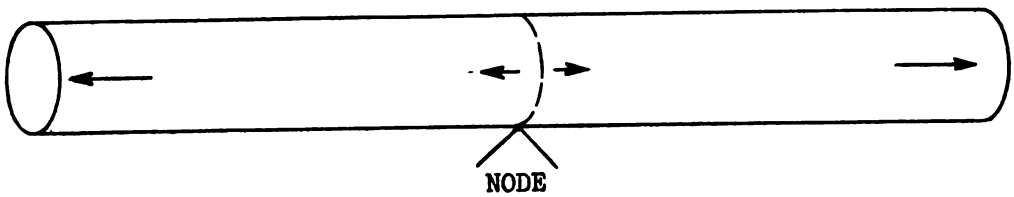


FIGURE 16

FUNDAMENTAL LONGITUDINAL MODE

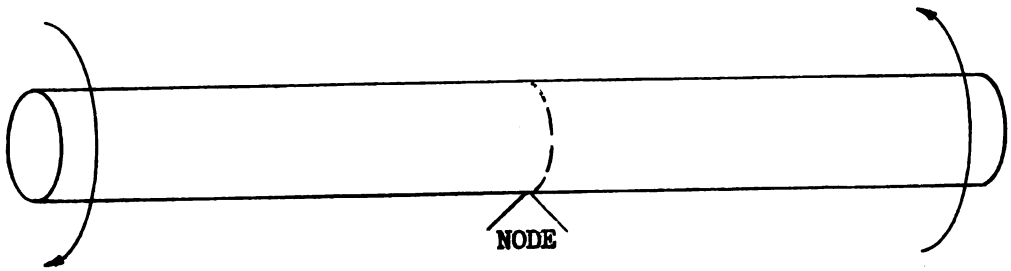
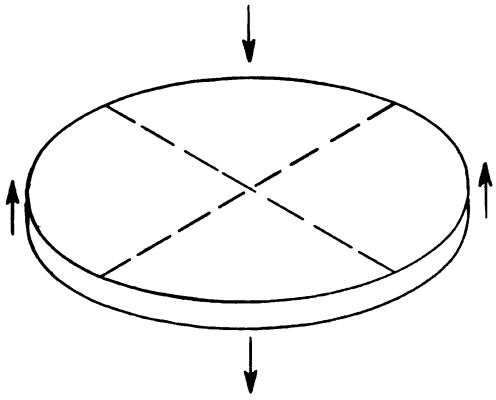


