ELECTRO-MAGNETIC TESTING OF WINDING ROPES.

A Thesis

Presented to the Faculty of Engineering of the University of Cape Town

for the degree of

Ph.D.

by

A. SEMMELINK.

1936.

Return to Stackroom 10

The Transactions of the South African Institute of Electrical Engineers

FOUNDED—JUNE, 1909 INCORPORATED—DECEMBER, 1909

Honorary Editor: A. W. LINEKER, B.Sc.
Assistant Honorory Editors: H. P. ALEXANDER, B.Sc. (Eng.), W. CORMACK, D.Sc.

Volume 44 MAY 1953 Part 5

PROCEEDINGS AT THE FOUR HUNDRED AND THIRTY-THIRD GENERAL MEETING

Held at Kelvin House, corner Marshall and Hollard Streets, Johannesburg

Thursday, 28th May 1953

A. R. MULLINS (President) was in the Chair and declared the meeting opened at 8 p.m.

There were present 105 members and visitors and the Secretary.

OBITUARY

THE PRESIDENT referred with regret, to the death in England on the 23rd April 1953, of Mr J. H. Rider, a Foundation Member of the Institute who was President in 1911/12 and elected an Honorary Member in 1927.

As a mark of respect to the memory of the deceased and in sympathy with the bereaved the meeting rose and observed silence for a few moments.

MINUTES

The minutes of the monthly general meeting held on the 23rd April 1953, were taken as read and were confirmed.

MEMBERSHIP

THE PRESIDENT announced that in terms of By-Law 5.2.4 the Council had elected the undermentioned candidates to membership of the Institute in the following grades :—

Associate Members : ANDRIES STEPHANUS DU PLESSIS, FREDERICK JOHAN HAMELBERG, RONALD NICHOLAS FORREST SMIT.

Graduates : JOHANNES JACOBUS GROBLER, JACOBUS COENRAD STRAUSS.

Students : HYMIE LESLIE AMOILS, CYRIL ETTIENNE BLOCH, NICOLAAS JACOBUS BOTHA, EDWARD BRAVER, GERALD HASTINGS DAWSE, JOHN VINCENT DOWNEY, DENIS REGINALD DUFFIELD, DAVID MAURICE GRAFF, ANTHONY HENRY WOUTER HUGO, EUGENE KRAFT, JACK WINNETT MACHANIK, GEORGE STUART PYNE MERCIER, ANTHONY MERRY, DAVID GEORGE NORMAN, IVOR SELWYN SACKS, EDWARD HIGHAM SOLOMON, PIERRE ANTHONIE STOFFBERG, LOUIS VAN BILJON, ANDRIES HENDRIK JANSEN VAN NIEUWENHUIZEN, DANIEL PETER VILJOEN.

Transfer from Graduate to Associate Member : DENNIS ALFRED GARDNER.

Transfer from Student to Graduate : DESMOND RHODES DAVIS, JOHN MICHAEL JARVIS, RONALD ALEXANDER LEIGH, GUILLAUME JOHANNES VAN ASWEGEN.

Transfer from Student to Associate : WILLIAM ROWLAND THOMPSON GOOSEN.

CO-OPTED MEMBER OF COUNCIL

THE PRESIDENT announced that, in terms of Clause 3.8 of the Institute's Constitution, the Council had co-opted Mr M. Hewitson as a member of Council from the 19th May 1953, representing the Union Department of Posts and Telegraphs.

PAPER AND DISCUSSION

The paper entitled 'Electro-magnetic testing of winding ropes,' was presented by A. Semmelink (Associate Member).

THE PRESIDENT proposed a vote of thanks to the author for his paper and B. L. Metcalf, Professor R. Guelke, H. C. W. Schmuhl (Associate Member) (these three contributions were read), O. Rau, L. T. Campbell Pitt, I. S. Haggie, C. W. H. du Toit (Associate), B. Stain, D. J. Stern, W. A. Pitts (Member) and C. F. B. van Wyk contributed to the discussion.

Mr Semmelink replied to a number of the questions raised.

There were no contributions under the remaining items on the agenda.

The President declared the meeting closed at 10 p.m.

Book Reviews

'FILTER DESIGN DATA FOR COMMUNICATION ENGINEERS,' by J. H. Mole (Spon.) (63s.).

Let it be stated at the outset that 'Filter design data for communication engineers' is a book for the filter specialist who is intimately acquainted with modern filter theory, and who is in need of a handbook, for ready reference to graphs of quantities relevant mainly to specialist filter design.

In the preface to this book, Dr Mole states 'It has been assumed that the reader has an elementary knowledge of the principles of filters, such as is usually given in University courses.' It is the opinion of the reviewer that the knowledge needed to assimilate and appreciate Dr Mole's work far exceeds that given in a University course on the subject—indeed for the proper appreciation of the book, the reader should be a specialist in the field of filters, and who in his work has need of quantities such as 'return loss, mismatch loss, bridging loss, series loss and effective loss' in addition to the more usual 'reflection loss.'

Dr Mole's work is essentially a handbook—we find in the preface the statement 'In order to keep the book of reasonable size, derivations of formulae have been omitted—and attention has been confined to the statement of results and the explanation of design methods.' One has only to subject the book to a cursory glance to be quite convinced of this, since no equation in the book has been honoured with a number for purposes of reference. In this regard, Dr Mole's favourite remark seems to be :—'The following expressions are given here for reference,' upon which the reader is abruptly and rudely asked to make acquaintance with some three or four complicated expressions which, he is told, are necessary for the topic under discussion. Should the reader be a filter specialist to whom the given equations have been introduced elsewhere under more polite circumstances, the situation is saved, but to the average communications engineer, this first meeting is too rude and abrupt to be pleasant or acceptable.

One redeeming feature in this connection is the large number of worked examples given to illustrate the methods of design.

To summarize therefore, this is not a book which can be used as a first text, it is a handbook to which reference will most usually be made by the filter specialist. K.P.

'WORKED EXAMPLES FOR ADVANCED ELECTRICAL STUDENTS,' by D. I. Williams. E. and F. N. Spon, Ltd., London, 1952. First Edition, 158 pages, 118 diagrams, plus index. Price 18s. in England.

The author has set out to provide worked examples for students working for the Higher National Certificate and Part II of the I.E.E. examination. The standard is about third year B.Sc. standard in this country and despite the criticisms below the book can be of considerable use to students with a good knowledge of electrical machine theory.

The problems are divided into chapters, each dealing with a specific type. The divisions are the a.c. circuit, transformer, induction motor, synchronous motor, d.c. machine. Each chapter commences with a short summary of the essential theory and the author emphasizes many points with which students frequently have difficulty. The problems are fully worked out in every case, and many examples are drawn from past I.E.E. examination papers.

It is unfortunate that so many printer's errors have been allowed to remain and the number of loose statements is somewhat disturbing. One typical example on page 26 is the statement that 'the current leads the capacitive reactance, which is of course a fundamental conception.' Surely it would require little effort to state that the current leads the *voltage across* a capacitive reactance.

Some inconsistency is also apparent; while on page 14 the importance of working in phase quantities is emphasized, chapter 4 on the synchronous machine deals with line quantities in a very confusing manner. Fig. 60 on page 96 is also poorly drawn and does not agree with the context. The last chapter, on d.c. machines, is scrappy and while this is probably due to the fact that the d.c. machine is rare in general, nevertheless one cannot help feeling that material on series traction motors is most desirable. G.R.B.

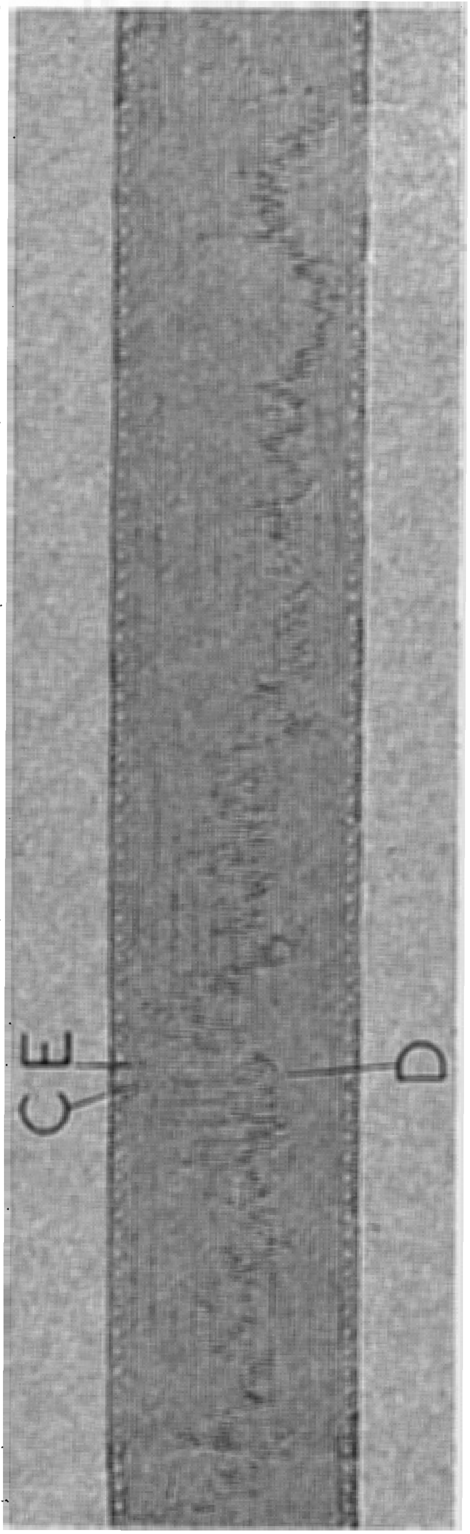

Fig. 1—Chart of St Helena test, July 1950

2·3 *Early Union Corporation experiments*

The first Union Corporation experiments with an electromagnetic method were conducted in 1946. A magnetizing coil of twenty turns of welding cable was used carrying a current of 100 amperes at 50 c.p.s. together with a searchcoil of several thousand turns; the distance between the coils could be varied. The rope was passed through the centres of both coils. On testing a rope just before it was taken off it was found that all visible corrosion and broken wires caused voltage variations in the searchcoil. A peak-reading valve voltmeter and an oscilloscope were used to measure these voltage variations. The results from this test were sufficiently encouraging to lead to the decision that further research work should be done. The author was appointed to do this, some equipment was ordered, a drawing board in the engineer's office at Marievale mine was made available as a laboratory and work started in April 1950. In July a test was made on a non-spin rope at St Helena gold mine, the variations along the rope were recorded on a sound-level recorder. A record of this test is shown in Fig. 1.

Visual inspection of the rope at points where the chart showed peaks, showed severe corrosion and broken wires. Samples were selected and later tested in the Government Mechanical Laboratory at Cottesloe. Some samples selected as a result of peaks on the chart broke at approximately half the initial breaking load, while others selected away from the peaks had normal breaking loads. It was then decided to set up a small laboratory and to make equipment with which to carry out tests on all main winding ropes in the group. More equipment was obtained, as well as a ¾-ton panel van to carry the apparatus; later a trailer was added to carry a tensometer, and recently a building has been occupied by the rope-testing department.

After the test on the St Helena rope, the apparatus has been twice altered extensively, and at present service equipment based on the last experimental equipment is being designed.

3. DATA ON WINDING ROPES TESTED

Before describing the equipment mentioned in Section 2·3, the winding ropes tested and the magnetic and electric properties of their wires will be discussed.

3·1 *General*

The main winding ropes—about fifty in number—which have been tested with the equipment described in this paper, are manufactured locally of South African 'basic' steel. The tensile strength of the wire is either 123/134 tons (2 000 lb) per sq. in. or 128/140 tons per sq. in. The ropes have six triangular strands of approximately thirty wires, laid up on a sisal core, which is impregnated with lubricant. Diameters of these ropes vary from 1¼ inches to 2 inches, while the breaking loads of the new ropes vary from 90 to 200 tons. In addition one non-spin rope of 1½ inches diameter which had fifteen strands each of ten wires has been tested.

The winders concerned all have cylindrical drums ranging from 11 feet to 16 feet in diameter, on which the number of layers of rope rarely exceeds three.

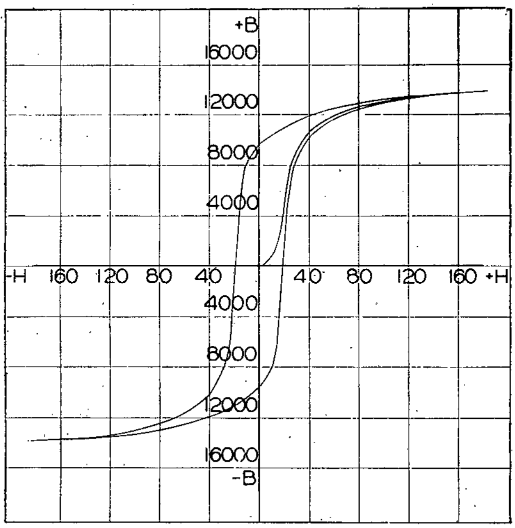

Fig. 2—*B*—*H* curve for ring specimen of local 'basic' steel

3·2 *Magnetic and electric properties of the steel wire*

The magnetic and electric properties of South African 'basic' steel wire used in the manufacture of winding ropes are of importance to the selection of a method and to the interpretation of results. A number of tests to determine these properties have recently been made. The wires for these tests were of 0·070 inches diameter and varied slightly in composition.

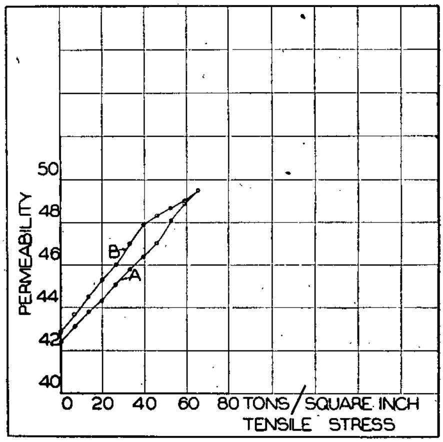

Fig. 3—Variation of permeability by stress variation
A—Increasing stress. *B*—Decreasing stress

3·2·1 Determination of the *B*—*H* curve

The *B*—*H* curve, Fig. 2, was determined for a ring specimen of wire of one composition.

Next, curves were made for single straight wires in a long solenoid. These were compared with the curve for the ring specimen. We concluded that the test on a single straight wire in a long solenoid gave sufficiently accurate results and that the slight variation in composition had little effect on the magnetic properties. Some typical results are shown in Table I.

TABLE I

Permeability = 44 for a magnetizing force less than 1 oersted
Maximum permeability = 320 for a magnetizing force of 25 oersted
Maximum flux density = 14 000 gauss for a magnetizing force of 200 oersted
Retentivity = 9 500 gauss
Coercive force = 20 oersted
Hysteresis loss = 0·35 watts per c.c. at 50 c.p.s.

3·2·2 Changes of permeability

It was found that increase of tensile stress in the wire caused an increase of permeability. For a stress of 65 tons/sq. in.

the increase in permeability was 14 per cent. Fig. 3 shows the way this variation takes place, when the stress is increased and then reduced to zero. The magnetizing force was less than 1 oersted.

Twisting of the wire caused a decrease of 8 per cent of permeability for 180° of twist per foot of wire. Other possible causes of permeability change such as bending, fatigue and temperature variation have still to be investigated.

3·2·3 Change of resistivity

The resistance of a length of 0·020 inch diameter steel wire was determined for stresses varying from zero to 70 tons/sq. in. The resistance increase over this range was 1·1 per cent, which agreed with the percentage increase of length due to elasticity. The resistivity of the steel must be very nearly constant over this range of tensile stress.

3·3 *Eddy currents in ropes*

When a steel wire rope is placed in a longitudinal a.c. magnetic field, eddy currents will be induced in the wires, in the strands, as well as from strand to strand. Fig. 4 shows a cross-section of a triangular strand rope as used by our mines.

In Fig. 4 there is no contact between the strands. This is the case for newly laid-up ropes. When the rope is put into service the strands will touch each other due to bedding into the sisal core, and eddy currents will then be able to flow in a path around the core. The amplitude depends on the voltage induced in and on the resistance of each path, while the voltage is proportional to the frequency and to the flux linkage. When the magnetizing force is low enough to make hysteresis losses negligibly small, eddy currents determine the phase-angle between the magnetizing current and the voltage induced in a searchcoil surrounding the rope. In the absence of eddy currents this angle will be 90°. In addition to their effect on the phase angle, eddy currents will reduce also the total flux in the rope, as their direction of flow is opposite to that of the magnetizing current. As the largest flux linkage occurs in a path surrounding the core, the currents flowing from strand to strand will have considerable influence on both the amplitude and phase angle of the flux. This path will also be subject to the largest variations; when there is no contact between the strands the resistance in infinite; when the contact is good and the wires are bright the resistance will be a fraction of an ohm; when the surface of the wires is corroded the resistance may increase appreciably.

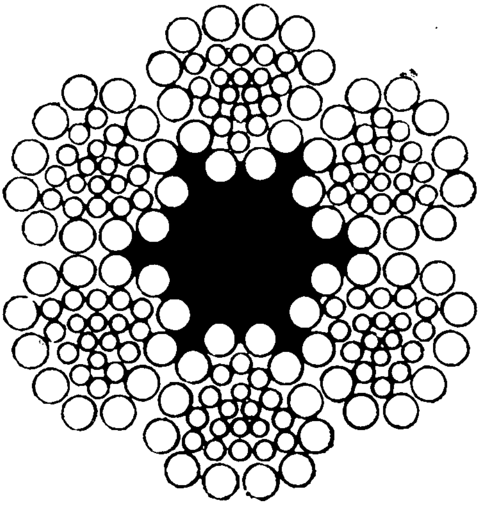

Fig. 4—Cross-section of triangular strand rope

4. DEVELOPMENT OF EQUIPMENT

4·1 *Basic methods available*

The methods considered all use longitudinal magnetization of the rope. The magnetizing force may be either d.c. or a.c., and if a.c. there is a wide choice of frequencies. The field may be small enough to work at initial permeability or large enough to ensure magnetic saturation. The magnetic field may be applied by means of a coil surrounding the rope or the coil may be carried by a laminated yoke of which the polepieces surround the rope. The flux variations may be detected by a searchcoil arranged to measure either the total flux in the rope or the radial field occurring at broken wires.

Existing d.c. methods use magnetic saturation, the flux will vary with the cross-sectional area of the rope only as the flux density at saturation is a constant, provided the applied field remains constant. When a galvanometer is used to detect the changes of flux, an even speed must be maintained and deflections will occur only at discontinuities such as broken wires.

4·2 *Selection of method*

With a.c., magnetic saturation causes severe heating of the rope unless a very low frequency is used, in which case the rope speed has to be very slow to allow variations to register. For this reason a small magnetizing force is preferable. This has the added advantage of better penetration of the rope by the magnetic flux due to the small initial permeability of the steel used in our ropes. Accordingly a low magnetizing force was adopted.

For small fields a coil around the rope is mechanically simpler than a yoke, where airgaps must be kept constant to ensure a constant field. The coil must be arranged to give as uniform a field as possible at its centre where the searchcoil, also surrounding the rope, is placed. A Helmholtz coil which consists of two identical co-axial windings at a distance equal to their diameter, has at its centre a nearly uniform field. It was decided to use this arrangement and to make these coils detachable by splitting the former on which they are mounted. This saves valuable operating time when the ropes are tested in the shaft.

The flux induced in the rope by the current in the magnetizing coils varies with permeability, cross-sectional area and eddy current path. It is measured by the searchcoil at the centre of the magnetizing coil. To detect changes of flux occurring over a short distance as may be caused by broken wires, the diameter of the searchcoil must be as small as can be reconciled with the requirement that the rope must run freely through the coil. A diameter of $2\frac{1}{2}$ inches was chosen for the first coil design, which could be used for testing ropes having diameters up to $1\frac{7}{8}$ inches.

As eddy-current losses increase with frequency, the flux in the rope will decrease with frequency. Measurements on rope samples had shown that for the same magnetizing current the flux at 1 000 c.p.s. was some 15 per cent less than the flux at 50 c.p.s. For the first tests a frequency of 1 000 c.p.s. was chosen.

The variations of flux along the rope were expected to be small and it was considered essential to use a balancing circuit to detect them.

4·3 *Description of experimental equipment*

As mentioned in Section 2·3, the apparatus was twice altered extensively after the test on the St Helena rope. That used at St Helena will be called Model I, the first modification Model II and the experimental equipment now in use Model III. Each will be described separately.

4·3·1 Model I

The equipment used for the St Helena test in July 1950 was constructed on the lines set out in Section 4·2. The split coil former was 6 inches long and 5 inches in diameter, 2 inches bore and made of hardwood. It was clamped over the rope by two copper straps, which also formed the magnetizing coil. A stepdown transformer mounted on the former connected the output of a beat-frequency oscillator, set to 1 000 c.p.s. to this coil. A co-axial searchcoil of two turns was placed half way between the two magnetizing windings where the diameter of the former was reduced to $2\frac{1}{2}$ inches. A second transformer was inserted between the searchcoil and the balancing circuit which consisted of a potentiometer followed by a phase shifter. The circuit is shown in block form in Fig. 5a.

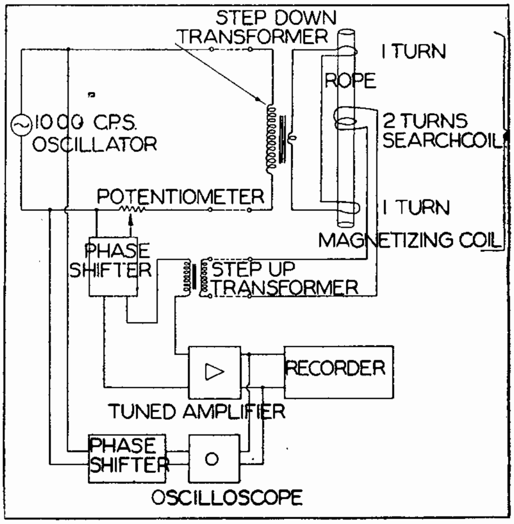

Fig. 5a—Block diagram of Model I

A permanent record of the flux variations along the rope was obtained from a sound-level recorder connected to the output of the balancing circuit through an amplifier tuned to 1 000 c.p.s. An oscilloscope was used to determine whether these variations were caused by changes of flux amplitude or phase angle.

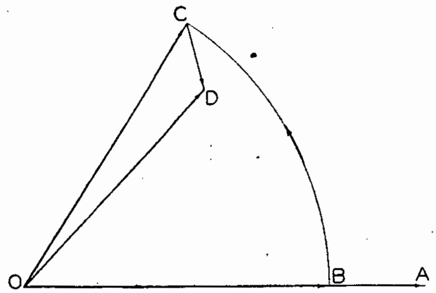

Fig. 5b—Vector diagram of Model I

Fig. 5b shows a vector diagram of Model I, where :—

OA = voltage across potentiometer
OB = input voltage of phase shifter
OC = output voltage of phase shifter, which is made equal to searchcoil voltage after the step-up transformer at balance point
OD = searchcoil voltage at some point along the rope, where the circuit is out of balance
CD = input voltage to tuned amplifier. The amplitude of this voltage is after amplification recorded on the chart.

As OD may be smaller or larger than OC in both amplitude and phase angle, CD can lie at any angle to OC.

Fig. 1 shows a record obtained with this apparatus at St Helena in July 1950 of a 1½ inch diameter non-spin rope. It was known that excessive corrosion occurred at a number of points in this rope, corresponding to points such as C and E on the chart. It was found at tests in the Government Mechanical Laboratory that the breaking load of the rope at C was 61·3 tons, at E 68·3 tons and at a point D between these two 115·5 tons, which was near to the initial breaking strength of 120·0 tons.

Tests with this equipment indicated that interpretation of results would be simpler if changes of amplitude and phase angle could be recorded separately, and if the movement of the chart could be made proportional to the movement of the rope. This led to the development of Model II described in the next section.

4·3·2 Model II

In March 1951, a small laboratory was set up at East Geduld. It was decided to make records of all main winding ropes in the Group and to follow up by inspecting the ropes at points corresponding to particular peaks on the charts. To meet the requirements mentioned above (Section 4·3·1) the circuit was redesigned and a selsyn link was arranged between the recorder and a pulley running on the rope.

As initial tests on this model showed that when the frequency of the magnetizing current was increased to 10 kc/s, the same variations were shown as with the frequency of 1 kc/s, the new circuit was designed for 10 kc/s.

A new coil was constructed on the same principle as the old on a bakelite former having two magnetizing windings of two turns each of 5 inches diameter and a searchcoil of five turns of 3 inches diameter. The two halves of the coil were connected by means of two sets of plugs and sockets.