FIGURE 17

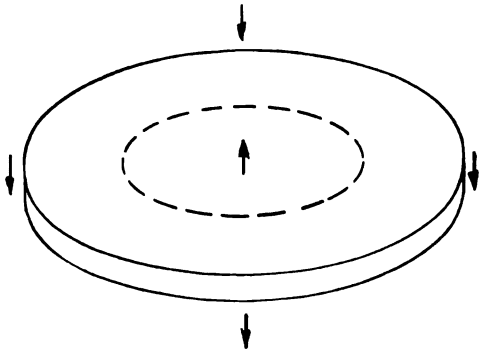
FUNDAMENTAL TORSIONAL MODE



NODES ARE
SHOWN DOTTED

FIGURE 18

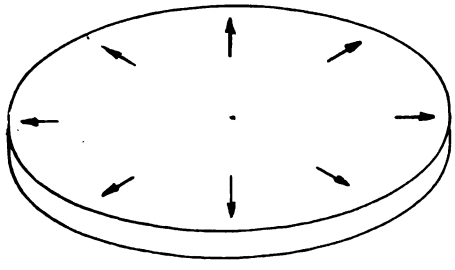
FUNDAMENTAL DIAMETER MODE



NODE IS
SHOWN DOTTED

FIGURE 19

FUNDAMENTAL FLEXURAL MODE FOR A THIN DISC



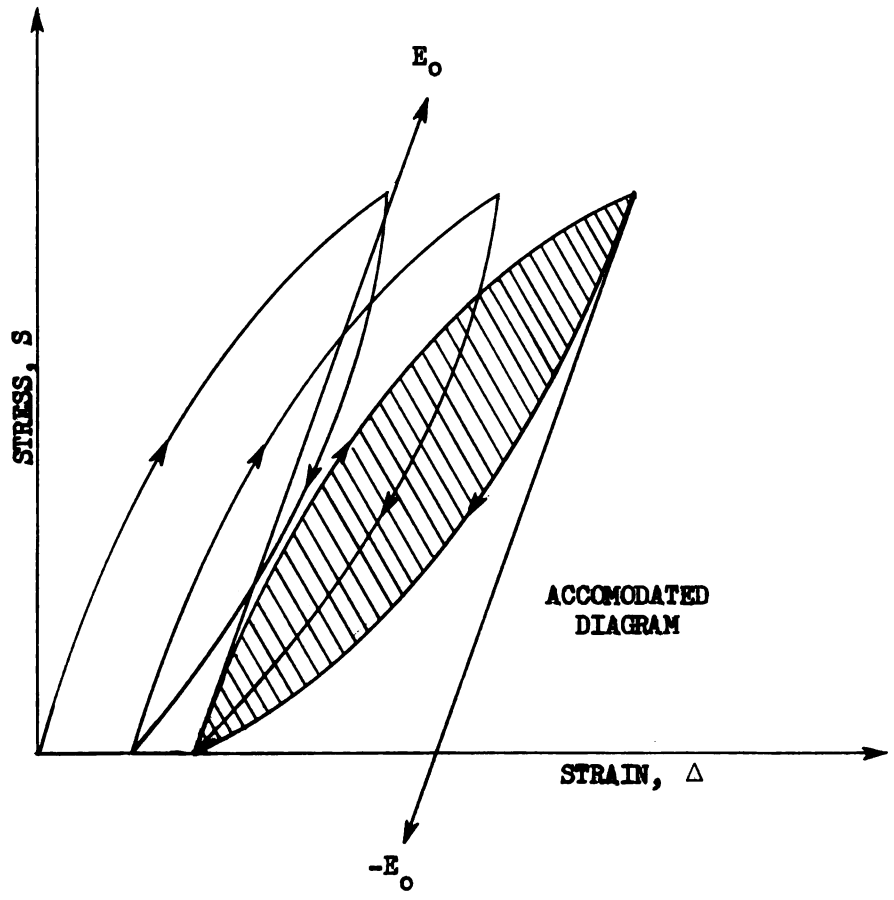
NODE IS AT
CENTER

FIGURE 20

FUNDAMENTAL RADIAL MODE

FIGURE 21

ACCOMODATED STRESS-STRAIN
DIAGRAM



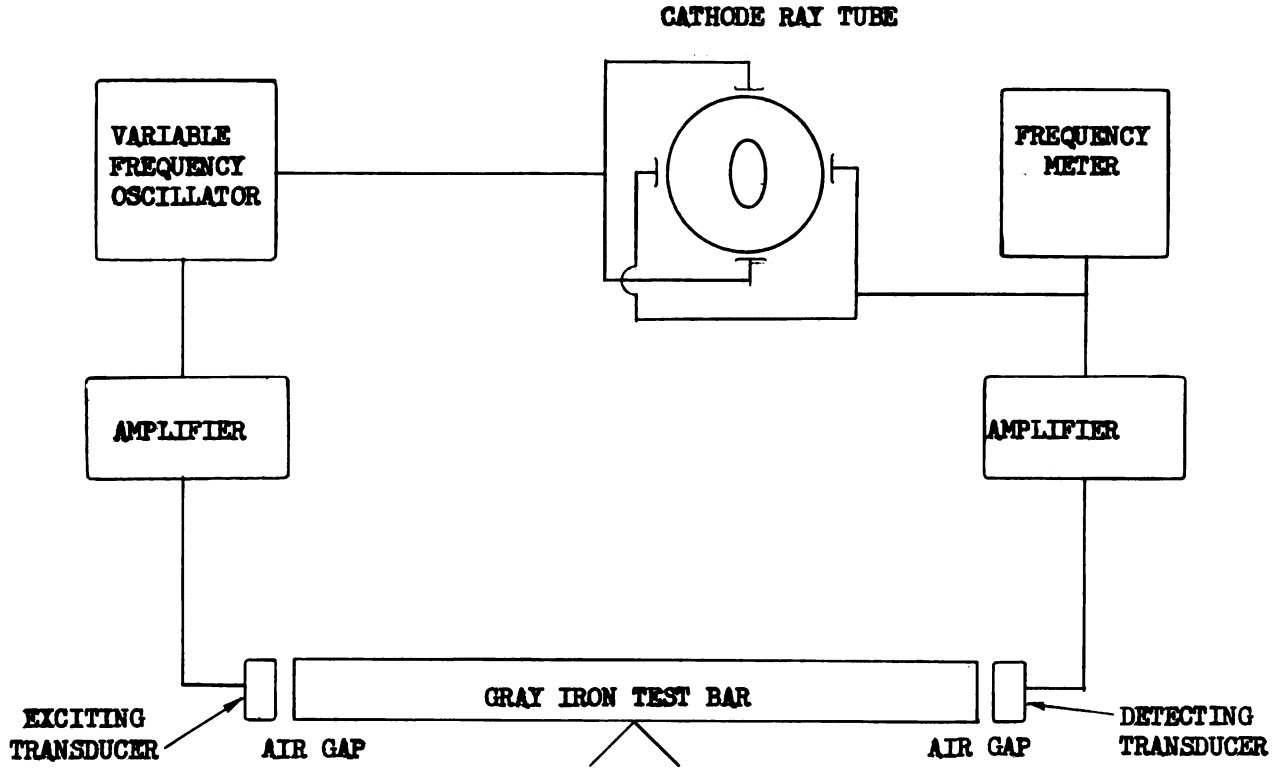


FIGURE 22

SCHEMATIC DIAGRAM OF SR-100 RESONANCE TESTER

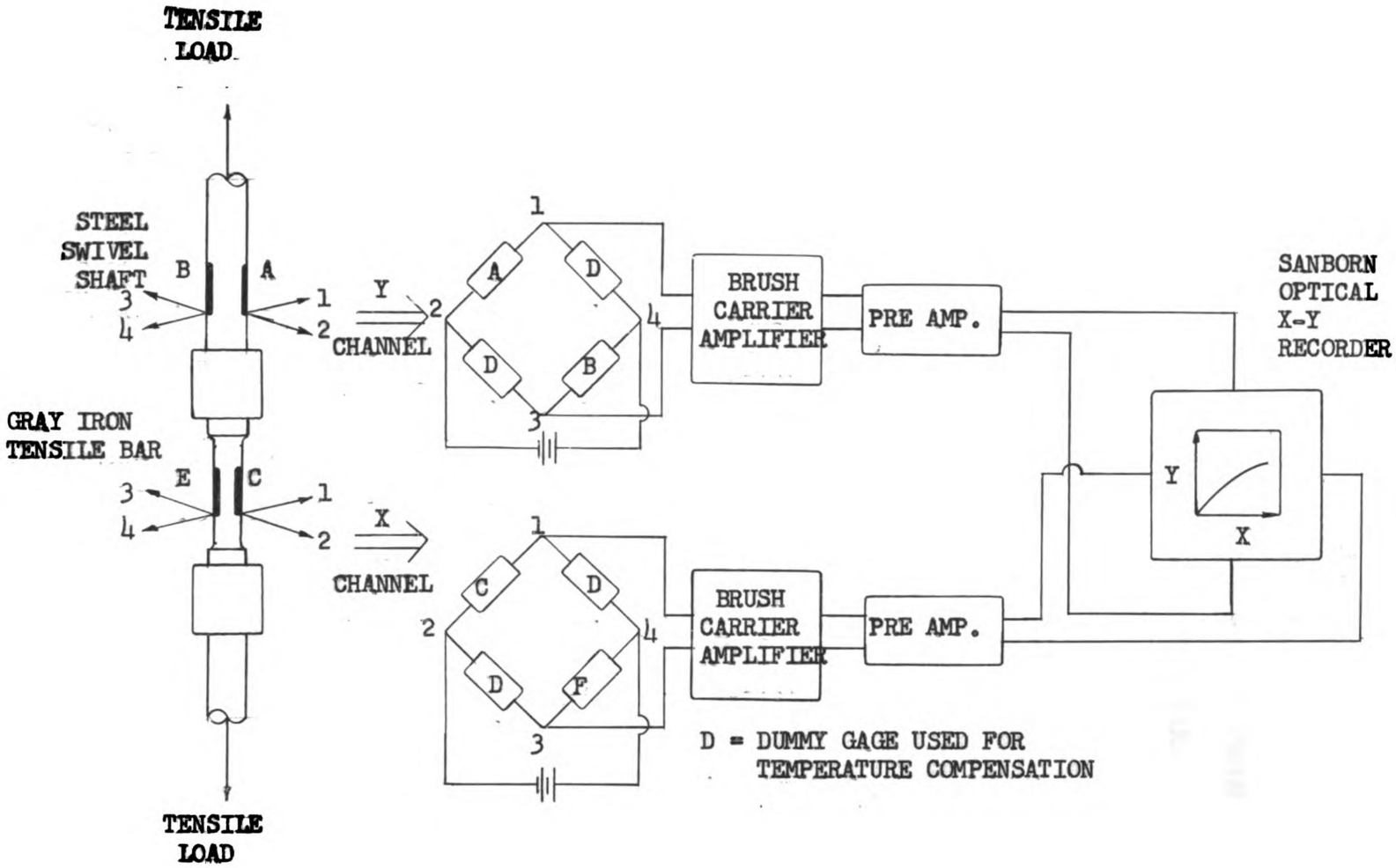


FIGURE 23

TEST SET UP FOR RECORDING STRESS-STRAIN CURVE IN ORDER TO DETERMINE STATIC ELASTIC MODULUS

FIGURE 24

TENSILE STRENGTH VS. RESONANT FREQUENCY

FOR FIVE AS CAST TEST BARS

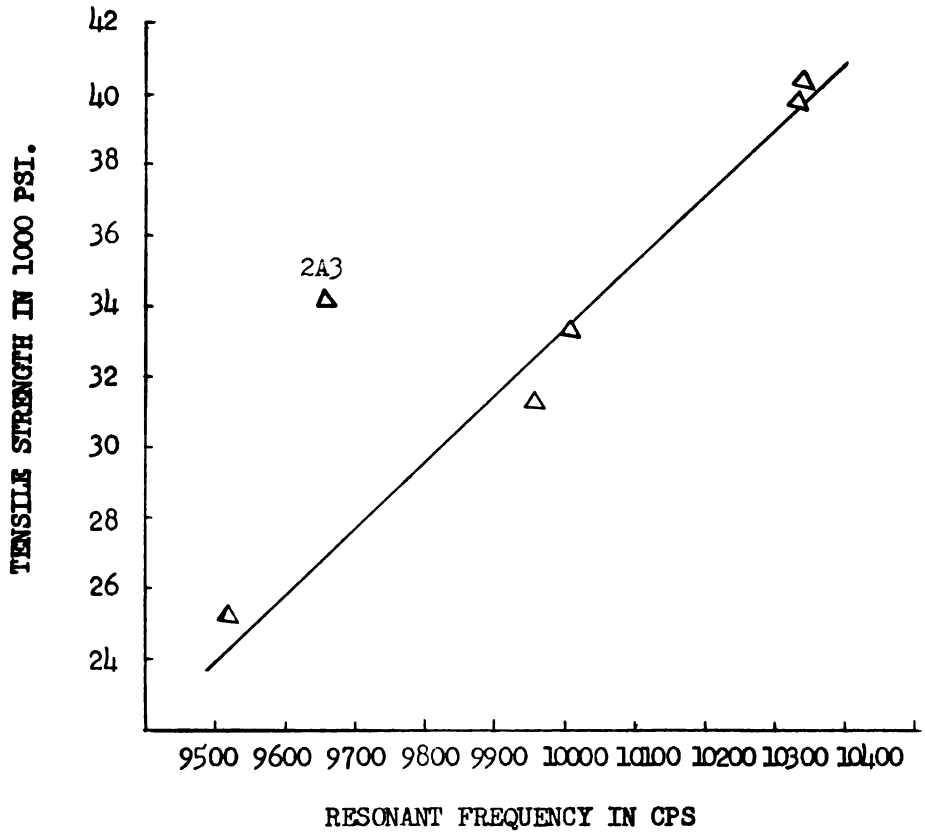


FIGURE 25

BRINELL DIAMETER VS. RESONANT FREQUENCY

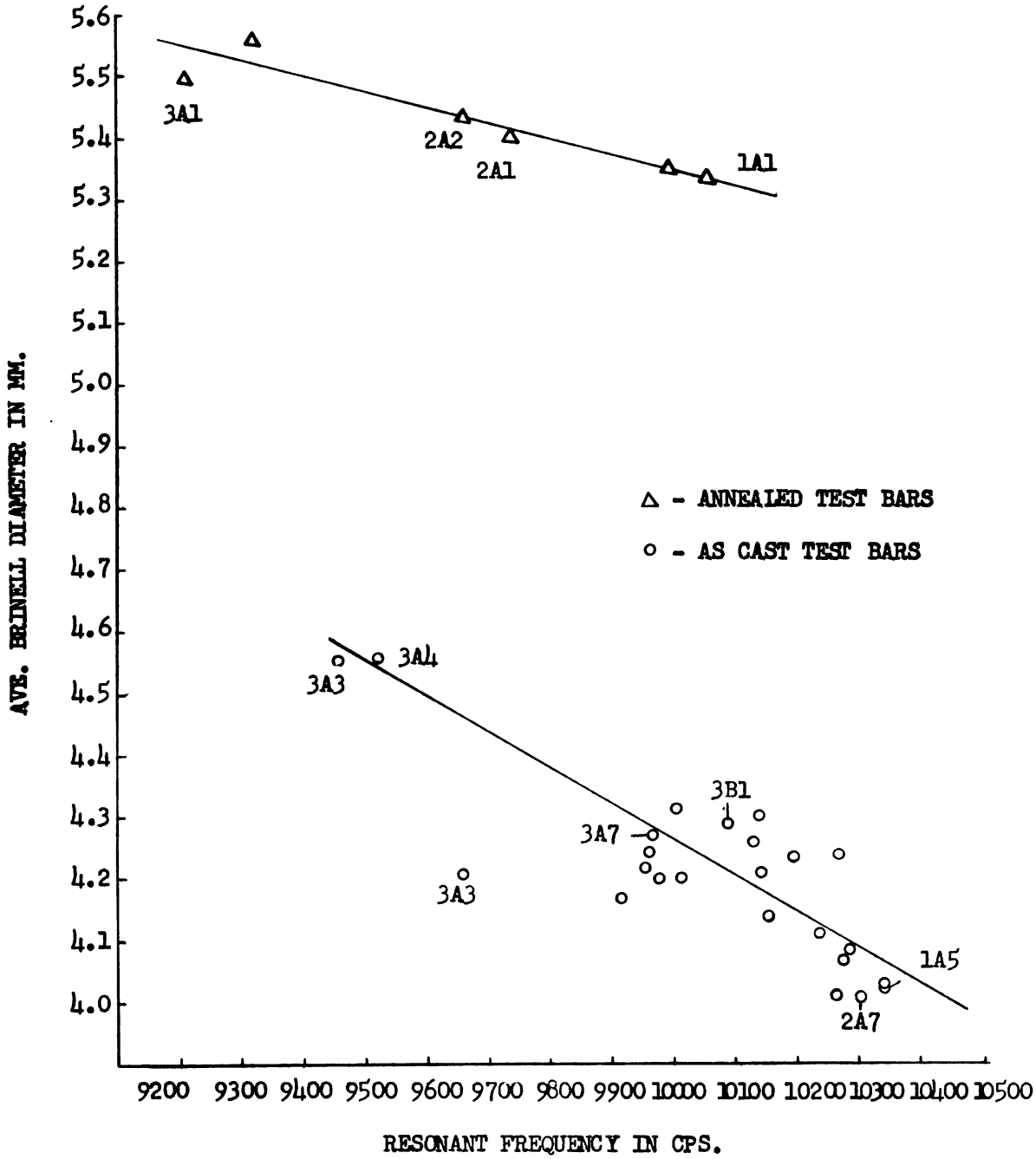


FIGURE 26