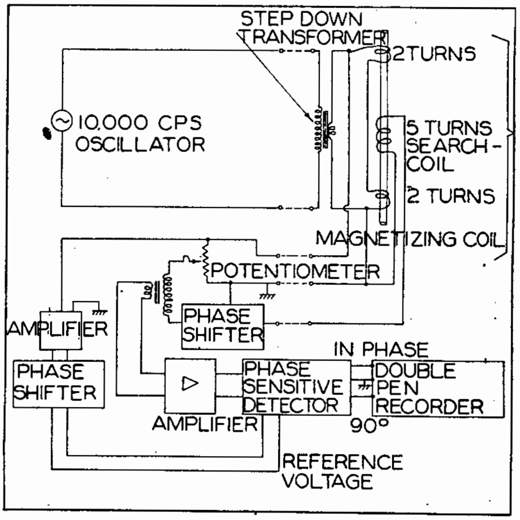

Fig. 6a—Block diagram of Model II

This coil could be used for tests on all the ropes in the Group, including ropes of 2 inches diameter.

The searchcoil voltage was balanced against the voltage across the magnetizing coil by a potentiometer and a phase shifter as shown in Fig. 6a.

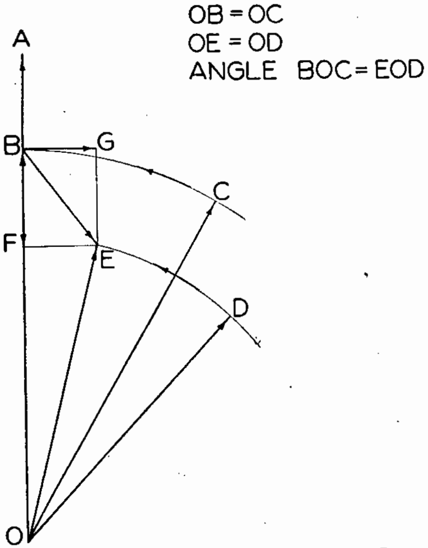

Fig. 6b—Vector diagram of Model II

The output of the balancing circuit was connected as before to an amplifier, but followed by two phase-sensitive detectors and a double-pen recorder. One of these detectors gave an output proportional to amplitude changes while the output of the other was a measure of the change in phase angle. Fig. 6b shows the vector diagram, where :—

OA = voltage across the magnetizing coil, which is the same as that across the potentiometer

OB = output voltage of potentiometer, which is made equal in amplitude to

OC = searchcoil voltage at point of balance, which is shifted to be in phase with OB

OD = searchcoil voltage at some point along the rope away from balance

OE the same after phase shifting. The setting of the phase shifter is not changed after balancing, therefore angle $EOD = BOC$

BE = input to amplifier. After amplification BE is analyzed into

BF = in-phase component recorded on the top trace and

BG = 90° component recorded on the bottom trace of the charts.

Upward deflection of each trace shows increase of the corresponding component and *vice-versa.*

With this apparatus all main winding ropes in the Group were tested in February and March, 1952. Some of the charts obtained are shown in Fig. 7.

At a point corresponding to point *A* on the chart the No. 3 compartment rope was opened up to find out whether the deviation was caused by corrosion as suspected. Some scale was found on the wires, but not at point *B* which was also opened up. The bottom trace of these charts which recorded the change of phase angle, showed very little variation. It was thought that greater variation of phase might show up if other frequencies were used. This led to the decision to redesign the equipment to enable tests to be made at a number of frequencies from 10 to 20 000 c.p.s.

4·3·3 Model III

By this time special components and cable ordered had arrived and it was possible to construct equipment which avoided some of the shortcomings of the previous models. By placing the step-down transformer for the magnetizing coil with the balancing circuit, it was possible to simplify this circuit and increase its accuracy. By doing this it was necessary to redesign the coil as well. To keep losses in the connecting cable small the magnetizing current had to be smaller and the number of turns larger. Two windings of ten turns each of 5 inches diameter were used for the magnetizing coil and ten turns of 3 inches diameter for the searchcoil. The two halves of the coils were connected by means of flat spring-loaded contacts mounted on insulating boards on the sides of the former. The coil was clamped over the rope with four bolts and supported on a bracket fastened to a tensometer. This is shown in position on the rope in a shaft in Fig. 8.

The searchcoil voltage is balanced by resistive and reactive components obtained from a resistance and a mutual inductance in series with the magnetizing coil. As this

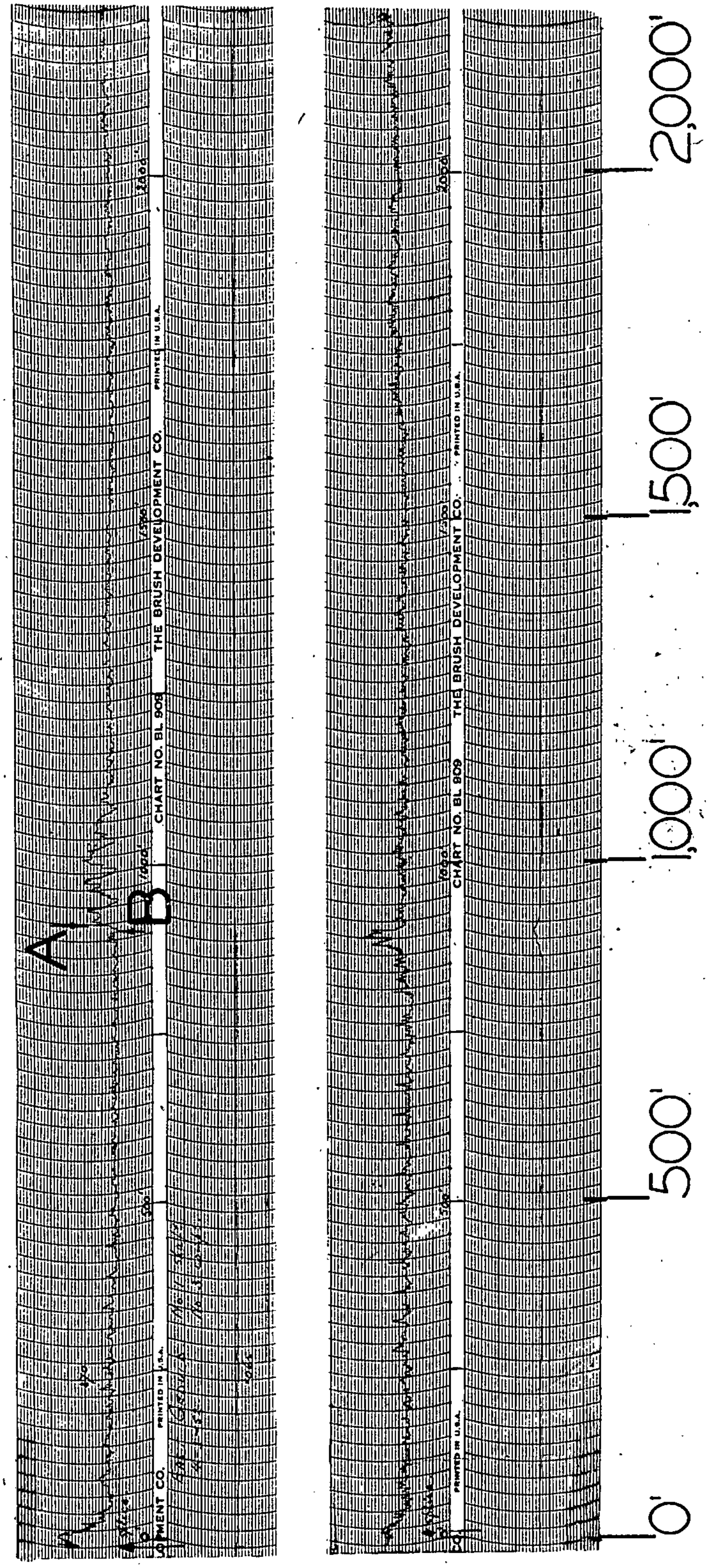

Fig. 7—Charts of East Geduld, No 1 shaft, Nos 2 and 3 compartments ropes, tested March 1952

voltage varied for the range of frequencies used by a factor exceeding forty, multipliers have been inserted for both *R* and *X* components. The reactance of the magnetizing coil at the higher frequencies caused an appreciable reduction of current; series condensers were used to balance this reactance at these frequencies. The magnetizing current was approximately 0·5 amperes, giving a magnetizing force of approximately 1·5 oersted. A simplified circuit and block diagram is given in Fig. 9a, while Fig. 9b gives the vector diagram.

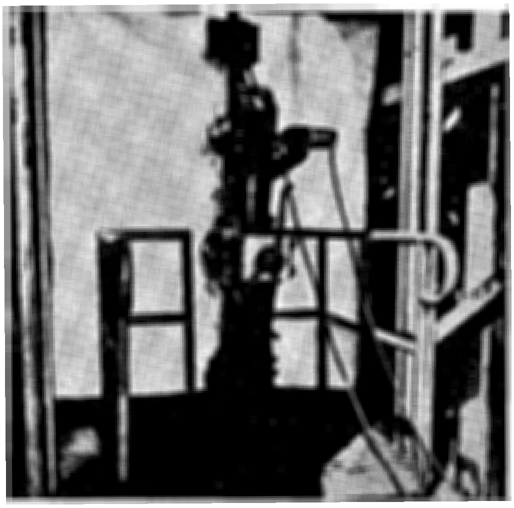

Fig. 8—Coil and tensometer in position on the rope

The balancing circuit is connected to a valve voltmeter. This is a three-stage amplifier and an outputmeter. It was adjusted to give full-scale deflection for an input of 2 millivolts. The voltmeter could also be used to measure the voltage across the searchcoil as the *R* control or the *X* control. The amplifier output was connected to two phase-sensitive detectors. The reference voltage for these was obtained from the oscillator output through phase shifters. These were adjusted at each frequency to give one output of variations in phase with the flux and a second 90° out of phase with the flux. The first connected to the top trace of the recorder showed amplitude variations and the other connected to the bottom trace showed phase-angle variations.

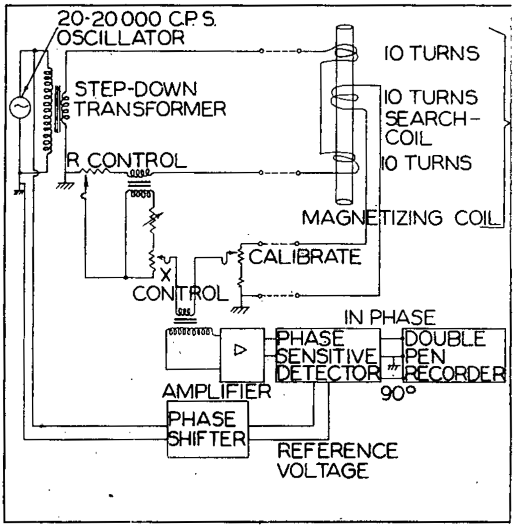

Fig. 9a—Simplified circuit and block diagram of Model III

In the vector diagram Fig. 9b :—

I_M =magnetizing current which is in phase with

E_R =voltage across the *R* control, which in turn is 90° out of phase with

E_X =voltage across the *X* control

OR and *OX* are the fractions of E_R and E_X required to balance the voltage *OA* across the searchcoil at balance

OB =searchcoil voltage at some point along the rope away from balance

AB =input to amplifier. After amplification this is analyzed into

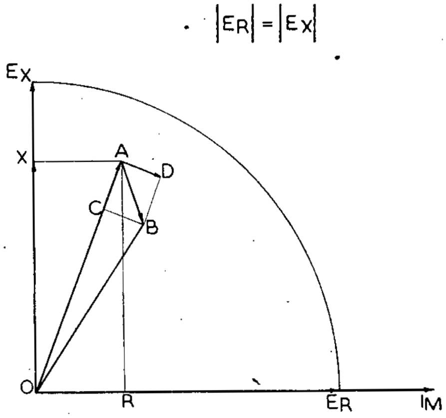

Fig. 9b—Vector diagram of Model III

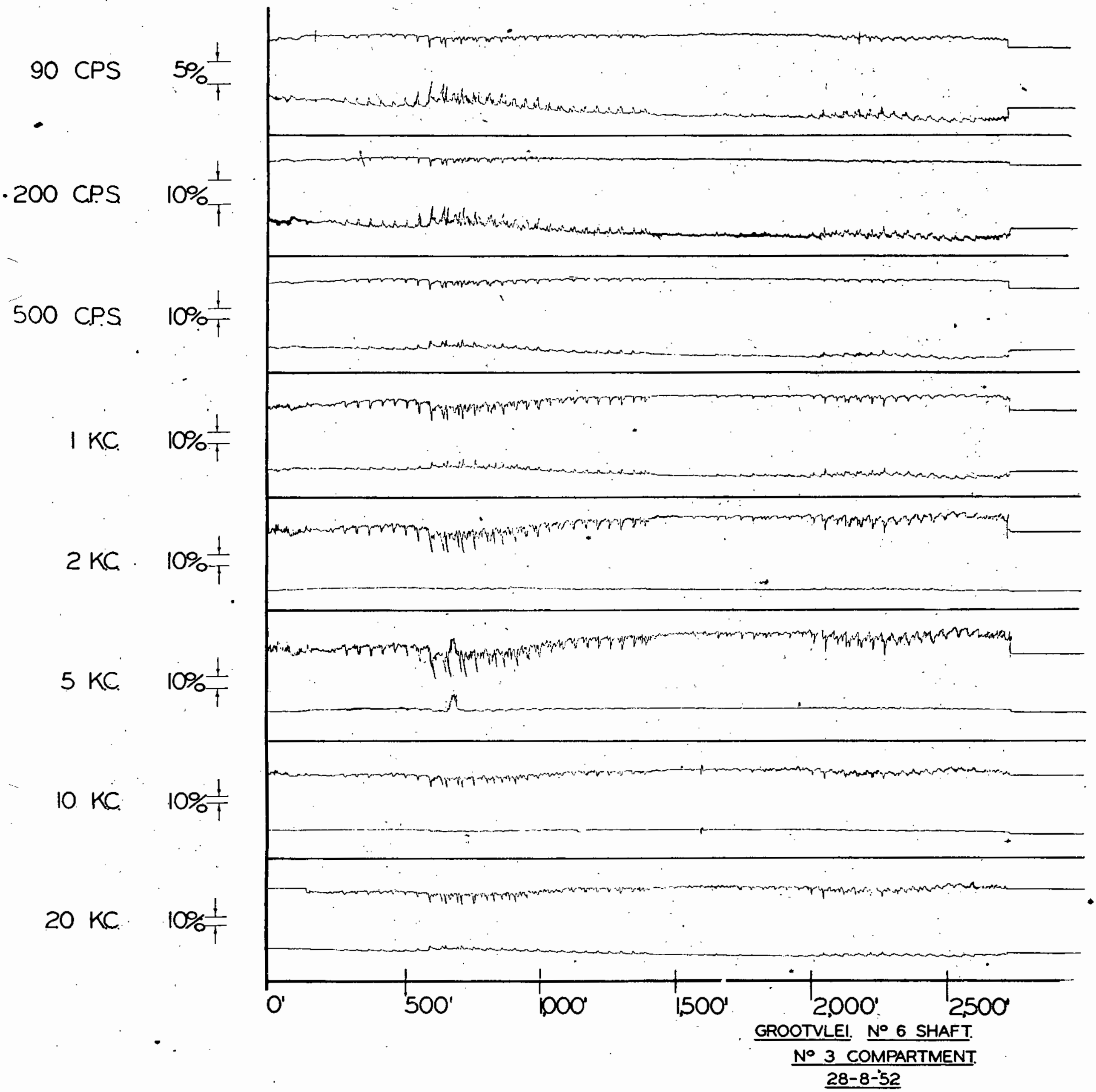

Fig. 10—Test with eight frequencies for Grootvlei No 6 shaft, No 3 compartment rope on 28th August 1952

AC = in-phase component, shown on the top trace and

AD = 90° component shown on the bottom trace of each chart.

As before upward deflections of the top trace correspond to increase of the in-phase component and *vice versa*, while the same applies for the bottom trace with respect to the 90° component.

The object of splitting the flux variations in two components was to separate changes of permeability and cross-sectional area on the one hand and changes of eddy current path on the other. Subsequent tests indicated that this could be done.

4·3·4 Tests on different frequencies

A rope in Grootvlei No 6 shaft, No 3 compartment was tested with eight frequencies. The charts are shown in Fig. 10.

The sensitivities used for the top and bottom traces were the same, calibration in per cent variation of total flux is shown to the left of the top trace for each frequency. From the R and X control settings recorded on the traces the flux can be calculated in amplitude and phase angle. The circuit was balanced for each frequency with the conveyance just below the surface. The rope concerned was of triangular strand construction, $1\frac{3}{4}$ inches in diameter and coiled on a multi-layer drum. At the time of testing, it had completed nearly eight years of service and it was discarded shortly afterwards.

4·3·5 Survey of winding ropes

From the tests in Section 4·3·4 and subsequent tests in the laboratory it was found that for the separation of permeability and cross-sectional area changes and changes of eddy-current path, frequencies of below 100 c.p.s. were preferable. At frequencies below 70 c.p.s. not only had the rope speed to be very slow but the equipment gave a low signal-to-noise ratio. Due to these considerations and in order to avoid interference with harmonics of the mains supply frequency 85 c.p.s. was chosen. A second survey of the main winding ropes in the Group was started in September 1952 and 46 ropes have been tested at this frequency.

4·4 *Design of service equipment*

The results of this survey, which will be shown and discussed in Section 5, are promising. Service equipment based on this model is now being designed. The intention is to combine the oscillator, balancing circuit, recorder amplifier and power supply in one instrument. The oscillator is to have fixed frequencies of 20 and 80 c.p.s., the lower frequency to be used for checking particular points shown on the charts obtained with 80 c.p.s. The balancing circuit will be made simpler and more accurate.

4·5 *Broken wire detector*

A rope having broken wires was tested with Model II in March 1952. These did not show on the chart. Some work was then done on the construction of a coil to measure the radial magnetic field occurring at broken wires. It was found possible to detect broken wires with this coil. More work has, however, to be done on this detector to make it suitable for routine field work.

5. INTERPRETATION OF CHARTS

The charts obtained during the survey with Model III using a frequency of 85 c.p.s. show that variations for new ropes seldom exceed one-half per cent of total flux on either trace, while for older ropes the variations on the top trace may be 2 per cent and those on the bottom trace 4 per cent. Such variations are usually shown at points of the rope where extra wear may be expected such as near the splice, at cross-over points, etc.

The top trace which records the variations of the in-phase component, is a measure of the variation of the area of the steel and of the permeability along the rope. The bottom trace showing the changes in the 90° component, caused by changes in eddy currents, is a measure of the contact between the strands and between the wires in a strand. Resistivity changes which might cause variations of eddy current are believed to be small enough to be negligible. Most changes on the top trace are accompanied by changes on the bottom trace. These read in conjunction with each other give a picture as to what is happening in the rope. Usual combinations are :—

(*i*) Increase on top trace, decrease on bottom trace
(*ii*) Decrease on top trace, increase on bottom trace
(*iii*) Decrease on top trace, decrease on bottom trace.

Examples of each of these combinations will be shown in the next sections.

5·1 *East Geduld, No 2 shaft, No 2 compartment rope*

Only part of the chart of this rope is shown in Fig. 11. At the time of testing the rope had been in use for only half a year.

The increase on the top trace is here accompanied by a decrease on the bottom trace. This corresponds to an increase of flux and a decrease in eddy currents. It is thought possible that the increase of flux was caused by the decrease in eddy currents and that the complete separation of flux changes which had been aimed at has not been achieved.

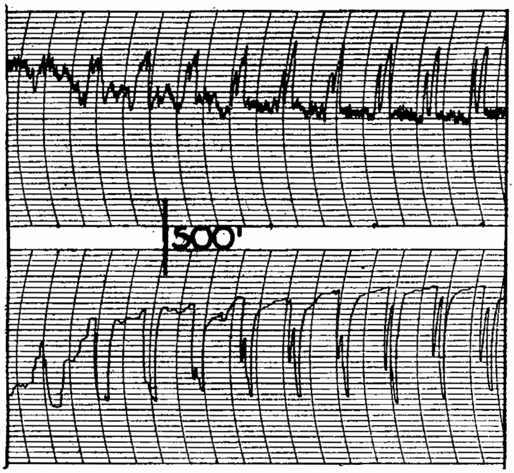

Fig. 11—Part of chart of East Geduld rope, tested 8th March 1953

When the service equipment is available this can be quickly checked by carrying out a test at 20 c.p.s., where eddy current effects should be negligible. It will be seen that the peaks occur at regular intervals, equivalent to 45 feet of rope, which corresponds almost exactly to the circumference of the drum. These winder drums have parallel grooves and at each revolution of the drum the rope has to cross over to the next groove. This is shown in Fig. 12.

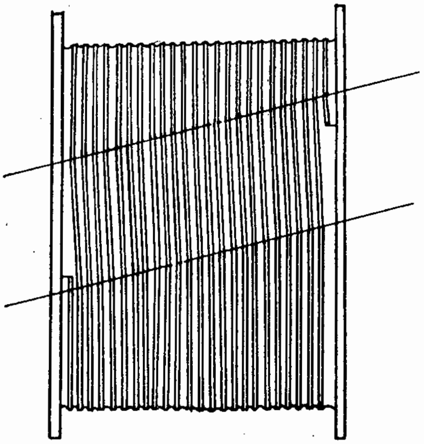

Fig. 12—Diagram of drum, showing crossover points

At these points the rope is subject to forces which may affect it in different ways. In the case of the rope of Fig. 11, the peaks appear to be a result of a tendency for the rope to untwist at the crossover, resulting in decreased contact between strands and decreased eddy currents. These peaks appear without any sign of plastic work.

5·2 *Grootvlei, No 4 shaft, No 3 compartment rope, tested 26th February* 1953

Another effect observed at crossover points is that of increased plastic wear of the outer wires of the strands, possibly combined with work-hardening of these wires. In plastic wear the shape of the wires is distorted, causing neighbouring wires to form an almost continuous layer of steel. If the rope is allowed to remain in the same position on the drum for a long time the wires will start to crack at the crossover points. To prevent this the rope is pulled in at the drum end at regular intervals, thus shifting the points of increased wear.

Fig. 13 shows a part of a chart of a rope tested shortly before it was taken off. Each variation shown consists of a decrease on the top trace and an increase on the bottom trace, or a decrease of flux and an increase

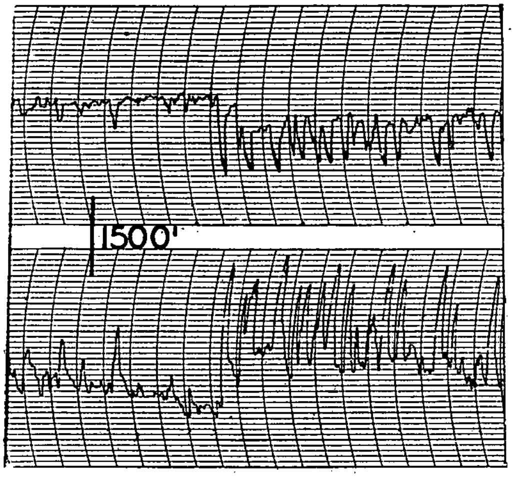

Fig. 13—Part of chart of Grootvlei rope, tested 26th February 1953

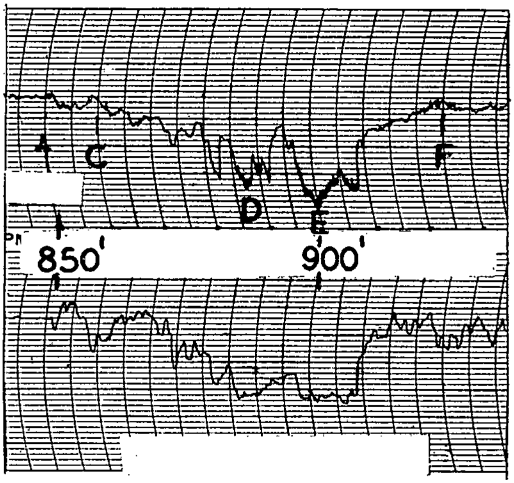

Fig. 15—Detail of chart shown in Fig. 14A

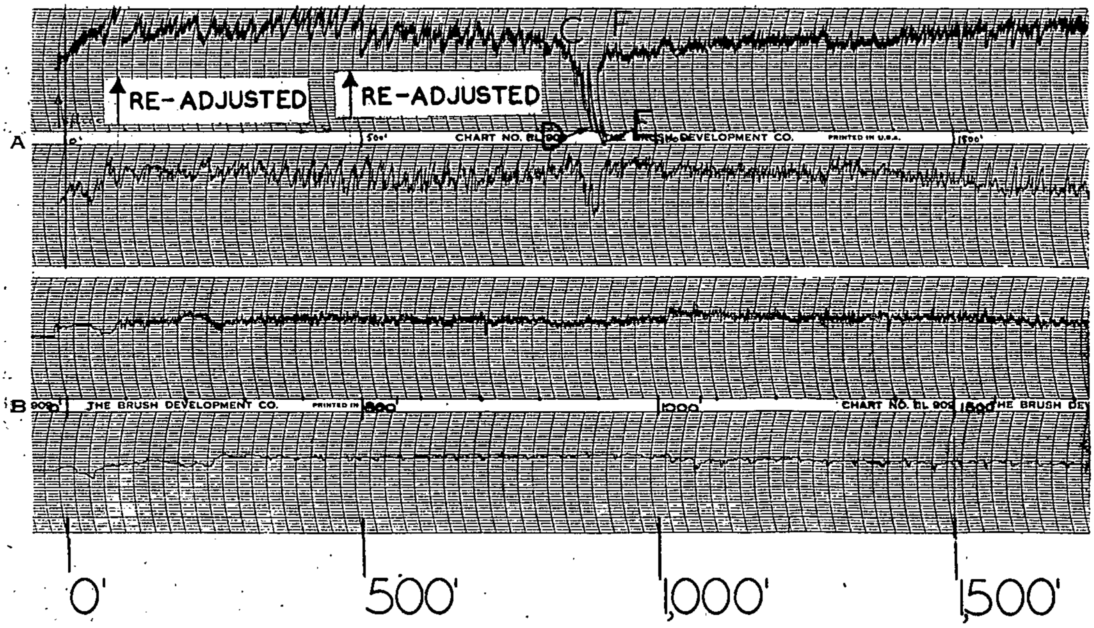

Fig. 14—Charts of East Geduld No 1 shaft, No 4 compartment

A—Old rope tested 3rd October 1952

B—New rope tested 27th October 1952

of eddy current. The increase of eddy current may be explained by the improved contact between wires at points of plastic wear, while the decrease of flux may be caused either by the increase in eddy current or by a decrease of steel area or permeability. As the rope has been pulled in at the drum end a number of times, the peaks are evenly distributed. Tests for breaking load on rope specimens having this type of plastic wear show little difference from initial breaking load.

5·3 *East Geduld No 1 shaft, No 4 compartment rope*

The old rope traces show considerable decrease of amplitude and also a decrease of eddy-current loss at a point about 900 feet from the splice. Visual examination of the rope did not, however, show any defect. As the rope was discarded shortly afterwards, samples were taken at points marked *C, D, E* and *F* on the chart, as shown in the detailed chart Fig. 15.

D and *E* showed 3 per cent and 4 per cent decrease, while *C* and *F* were normal samples taken for comparison purposes. On testing the breaking loads were found to be:—$C=157\cdot0$ tons, $D=137\cdot7$ tons, $E=130\cdot0$ tons and $F=154\cdot5$ tons. A load-elongation diagram for these specimens is given in Fig. 16.

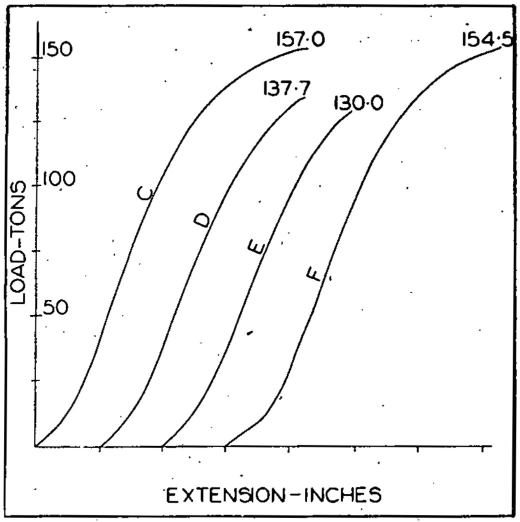

Fig. 16—Load-elongation diagrams of samples

The original breaking load of this rope was 159·3 tons. Examination of *D* and *E* after the test showed excessive corrosion inside the strand, some inner wires were entirely corroded through. Fig. 17 shows the inside and outside of a corroded strand.

It will be noted that the charts show a decrease of both amplitude and phase angle. This combination is considered to be indicative of internal corrosion. Subsequent tests seem to confirm this.

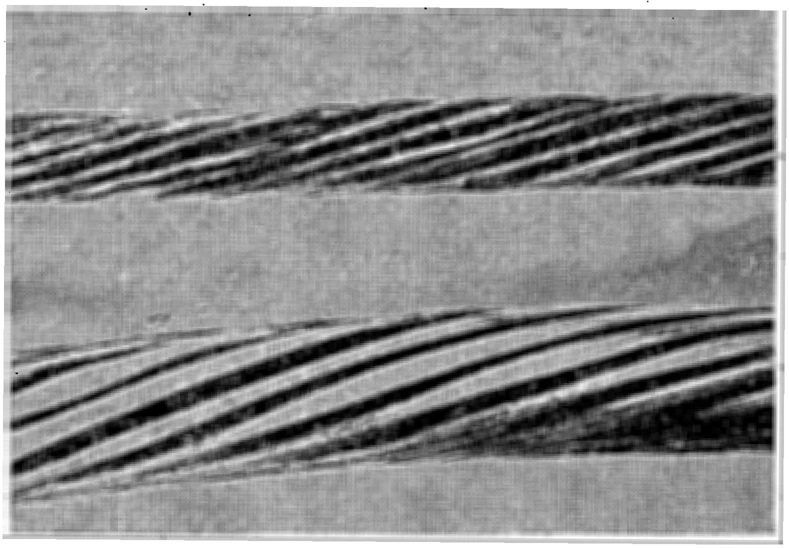

Fig. 17—Inside and outside views of strands

5·4 *Marievale No 1 shaft, No 2 compartment rope*

The regular peaks on this chart, showing points of plastic wear as discussed in Section 5·2, are typical of crossover points with a cylindrically grooved drum. This rope has been taken out of commission and samples have been tested at points *A—F*, with the object of finding the reason for the variations near the splice. The results are given in Table II.

The rope of $1\frac{3}{4}$ inches diameter has an original breaking load of 150·7 tons. The

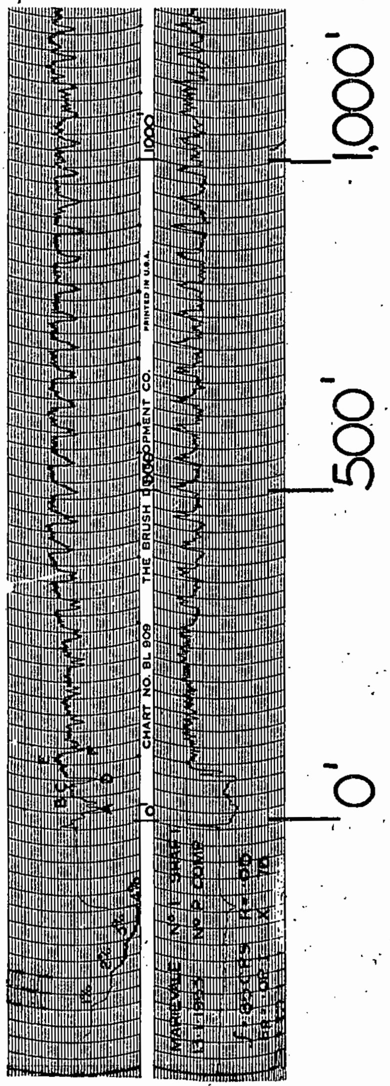

Fig. 18—Chart of Marievale No 1 shaft, No 2 compartment rope, tested 13th January, 1953

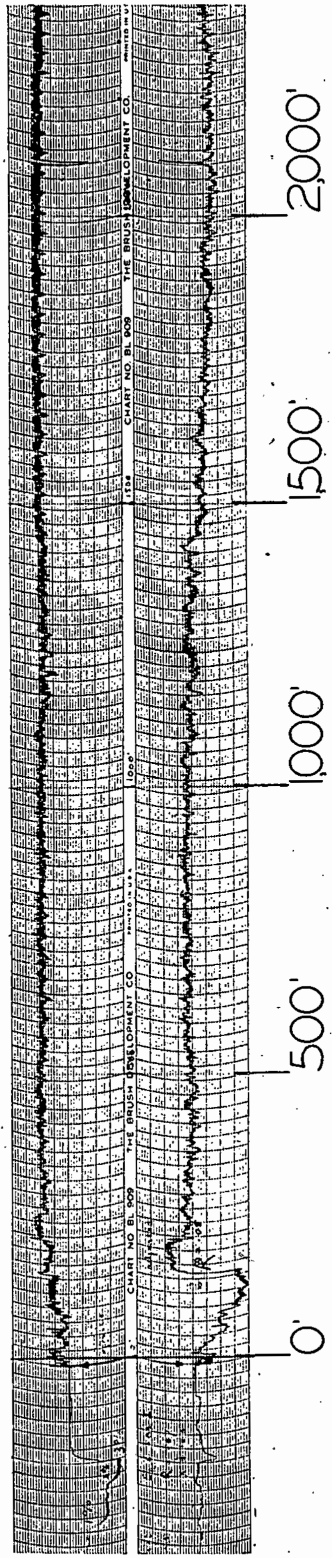

Fig. 19—Chart of Marievale No 5 shaft, No 1 compartment rope, tested 23rd September, 1952

TABLE II

Specimen	Breaking strength tons
A	143·8
B	145·0
C	145·0
D	139·0
E	150·5
F	148·8

reduction in breaking load of these specimens may be due partly to corrosion and partly to corrosion fatigue. The weakest section—Specimen *D*—corresponds to a sharp decrease on each trace.

5·5 *Marievale No 5 shaft, No 1 compartment rope*

This rope was first tested with Model I ten days after it was put on. Since then several tests have been made with both Model II and Model III. At a point some 2 000 feet from the splice a decrease in amplitude of approximately 10 per cent was found with the first two models. The chart, shown in Fig. 13, taken during the last survey with Model III shows a reduction of 3 per cent in amplitude; the increase on the lower trace is a transient originating in the equipment, which disappears if the rope moves slowly.

CONCLUSION

The charts are a useful history of a rope, especially when they can be taken at regular intervals of time. They are a valuable indication to the engineer responsible as to where to examine the rope. It is considered that experience will prove that electro-magnetic inspection will be a valuable addition to the existing methods of rope examination.

ACKNOWLEDGMENTS

The author wishes to express his thanks to the Union Corporation Group of Mines for permission to publish this paper; to the Consulting Mechanical Engineer and his staff for their assistance in carrying out the research work and in the preparation of this paper; to the mines' staffs for assistance in carrying out tests and for making parts of the equipment; to the Government Inspector of Machinery and the Director of the Government Mechanical Laboratory for carrying out numerous tests without which this work could not have been attempted; to Prof R. Guelke for his advice and permission to use the Electrical Engineering Laboratories of the University of Cape Town to do the measurements described in Section 3·2·3; to Mr I. Haggie, of Messrs Haggie, Son and Love for samples made in their factory and tests on rope samples in their works laboratory; to the Director of the National Physical Laboratory, Pretoria, for permission to borrow apparatus.

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DISCUSSION

THE PRESIDENT: Before calling upon our contributors, I would like to make one or two remarks regarding the Union Corporation Group's policy in regard to the development of this equipment.

Firstly, it is not intended to take away from the Resident Engineer any of his responsibility. The development of this equipment is purely an aid to him in his responsibility for his ropes.

The first tests carried out showed immediately that the traces obtained did show to the Resident Engineer the points on the rope where it should be examined; in fact, it was remarkable how close those points were. They did not stretch over long lengths of rope. In one particular test at Van Dyk a peak occurred. At the start of the peak a bit of string was tied round the rope and, at the end of the peak, another bit was tied on, about 18 inches from the first piece. The rope was then run in onto the drum and as the pieces of string came in onto the drum they exactly hit the kick-over plate on the drum cheek used to throw it onto the next layer. Thus the peaks on the trace of the earliest instrument showed plastic wear on a length of something less than 18 inches.

The proof of the assistance that the equipment is giving to Resident Engineers is shown in the fact that they have many times been known to ring up Mr Semmelink and say, 'Please come and examine my rope.' I do not think they would do that unless they were interested in the traces shown by the instrument.

This experimental work is only now beginning to show its value. Although we have felt, from the start, that there was sufficient encouragement to proceed with this work, far more work has to be done, and the equipment has to be tried on many more ropes than we have got. We would welcome the co-operation of other groups in allowing us to investigate ropes which they may consider will show up interesting points, especially, if there is any suspicion of internal corrosion.

The existing methods of external examination will show up defects due to plastic wear, etc. but nothing, to date, has definitely been able to indicate internal corrosion. The evidence in the last few figures in the paper is the first indication that we have had that this is a possibility. We would welcome the co-operation of other groups where they have got ropes of interest, because the more we know about the subject the greater safety there will be in the future use of ropes.

B. L. METCALF (*contributed*): Mr Semmelink's paper forms an interesting addition to the work published on this important subject. The number of papers already published is reflected in the surprising length of the bibliography; while the diversity of the methods described and outlined in the early part of the present paper is a reflection on the complexity of the problem.

During my recent visit to South Africa, I was very interested to examine the service equipment which has already been put into action as described in Section 4·4. The first engineer to produce equipment which can depict with regularity, reliability and accuracy what deterioration is taking place inside a stranded rope will have made a great contribution towards rope inspection and safety. The equipment must also be such that it can be used by the engineering staff at the mine.

The author of this paper has clearly carried this research a step forward and is modest enough not to make any extravagant claims. There are still many difficulties to overcome and from the author's conclusions it is evident that the development of a fool-proof instrument is by no means a certainty. Nevertheless we must look upon this paper as an interim report and express the hope that the author will succeed where others have so far failed. The problems of detection and analysis of the conditions affecting the rope should be capable of solution and the author is well equipped and has at his disposal the most modern methods of electronic analysis.

There are obvious difficulties in both the detection and the analysis and it would be of considerable interest if some further information or opinions could be given on certain points, particularly when considering the application of this technique to the types of rope in use in Great Britain.

(*a*) The accuracy of the charts reproduced in the paper indicate a minimum length over which a change is detected which seems to be of the order of a few feet. Does the author consider it practicable without greatly slowing down the rope speed and hence extending the inspection time, to detect faults over shorter distances arising from the action of corrosion fatigue which can start over very short distances and build-up rapidly with disastrous results.

(*b*) What is the author's opinion as to the possible application of the technique to the locked-coil construction of rope, largely used in Great Britain, which contains a much higher proportion of steel for a given diameter, and may have two, three or four sheaths, which are virtually completely circular in the electrical or magnetic sense. Would the effect of corrosion or loss of lubricant in the inner core be detected under these conditions ?

(*c*) From the point of view of analysis the author mentions in his footnote to paragraph 11 in Section 5·1 that a complete separation of the in-phase and out-of-phase effects has not been achieved as had been hoped. Such a secondary interaction between the two recorded components might well mask any defect which would be recorded in one of them. Does the author consider that this defect is merely due to limitations of the earlier types of analytical equipment which can be eliminated with some advanced designs ?

These comments are an attempt to put the point of view of the practical engineer rather than the research worker. The Scientific Department of the National Coal Board are carrying out similar investigations on the electro-magnetic testing of ropes. Unfortunately the time available was insufficient for the report to be adequately studied by them in time to submit a contribution to the discussion.

A. SEMMELINK (*in reply*) : I thank Mr Metcalf for his contribution. The equipment shown to Mr Metcalf was the experimental apparatus described as Model III in the paper and not the service equipment. I do not agree with Mr Metcalf's requirement that rope-testing equipment must be such that it can be operated by the engineering staff of a mine. In common with several other non-destructive testing methods the interpretation of results should be done by a trained operator.

In reply to point (*a*), the length over which a change can be detected is of the order of six inches for a change corresponding to a single broken wire and shorter distances for larger changes. As locked-coil ropes are not used in our Group or anywhere else on the Rand, I cannot give a definite answer to point (*b*). On theoretical grounds I would say that eddy currents will be considerably larger but changes of eddy currents much smaller, therefore, penetration of the magnetic field will be somewhat smaller, but smaller changes of amplitude can be detected. However, the only way to prove this is to use the equipment on a locked-coil rope. With regard to point (*c*), the separation of in- and out-of-phase components, tests in the laboratory have shown that this can be done. The service equipment now being designed will be based on this requirement.

PROFESSOR R. GUELKE (*contributed*) : Mr Semmelink is to be congratulated on a most interesting paper which describes test procedures that are likely to be of great practical importance. He has definitely established the possibility of assessing weak points in a rope by electro-magnetic measurements. Of particular significance is the test reported in Section 5·3 where an indication on the instrument is definitely associated with a decreased breaking load.

At this stage it appears that electro-magnetic testing is very much simpler in practice than the usual visual inspection and probably gives more useful information. It can probably be used to replace certain of the ordinary visual tests and because it requires much less time this will already represent a financial gain.

The further development of this method, however, shows great possibilities. If it can be shown that a weakness in a rope can always be detected by electro-magnetic means, then the useful life of many ropes can be prolonged considerably. The only practical way in which this can be done is to undertake a thorough theoretical investigation into the variation of the electro-magnetic properties of the steel with fatigue, strain, etc. Of course, if the failure of haulage ropes could be contemplated with equanimity it would be possible to carry on with an empirical method and investigate on a purely statistical basis the frequency of breakage in relation to the indications of the instrument. Such a method is impractical for obvious reasons. A thorough theoretical investigation has the further advantage that it will also indicate the best method to use—information which it is very difficult and time-consuming to obtain empirically.

If the responsible engineer is to allow a rope to continue in service after testing, it is not only necessary to show that the electro-magnetic instrument will show a weak spot in the rope, it is necessary to show that the instrument will discover *every* weak spot that can possibly occur in the rope. Such a correlation can be established only by a thorough theoretical investigation. I have no doubt that such an investigation will now be prosecuted with all resources. It will be assisted to a very great extent by the investigation reported here which is mainly empirical but the value of which, as a preliminary indication, is beyond question.

The final result will no doubt be of considerable practical and financial value to the company concerned.

H. C. W. SCHMUHL (Associate Member) (*contributed*) : The title of the paper states specifically the ' testing ' of winding ropes by the electro-magnetic method. It suggests that the author had in mind to ascertain and prove the ills of a winding rope much in the same manner as the doctor employs his cardiograph. It is also noted that other authors dealing with the same subject likewise use the word ' testing,' but, if one considers that the word ' to test ' means to prove the genuineness of anything by experiment, one wonders whether the author together with his confreres has not set himself too high an ideal. I would suggest that the words ' analysis or detecting the defects ' instead of ' testing ' would be more appropriate. I suggest this, because the author does not mention embrittlement of the wires anywhere in his paper. If one bears in mind that any alteration in the mechanical properties results in an alteration in the magnetic properties of the material, embrittlement must be considered a defect in a winding rope detectable by the method employed by the author. It would be interesting to learn from the author his views on this aspect and whether he intends extending his experiments to detect this important defect in winding ropes, as well as broken and damaged wires.

It is not the intention in this discussion to say much on the technical aspect or the method employed to detect the ills of winding ropes. This has not proved possible in the time available, but, if it is noted that the d.c. electro-magnetic method will detect a single broken wire in a rope containing 200 wires, the author must have had more weighty reasons than those mentioned in the paper for departing from a method capable of the degree of sensitivity mentioned. Indeed, one would have thought this to be the ideal method to build on and it would be interesting to learn from the author his reasons in greater detail for selecting the a.c. method rather than the apparently more promising d.c. method. The much more difficult a.c. method with the introduction of eddy currents and phase relationship was adopted and the author is to be congratulated on the manner in which he solved the various difficulties met with. His method of constructing the magnetising and search coils and of recording the results obtained especially deserve mention and have very greatly added to the practical use of the apparatus.

The apparatus developed by the author seems to be very effective in detecting corrosion in ropes. Selected specimens which were corrosion suspect, submitted for test at the Government Mechanical Laboratory, had shown losses in breaking strength varying from 8 per cent to 20 per cent. Examination of the specimens after test revealed that such corrosion had taken place inside the rope and that it could not have been detected from a mere external examination. The loss in breaking strength can, consequently, only be ascribed to the internal corrosion.

Apparently, however, the apparatus is able to detect such defects only where portions of the rope deviate from the average condition and it would appear that no defect due to corrosion would be revealed were the rope uniformly corroded throughout its length.

With the introduction of the Koepe winder on the goldfields the electro-magnetic detection of defects in winding ropes assumes special importance as with that system of winding drawing in or cutting of the rope for test purposes is not practicable. To those engineers responsible for Koepe winders it will be a most invaluable aid even in its present form of development. The author is well on his way to giving the industry an apparatus which will enable the engineer to ascertain the condition of every foot length of his winding rope irrespective of the type of winder in use and every encouragement should be given him in continuing his researches. In so doing he will have contributed much to the elimination of that doubt which still remains even after a careful examination of a winding rope.

A. SEMMELINK (*in reply*) : I have used the word 'testing' intentionally, as I believe that, as Mr Schmuhl suggests, the magnetic properties alter whenever the mechanical properties change. Whether this change can be recognized on our charts remains to be proved and will be the subject of further work.

The d.c. method is essentially a broken-wire detector and will not produce other information about the condition of the rope.

When charts are made of a rope at regular intervals, changes which affect the rope uniformly can be detected. However, I believe that the chances of a rope being uniformly corroded are remote.

O. RAU : I would like to add a few words to the contribution of Mr Schmuhl to the discussion on this paper.

I feel that the author deserves every encouragement in his endeavour to develop a reliable method of testing ropes non-destructively. My department is very interested, and will continue to assist by carrying out any destructive tests to confirm or otherwise the results obtained by the electro-magnetic method. I only hope that other groups will, as you suggested Mr President, come to your assistance by making ropes available which are suitable for these tests and by supplying information which will help you in your investigations. As I have already said, the Mines Department is extremely interested in this development and I must thank the author for his very interesting and valuable paper. I wish him and his sponsors every success with their testing apparatus to the further development of which we are all looking forward.

L. T. CAMPBELL PITT : In the introduction to his paper, Mr Semmelink draws attention to the successful development of non-destructive testing of material and particularly electro-magnetic methods. The task he undertakes in applying these methods to steel wire ropes is a very much more difficult one than material testing because a rope is a complex structure consisting of up to some 200 members each sharing some but not an exactly equal portion of the whole structure's duty. Unlike other structures, the members are not fastened together, in fact, they are lubricated so that they will not hold together. In some respects the rope structure is more like a machine whose components work in unison. Each component is a helix subject to changes in relative position and pitch as load is varied and the rope is flexed.

The need for a reliable and readily applied means of non-destructive testing is both necessary and urgent. The inspecting engineer of a steel wire rope has to assist him in his decision a periodic destructive test and subsequent examination of a few feet of rope at the conveyance end. It has been stated that that portion is the weakest —a comforting thought if it were true, but it is not. I do not wish to discuss this controversial subject here, but would say that the weakest portion is usually at the lower end of the rope. This very meagre positive test—denied him in some winding systems—is augmented by physical measurement for wear which is a most inexact operation since diameter is affected by rope elongation, compression of core, cold plastic flow in the outer wires and other factors. He has other indications such as broken and loose wires, and visible pitting. He cannot see the inside of the rope unless he opens it which is an operation requiring great care and one that should seldom be resorted to and, in any case, is impossible in a lock-coil rope.

These are the factors upon which an engineer inspects one of the most vital portions of the plant under his charge. A portion upon which the lives of thousands depend daily. It says a great deal for his skill or intuition that the rope safety record is so good. In the absence of a more scientific means no one would blame the responsible engineer if he discarded a rope on suspicion which would remain in service if the suspected deterioration was not confirmed. There is, in addition to safety and, of course, secondary to it, an economic aspect to better testing.

Whilst measurement of condition by a simply understood and reliable field instrument should be the ultimate aim, there are many benefits that could be derived from the intermediate steps. Indication of an unusual condition which attracts more detailed visual inspection alone is of great value. I do not mean to infer that Mr Semmelink has not progressed further than that. He has given evidence that a great deal has been done. The tests at East Geduld No 1 Shaft, for example, showed the value of electro-magnetic testing.

When Mr Semmelink says that visual examination did not show defects does he mean the routine visual examination whereby only small portions of the rope at intervals of, say, 200 ft are cleaned and closely inspected, or does he mean that when attention had been drawn by electro-magnetic means to an abnormal condition, a visual inspection of those points was made ?

In the conclusion of his paper I think Mr Semmelink has all too briefly summarized the very considerable progress he has made. May I ask if the stage has now been reached when a field instrument can be produced such that in the hands of the responsible engineer he has his attention drawn to portions of the rope which call for special attention ? Could such an instrument be used by the engineer to obtain comparative records at intervals throughout the life of the rope without specialist assistance ? My impression is that work has still to be done before electro-magnetic testing gives exact measurement of condition even in a specialist's hands. Rope deterioration is by wear, corrosion, fatigue, corrosion fatigue, work hardening, broken and loose wires, and core failure. Since each of these defects has a different degree of effect on rope life and a different rate of rope deterioration it is important that each be identified and then its degree assessed. There is, however, so much value in the stages reached at present that use should be made of it.

All this is a very considerable achievement. The Union Corporation has rendered a great service to Mining. Mr Semmelink has very competently carried out the task entrusted to him and will, I hope, continue to do so. May I hope that this paper is an ' interim report.' Finally, we should not forget to recognize the leadership in this important achievement by yourself, Mr President.

A. Semmelink (*in reply*) : The visual inspection of the rope referred to in Section 5.3 was made at point *E* in the charts in Figs. 14 and 15 over a length of about six feet. In addition, the samples *C*, *D*, *E* and *F* were inspected before the breaking-load tests without showing external evidence of their internal condition.

Though the service equipment will be very much simpler than the experimental Model III, I do not believe that the responsible engineer should operate it. With the group system it should be a simple matter to train one engineer in each Group to carry out regular rope tests.