AVERAGE BRINELL DIAMETER VS. RESONANT FREQUENCY

FOR SOME AS CAST PARTS,

PART NO. 5692885

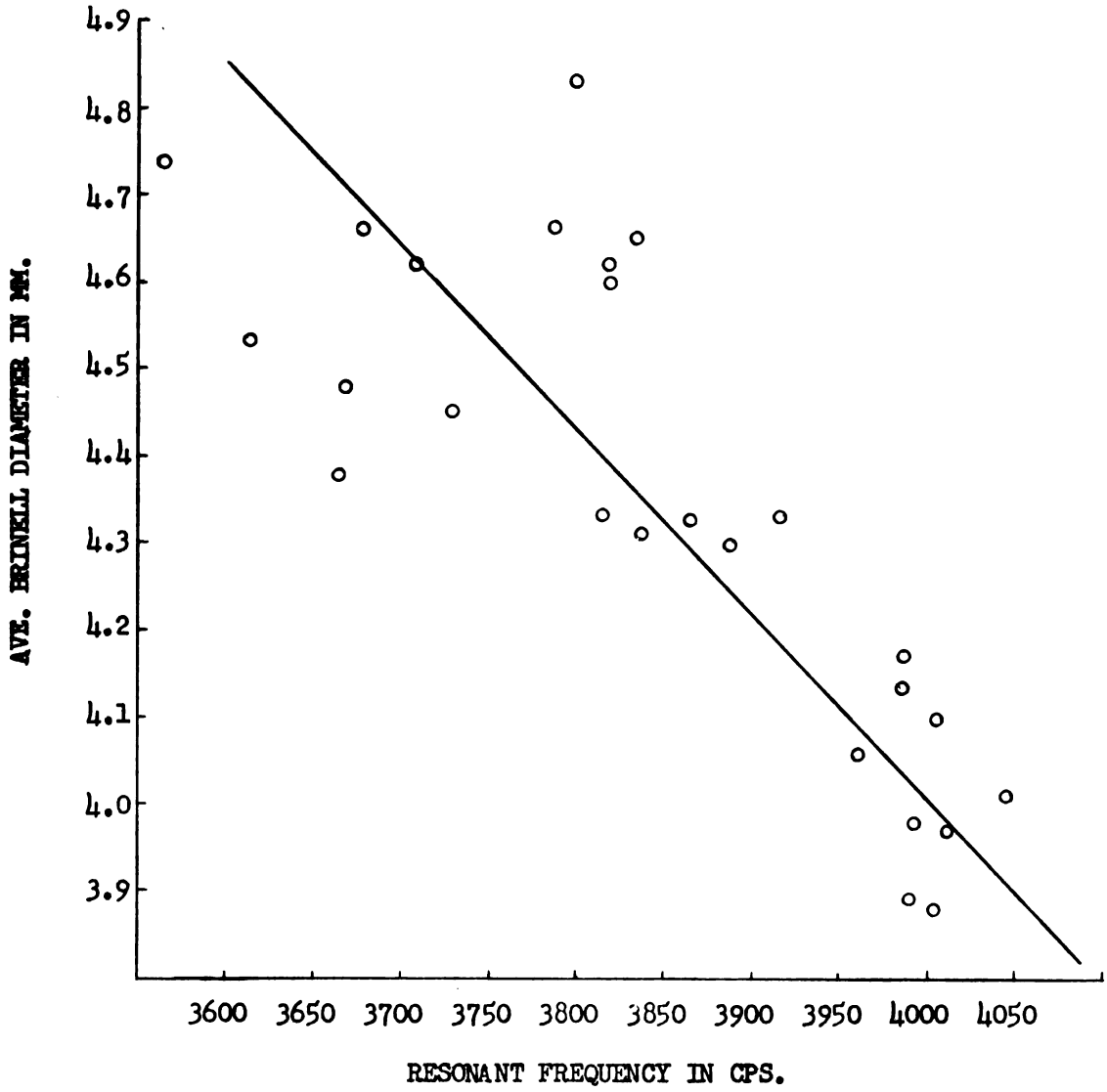


FIGURE 27

THERMAL ARREST CARBON EQUIVALENT VS. RESONANT FREQUENCY

FOR SOME AS CAST TEST BARS

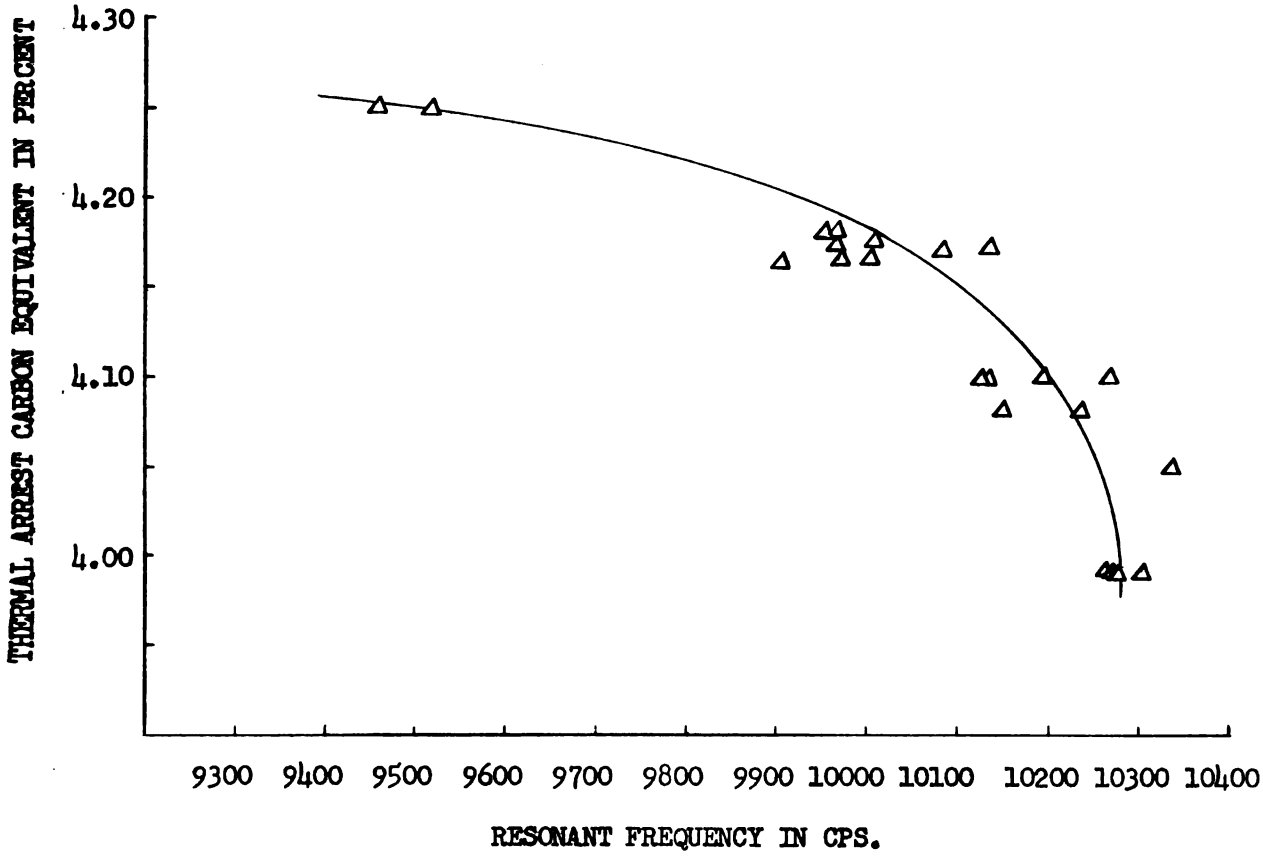
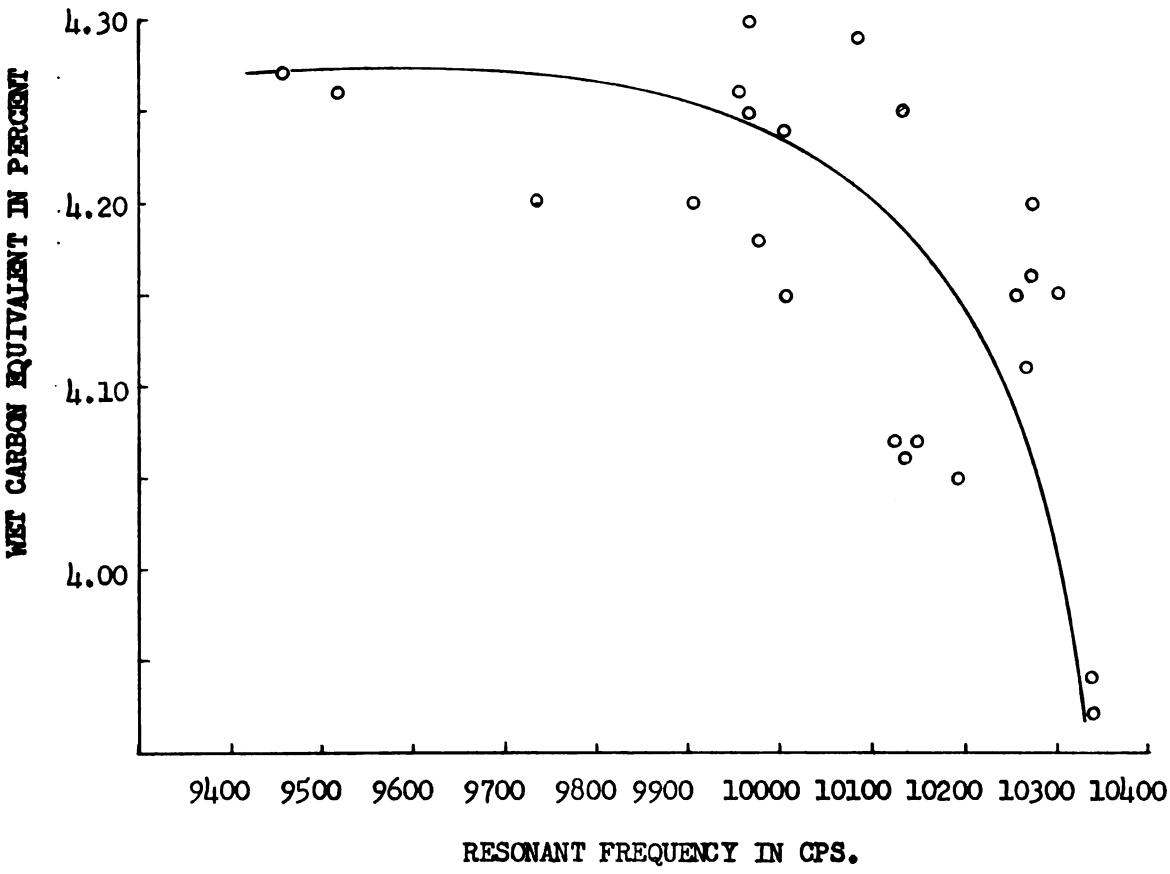


FIGURE 28

WET CARBON EQUIVALENT VS. RESONANT FREQUENCY

FOR SOME AS CAST TEST BARS



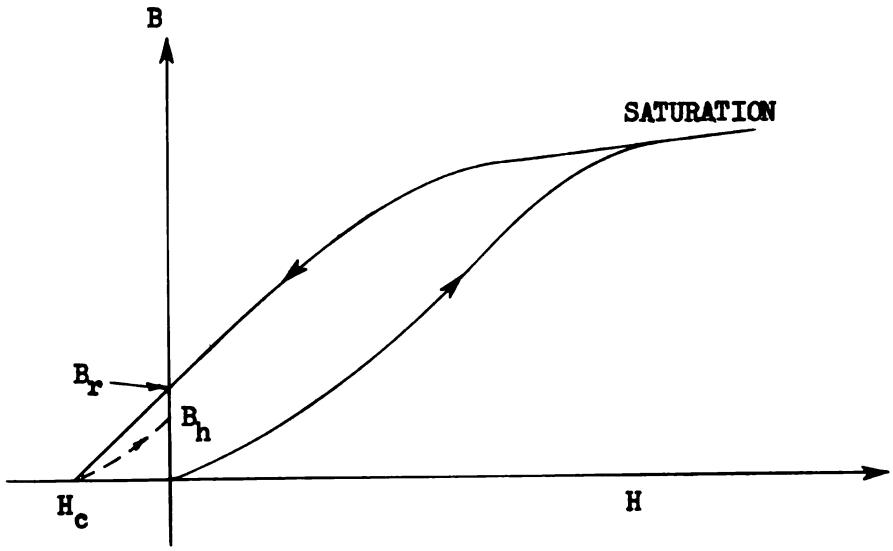


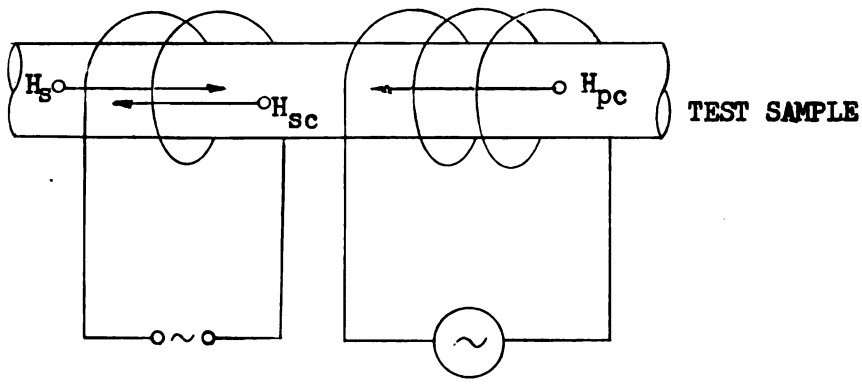
FIGURE 29

DIRECT CURRENT MAGNETIZATION CURVE

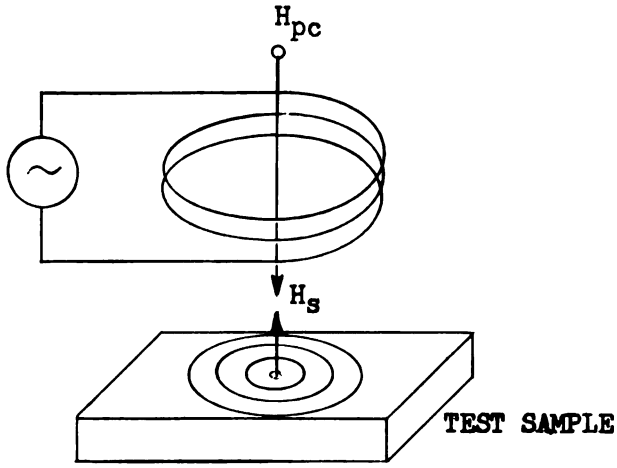
B_r = Retentivity

H_c = Coercive Force

B_h = Residual induction which results after measuring coercive force (H_c)



(A)



(B)

FIGURE 30

PROBE COIL AND TEST SAMPLE ARRANGEMENTS

(A) Primary and secondary coil arrangement with test sample within the coils.
(B) Probe coil with axis perpendicular to surface of test sample.