I. S. Haggie : This is a paper on a subject that has been given considerable attention not only in this country but also in Canada and on the Continent, and I understand that the work done by Mr Semmelink and his group is, if anything, in advance of that done overseas.

I would like to take this opportunity of congratulating him on his very excellent paper and his contribution towards further safety in mines. I think he will be the first to admit that the use of electro-magnetic testing equipment would be an additional tool for the engineer in his rope inspections rather than to supersede present methods. The well known engineer's saying of ' When a rope makes me loose sleep, it's time for it to come off ' is very true. This advice will in time, we hope, lessen those sleepless hours.

One is at first apt to be sceptical of this method of testing ropes as there appears to be so many variables which can affect the instrument. It might also appear that such an instrument would be too sensitive for practical purposes. It is apparent, however, that the meticulous work that has so far been done has shown the value and practicability of such a test method. The experiments to date have undoubtedly shown the way for corrosion detection and have shown that it may be possible to develop means of estimating the amount of work hardening and possibly fatigue which is taking place in a rope during service.

I speak as an observer of the work that has been going on and I hope the conclusions are in fact an accurate summary of the situation. It is now evident that this particular instrument is not designed as a broken-wire detector, and major modifications are required to make it so, but as we already have a most complicated device for that purpose, to wit, the resident engineer, there would seem little reason to perfect another.

It does, however, appear that the device has gone a long way towards being able to detect the position and degree of internal corrosion.

The two possible future developments of the equipment would appear to be in investigating the amount of work hardening and fatigue which take place at crossover and in the region of the cappel and deceleration points. I understand that such work calls for considerably more experiments, and we will watch with interest how they develop. Fortunately the effects of fatigue and cold work are in the main visible in the form of broken wires and plastic wear so an engineer can to a certain extent anticipate the trouble, but it would be of advantage to know in advance if such a condition is developing in a rope.

To return to corrosion, I feel that the instrument has already proved its worth in being able to detect deterioration which is not visible in routine inspections. Fortunately on the Witwatersrand we are relatively free of serious internal corrosion and few ropes suffer from corrosion which is sufficiently serious to call for anything but the normal attention. In the Orange Free State, however, the saline nature of the water, of which there appears to be more than enough underground, is a source of worry and it is a serious menace to winding ropes. It is to be hoped that when shaft sinking is complete and the shafts are relatively dry, this trouble will be minimized, but we do know that should this water be allowed to percolate into ropes, even over a short period, serious damage is done. To have an instrument to detect cases of such deterioration would certainly make me a happier man if I was responsible for the condition of the ropes.

From the test results shown us to-night and the other tests I have seen, the effectiveness of Mr Semmelink's equipment seems to be quite proven in so far as corrosion detection is concerned. It would seem necessary to confirm over a period of months or years that the results obtained are consistent and be able if possible to correlate the deflections of the instrument with the degree of corrosion. The magnetic oxide which forms during corrosion may have an effect on such calibrations, but it would seem that already there is a relationship between the instrument's deflections and the extent of the corrosion.

It is interesting to note that the loss in weight of wires over a typical corroded area bears a very close relationship to the loss in breaking strain as will be seen from samples of wire examined. I would like to mention that these samples have been collected from ropes over a number of years and so represent quite a large proportion of the actual cases of serious corrosion. I would be committing a serious crime against the engineering fraternity if you were lead to believe that wires in this condition were a frequent occurrence.

It would be interesting to hear from the author how long it takes to carry out an inspection on the average winding rope and whether different constructions have any material influence on the readings. Would he be confident at this stage, for instance, to say that corrosion will always cause a decrease in both amplitude and phase angle, whilst any other factors will have a different effect on the traces.

A. Semmelink (*in reply*) : The time taken for the inspection of one rope is approximately thirty minutes ; this will be considerably increased if visual inspection is made of particular points after the magnetic test is completed.

Different constructions of rope will affect the readings in so far as the eddy-current path in the rope differs. With the exception of the locked-coil construction, I believe that the charts will be similar. For the locked-coil construction experiments will have to be carried out before it is possible to estimate the effect of the magnetic screening of the outer layers.

I should prefer to say that corrosion will usually, rather than always, show a decrease in amplitude and phase-angle. It is possible to imagine a combination of faults giving different results.

C. W. H. du Toit (Associate): This paper is a valuable contribution to the literature on non-destructive testing.

It was of interest to note that the testing of winding ropes by magnetic methods has been used elsewhere for many years. Why these tests were discontinued in England is not quite clear. It seems, however, that the results obtained were either of doubtful value or difficult to interpret.

The main requirements of electromagnetic rope testing equipment seem to be that

(*a*) broken strands should be detected without fail, since this will indicate the end of the useful life of a rope; and
(*b*) periodic testing of a rope should warn of impending failure by indicating gradual weakening of the rope if it occurs at all.

The equipment described does not yet seem fully capable of meeting the first of these requirements, and its usefulness for the second probably still remains to be established by sufficient tests to provide data for statistical analysis. The author is still engaged on these further tests.

Referring to the first criterion, the method used in Germany for rope testing definitely claims the ability to detect broken wires. This method is, however, dismissed by the author as unsuitable for various reasons, the main ones of which seem to be problems of technique.

Surely these could be solved by the use of automatic coil-winding equipment and the development of a suitable amplifier-recorder for use in place of a galvanometer and photographic paper?

The equipment described seems to be designed principally to fulfill the second requirement. The importance of this function should not be overlooked because results indicating the changes occurring in the physical state of a rope, if correlated with its service history, may have important effects on operating and maintenance schedules. These alone may economically justify the routine testing of ropes.

Early in the paper mention is made of the automatic comparison of physical properties of two pieces of the same material as a method of non-destructive testing. This method can be realized in this instance by using a differential pick-up consisting of two narrow coils spaced a short distance apart and connected in opposition. This may have certain advantages over the pick-up method used by the author. Such a system may produce recorded traces which show fewer apparent deviations of the rope from the normal, by balancing out spurious effects; the interpretation of results may thereby also be easier.

It would be interesting to know if the author tried this method of detection, using his present methods of magnetization, and with what results.

It would be of interest also to know if the author obtained different results when the same rope was

(*a*) going down with a load
(*b*) coming up with a load,

or whether when coming up with a load the recorded traces show deflections corresponding to the points of the step-up of the hoist controller or if the change in rope loading due to its own weight caused sufficient change of magnetic properties to show a difference between drum and cage ends of the rope.

I fully realize that the author's work is not completed, and that it may be impossible at this stage to estimate the impact of these tests on current ideas on economic rope life, but it would be of interest to hear the final outcome of this investigation in perhaps a further paper.

The principle described by the author has been used in other fields. Equipment is for instance available for testing bright bar, welded piping and single wires by electromagnetic means, for flaws. The magnaflux apparatus can also now frequently be replaced by a permanent magnet as exciter, and a search coil as pick-up. By this means large items like boilers can be magnetically examined on site. Such tests are more economical also than magnaflux tests.

Some of these equipments are in use in our laboratory.

I hope this paper will stimulate interest in magnetic testing, also in other fields, as there is wide scope for the application of non-destructive testing in South Africa.

A. Semmelink (*in reply*) : Mr du Toit states that a main requirement seems to be that broken wires should be detected without fail. It may be of advantage to give the results of an experiment carried out in collaboration with rope makers and the Government Mechanical Laboratory, which was designed to study the effect of broken wires on the breaking load of ropes. The following table gives the result of this test :—

Specimen	*Number of broken wires*	*Breaking load in tons*	*Percentage reduction*
A	None	117·5 (at collar)	0
B	None	115·5 (at collar)	1·7
C	Two in one strand	114·5	2·6
D	Four in one strand	100·0	14·9
E	Six in one strand	91·5	22·2
F	Six (two in three strands)	109·0	7·2

The samples were all cut from the same unused rope. The tests indicate that the breaking load of a rope having two broken wires, each 3 000 lb or 1·3-per cent breaking load, is diminished by just the breaking load of these wires. For four or six wires broken in one strand the difference in breaking load is very much higher, while if the broken wires are evenly distributed the difference is again equal to the breaking strength of the broken wires. From this it is clear that it is not important to detect occasional broken wires, especially if widely spaced, but it is essential that the charts should show when several are broken in one strand. Tests in the laboratory show that our equipment will do this and further tests will be carried out. No charts of ropes in the shaft having such broken wires have been taken, as they are inevitably detected in the daily rope examination and the rope is taken out of commission as soon as possible. For these reasons the development of a broken-wire detector was not considered as important as the development of ‘ condition testing ’ equipment. Section 4.5 of the paper indicates that it is possible to modify our coil to detect broken wires.

The use of a differential coil arrangement was considered, but abandoned as we wanted to measure the condition of each section of the rope and not the difference in condition between adjacent sections.

A study of the published charts will show that the records of flux amplitude—i.e. top traces—indicate a gradual increase when the rope goes down, when the tension increases due to the added weight of the rope itself. This corresponds to the increase of permeability with increased tension as shown in Fig. 3. When charts are taken with the rope going down and coming up, the only difference shown is a small shift in level on the top trace. The explanation probably lies in the difference in shaft friction which must be subtracted going down and added coming up.

B. Stain : I am confining my discussion to the mechanical aspect of the electromagnetic inspector when used to assist the engineer in his determination of the condition of the winding ropes for which he is responsible ; at present he has to rely mainly on his practical experience in assessing by external examination the condition of the rope.

The usual procedure is to examine the rope at a creep speed of 200 to 300 ft per minute in order to detect any obvious defects such as broken wires (these being easily detected in the old days by the quick removal of several of the ropeman's fingers whose practice it was to handle the ropes), for kinks, lubrication and the general condition of the ropes.

Stops are made at regular intervals throughout the length of the rope, and at points where heavy wear is expected, i.e. where the rope is in contact with the sheave during acceleration and deceleration, and crossover points on drum where plastic wear occurs, the rope is cleaned and measured and the results logged.

A close watch is maintained for external corrosion and any unaccountable reduction of diameter which may be due to either internal corrosion or collapse of core. Where any internal defects are suspected the actual internal condition can be ascertained only by opening up the strands. This disturbance of the rope would thereafter provide easy ingress for moisture and thus promote internal corrosion as the strands could not be replaced in their original position.

In addition to the monthly visual examination conducted by the engineer a complete history of all ropes for each hoist is recorded, consideration being given to the particular conditions under which the rope operates, such as single- or dual-purpose hoisting, the amount of work performed in foot-tons, wet or dry, up- or down-cast condition, and load-extension continuation charts of periodical tests in respect of each rope are kept.

The estimated life of each rope is then carried on a chart from which the responsible engineer can immediately see when any rope is nearing the end of its useful life and a more careful scrutiny of the rope is then maintained.

In spite of the fact that with little variation these methods have been in general use for many years throughout the mining industries very few accidents are attributable to rope failures.

In an endeavour to ascertain by actual test whether the bad points detected during a visual examination were being picked up, the following tests were conducted on a discarded rope which was operating at a speed of 1 200 ft per minute on a winding engine in a vertical upcast shaft and developed very active external corrosion over at least half its length. This corrosion had increased over the external crown wires despite all effort to arrest it.

Six specimens were cut from the rope and the following data obtained :—

New rope, 13(7/6△) construction, 0·124-inch outer wires. Breaking load 67·2 tons.

Corrosion varied from 'very slightly pitted and corroded outside' on No 2 specimen to 'more than slight to considerably pitted and corroded outside' on No 4 specimen.

Due to the varying conditions of the above specimen it was anticipated that a large variation in the breaking loads would be obtained, especially at the points of crossover where plastic wear would occur and at the most heavily externally corroded section (No 4), but this was not borne out in practice as indicated by the tests, as only little variation in the breaking loads were obtained.

The author mentioned in his paper that various points on the ropes undergoing examination were picked up by his electromagnetic inspector and specimens removed for test.

The breaking loads of these specimens were *C* — 157 tons, *D* — 137·7 tons, *E* — 130 tons and *F* — 154 tons as compared with the new rope breaking load of 159·3 tons. Examination of these specimens revealed excessive internal corrosion at points *D* and *E* with a reduction in breaking loads of 21·6 and 29·3 tons respectively.

It would be interesting to know if the break in the test specimens occurred at the actual point detected, or at the metal collar, as our experience has shown that considerable differences in the breaking loads have been obtained in tests conducted by the government laboratory, especially on larger-diameter ropes.

The load-extension continuation chart shown in Fig. A represents the original and periodical tests on a 1·736-inch diameter rope of 30(12/12/6△) construction operating

No.	Position	Results
1.	Splice end	Most worn wire 0·122 inch, broke at 68·8 tons
2.	270 ft from splice, on bottom of drum when cage at bank (internal corrosion suspected)	,, ,, ,, 0·117 inch ,, ,, 68·4 ,,
3.	1 130 ft from splice, top layer crossover point (plastic wear)	,, ,, ,, 0·117 inch ,, ,, 68·6 ,,
4.	2 016 ft from splice, excessive external corrosion ...	,, ,, ,, 0·118 inch ,, ,, 67·9 ,,
5.	2 614 ft from splice, bottom layer crossover (plastic wear)	,, ,, ,, 0·117 inch ,, ,, 68·5 ,,
6.	2 770 ft from splice, cage at lowest loading point and rope in contact with sheave during acceleration ...	,, ,, ,, 0·118 inch ,, ,, 68·0 ,,

on a 6 600-ft vertical wind with an original breaking load of 154 tons when the test piece failed at 18 inches from the metal collar, Curve A on diagram.

In order to comply with the conditions imposed by the Mines Department it was necessary for this rope to be tested after having been in service for one month ; a test specimen, together with an additional 40 ft was removed to equalize the rope lengths.

The result of this test revealed that the specimen had broken at the metal collar (shown by *B* in Fig. A) with a breaking load of 142·5 tons ; this was 11·5 tons below the original breaking load. In no case was corrosion or any defects apparent, yet the curve shows comparatively little elongation indicating brittleness of the wires, due either to fatigue, which is generally accepted as being concentrated at the splice end of the rope, or corrosion, which was incorrect insofar as the rope was new and had done insufficient service to produce these conditions.

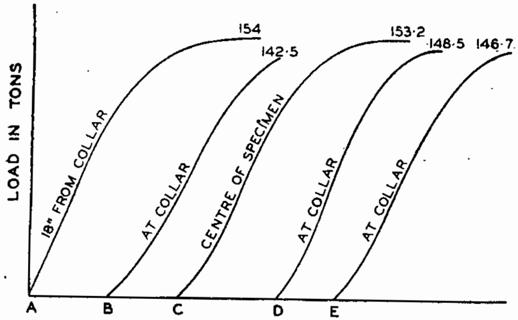

Fig. A

This large decrease in the breaking load was most alarming as little latitude now remained as the breaking load called for at discard is not to be lower than 139·6 tons i.e. a difference of only 2·9 tons, and in order to remove any doubt about the condition of this rope a test length cut from the 40 ft equalizing portion was sent to the laboratory for a special test. This specimen fractured in the centre and a breaking load of 153·2 tons was obtained, shown by Curve *C*, being a difference of only 1·8 tons on the original breaking load.

The results of the investigations conducted on these two ropes show that visual inspection leaves much to be desired, as where a low breaking load was to be expected the opposite was the case and vice versa. If the electromagnetic inspector could be relied on implicitly to detect any change of tensile stress caused by fatigue, corrosion, plastic wear, broken wires etc., then the doubt which presently exists would be eliminated and unless this is so, ropes will be discarded prematurely and thus reduce the useful life unnecessarily.

I would emphasize that the apparatus be light, quickly positioned and easily handled to facilitate transport from rope to rope and shaft to shaft.

In conclusion I should like to congratulate the author on his very fine paper and if his electromagnetic inspector be perfected to pick up every defect with absolute certainty it will become of the greatest assistance as an aid to rope examinations and will obviate all uncertainty existing at the moment particularly insofar as the internal condition of the rope is concerned.

A. Semmelink (*in reply*) *:* With reference to the test described in Section 5.3, the specimens broke as follows :—

Specimen *C* 10 inch from collar
D at collar
E centre of specimen
F at collar

Specimen *E* broke at a point corresponding to the peak on the record, while specimen *D* broke at the collar. A study of Fig. 15 reveals that at points approximately five feet from the peak labelled *D* there are other peaks of the same amplitude. Examination of the specimen after the test showed excessive corrosion both at the point of breaking and at the centre.

D. J. Stern : The most interesting and extremely well prepared paper of Mr Semmelink is a valuable contribution to the literature on mine rope testing, and is particularly valuable because it is the first evidence of practical non-destructive tests on mine ropes done in South Africa.

It is, in fact, amazing that one of the largest mining communities in the world has entirely neglected non-destructive test methods on steel wire ropes, although these methods were already for 25 years success-fully applied in Germany and have been officially applied with success for the last seven years by the Department of Mines of the Province of Nova Scotia in Canada.

A few months ago, I met Mr Semmelink, and it was a surprise when we realized that without knowing each others' work, we have been doing parallel development of non-destructive methods for testing of steel wire ropes.

The laboratory with which I am associated is developing a wire rope-testing method which will be particularly suitable for South African mining conditions and it is hoped that the preparatory work based on both German and Canadian experiences and instrumentation and forming a compromised solution of the problem, will be completed shortly so that the results can be published.

At present I am not in the position to reveal particulars of the method under development; it might be, however, of interest to describe the theory of the Canadian method, which forms in part the base of our development work.

The testing method is an a.c. method in which ferro-magnetic material is magnetized by a low-frequency current to a low field strength. The low frequency is required to enable examination of large-diameter ropes, namely to increase the flux penetration in the ferromagnetic material which follows the formulae for skin depth.

$$P = 3\,560\,\frac{R}{\mu . f}$$

where P = current penetration in cm
R = resistance in ohms
f = frequency in cycles per second
μ = magnetic permeability.

This formula, although basically sound, needs however, certain correction as the magnetic permeability is not a constant but a function of temperature, and at the Curie point or magnetic transformation point, namely 770°C, the material ceases to be ferromagnetic. Fig. B shows the relation between frequency and penetration.

A low-strength field has to be maintained to increase the effective test volume in the test piece. The penetrating volume being

$V = K.P.r$
K = constant depending on instrument sensitivity
P = penetration depth
r = radius of sample.

One sees from the above that penetration is inversely proportional to permeability and frequency, and as permeability at a low-strength field is only between 0·1 to 0·001 of that at a strong field, it is necessary that one works at a low field strength. One should notice that penetration of wire ropes which are actually stranded structures is easier than penetration of solids. It is claimed that by the method used in Canada, full penetration was obtained at rope thicknesses of $1\frac{1}{8}$ inches diameter.

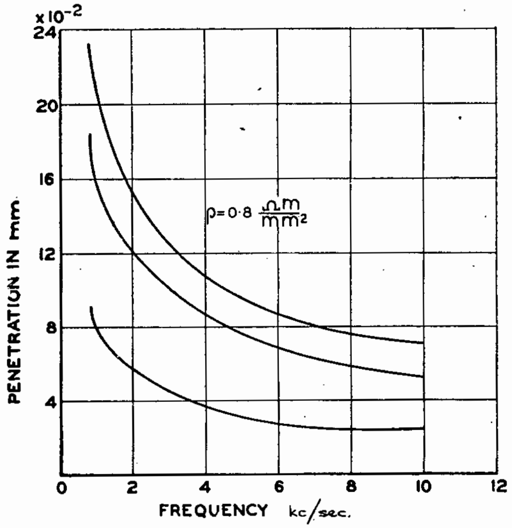

Fig. B

The testing is based on facts that stresses affect magnetic properties and under certain circumstances tensile stress of 5 000 lb/sq.in. can change the flux density B up to 10 000 gauss. The effect of tension on magnetization is characterized by increasing magnetization at small field strengths, and decreasing it at high field strengths. (See Fig. C.) Although one is interested at present only in stress-magnetization relation, in fact it boils down to strain-magnetization relation known often as effect of magnetostriction. This points again to the convenience in keeping the field strength low.

Magnetostriction, namely the slight increase in length in the direction of magnetization and the decrease in direction perpendicular to magnetization, is an effect of the crystallic anatomic structure of iron to maintain an equilibrium between magnetic forces and elastic forces in the crystals where in each crystal the atoms have a definite magnetic moment resulting from the spin and circumferential movement of electrons. The effects of strains on magnetization is the reciprocal property of magnetostriction.

The strain effects on magnetization are complicated phenomena and one of their peculiarities is the fact that with severe hard working the changing of magnetism becomes more difficult, namely, same stresses will not produce identical magnetization changes in materials which were cold worked, plastic deformed or are in an unworked state. From here a certain analogy can be drawn between mechanical and magnetic hardness, and in general by measuring the changes in magnetic properties due to changes in mechanical properties and characterized by magnetic losses in the circuit, one can draw a conclusion to the magnitude and location of mechanical changes in material under examination.

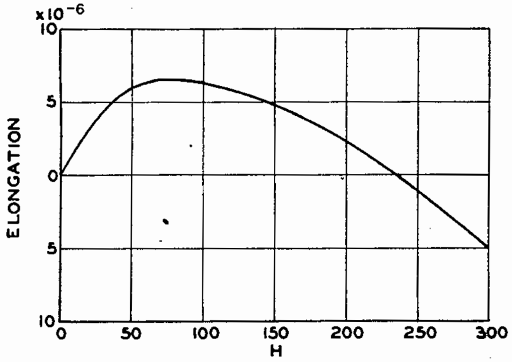

Fig. C

An important point not to be overlooked in examination is the choice of a suitable frequency and to find out at which frequency best discrimination is possible.

In particular cases where a ferromagnetic material is placed within a coil which forms a part of an oscillatory circuit the variation of stresses in the material will cause variation in the energy output of the oscillator and these variations can be detected and recorded by means of a cathode-ray tube screen.

Equipment made on this principle is the cyclograph mentioned in the paper and used with remarkable success on non-destructive testing of steel wire ropes in Canada. The speed of testing is between 15 to 40 ft per second and records are made on charts in the scale 200 ft wire length per 1 inch scale. An interesting addition to the improved cyclograph for testing steel wire ropes is a recording dynamometer which measures and records the actual pull on the wire rope while in motion. Dynamometric charts are examined simultaneously with the cyclograph charts. From tests conducted in laboratories and in the field it is certain that point of failure in a steel wire rope can be predicted.

The cyclograph method is sensitive and reliable in detecting stress changes and structural changes, but it does not respond readily to cracks or other material defects which do not influence the properties detectable by the cyclograph.

Crack detection and detection of other material flow defects are done reliably and with great accuracy by the d.c. magnetizing method developed mainly in Germany and used also by German mine authorities for the testing of steel wire ropes.

The basic requirement for this method is the magnetization of the rope to saturation. This magnetization is achieved by coils wound around the ropes. The coils are wound on split cores with a special winding machine which is capable of winding both coils in half an hour. The inside diameter of the coil is about 10 mm bigger than the rope diameter.

The search coil which lies between the two magnetization coils is also split. Its inside diameter should be not more than 2 mm larger than the diameter of the rope.

The number of turns on the magnetization coils is 1 200, and the number on the search coil is 100 double windings. Winding of the search coil is bifilar. The magnetization current is not more than 5 to 6 amperes.

Recording of the findings is done on a ballistic galvanometer and with an interpolated amplifier can be recorded on a recording chart.

The interpretation is based on long years of experience and on hundreds and hundreds of ropes which have been tested within the last 25 years. The test is not applied regularly on all ropes but only in cases where strand breakages are suspected by the authorities, or when a rope is declared by mining authority as unsuitable before its expected lifetime is finished, and the mine owner calls in the testing authorities for arbitration.

By combining these two principles in one test method one achieves double advantages. Corrosion effects, cold working, abrasion and kinking can be easily detected on charts recorded by examination with the a.c. method and by comparing such charts taken over a time period. Breakages in wire strands can however be detected and recorded by the d.c. method. Such a double checking would not leave any possibility of overlooking a defect which might cause failure of the wire ropes. It gives to mining authorities which look suspiciously on non-destructive testing of ropes a guarantee that results obtained by such methods can be regarded as reliable indication of the condition of steel wire ropes. There is no doubt that a sufficiently accurate method for non-destructive testing of mine wire ropes is possible and I am confident that such a method will very soon replace the visual examination and the post mortem mechanical testing.

A. SEMMELINK (*in reply*): I am very pleased to learn that Mr Stern is developing electronic rope-testing equipment and am looking forward to comparing notes in the future.

Regarding the practicability of using a search coil with a diameter 2 mm larger than the diameter of the rope, our experience was that lumps of rope dressing and broken wires were sufficient to break the coil and it is now at the bottom of the shaft.

W. A. PITTS (Member): The subject of the paper is of very considerable interest and importance to the Mining Industry, not only in South Africa, but also in many parts of the world where mining operations are taking place. For many years it has been realized how valuable to the Mining Industry would be a practical non-destructive method, which used a not too involved or complicated technique, and which could be applied 'in situ' to locate with reasonable speed and accuracy a portion or portions of an 'in service' winding rope, where deterioration was taking place in the desirable tensile and other physical properties of the wires of the rope.

The method and apparatus visualized should possess the feature of automatically recording a chart or diagram. The 'shape or form' of this diagram should be interpreted by information supplied by those responsible for the development of the method and apparatus. This should supply reliable information regarding the nature, and possibly the extent or magnitude, of the detected defective sections of a winding rope.

From the paper, it would appear that the author and those associated with the experimental work have achieved something approaching to that visualized. The tests made have certainly been the means of indicating portions of a winding rope suspected of deterioration and subsequent investigation has confirmed the existence of corrosion.

The economic value, as well as the safety-in-working aspect of the development and introduction of any method and apparatus, would naturally be dependent on the efficiency and particularly the reliability of the interpretation of the test results obtained by the non-destructive method of testing. Whatever success is achieved in the above direction, I venture to say it will for some years remain a supplementary aid to the persons who are responsible for carrying out the statutory daily, and less frequent periodical examinations called for by the Mines, Works and Machinery Regulations in the Union of South Africa, and perhaps in other parts of the world where similar regulations apply.

The production of statistics to show the number of winding ropes and the aggregate length in feet of winding rope in use today even in South Africa alone, would be a revelation—as regards the thousands of feet of rope to be examined daily. I think it can be said and with little fear of contradiction that, in the case of the many long winding ropes, it is practically impossible to make other than a superficial daily examination, and that the examinations in many instances become a perfunctory duty. As the ropes are usually well covered with rope-dressing or some compound to protect the ropes from corrosion, and unless the rope strands or wires are seriously damaged and disturbed, it is very difficult to see undisturbed broken strands or wires. In order to assist in the detection of broken wires it is known that some examinations are made by the assistance of a person applying his hand in contact with the slowly moving rope; in view of the danger of injury to the hand, it is not a very desirable practice. From the above remarks, it can be appreciated how valuable a complete non-destructive rope test would be, particularly by the method described in the paper.

The most thorough examinations of the ropes are carried out at least once per month, and at this examination selected portions are cleaned for careful examination and measurements. It can be readily understood that usually the distances between parts examined are appreciable. At the selected portions it is not possible in all cases to detect if internal wear or corrosion of the wires is taking place, unless the rope is opened up. The indiscriminate opening-up of a rope is not recommended and usually is not done, unless the external examination shows a condition which gives rise to a suspicion of unsatisfactory internal conditions. I recollect seeing some of the early experimental work, commencing about 1946, and, consequently have been interested in noting the progress made in the development of the improved methods, and the alterations in the equipment used for Model I to Model III, as recorded in this paper. The practicability of the application of the present method and the apparatus, has certainly been brought within the range of rendering valuable aid to the responsible engineer by providing means of checking up on the paid-out portion of winding ropes. The conclusion arrived at by the author, is I consider not an over statement.

I consider, however, that the provision of reliable means of interpreting the 'form or shape' of the charts produced as the rope is passed through the test apparatus, is of paramount importance. The author and those associated with the experimental work have no doubt had quite an awakening as to the number of variables which are encountered in connection with winding ropes and these variations have no doubt rendered the interpretation of the resulting charts all the more difficult. It would at the present stage be of aid to the engineer, if the non-destructive method of testing were applied to a rope when newly put on, when the rope had bedded down to the winding operation conditions and thereafter at least once in six months. The information obtained by a comparison of the test charts should be helpful to the engineer responsible for winding ropes.

In conclusion, I wish to thank you for the opportunity to contribute to the discussion, and to add my quota to the congratulatory remarks of the previous speakers, to the author of the paper which will be a valuable addition to the proceedings of this Institute, and I would like to couple the name of Mr M. R. Gericke who has for some years given considerable thought and attention to the subject of non-destructive tests on winding ropes. It is hoped that the useful work will proceed with continued success in the development of improvement in the method and results.

C. F. B. van Wyk: I was privileged to have had a few opportunities of having ropes examined by some of the instruments described by Mr Semmelink.

The first of these ropes which was examined with a very early model in 1949 was a non-spin rope of 15-strand (9 over 6) construction on a sinking shaft. This rope had shown very marked signs of corrosion at certain points in its length.

At the time of the test—when it had already been decided to discard this rope—I felt that I knew where every corroded area in the rope was, namely—

at 400 ft to 500 ft from the splice, slight corrosion;
at 1 000 ft to 1 200 ft from the splice, more than slight corrosion;
at 2 200 ft to 2 500 ft from the splice, very slight corrosion;
at 4 350 ft to 4 500 ft from the splice, extremely severe corrosion;
at 5 800 ft to 6 100 ft from the splice, slight corrosion.

The rest of the rope appeared to be in good condition.

The rope was then examined with the instrument and the indications corresponded very closely with the previous visual examinations. What impressed me most was that the instrument indicated that something was amiss at a point 3 100 ft to 3 150 ft from the splice—in a portion of the rope which had up to then been considered to be in good condition. On carrying out a close visual examination, no evidence of corrosion was found. The instrument was still persistently indicating reduced metal area and it was decided to open up the rope at this point. To our surprise severe internal corrosion was discovered between the inner strands of the rope at this point. The rope was also opened up at two points approximately 30 inches on either side of this severely corroded portion, where the instrument did not indicate anything untoward, and here the rope was found to be sound.

More recently, a $1\frac{1}{2}$-inch rope of flattened-strand construction which had been in use for only a few months, was examined with a much later instrument, because a point was discovered where the rope diameter was reduced by $\frac{1}{16}$ inch over a distance of 8 inches.

Mr Semmelink, in interpreting his charts, had no hesitation in saying that it indicated that there was better contact or more pressure between strands at this point; furthermore he asked for the rope to be examined at another point approximately 50 ft further up where he found similar indications. At this point the rope diameter was found to be nearly $\frac{5}{64}$ inch less than the rest of the rope, over a distance of about 2 feet.

I hope that these experiences will indicate to those people who might be sceptical about a new and strange ‘toy’ that the instruments described to-night, can be of the greatest assistance to the mine engineer in finding hidden defects in winding ropes.

Government Laboratory tests, of samples cut thousands of feet away from a point where danger may be lurking, and visual examination, which can so often fail to disclose internal conditions, need no longer be his only guides in assessing the quality of the rope.

I wish to congratulate Mr Semmelink on his very timely paper and can assure him that mine engineers will certainly appreciate the assistance which this instrument will provide in the examination of winding ropes.

W. M. Kinghorn (*contributed*) :
Throughout the mining world, equipment for testing wire ropes has been wanted for many years as a scientific aid to the crude but remarkably successful examination methods at present in general use. Until now, safeguarding of human life and equipment associated with winding ropes has depended on the uncanny sense of judgment developed by the examining engineer as a result of visual inspection. I feel quite sure that the engineers will incorporate this new device as standard practice in examination procedure for locating the position and nature of defects in winding ropes.

It would perhaps augment the value of this excellent paper and also assist the less experienced rope examiners to have a brief description of the more general defects found in winding ropes together with their causes, effects and significance. These troubles may be summarized under the headings of wear, broken wires and corrosion which, ultimately combined, lead to fatigue and the complete collapse of the winding rope.

Wear is shown by the flattening of crown wires on the rope strands. Should the wear become evident in the early life of a rope and extend generally throughout the working length, then the trouble may be due to soft steel used by the manufacturer; but what is far more likely, it may be traced to the headgear sheave having inadequate groove clearance. The sheave groove should be turned out to a radius 10-per cent greater than the unstressed rope. If wear is found confined to intermittent sections of rope the trouble may be found in bad coiling on the drum and remedied by recoiling with a heavy load. The most usual position of wear is on crossover points on the drum and confined to short lengths or individual strands. The worst possible position for a crossover point is that coincident with the end of the acceleration period. Here the crossover shock is accompanied by maximum stress to give rapid wear and metal fatigue. The evasive action called for consists in pulling in at the drum end any satisfactory length comprising an odd multiple of half turns. In general, wear commences with an initial flattening of the crown wires and, even when this has developed to an obvious extent, there will be little deterioration to the breaking load of the rope until the wires take the form of a U with turned over ragged edges. In this final stage fatigue will develop rapidly and broken wires are imminent.

The next defect for consideration is the broken wire. The disclosure of an occasional broken wire, although unusual, is no cause for alarm and is probably due to faulty welding during manufacture. The wire concerned should be broken back to a position where the ends are away from the strand crown and shrouded by the adjacent wires. If, however, a number of individual broken wires are found at widely-spaced intervals it is possible that fatigue is developing. A test length should be cut off and a careful examination made of the. stress/strain graph up to the point of rupture. The deterioration in the elastic-limit condition is indicative of fatigue development. The most usual broken-wire condition is the disclosure of a number of failures confined to a short length of rope and may be traced to shock loading at a crossover point. The action demanded is to cut off a length from the drum end equivalent to an odd multiple of half turns. The cause of broken wires may sometimes be traced to a flaw in the headgear sheave tread and cases have been found of cutting brought about by loose countersunk bolts on kickover plates. It is not uncommon to find broken wires on the lower layers of the drum particularly on the dead turns which do not come off during normal winding. This is due to the crushing of upper turns on slack layers and the rope should be pulled in at the drum end and recoiled tightly. The danger signal indicated by broken wires is the occurrence of a number of breaks in close proximity each showing the typical fatigue section fracture instead of the tensile fracture.

The most insidious disease in a winding rope is corrosion. In the initial stages a rusty sludge deposit is found between the wires. At the next phase pitting shows up on the wire surfaces. This condition is sometimes masked by plastic deformation of wires which increases the difficulty of visual detection. The penultimate condition of the wire rope corrosion is indicated by slack crown wires on a loaded rope and rusty sludge is expelled in response to a sharp blow from a marlin spike.

In practice, ropes are usually discarded because of a combination of wear and corrosion developing into a fatigue condition. During the early life of a rope, the wires are found to work harden and give a slight increase in ultimate breaking load. This new breaking load is maintained throughout the normal life and, immediately there is a falling off of breaking load rapid deterioration is about to occur. On no account must a rope be permitted to remain in service when corrosion fatigue becomes evident. The evidence of corrosion fatigue is slack crown wires accompanied by rust particles showing a maldistribution of wire loadings. After the rope has been discarded this can be substantiated by opening up a strand to disclose badly corroded core wires. The final proof test will undoubtedly show that the rope has fallen below the limit for safe operation.

I have given a brief outline of some rope troubles, and have no hesitation in welcoming this new aid to rope examinations. The device will undoubtedly lead the inspecting engineer to the trouble zone and even indicate and record the nature of the trouble. However, I beseech the engineer not to allow this device to supplant that uncanny sense of judgment which has been developed to the extent of being almost infallible. This developed intuition must on no account be permitted to lapse into one of the lost arts.

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(FOUNDED JUNE, 1909, INCORPORATED DECEMBER, 1909.)

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ELECTRO-MAGNETIC TESTING OF WINDING ROPES.

A Thesis

Presented to the Faculty of Engineering of the University of Cape Town

for the degree of

Ph.D.

by

A. SEMMELINK.

1956.

ELECTRO-MAGNETIC TESTING OF WINDING ROPES.

A. Semmelink.

SUMMARY.

The electro-magnetic method of testing winding ropes is described. A large number of ropes have been tested with the apparatus built for the purpose. This apparatus is described and the results obtained are discussed. Valuable indications of the deterioration of the ropes tested have been obtained and in many cases the extent of the deterioration can be predicted.

CONTENTS.

1. INTRODUCTION.

In a paper read before the South African Institute of Electrical Engineers in May 1953 (ref.1) experiments were described which lead to the developement of an electro-magnetic rope testing method. This method has been in regular use by the Union Corporation Group of mines since September 1952. During 1953-54 service equipment was designed and constructed, smaller and simpler in operation than the experimental equipment, Model III, described in the first paper.

In that paper a short history was given of experiments and methods in use in South Africa as well as overseas. Since then two other methods have come to our notice, the first based on the German D.C. method (ref.2) claims to be able to detect very small changes in area of the rope as well as cracks and broken wires. the second is a magnetostriction method (ref.3) and is still being developed.

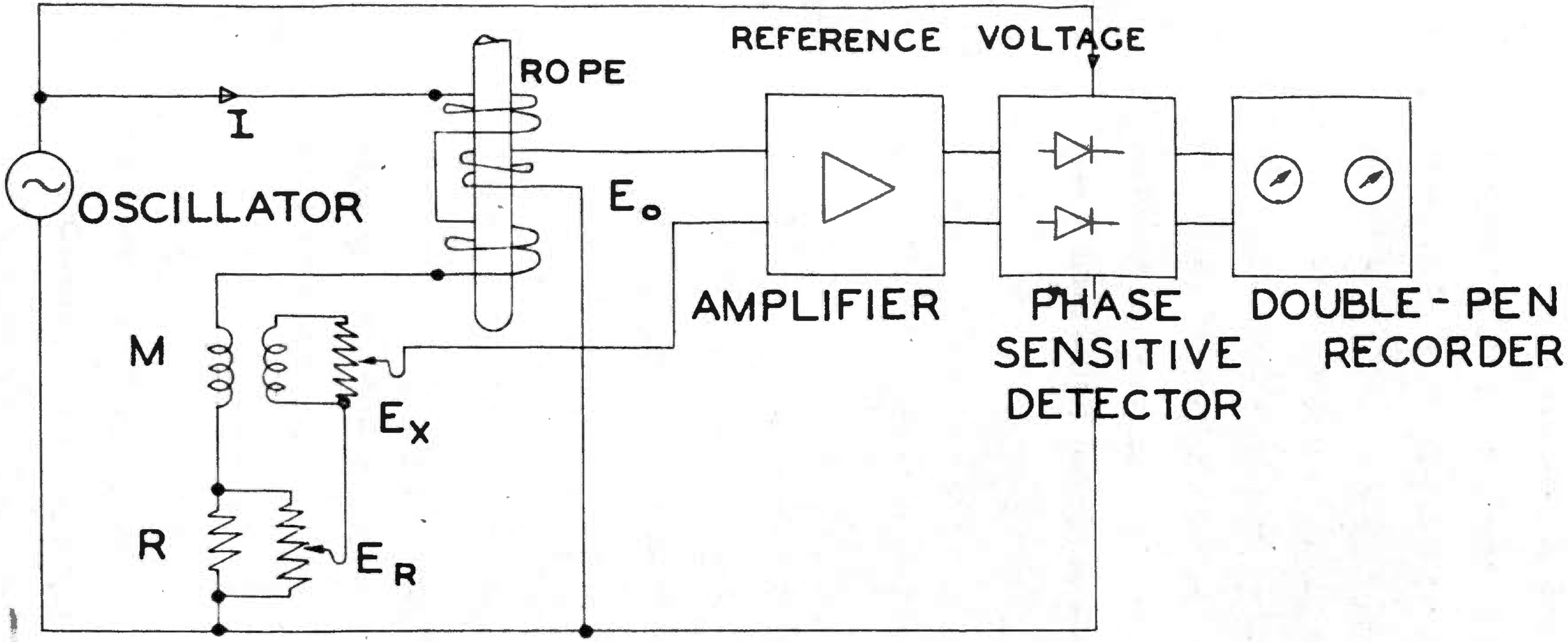
In addition to the routine tests on all main winding ropes in the Group special tests have been carried out at mines of other Groups. The aim of the tests is to assist the engineer in his responsibility under the Government mining regulations for all ropes, especially by bringing ~~under~~ to his notice any factor which may have resulted in or may lead to a reduction in breaking load. Numerous tests have been carried out at the Government Mechanical Laboratory to correlate breaking load with the readings obtained with the equipment. The purpose of this paper is to describe these tests and in addition to describe in greater detail the design and construction of the equipment.

2. APPARATUS.

Before describing the apparatus the method will be discussed, after which each section of the equipment will be dealt with.

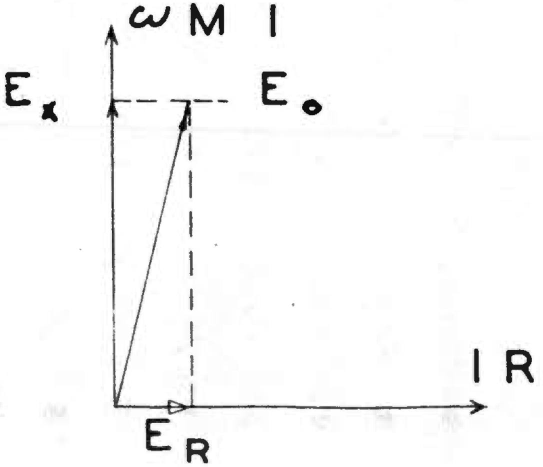
2.1 Method.

A set of coils comprising a magnetising coil and a search coil is clamped over the rope. The coils are designed so that the axis of the coils coincides with the axis of the rope. The number of turns of the magnetising coil and the current in it are chosen to produce a magnetising force of less than one Oersted, thus ensuring that the permeability of the steel does not rise appreciably above its initial value (ref.4).



SCHEMATIC DIAGRAM

FIGURE 1A



VECTOR DIAGRAM

FIGURE 1B

ELECTRO-MAGNETIC TESTING OF WINDING ROPES.

A. Semmelink.

SUMMARY.

The electro-magnetic method of testing winding ropes is described. A large number of ropes have been tested with the apparatus built for the purpose. This apparatus is described and the results obtained are discussed. Valuable indications of the deterioration of the ropes tested have been obtained and in many cases the extent of the deterioration can be predicted.

CONTENTS.

Hysteresis losses are negligibly small and due to the low frequency selected for the magnetising current and the low value of the permeability of the steel used in the manufacture of the ropes, eddy current losses are small, thus ensuring penetration of the rope.

The searchcoil co-axial with and at the centre of the magnetising coil measures the magnetic flux in the rope and in the area between the rope and the searchcoil. The voltage induced in this coil is proportional to the number of its turns, the frequency and the flux-linkage. The flux in the rope is proportional to the magnetising force, the permeability and the area of the steel in the rope. The magnetising force is, in the absence of the rope, dependent only on the dimensions of the coil and the current, but when the rope is inserted demagnetisation ~~will~~ reduces the magnetising force by a factor which for a given coil varies with the size and type of rope. Calculation of this factor is difficult and even when several simplifying assumptions are made, leads to a complicated integral equation (ref.4)(5). Experimental determination is however simple. This may be done by plotting values of searchcoil voltage against area for ropes made of steel of known permeability. Since for a given coil and instrument the only variables are permeability, area and construction of rope, the output voltage will be a function of those variables only.

When eddycurrent losses are zero searchcoil voltage E_o leads the magnetising current I by 90°; since these losses are not zero this angle ~~is~~ differs from 90° by a few degrees. To determine the value of E_o a balancing circuit shown in Fig.1a is used. Fig.1b shows the vector diagram. E_o is opposed by a reactive component E_X and a resistive component E_R obtained from potentiometers in parallel with a fixed mutual inductance and a fixed resistance respectively which are connected in series with the magnetising coil. For convenience the voltages across the two potentiometers are made equal in amplitude and the settings of the potentiometers are proportional to the reactive and resistive components.

Experiments described in the first paper led to the choice of a frequency of 79.6 cycles per second (circular frequency = 500). For six strand ropes it has been found that at this frequency E_R seldom exceeds 10% of E_X. Therefore E_o will differ from E_X by less than 1/2 % since $E_o^2 = E_X^2 + E_R^2$.

An advantage of this type of balancing circuit is that small

SUMMARY

ELECTRO-MAGNETIC TESTING OF WINDING ROPES

A thesis for the degree of PH.D. presented to the faculty of engineering of the University of Cape Town by

A. SEMMELINK.

This thesis describes an electro-magnetic method of testing winding ropes. The method consists of magnetising the rope longitudinnally at low frquency and in a weak field. The resulting magnetic flux is measured in two components, resistive and reactive, in phase and 90° out of phase with the magnetising current respectively. Variations of these components are recorded.

The apparatus built for this purpose consists of detachable magnetising and search coils; low frequency oscillator, balancing network, amplifier, phase-sensitive detectors, d.c. amplifiers, power supply and high-speed recorder. The design and operation of this apparatus are described.

Interpretation of the charts obtained over a period of more than three years are discussed. It is shown that the reactive component of the magnetic flux is proportional to the cross-sectional area of the steel in the rope and to the permeability of the steel; the resistive component varies with the eddy currents induced in the rope and is used to interpret the variations of the reactive component. Typical variations shown are found to indicate plastic deformation of the wires, internal and external corrosion and permeability changes.

Where deterioration of a rope is caused by decrease of area due to corrosion or other reasons the magnetic readings can be correlated with the breaking load. Several examples of actual tests are given.

A copy of a paper read before the South African Institute of Electrical Engineers is attached. In that paper a short history of electro-magnetic rope testing is given and experiments are described.

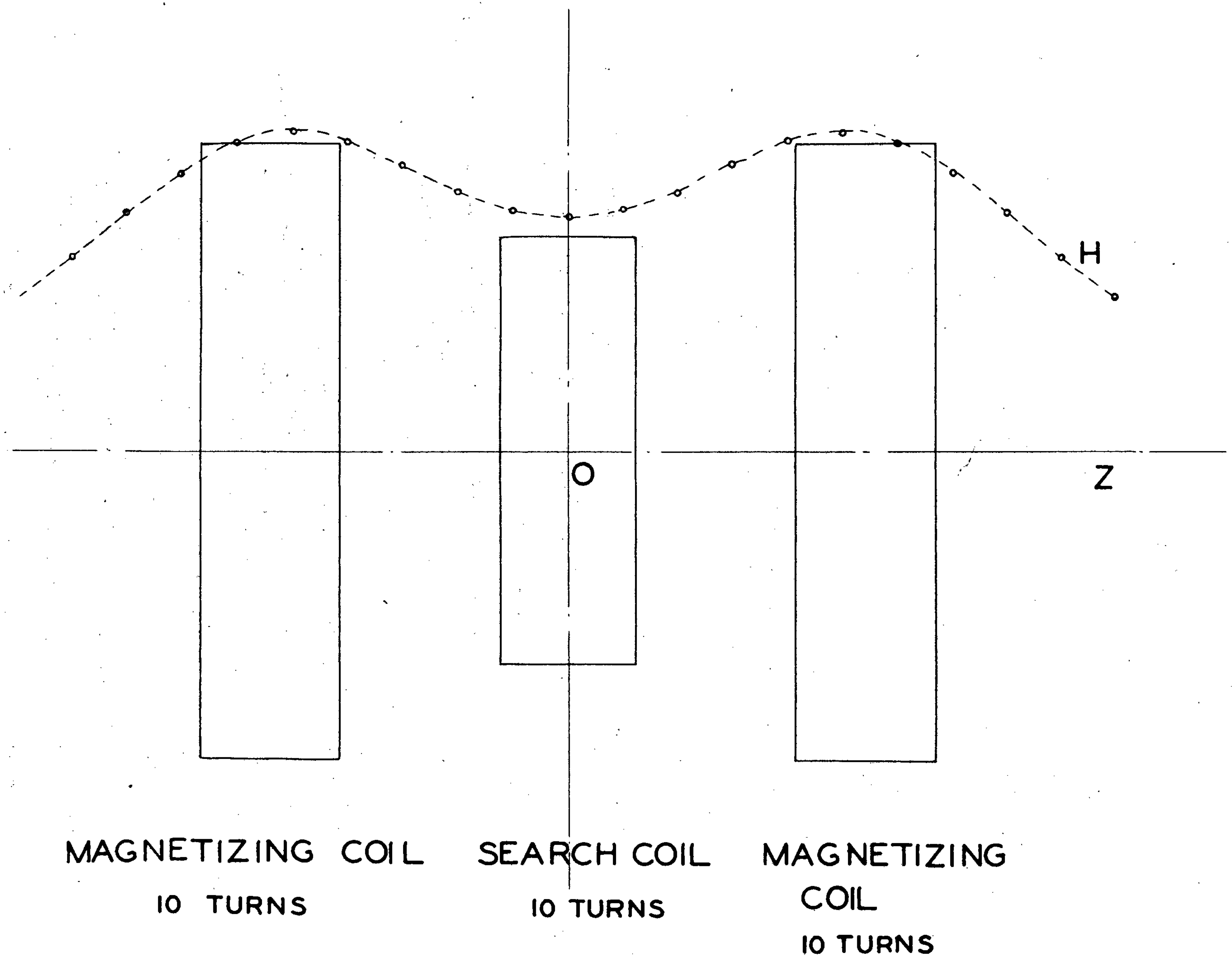

H
O
Z
MAGNETIZING COIL
10 TURNS
SEARCH COIL
10 TURNS
MAGNETIZING
COIL
10 TURNS

FIGURE 2B

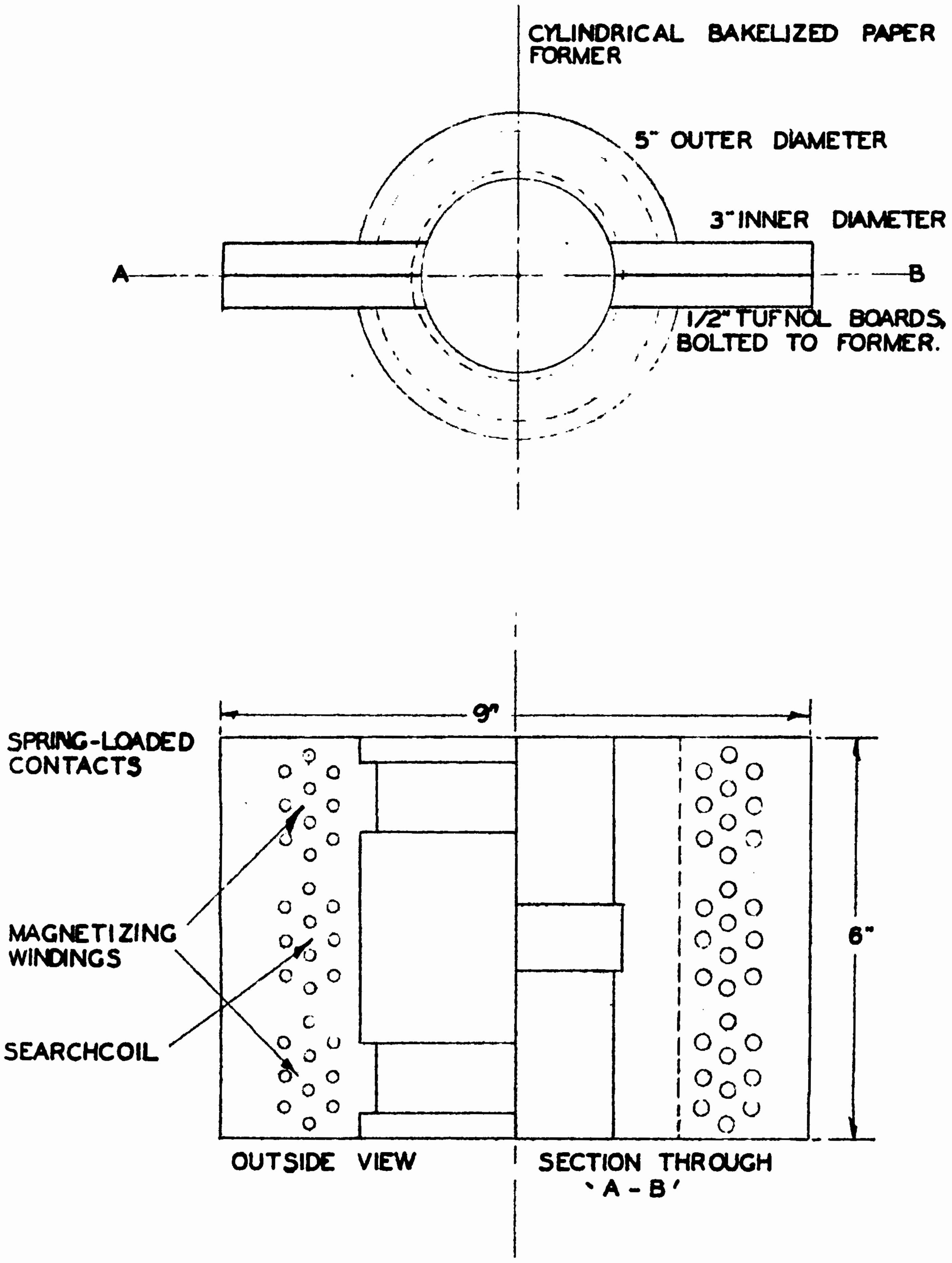


FIGURE 2A. COIL-FORMER

variations of frequency and of current such as may occur in a portable instrument will not affect the reading of the reactive component.