H_{pc} = Primary coil field

H_{sc} = Secondary coil field

H_s = Secondary field produced in test sample

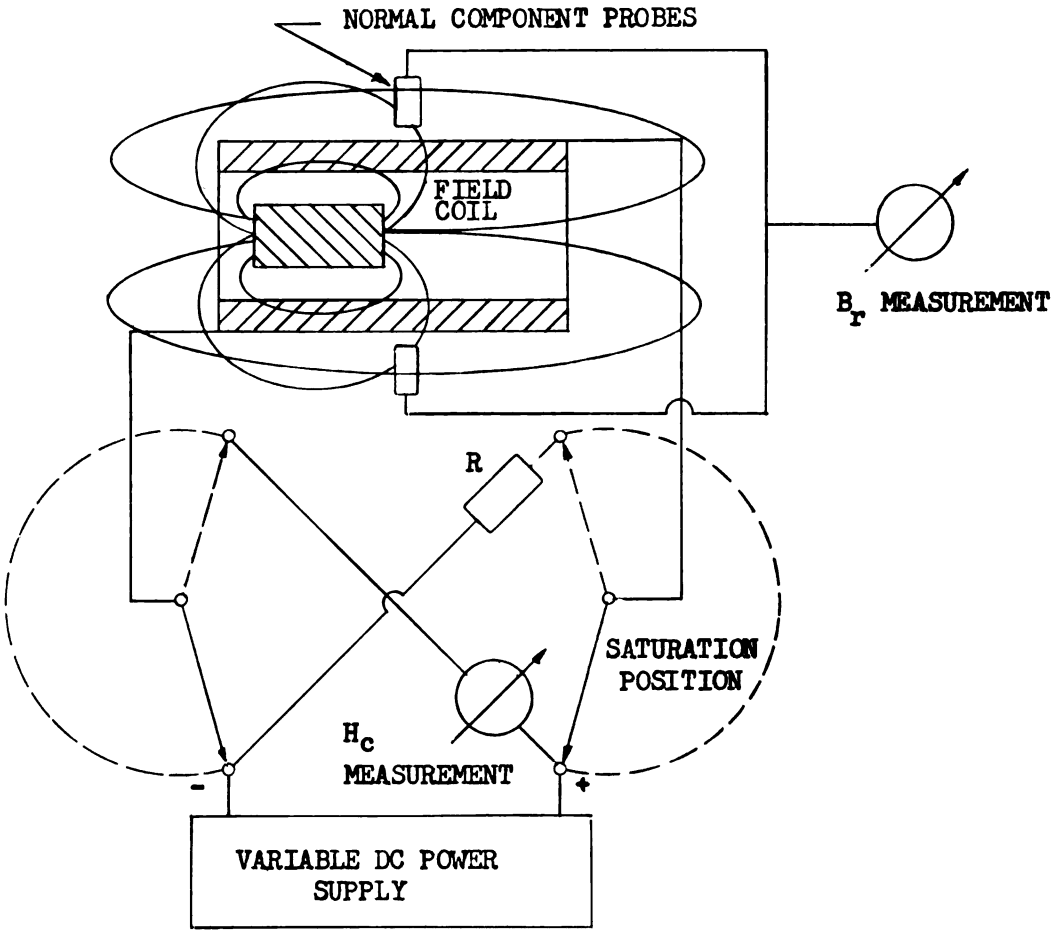


FIGURE 31

SCHEMATIC DIAGRAM OF COERCIVE FORCE METER

H_c = Coercive force

B_r = Relative magnetic retentivity (normal component of the residual field measured at position shown)

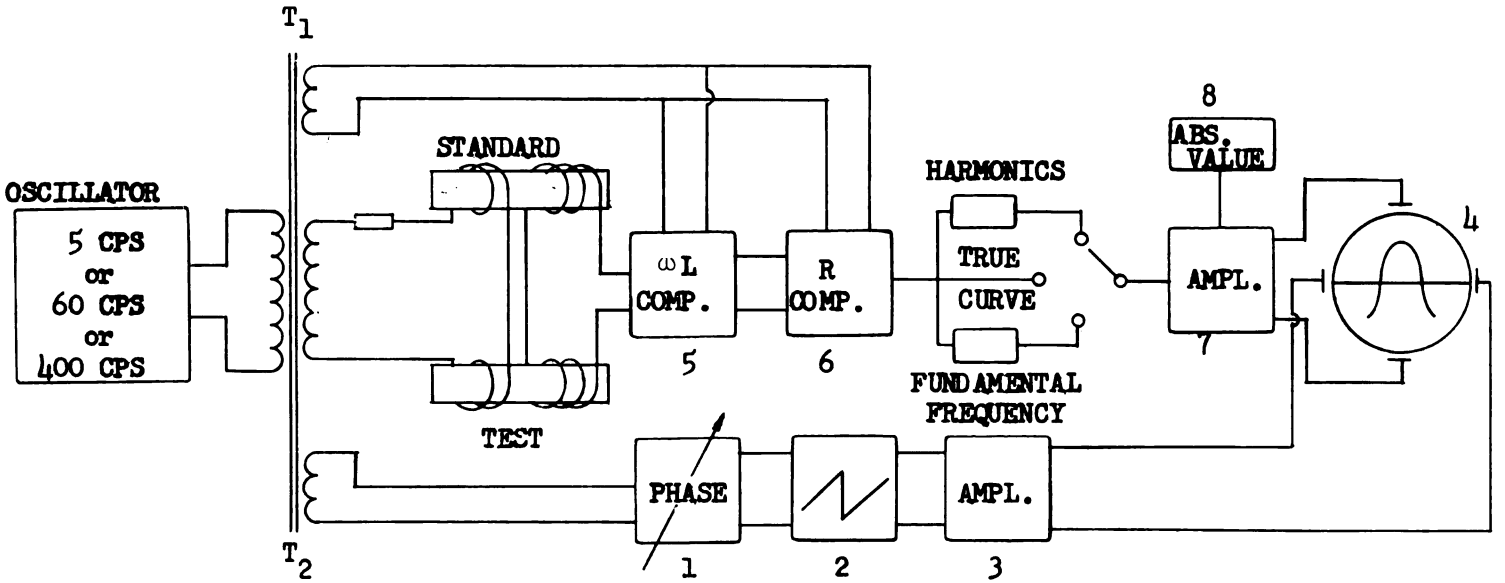


FIGURE 32

FOERSTER MAGNATEST Q COMPARATOR: A LINEAR TIME-BASE INSTRUMENT SIMILAR TO THE QC - 1000 COMPARATOR

1. Phase Shifter
2. Saw-Tooth Generator
3. Amplifier for Horizontal Channel
4. Cathode Ray Oscilloscope
5. Inductive Compensator
6. Resistive Compensator
7. Amplifier for Vertical Channel
8. Calibration Control which gives percent of "absolute value" corresponding to 1 inch beam deflection, where "absolute value" is the voltage effect due to test object without the standard.

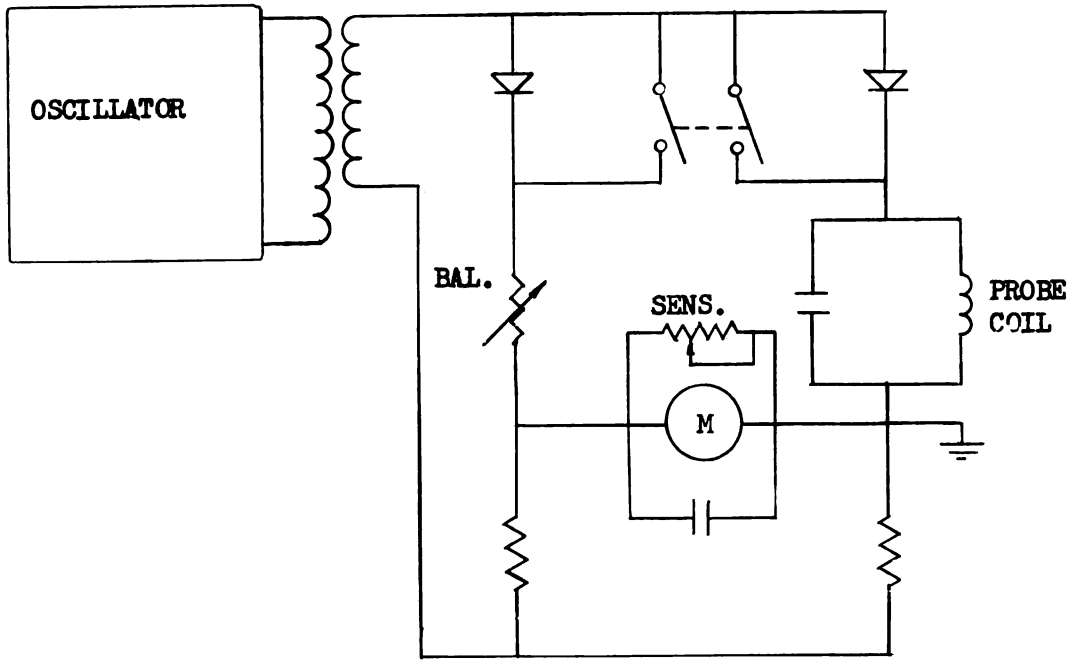


FIGURE 33

CIRCUIT DIAGRAM OF ED-500
(SIMILAR TO ED-300)