As it is required to record the variations of E_0 along the length of the rope the balancing circuit is followed by an amplifier and two phase-sensitive detectors; the output of one is proportional to the variations of E_X and that of the other to those of E_R. These outputs are recorded on a high-speed recorder with two pens.

The rope speed during a test depends on the response of the recorder and of the detector circuit. Due to the choice of a low operating frequency the response of the detectors cannot be ~~high~~ fast. A time constant of .1 second is used and if the shortest variation to be detected along the rope is 4 inches, the rope speed must not exceed 4 inches in .1 sec. or 200 feet per minute.

The variation of E_X is a measure of the variation of the area and of the permeability of the steel in the rope. The variation of E_R is a measure of the eddy currents in the rope.

2.2 Design of coils.

The coils are wound on a bakelite former, 6" long, 5" outer diameter and 3" inner diameter, as shown in Fig. 2a. The magnetising coil consists of two windings ten turns each on the outside of the former. The variation of the fieldstrength along the axis is shown in Fig.2b, the field at the centre was calculated to be .43 Oersted, for a magnetising current of ~~xx~~ .5 Ampere. The searchcoil of ten turns is placed on the inside of the former.

As the coils must be easily fitted over the rope, the former is split and the windings are connected by means of springloaded contacts which have proved to be more satisfactory than plugs and sockets, which are difficult to keep clean.

The coil former is mounted in a frame with four tufnol pulleys which ride on the rope and serve to keep the rope along the axis of the coils. One of the pulleys drives a magslip generator which is part of a synchronous link for the recorder. The frame is hinged on one side, is fitted with a simple clamp on the other side, while two rubber belts prevent the contacts from opening. The whole is illustrated in Fig. 3a and 3b.

Figure 3a, Coilframe opened.

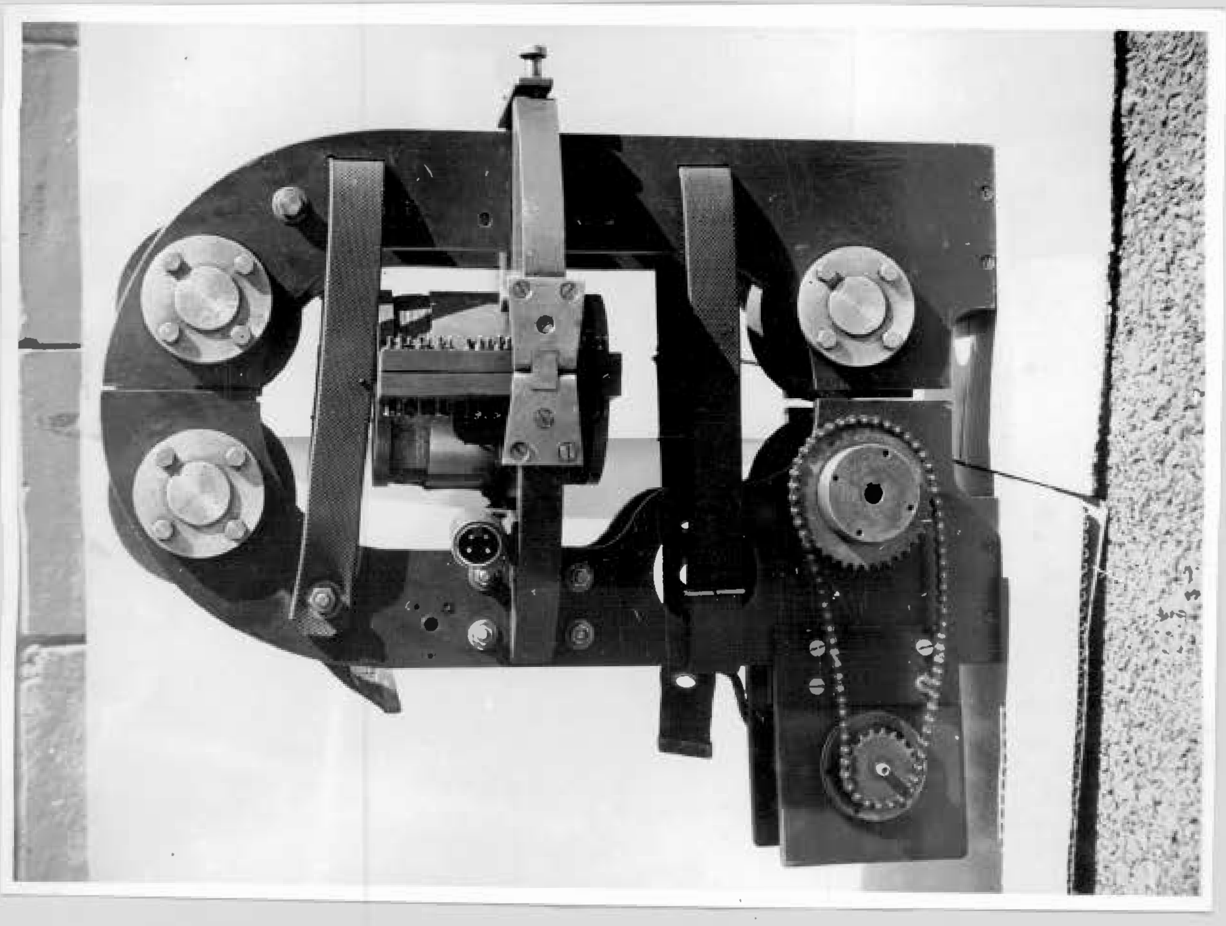


Figure 3b. Coilframe closed.

2.3 Balancing circuit.

The accuracy of the apparatus depends to a large extent on the design of the balancing circuit. The searchcoil voltage for the largest ropes - diameter 2" - is nearly ten millivolts for a magnetising current of .5 Amperes. The variations of this voltage, even for a used rope, seldom exceed four percent or 400 microvolts.

The voltage across potentiometers R_3 and R_5, which are used to balance out the resistive and reactive components respectively, has been adjusted to ten millivolts or .02 times the magnetising current by means of R_2 and R_4. R_3 and R_5 are ten-turn potentiometers with dials calibrated in 1000 divisions. The linearity is claimed to be better than .1 percent.

The mutual inductance is wound on a toroidal hardwood former, the dimensions of which are 1" inner diameter and 1" square section. It has 117 primary turns of 21 s.w.g. and 99 secondary turns of 18 s.w.g. wound over the primary turns. It is paraffin-wax impregnated and mounted in a cast aluminium box. The measured mutual inductance is 50 microhenry.

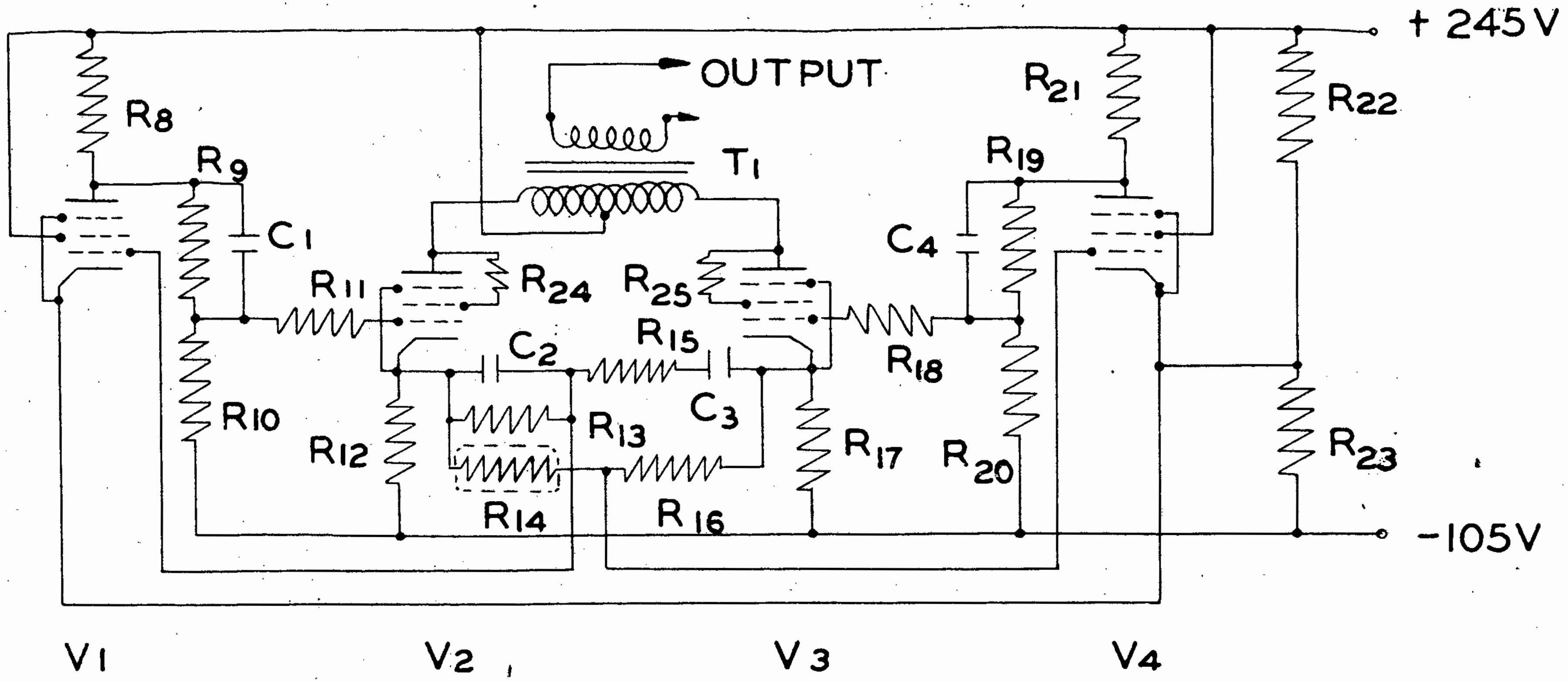
Meter M_1 measures the magnetising current and serves as a check on the proper operation of oscillator, connecting cables and coil-contacts.

The resistance connected across the secondary of the mutual inductance, 125 ohms, is large compared with the impedance of the secondary which is approx. .5 ohms. This ensures that the voltage across the secondary is in quadrature with the current in the primary. The total resistance of the magnetising circuit including the 50 foot connecting cable is approx. 2 ohms; the oscillator must therefore be able to supply 1 volt at .5 amperes and at a frequency of 79.6 cycles per second.

2.4 Oscillator.

Any oscillator capable of supplying the required output with good stability and low harmonic distortion can be used. The circuit chosen is based on a design by L. R. Grath (ref. 6). The output is taken directly from the oscillator valves V_2 and V_3, this is satisfactory because only one frequency is used.

The frequency is determined by condensors C_2 and C_3 and resistors R_{13} and R_{15}. Silver-mica condensors and high-stability resistors have been



OSCILLATOR CIRCUIT

FIGURE 5

R_8, R_{21} = 50k

R_9, R_{10}, R_{19}, R_{20} = 1 Meg.

R_{11}, R_{18} = 4·7 k

R_{12}, R_{17} = 4k

R_{13} = 20K ± 1%

R_{14} = 110V 6W LAMP

R_{15} = 10k ± 1%

R_{16} = 1·4 k

R_{22} = 15K, 10W, ww

R_{23} = 7·5K/2, 5W

R_{24}, R_{25} = 67 ohm

C_1, C_4 = ·5 mfd.

C_2 = ·10 mfd ± 1%

C_3 = ·20 mfd ± 1%

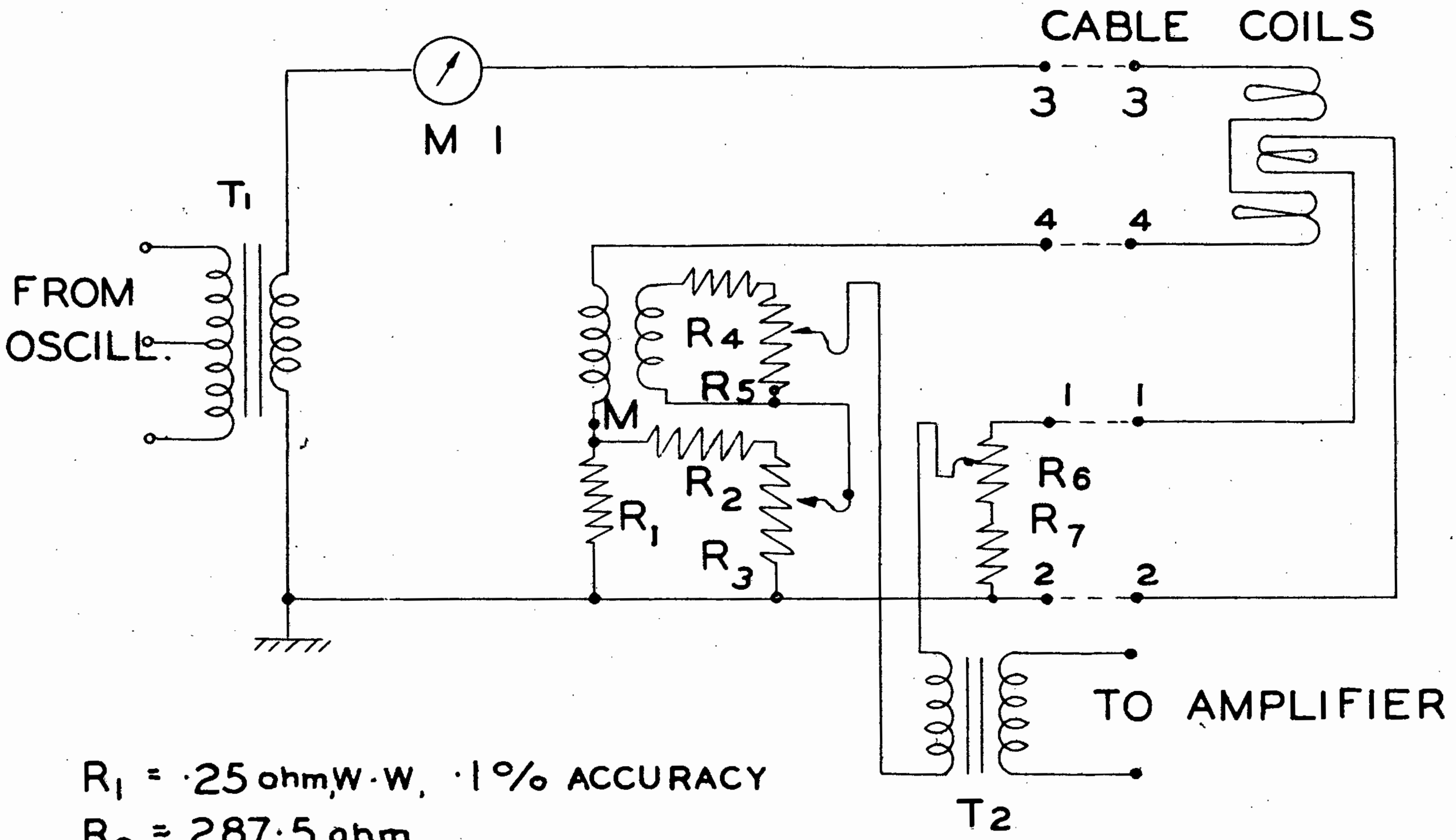
T1 = OUTPUT TRANSFORMER 40/1

V_1, V_4 = EF80

V_2, V_3 = EL41

BALANCING CIRCUIT

FIGURE 4



R_1 = ·25 ohm, W·W, ·1% ACCURACY

R_2 = 287·5 ohm.

R_3 = 25 ohm TEN-TURN POTENTIOMETER

R_4 = 25 ohm.

R_5 = 100 ohm, TEN-TURN POTENTIOMETER

R_6 = 25 ohm POTENTIOMETER

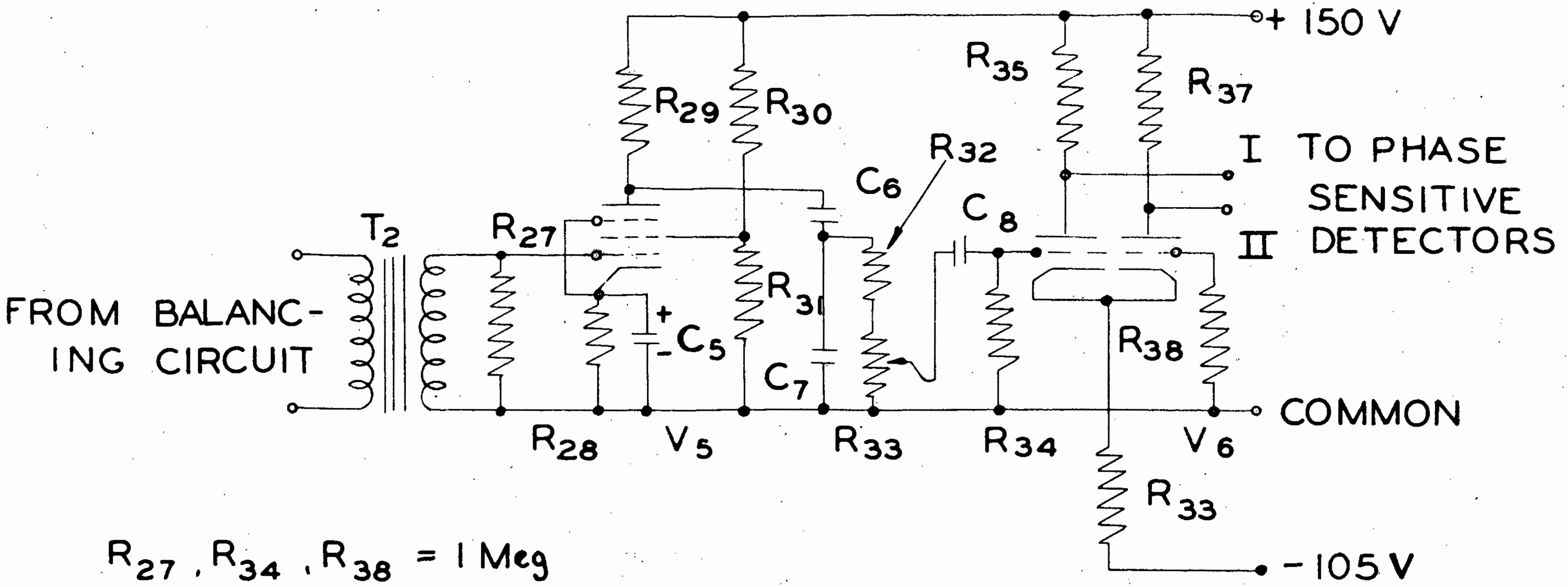
R_7 = 225 ohm.

M = MUTUAL INDUCTANCE = 50 μH

M_1 = 0-1 AMP A.C. AMMETER

T_1 = 40/1 OUTPUT TRANSFORMER

T_2 = 600/100k ohm TRANSFORMER



AMPLIFIER
FIGURE 6

R_{27}, R_{34}, R_{38} = 1 Meg
R_{28} = 22 K
R_{29} = 220 K
R_{30} = R_{36} = 47K
R_{31} = 22 K
R_{32} = 470K
R_{33} = 470K GAIN CONTROL
R_{35} = R_{37} = 100K

C_5 = 100mfd, 25V ELECTROLYTIC
C_6 = ·25 mfd.
C_7 = 1000pF
C_8 = ·5 mfd.
T_2 = 600/100K TRANSFORMER
V_5 = EF 86
V_6 = ECC83 12 AX7

used to ensure frequency stability. Measured frquency is 79.0 cycles per sec. after switching on and 78.4 cycles per second four hours afterwards.

Amplitude stability is obtained by a 110 volt, 6 Watt lamp R_{14} in one arm of the Wien bridge circuit, while the amplitude can be adjusted by means of R_{16} in the fourth arm.

The measured distortion, mainly third harmonic is .3 percent. This was obtained after the values of C_2, C_3, R_{13} and R_{15} had been chosen to make the voltages across the cathode resistances R_{12} and R_{17} equal. For this reason $C_3 = C_2 \times 2$ and $R_{13} = R_{15} \times 2$.

A 40 to 1 output transformer connects the oscillator to the balancing circuit.

2.5 Amplifier.

The sensitivity chosen for the instrument is full scale deflection from centre for four percent change of searchcoil voltage. For a 3/4" diameter rope this voltage is approx. 2.5 millivolts or .250 times .02 I. Four percent of this is 100 mirovolts. The detectors used need about 150 millivolts balanced input or 300 millivolts grid to grid.

The amplifier circuit is shown in Figure 6. The first stage is a resistance-capacity coupled low-mirophonic, high-gain pentode V_5. The gain-control is placed between the first and second stages. The series resistance R_{52} and parallel condensor C_7 are adjusted to give zero phase-shift at the operating frequency. Condensor C_8 and resistance R_{54} are inserted as valve V_6 has sufficient grid current to upset the balance of the d.c. amplifier whenever the gain-control is adjusted, when this control is connected directly to the grid.

The second stage is a symmetrical differential amplifier, chosen because of its insensitivity to supply voltage fluctuations.