FIGURE 34

RELATIVE MAGNETIC RETENTIVITY VS. COERCIVE FORCE

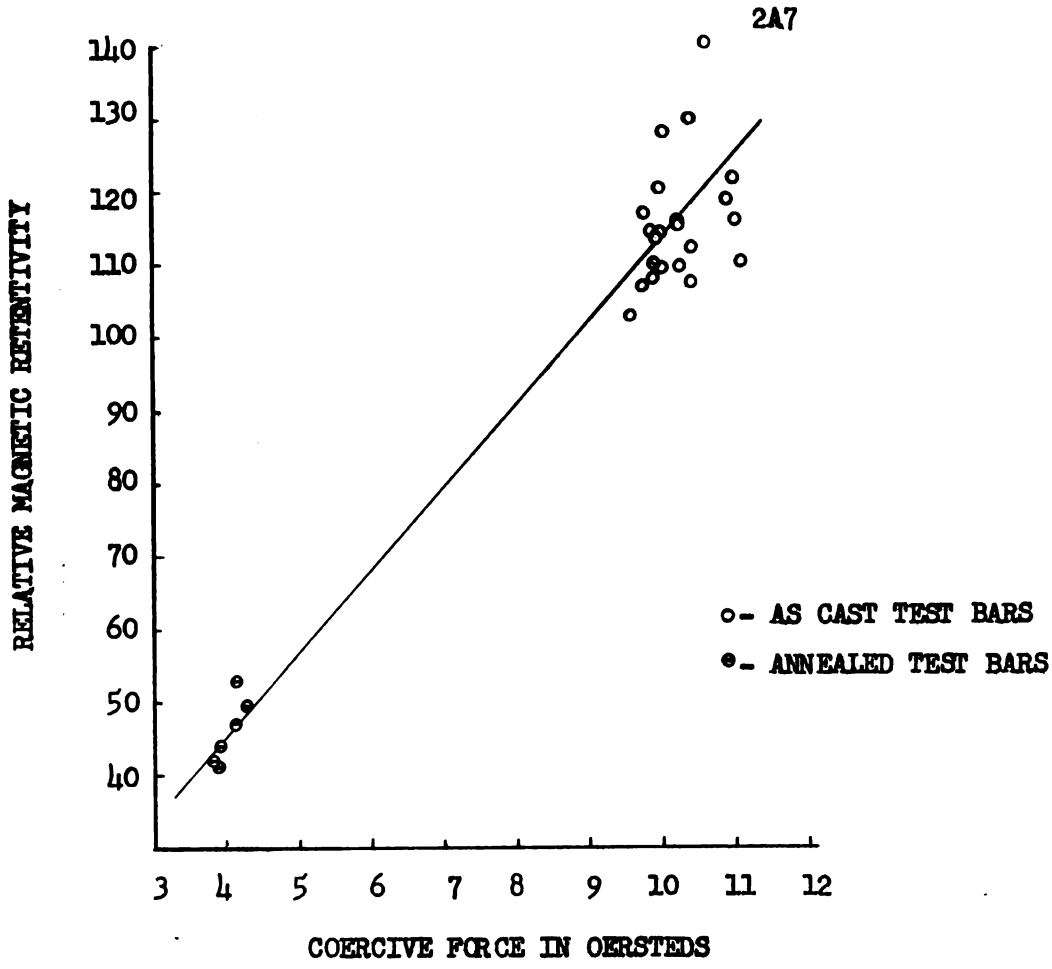


FIGURE 35

SURFACE INDICATIONS VS. CENTER INDICATIONS PER SAMPLE

FOR ED-300

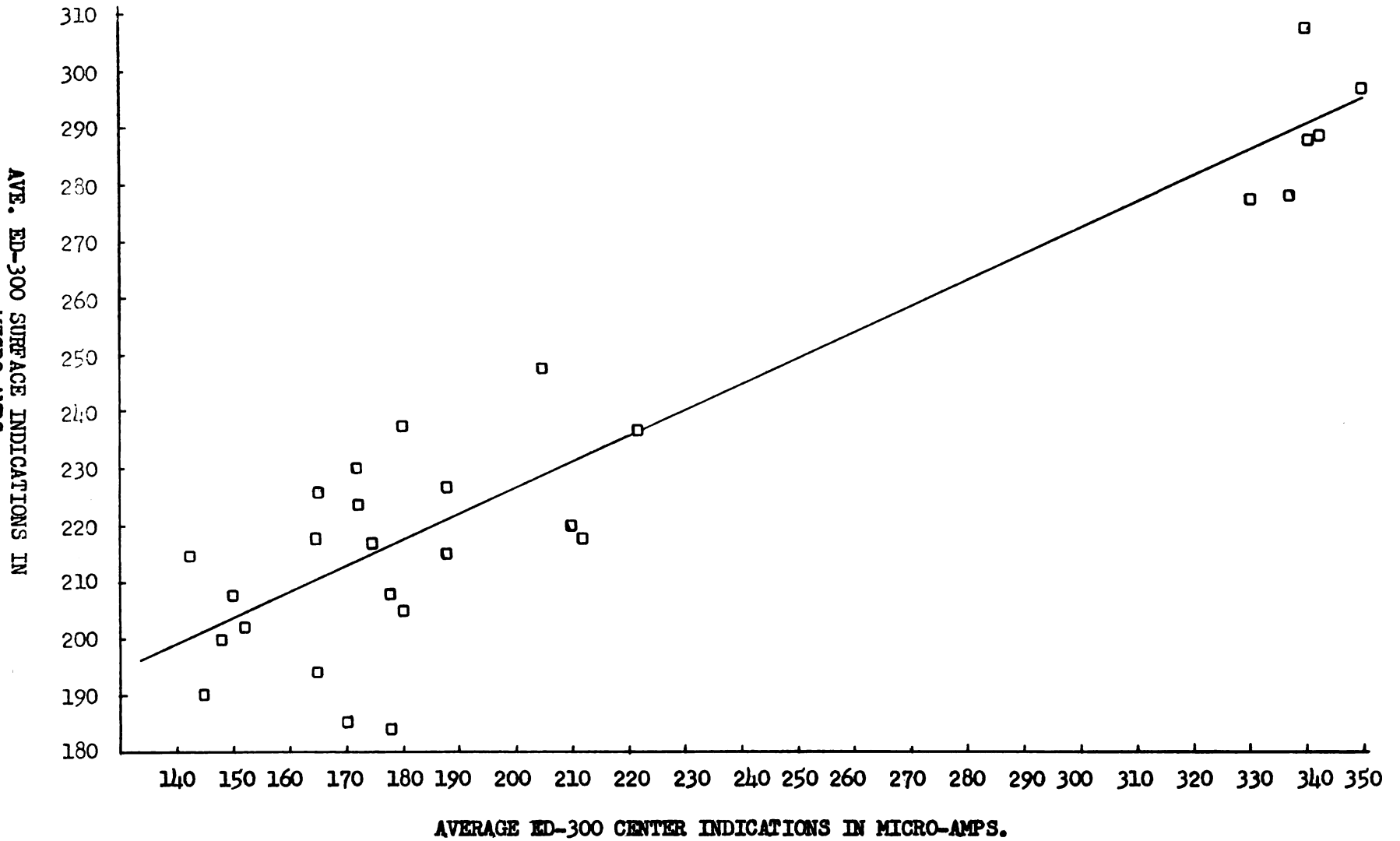


FIGURE 36

QC-1000 COMPARATOR INDICATIONS VS. ED-300 CENTER INDICATIONS

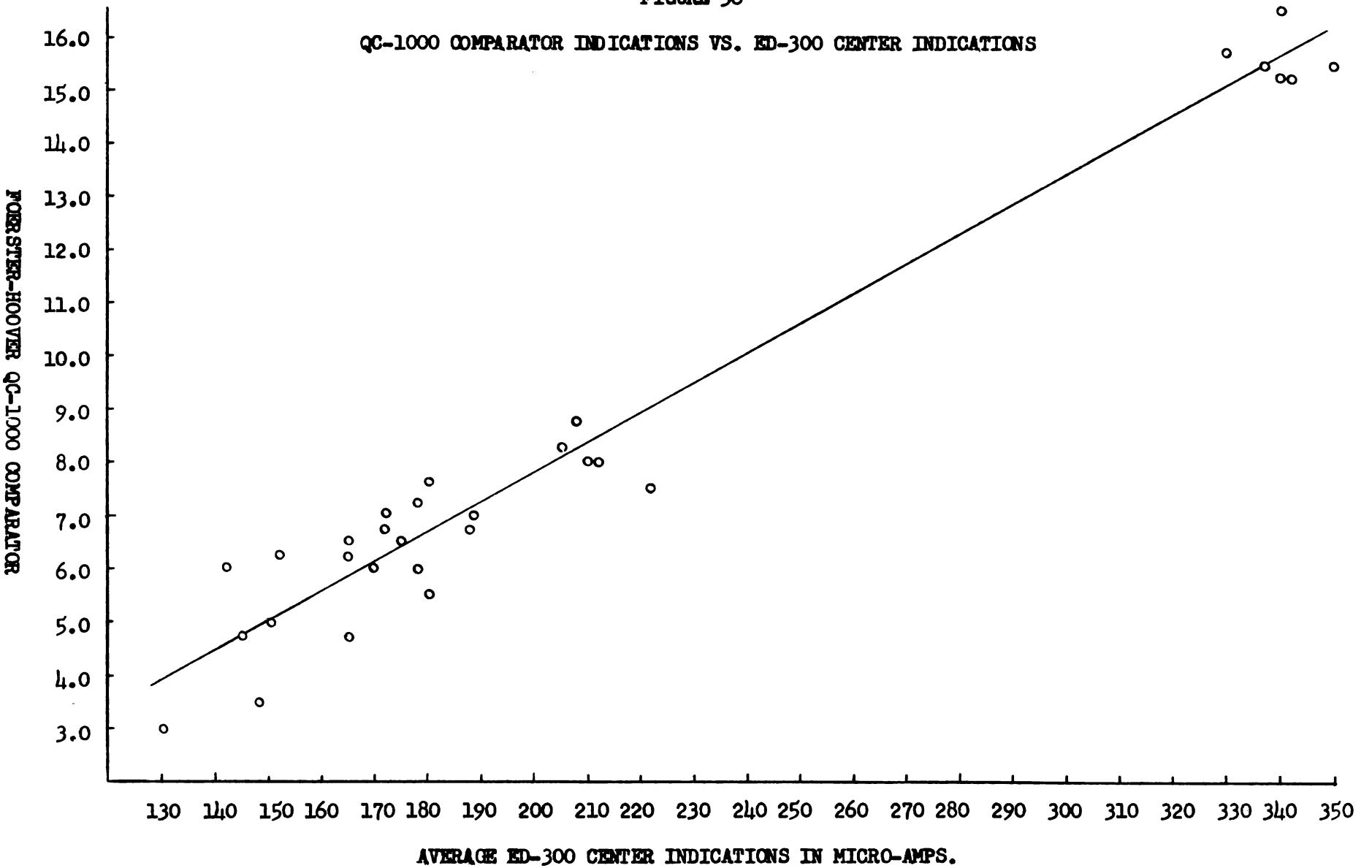


FIGURE 37

TENSILE STRENGTH VS. QC-1000 SCOPE DEFLECTION

FOR SEVEN SAMPLES

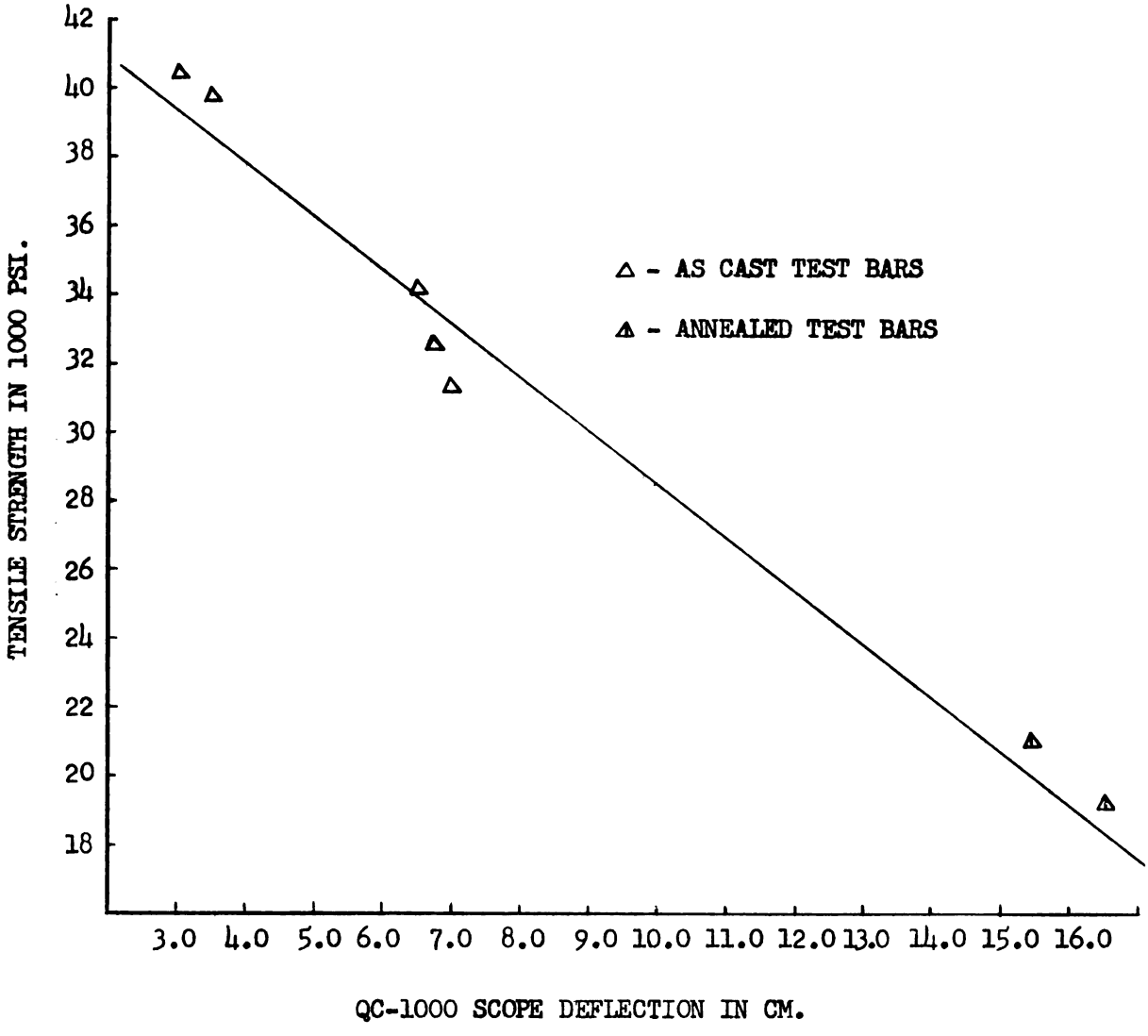


FIGURE 38

TENSILE STRENGTH VS. COERCIVE FORCE

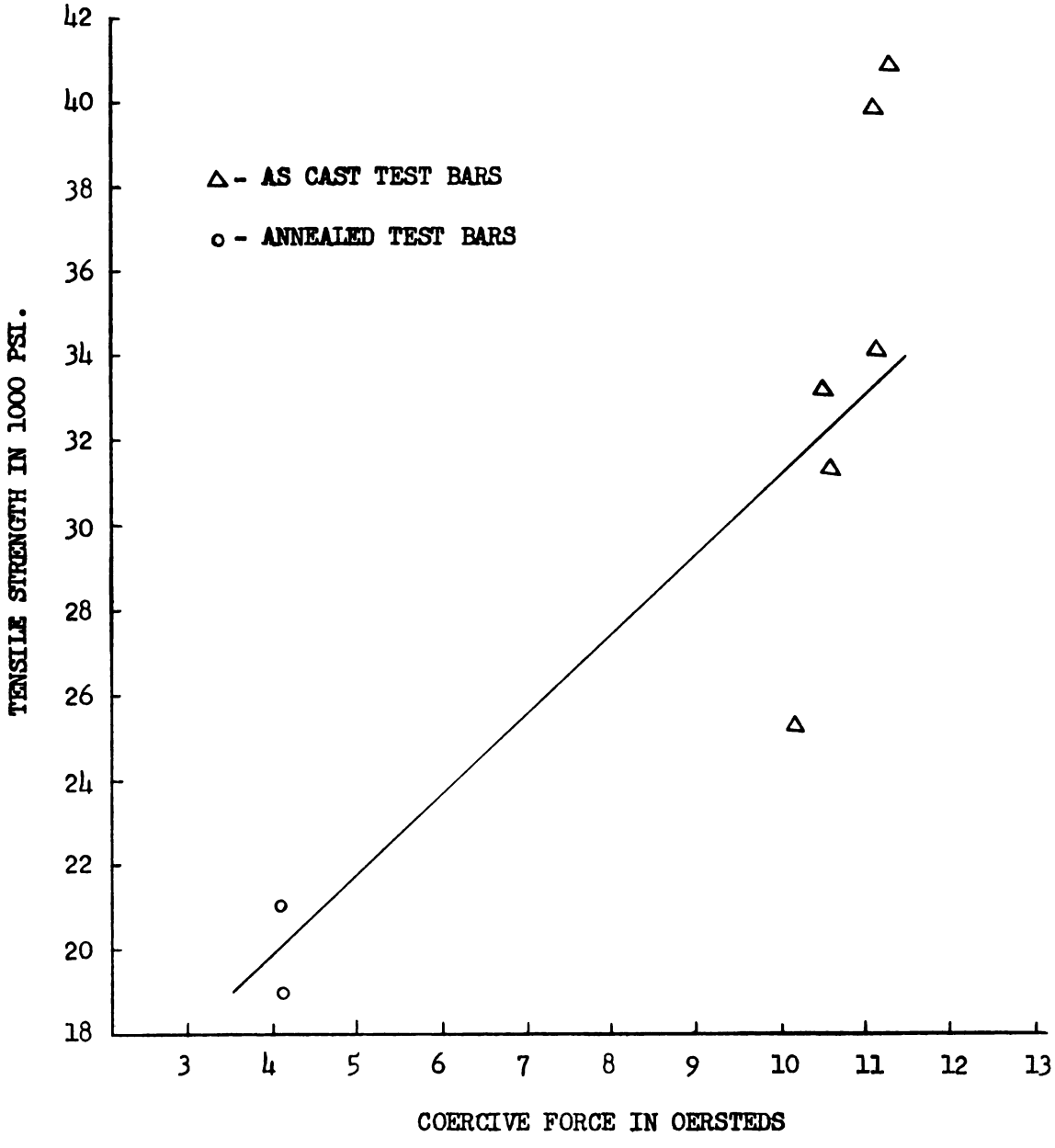


FIGURE 39

BRINELL DIAMETER VS. QC-1000 TEST INDICATIONS

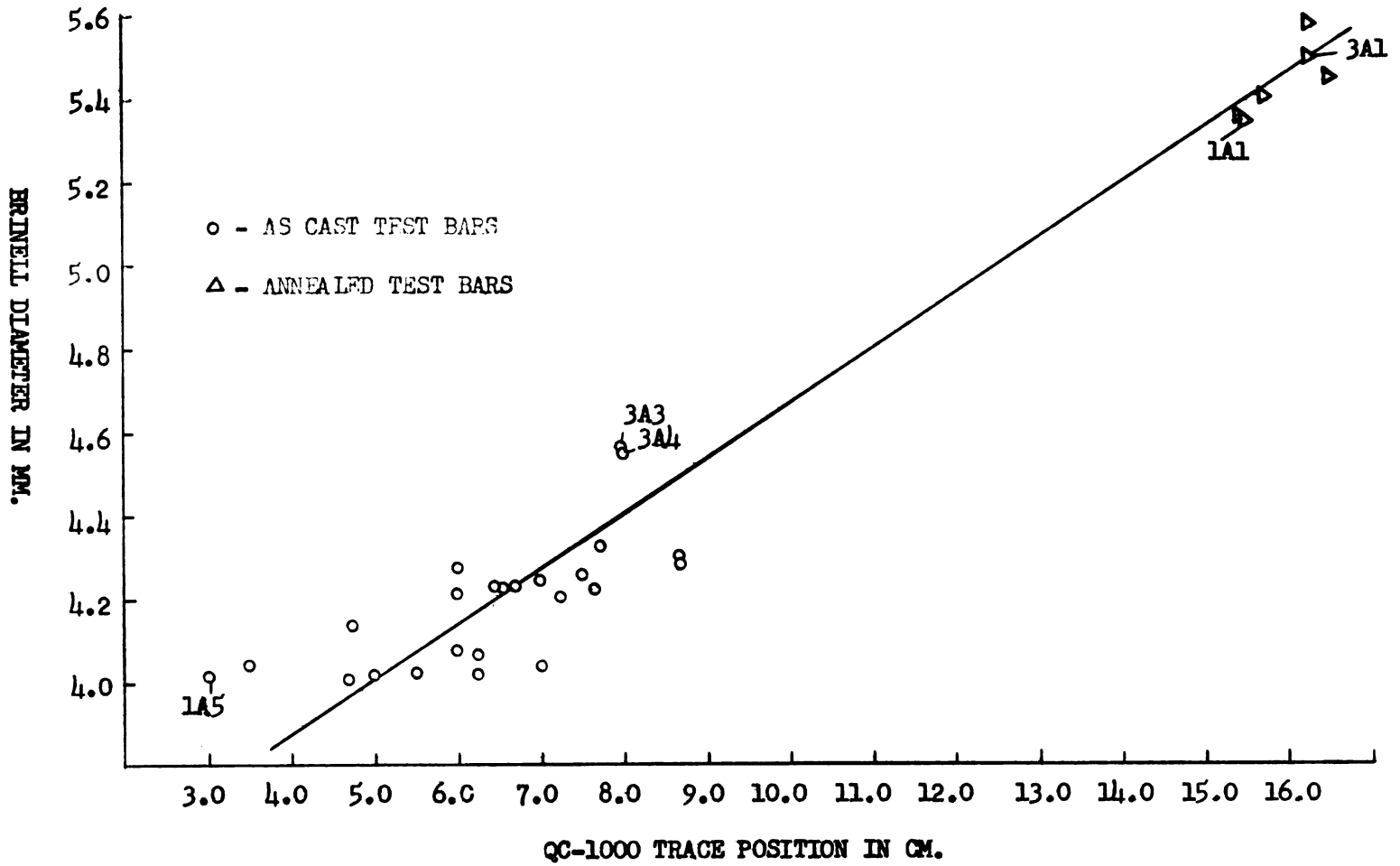


FIGURE 40

AVE. BRINELL HARDNESS DIAMETER

VS. QC-1000 COMPARATOR INDICATIONS

(PART NO. 5692885-AS CAST PART)