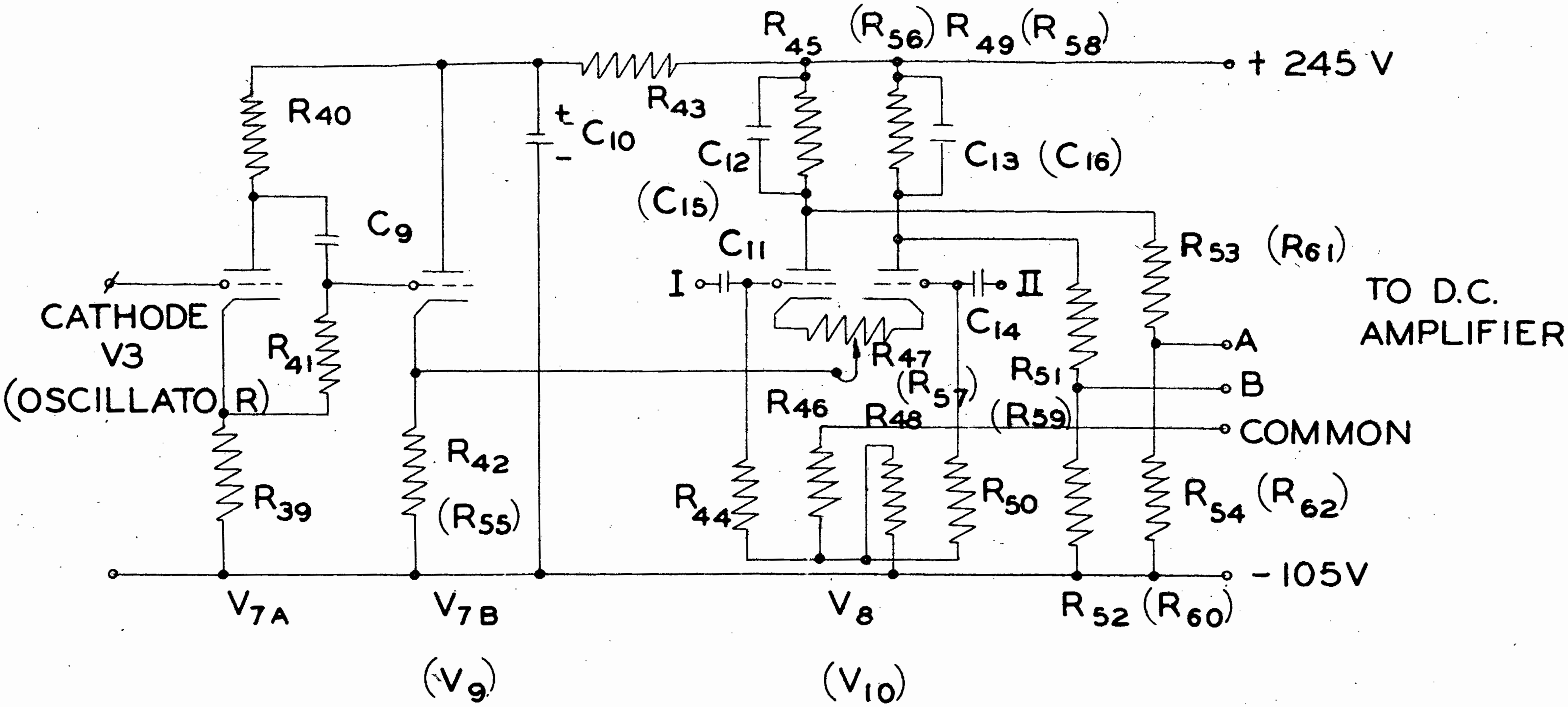
The total gain of the amplifier including the input transformer T_2 exceeds 2000 times, and due to the large cathode resistance in the differential amplifier the output is balanced.

2.6 Phase-sensitive detectors.

These are based on a circuit in ref.7 and are shown in Fig.7. For the resistive component the reference voltage is taken directly from the cathode of V_3 in the oscillator circuit; any phase difference that may exist

PHASE - SENSITIVE DETECTORS

FIGURE 7



VALUES IN BRACKETS REFER TO R COMPONENT DETECTOR WHICH CONSISTS OF VALVES V_9 AND V_{10}. RESISTANCES R_{55} TO R_{62} AND CONDENSERS C_{15} AND C_{16}.

THE GRID OF V_9 IS CONNECTED TO THE GRID OF V_{7A} AND THE GRIDS OF V_{10} TO THOSE OF V_8.

FIGURE 7. PHASE SENSITIVE DETECTORS.

R39, 40, 46 = 22k

R41, 45, 49, 56, 58 = 220k

R42, 55 = 80k

R43 = 47k/2 (2) 47k resistances in parallel)

R44, 50 = 1 Meg.

R47, 57 = 250 ohm potentiometer.

R48 = 100k/1 Meg

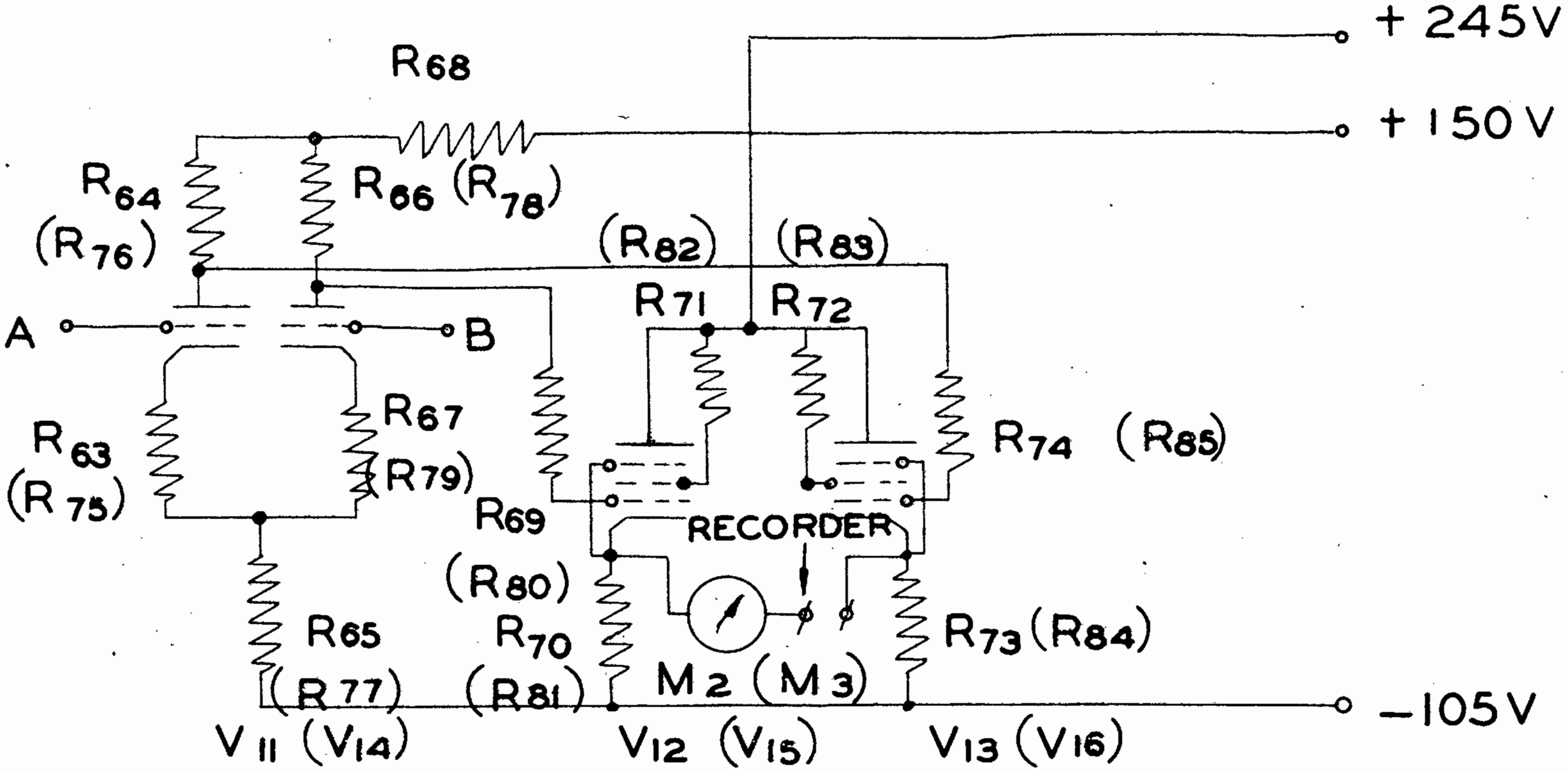
R51, 53, 59, 61 = 2.2 Meg.

R52, 54, 60, 62 = 470k

C11,12, 13, 14, 15, 16 = .5 mfd.

V7a, V7b, V9 = $\frac{1}{2}$ 12AX7 (ECC 83)

V8, V10 = 12 AX7 (ECC 83)



D.C. AMPLIFIERS

FIGURE 8

VALUES IN BRACKETS REFER TO R COMPONENT AMPLIFIER.

R_{68} IS COMMON TO R_3 X AMPLIFIERS.

$R_{63,67,69,74,75,79,80,85}$ = 4·7 K

$R_{64,66,76,78}$ = 120 K

$R_{65,77}$ = 22 K

R_{68} = 10 K

$R_{70,73,81,84}$ = 5 K 10 W, W. W.

$R_{71,72,82,83}$ = 100 Ω

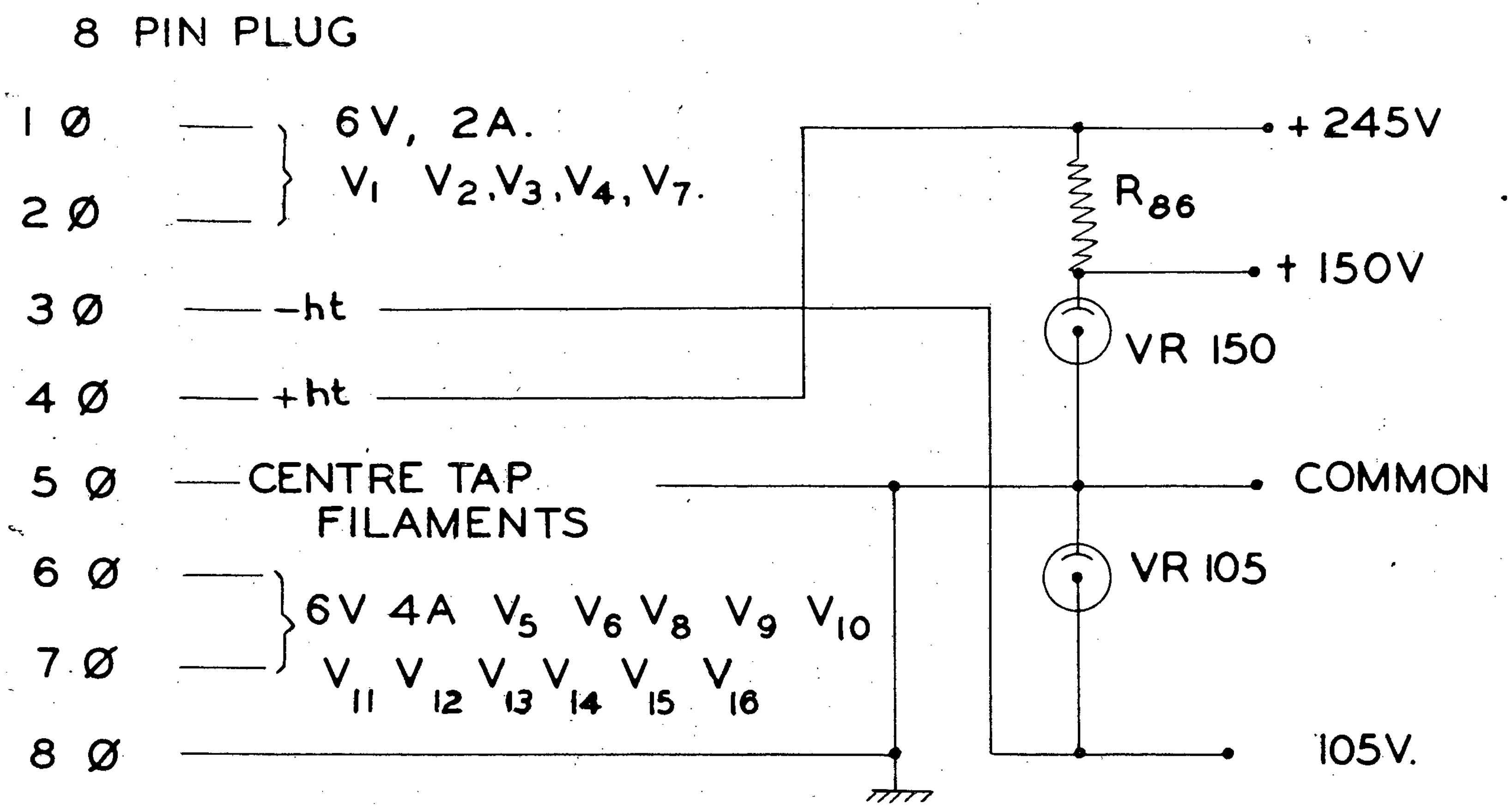
V_{11}, V_{14} = ECC82 (12AU7)

$V_{12,13,15,16}$ = EL84

$M_{2,3}$ = 10-0-10 mA, 4½" SCALE.

POWER SUPPLY CONNECTION

FIGURE 9



R_{86} = 3K 5W, W.W.

POWER SUPPLY STABILIZED 350V, 200 IN A

6 V 4 A } BOTH CENTRE TAPPED
6 V 2 A

is cancelled by the network connected across the gain-control in the amplifier. For the reactive component an additional stage V_{7a} is used to give a 90° phaseshift by the proper choice of C_9 and R_{41}.

Detector valve V_8 (V_{10}) combines high gain - 40 times - in terms of r.m.s. input to d.c. output and balanced output; but it has the disadvantage that the output is at a high d.c. level and some of the gain must be sacrificed in coupling to the d.c. amplifier.

The output for fullscale deflection is 12 volts plate to plate and 2 volts between terminals A and B.

2.7 D.C. amplifiers.

The high-speed oscillograph used for recording the variations along the rope requires 12.5 mA for fullscale deflection from centre; the impedance is 1500 ohms. The manufacturesrs recommend that the driving impedance should not exceed 250 ohms. The circuit adopted, shown in Fig. 8, has a differential cathode follower (ref. 8) as output stage. The output impedance is approx. 200 ohms. The sensitivity is approx. .55 mA per volt; for fullscale deflection a differential gridvoltage of 23 volt is required. To obtain this a differential amplifier is added. The choice of this circuit was largely dictated by the necessity of preventing zero drift as encountered in single-ended amplifiers and caused by the large mains voltage variations met in practic

2.8 Power supply.

A commercial stabilised power supply unit is used for all sections described above. It has an output of 200 mA at 350 volts as well as two 6 volt heater supplies. Two stabilising valves are used to decouple the different sections and to make the potential of the recorder nearly equal to earth potential. This is shown in Fig. 9.

2.9 Recorder.

As already stated the recorder is a high-speed oscillograph. It has a frequency response essentially flat from d.c. to 50 c.p.s. and falling to 120 c.p.s. It has two identical channels with centre-zero, one of which records the variations of the reactive component and the other those of the resistive component. The records are much easier to interpret when the longitudinal scale is proportional to distance along the rope. This is accomplished by means of a synchronous link, consisting of two magslips.

Figure 10. Apparatus in stationwagon.

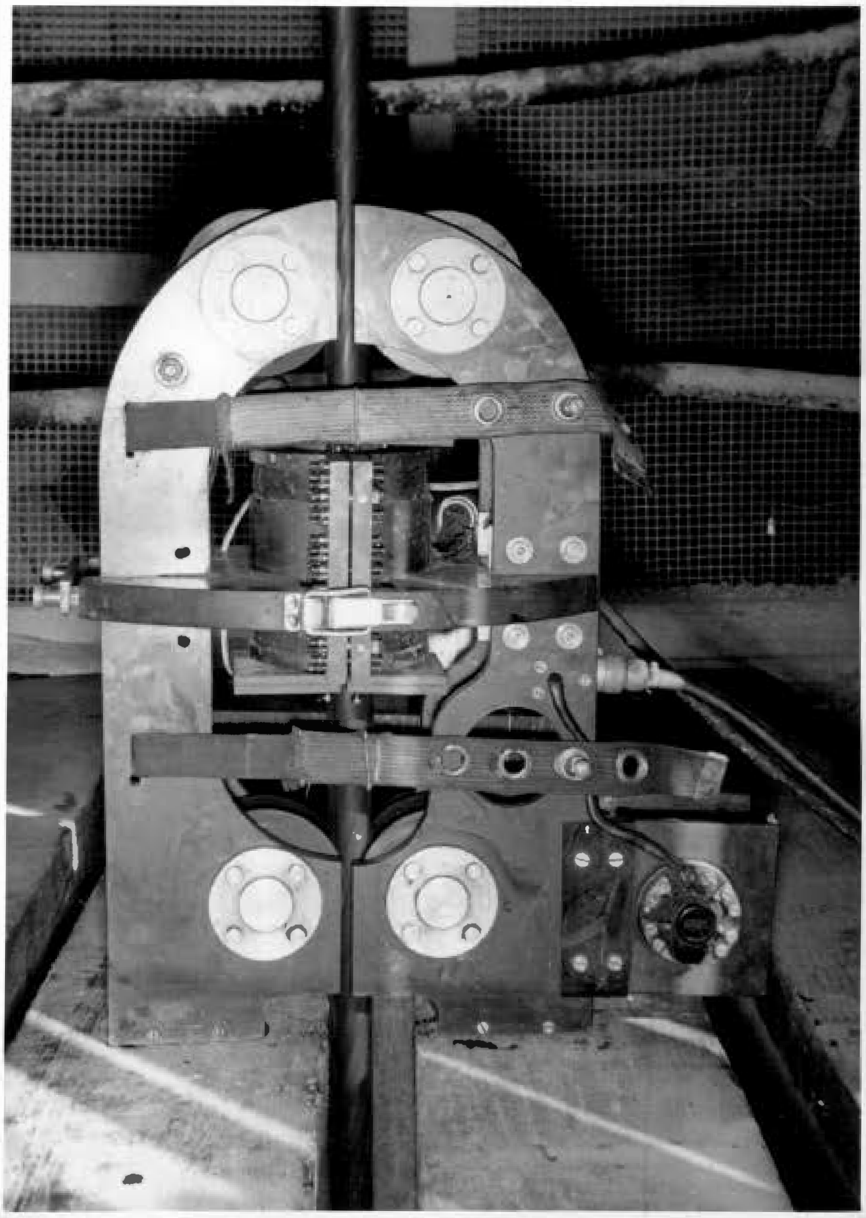


Figure 11. Coilframe on rope in vertical shaft- above and in incline shaft- below.

3. USE OF APPARATUS.

3.1 Operation.

When testing ropes of surface winders the apparatus is set up in the back of a station wagon and the coil frame is clamped over the rope after stageplanks or a platform has been placed over the shaft, as shown in Figs. 10 and 11. Cables are run to the mains and between equipment and coils. The output voltage is balanced out by means of the R and X controls, the gain-control is set to give four percent decrease for fullscale deflection from the centre of the chart, using the sensitivity control potentiometer connected across the searchcoil. All this can be done in less than five minutes. The rope is then run through the coil at a speed of approx. 200 feet per minute. The winding engine driver is asked to avoid sudden speed variations as these may cause permeability and eddy current changes. For a shaft of 5000 feet depth the complete operation need not take longer than half an hour.

The settings of the controls are marked on the chart and as variations seldom exceed four percent it is usually not necessary to readjust the controls; but if an adjustment has to be made the new setting is noted. The usual distance scale is one division of 5 mm. equals 25 feet of rope, but when greater detail is required one division may be five or even one foot.

The top trace of each chart shows the variations of the X-component. The sensitivity control causes a reduction of the searchcoil voltage of four percent and as the effect on the R-component is negligibly small, the calibration mark will appear on the top trace only. The R-component will however have the same sensitivity in terms of variation of output voltage, as the X-component , due to the use of identical channels.

An example of a chart is shown in Fig. 12. To the left the name of the mine, shaft and compartment number are noted, as well as the date of the test and the settings of the R and X controls. The calibration mark is marked minus four percent. The value of output voltage for any point along the rope may be calculated as follows; at point A the X reading is 475 and the R reading 025, while at B X = 456 and R = 013, the output voltage is obtained by multiplying the X reading by .02 x .5 Amperes to give millivolts. The rope concerned is of 1 1/4" diameter and 79.2 tons original breaking load.

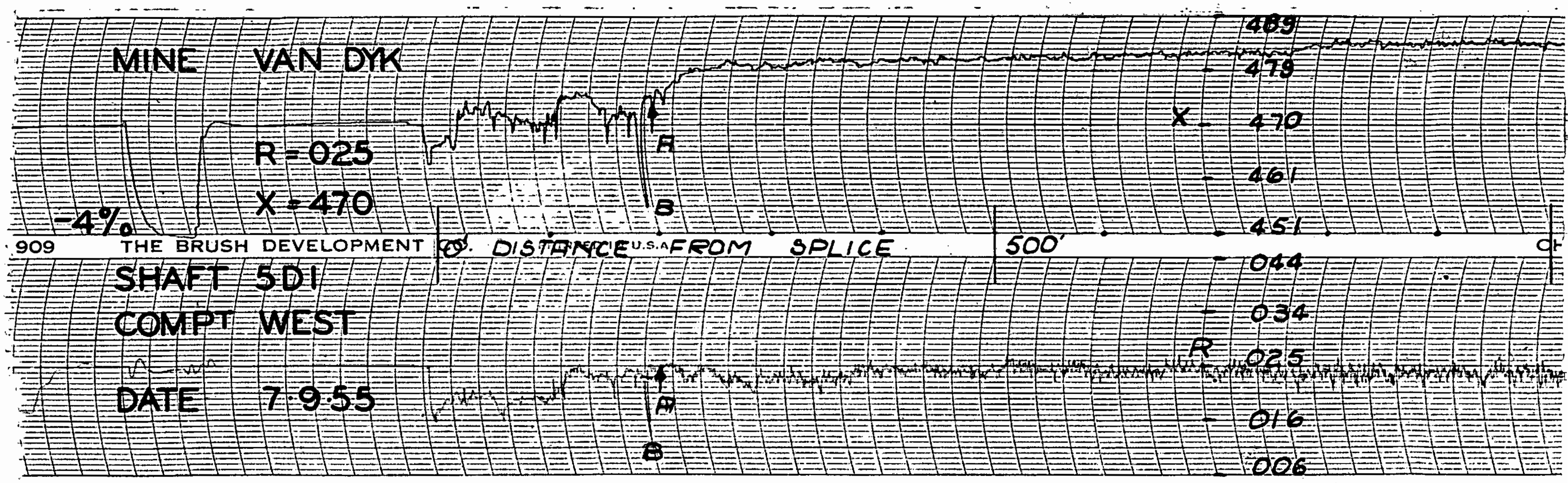


Figure 12, Example of chart.

3.2 Interpretation of charts.

In the first paper it was stated that common variations are:-

i. Increase on X trace, decrease on R trace.
ii. Decrease on X trace, increase on R trace.
iii. Decrease on both X and R trace.

The first two are both due to variations of eddy currents causing variation of flux and frequently occur at points where the rope traverses from one parallel groove to the next or at crossover points where the rope passes from one layer to the next. At such points the rope may slightly open or close, causing decreased or increased contacts between strands. Further use of the rope leads to the development of plastic deformation at such points with increased contacts between strands. In this case the eddy currents increase and the flux decreases. While these conditions lead to a distinctive pattern in the records, it has been found that the breaking load is not reduced unless the rope is run in the same position for excessively long periods. This may lead to deterioration such as cracked, split or broken wires and / or abrasive wear.

The third condition, i.e. decrease on both X and R trace, showing a simultaneous decrease of flux and eddy currents, has been found to indicate corrosion. Very slight corrosion appears to lead to a deposit of non-conducting material between thewires and to a reduction of eddy currents. Progress of corrosion leads to a wastage of the metal and thus to a decrease of the cross-sectional area of the steel and of thestrength of therope. An example of this is shown in Fig. 12, point B (X = 456, R = 013), while point A (X = 475, R = 025) does not show corrosion. The breaking load at A = 77.8 tons and at B = 75.0 tons, the original value is 79.2 tons.

The indication of corrosion is undoubtably the most important information arising from the magnetic test records. During the last three years a considerable number of records indicating corrosion have been obtaind. It has been found that serious conditions can exist inside the strands of a rope which are sometimes virtually impossible to detect by external examination. Wherever records showed the possibility of deterioration due to internal or external corrosion, samples have been tested in the Government Mechanical Laboratory. Some of these results showed severe reduction of the strength of the rope, certain samples breaking at as low as 57 % of the original strength.