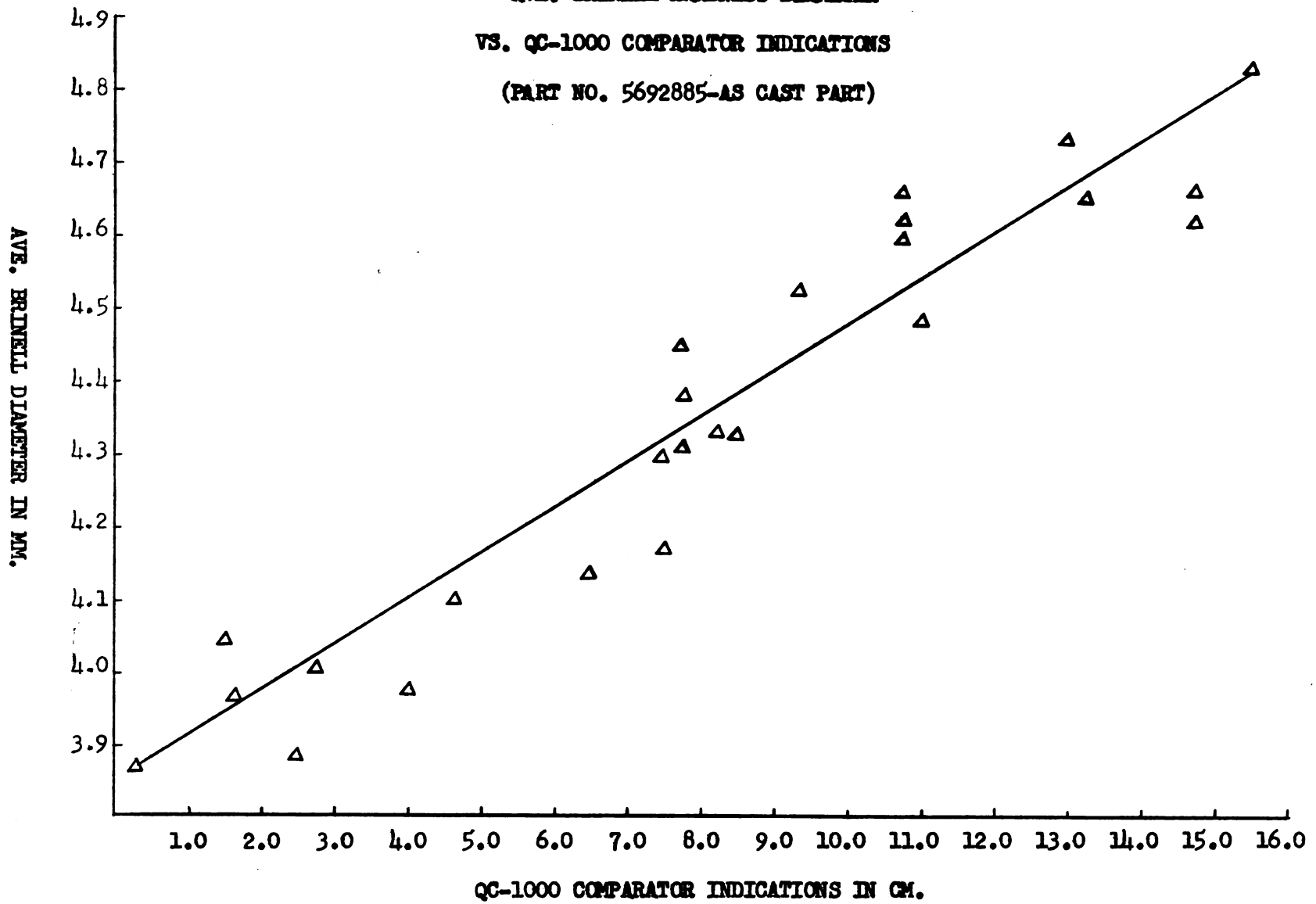


FIGURE 41

BRINELL DIAMETER VS. COERCIVE FORCE

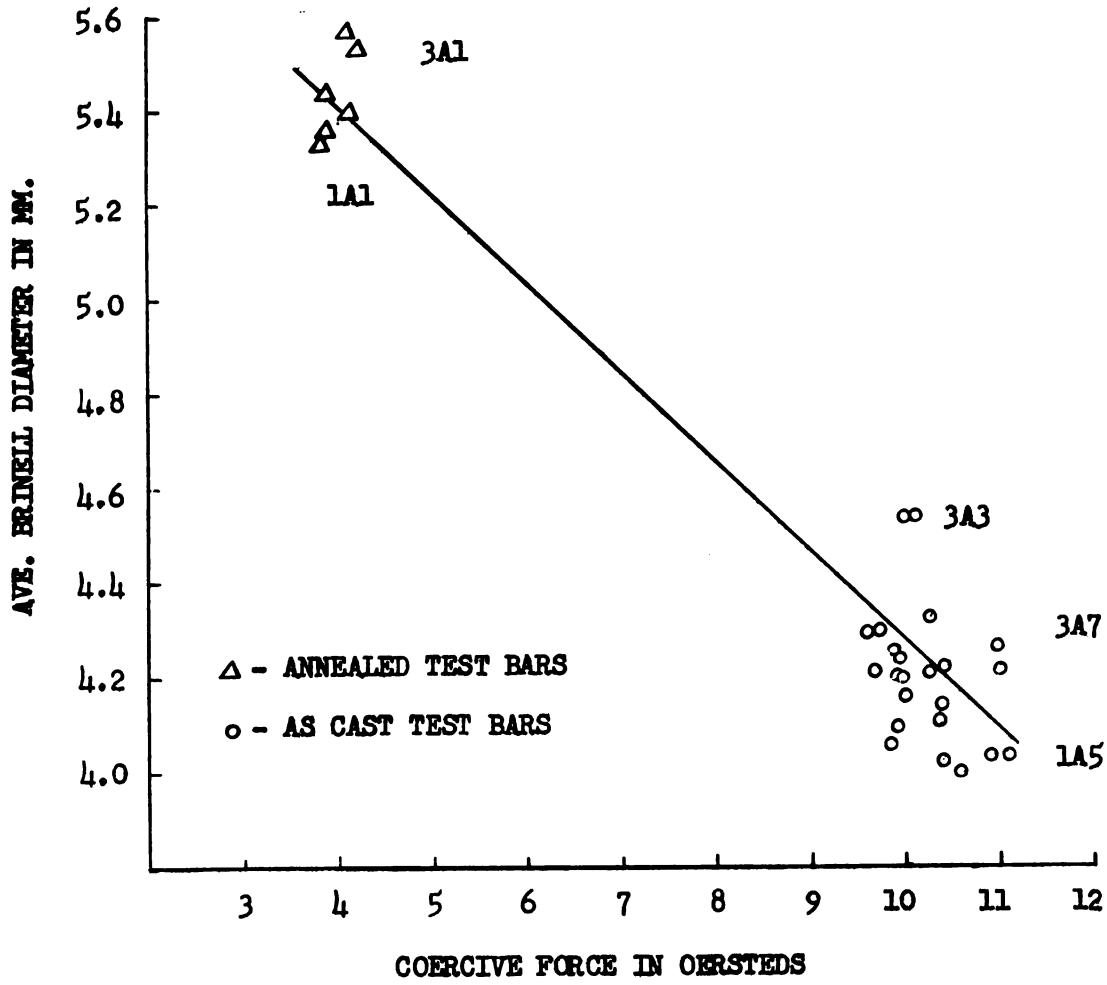
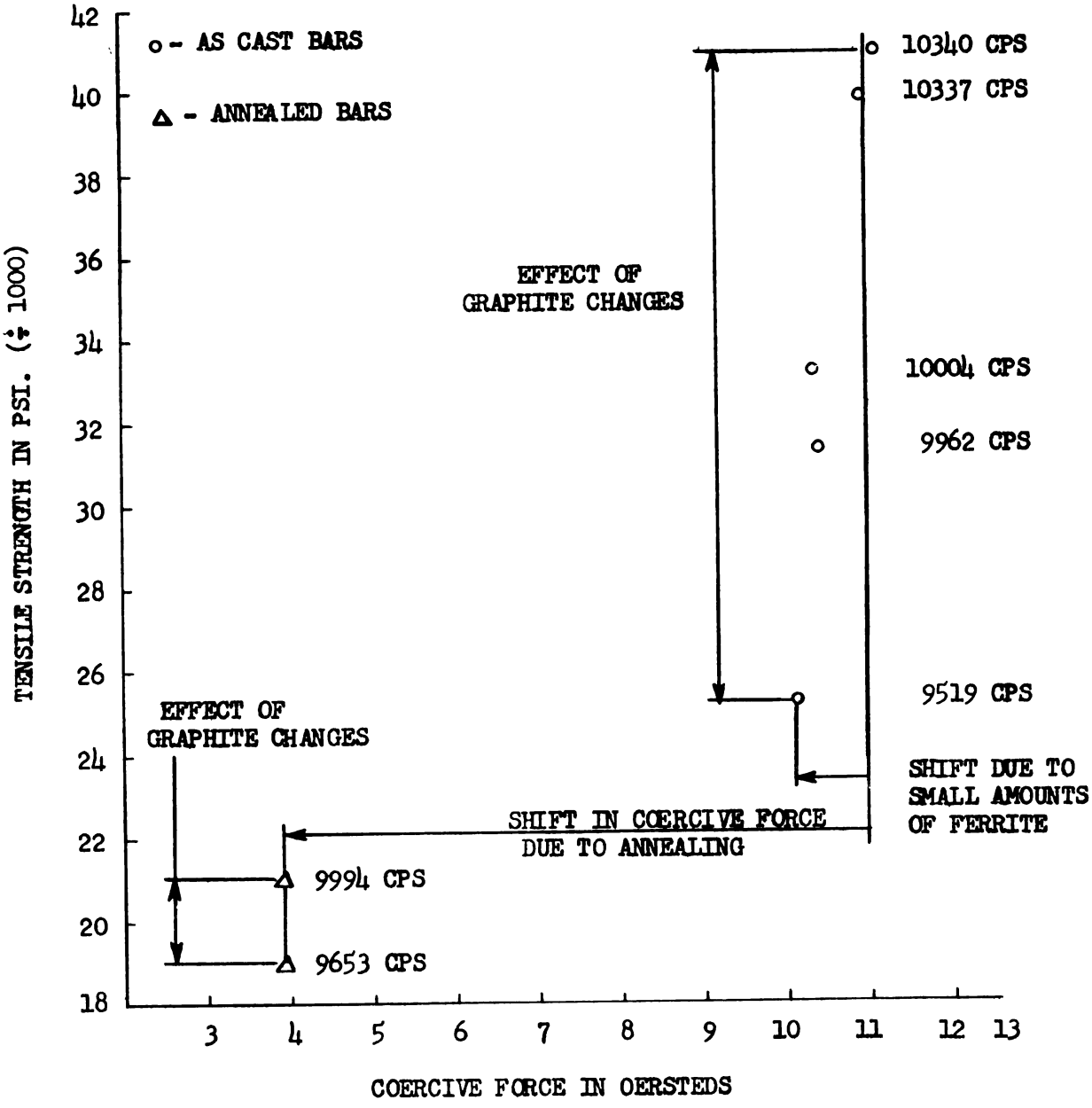


FIGURE 42

ANALYSIS OF TENSILE

STRENGTH VS. COERCIVE FORCE



APPENDIX B

TEST SET-UP FOR FOUNDRY CONTROL

TEST SET-UP FOR FOUNDRY CONTROL

Figure 43 on the following page shows the possible locations of test set-ups for inspection of quality at various points in the flow of production. The foundry control test set-up could be located close to the "shake-out" point as is shown. Environmental conditions must be closely considered when locating and designing test equipment.

Several factors must be considered before final designing of equipment. One preliminary step that must be taken is to make a thorough analysis of the variables which affect the structure of gray iron. A test object must be chosen. Synthesis of a test set-up must be considered. The final step would be to design and build the separate test components. This final step is not discussed here because much work is still required yet on preliminary considerations and design.

Analysis of Variables. In an unalloyed gray iron, the important variables which affect its properties are amount and coarseness of pearlite, amount of ferrite and amount of carbon and silicon dissolved in the ferrite, and amount and distribution of graphite flakes. In this investigation, it was found that the amount of ferrite could be determined by measuring coercive force. The amount of carbon and silicon dissolved in the matrix also affects coercive force. In this investigation, it was found that the graphite phase can be evaluated with the resonance test. Pearlite coarseness, an important variable, could not be investigated because the test bars studied had little variation in coarseness of pearlite.

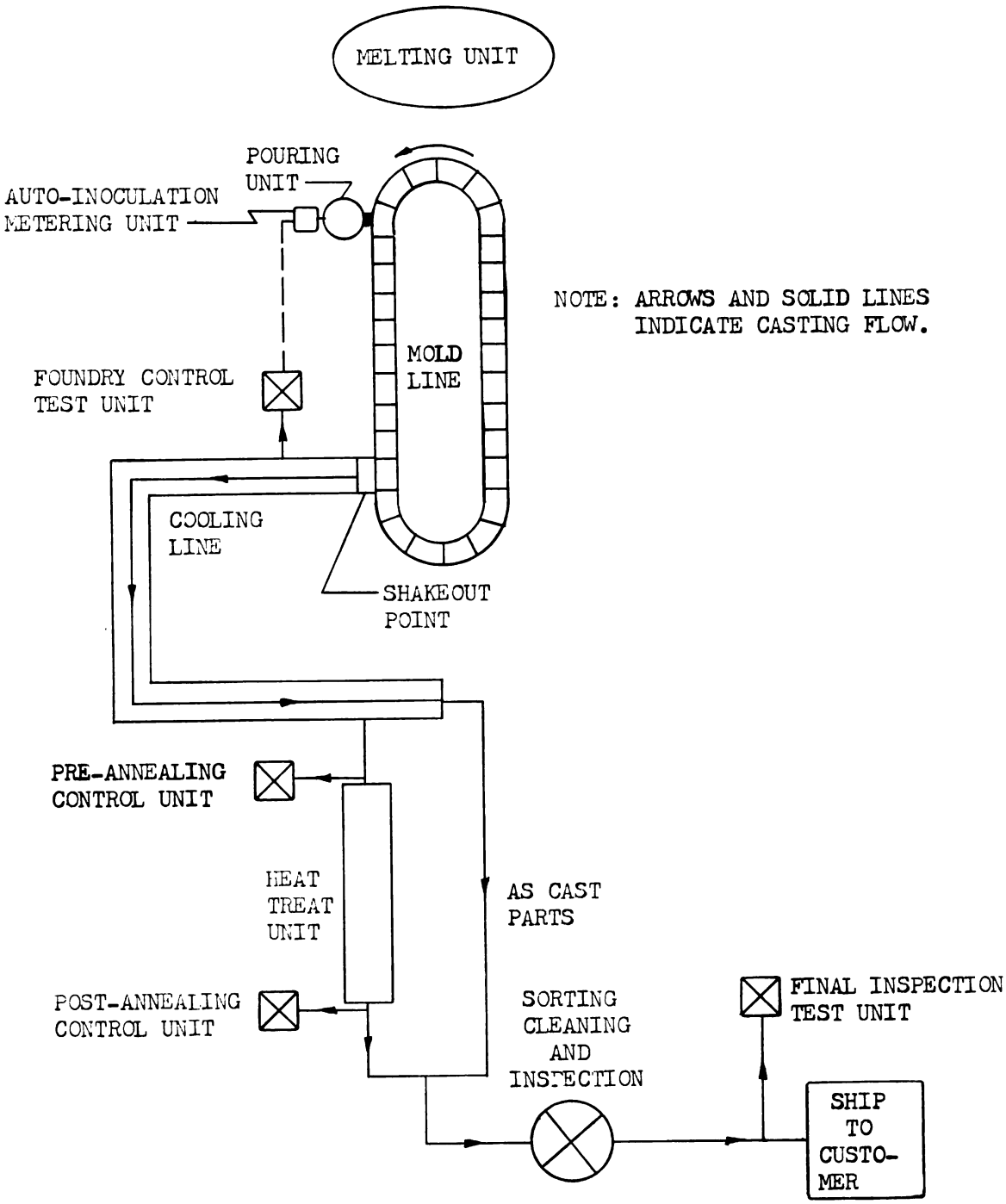


FIGURE 43

POSSIBLE LOCATIONS FOR
NONDESTRUCTIVE QUALITY TESTING

Thus far a foundry control device can be based only upon the amount of ferrite present in the matrix and the amount of constituents dissolved in the matrix, and the amount and nature of the graphite phase.

The amount of ferrite in the matrix of an unalloyed gray iron depends mainly upon the cooling rate through the lower critical transformation range and upon the carbon and silicon content. The amount of carbon and silicon dissolved in the matrix also depends upon the carbon and silicon content. In addition, the amount of carbon dissolved in the matrix depends upon the complete cooling history of the iron. The graphite distribution and amount depend upon the carbon and silicon content, the amount and type of inoculation, and the cooling rate through the upper critical transformation range.

In the foundry, mold line speed, initial pouring temperature, heat transfer properties of the mold, and section size control the cooling rate of the iron through the lower critical transformation range. Initial pouring temperature, heat transfer properties of the mold, and section size affect the cooling rate through the upper critical transformation range.

It is feasible in the near future with the use of electric furnaces that chemistry and pouring temperature can be held rather constant. Heat transfer properties of green sand molds should be investigated to determine if the variations in heat transfer properties from mold to mold significantly influence the cooling rate of the iron as it is cooling in the mold.

The effects of variations in section size can be off-set by using alloying elements and by controlled cooling through the lower critical transformation range after shaking castings from their molds.

An analysis of the variables affecting the amount of ferrite in the matrix and the graphite phase shows that coercive force might be used to control mold line speed and that resonant frequency might be used to control the amount of inoculation.

Type of Test Object. An ideal test object would be a long cylindrical test bar. However, to avoid wasting metal, a production part might be used as a test object.

If a test bar is used, it should be designed so that it could be gated to a production line gating.

Synthesis of a Foundry Control Test. The synthesis of a test involves design and placement of components and sequence of operation of the components.

In order to eliminate manual adjustment of an oscillator to measure resonant frequency (Figure 22), a method of automatic excitation shown in Figure 44 on the following page may be used.* The detecting transducer picks up background noise and feeds it back to the exciting transducer. The test sample will begin to vibrate if the noise contains

---

*Fuller, "A Simple Non-Destructive Test...," p. 368.

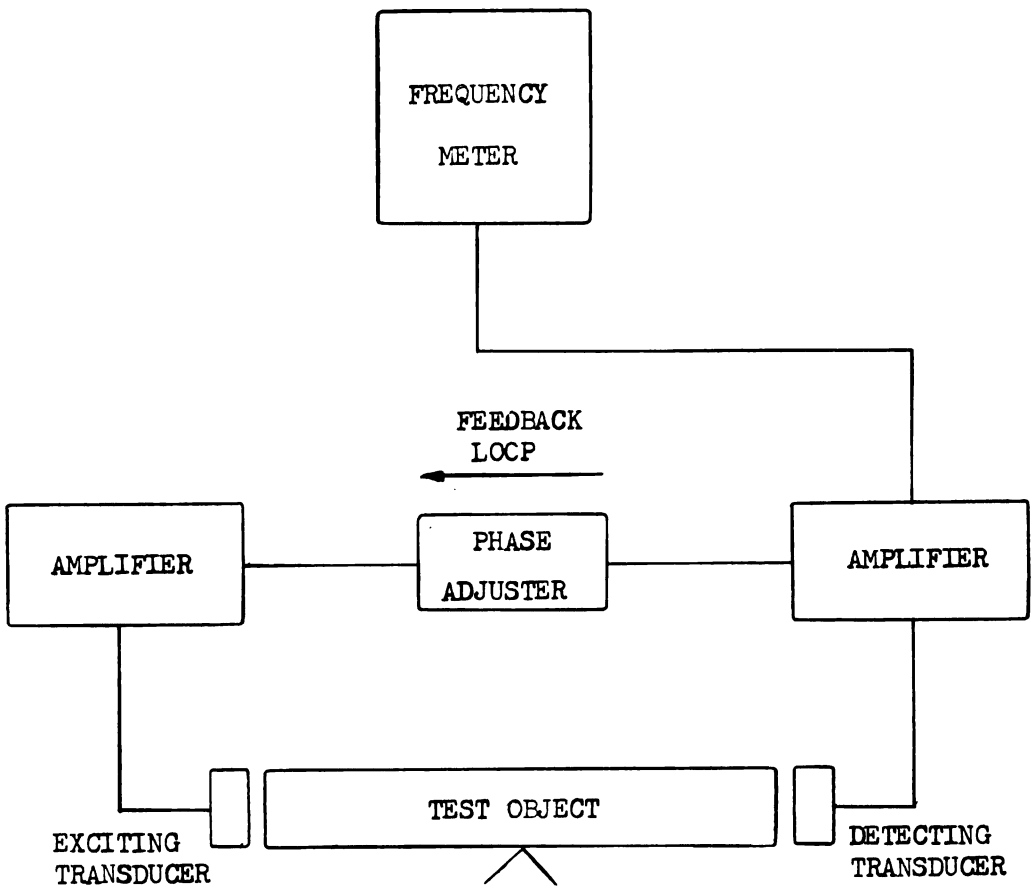


FIGURE 44

METHOD OF INDUCING RESONANCE BY
AUTOMATIC EXCITATION

a frequency which is equal to the natural frequency of the test sample. Power provided by the exciting transducer to sustain vibrations in the test object is obtained through a feedback loop as shown. This method of excitation provides a rapid means for measuring the resonant frequency of a test object.

A faster means of measuring coercive force also needs to be developed.

Figure 45 on the following page illustrates a synthesized test set-up for foundry control. The resonant frequency signal could be fed into an automatic inoculant meter to control the amount of inoculant. The coercive force signal could be fed into a mold line speed controller to adjust mold line speed. A suggested operation sequence is:

(1) Measure resonant frequency.

(2) Saturate the test object.

(3) Measure coercive force.

To summarize, foundry variables were analyzed to determine which variable to control with the coercive force test and which variable to control with the resonant frequency test. A test object must be decided upon. When synthesizing the quality test for foundry control, the separate test components should be as mechanized as is possible. Much more analysis and engineering is required before an adequate test for foundry control can be built.

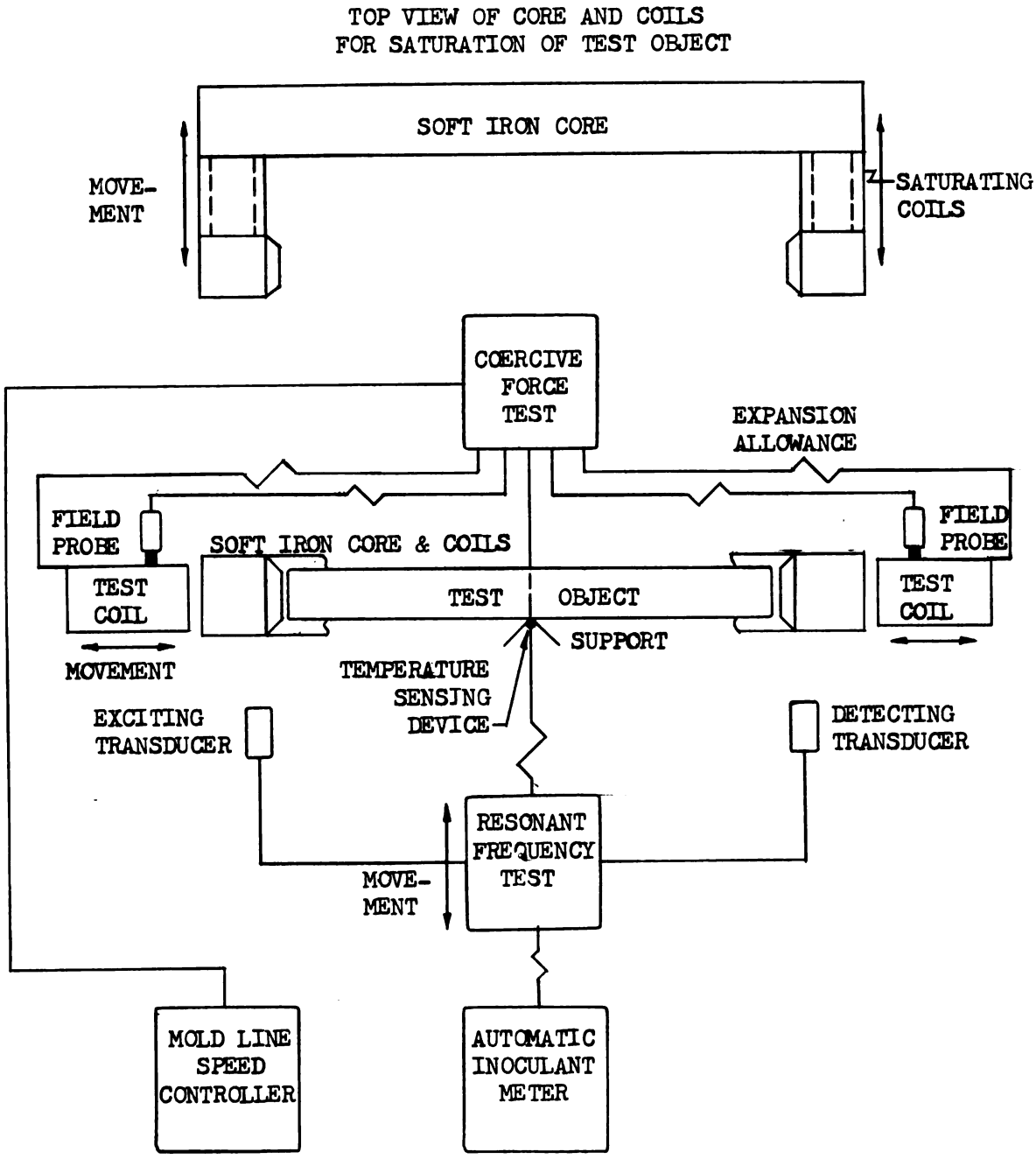


FIGURE 45

SYNTHESIS OF A FOUNDRY CONTROL TEST