PLOT OF B.L. AGAINST X

FIGURE 13

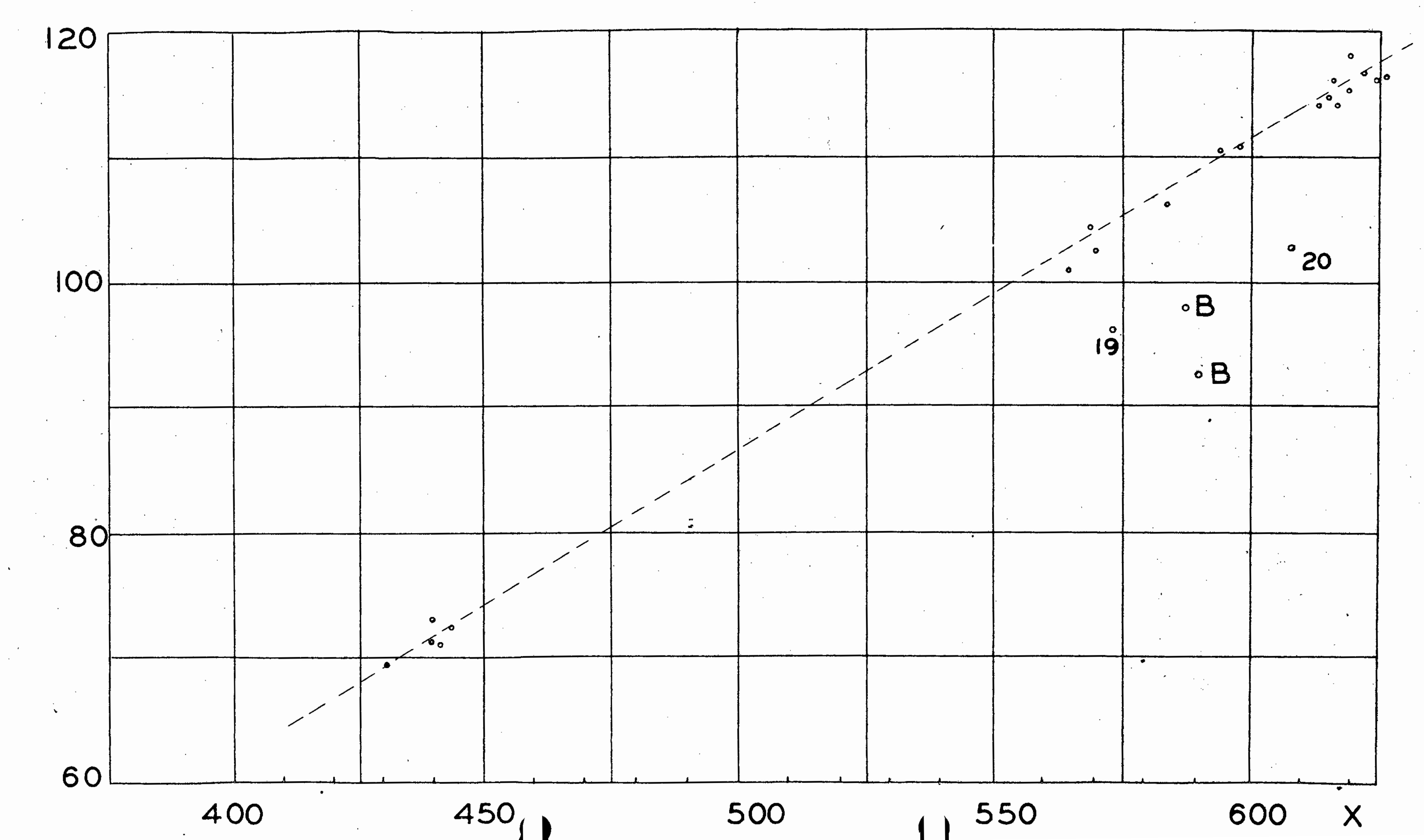


TABLE I.

Coil No.	Specimen No.	Distance from splice.	R	X readings.	Breaking load tons (2,000 lb.)	Original Breaking Load.
224 086	M'	705'	-	594	110.8	116.5
	Q	3300'	-	617	114.5	
	T	3750'	-	619	115.8	
224 087	I	150'	011	584	106.5	116.3
	3	171'8"	015	616	116.7	
	7	310'10"	010	569	104.8	
	9	332'6"	009	565	101.0	
	10	343'4"	009	570	102.8	
	15	1680'	016	619	118.5	
	17	3300'	013	598	111.0	
	19	3740'	009	573	96.0	
	20	3750'10"	015	608	103.0	
229 691	A	-	-	613	115.0	117.5
	B	-	-	588	98.0	
	C	220'	027	622	117.0	
229 690	A	-	-	613	114.7	117.3
	B	-	-	590	92.5	
	C	2950'	024	624	116.5	
	D	4300'	026	626	116.8	
223 431	J	560'4"	013	442	71.0	74.3
	K	705'	012	431	69.2	
	O	1894'	011	440	73.0	
	P	1900'4"	013	440	71.1	
	S	3752'	015	444	72.5	

A fourth type of variation, not mentioned in the first paper, may arise from a reduction of permeability caused by part of the rope being permanently magnetised; this gives:-

IV. Decrease of X, no change of R.

The following sections describe some of the work which has been carried out to establish the relationship between the records and the actual strength throughout the length of the rope.

5.21 Relation between breaking load and magnetic tests.

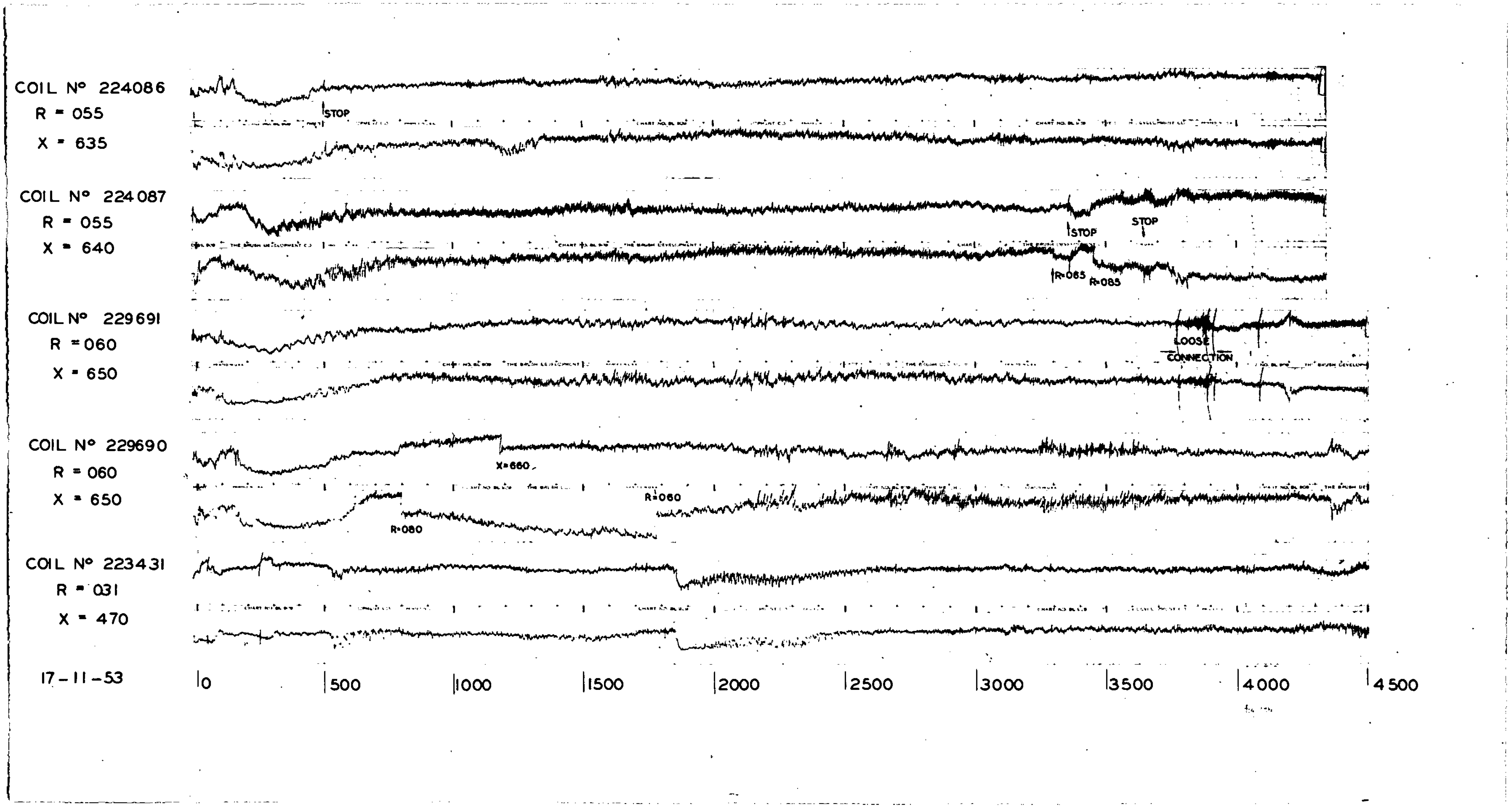
Towards the end of 1953 records were made of some ropes of a Free State mine where shaft conditions were such as to cause severe corrosion. Five of these ropes were taken off and samples were tested for breaking load. The results of these tests are given in Table I, in which the R and X values are taken in the laboratory and not in the shaft. Records of these ropes are shown in Fig. 13b. The first four ropes are of 6x28 compound triangular strand construction, 1 1/2" diameter, Langs lay, 123/134 tons per sq. in. The last rope is of 6x13 simple triangular strand construction, 1 1/8" diameter, Langs lay, 128/140 tons per sq. in.

When the breaking loads of the samples of Table I are plotted against X readings as in Fig. 13, it is found that most points lie near a straight line. There are however four exceptions; of these specimens 19 and 20, which differ by about 10 tons from corresponding values on the line, had damaged outer wires in addition to the internal corrosion; but for specimens marked B which differ by 10 and 17 tons no explanation was found at the time.

As a result of these tests arrangements were made with the Director of the Government Mechanical Laboratory and officials of the mining groups to test all the samples submitted for test at that laboratory over a period of time with the magnetic apparatus to obtain the relationship between breaking load and magnetic tests. The results obtained for ropes of triangular construction and of 123/134 and 128/140 tons per sq. in. steel are given in Table II and plotted in Fig. 14. This type of rope represents the bulk of the main winding ropes in South Africa (ref. 9, p. 224 and 254).

It must be appreciated that these tests were carried out on samples taken from ropes which have been in service for varying lengths of

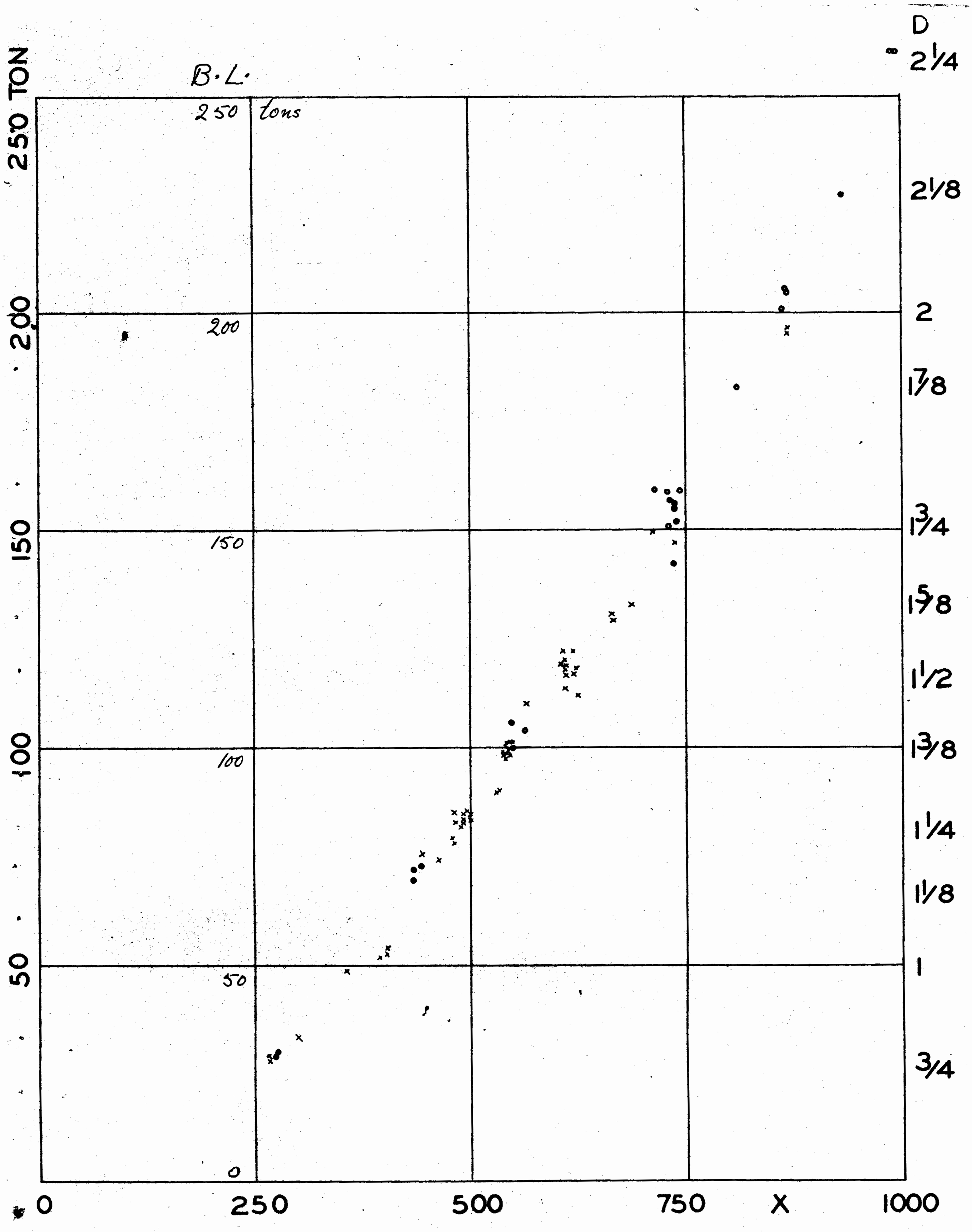
Figure 13b, Charts of Free State ropes.



time under varying conditions. In addition samples are taken from the splice end of the rope, where most permeability changes are experienced. This has resulted in a larger spread of the points in Fig. 14 than if only new specimens were tested. Unfortunately the number of new samples was only 12 out of a total of 84, insufficient for the determination of the B.L. against X curve.

When the rope sample breaks inside the white metal cones which are cast on its ends and are used as grips in the testing machine, the possibility exists that the breaking load will be below normal. The number of collar breaks was 18 out of 84. Of these only four showed breaking loads appreciably below normal.

From measurements carried out at Cape Town University and published in the first paper it was found that the difference in permeability for the two classes of steel is negligible. The breaking load of the 128/140 steel for the same X reading may be expected to be higher than those of the 123/134 steel. Most ropes from which the samples were taken are made of basic, Iscor special steel (ref.9, p.241).



B.L. AGAINST X

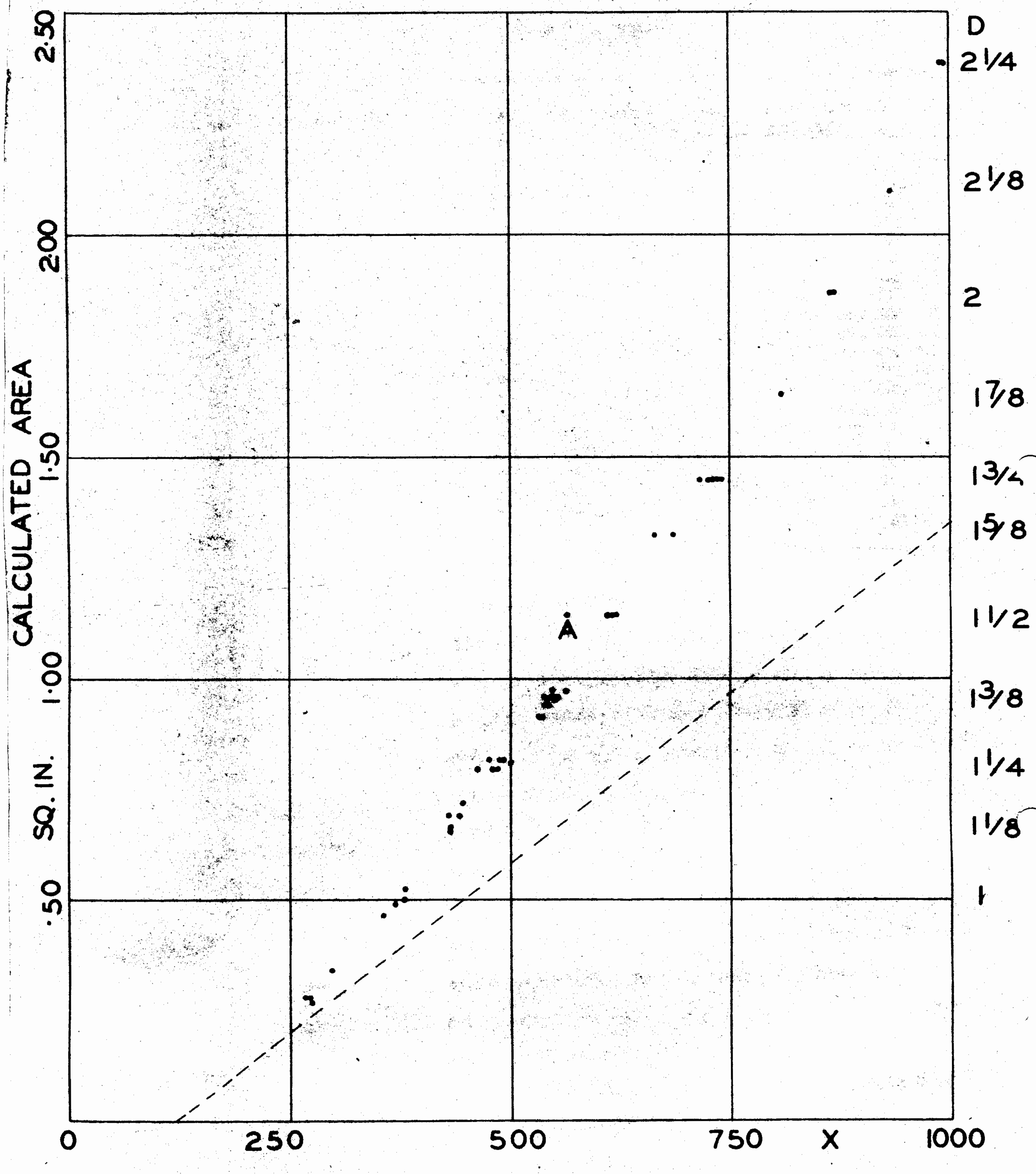
FIGURE 14A

O = 128/140 STEEL

X = 123/134 STEEL

TABLE II.

Coil No.	Class of steel 128/140	123/134.	Diam. ins.	R	X	B.L.	Calculated area, sq.in.	Collarbreak
227 856	x		2¼	033	990	260.5	2.398	
227 857	x		"	031	994	260.0	"	
265 358	x		2⅛	021	932	226.5	2.102	
210 983		x	2	026	867	196.5	1.870	
210 984		x	"	027	868	195.2	"	
265 666 new	x		"	019	865	205.8	"	
219 985	x		"	022	867	204.5	"	
219 986	x		"	021	861	200.8	"	
267 596 new	x		1-7/8	016	809	182.8	1.642	
236 289	x		1¾	021	736	155.5	1.497	x
236 290	x		"	020	737	156.5	"	
214 421	x		"	020	731	151.0	"	
214 422	x		"	020	732	157.5	"	x
226 739	x		"	021	736	142.5	"	Bad collarbreak
226 740	x		"	017	740	152.5	"	x
217 044	x		"	024	728	159.0	"	
217 045	x		"	030	744	159.7	"	
226 608	x		"	033	715	159.7	"	
226 609	x		"	031	715	159.7	"	
236 116		x	"	016	738	147.8	"	x
236 117		x	"	029	716	149.7	"	x
268 226 new		x	1-5/8	014	684	133.0	1.325	
222 608		x	"	029	665	129.5	"	x
222 609		x	"	026	662	130.7	"	x
225 629		x	1½	010	565	110.0	1.145	x
225 629		x	"	015	611	117.5	"	
243 923		x	"	023	609	118.2	"	
243 924		x	"	021	611	116.5	"	
255 229		x	"	020	616	118.3	"	
255 228		x	"	016	620	118.5	"	
180 126		x	"	020	610	119.8	"	
180 127		x	"	020	608	119.5	"	
244 507		x	"	017	619	118.0	"	x
244 508		x	"	016	620	116.8	"	
198 181		x	"	025	607	122.5	"	
198 182		x	"	019	617	122.5	"	
239 231		x	"	019	608	113.5	"	x
239 232		x	"	018	624	111.8	"	x
268 249 new	x		1⅜	010	563	103.8	.972	
201 047	x		"	014	547	105.3	"	x
226 505	x		"	014	549	101.7	.957	
226 506	x		"	015	547	101.8	"	
238 416		x	"	017	543	101.0	"	
238 417		x	"	016	542	100.8	"	
190 539		x	"	013	539	97.8	"	
190 540		x	"	012	541	99.8	"	
245 588		x	"	017	539	98.5	.950	
245 589		x	"	017	546	98.0	"	
244 526		x	"	014	538	97.0	.940	
244 527		x	"	018	541	97.5	"	
267 356 now	x		"	010	549	100.0	"	
216 487		x	"	017	533	90.0	.912	
216 488		x	"	016	531	89.8	"	
234 760		x	1¼	017	478	85.0	.817	
234 761		x	"	018	491	83.4	"	x
203 710		x	"	018	494	84.6	"	
203 711		x	"	017	494	85.5	"	
236 287		x	"	016	490	82.4	"	
236 288		x	"	018	489	82.8	"	
222 294		x	"	015	500	83.8	.810	
222 295		x	"	015	500	84.7	"	
220 189		x	"	012	463	74.0	.796	
220 190		x	"	013	483	82.3	"	



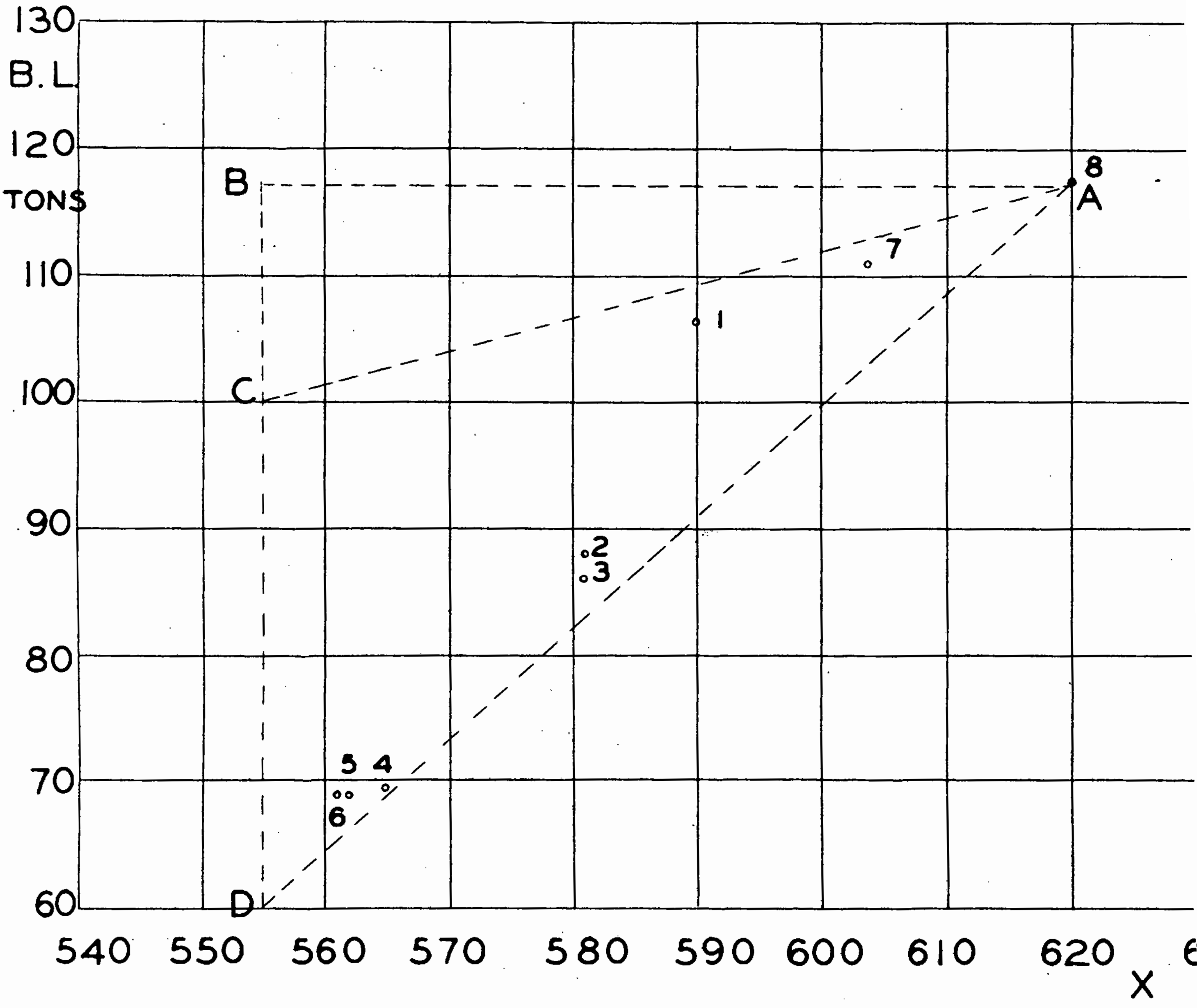
CALCULATED AREA AGAINST X

FIGURE 14 B

TABLE II (Contd.)

Coil No.	Class of steel		Diam.	R	X	B.L.	Calculated area.sq.in.	Collarbreak
	128/140	123/134.	Ins.					
206 333		x	1¼	014	478	79.0	.796	
206 334		x	"	016	480	78.2	"	x
242 157		x	"	016	486	82.0	"	
242 156		X	"	016	486	82.3	"	x
190 810		x	1-3/16	008	445	75.4	.721	x
190 811		x	"	008	445	75.4	"	x
234 820	x		1⅛	012	443	72.7	.688	
237 244	x		"	014	429	72.0	"	
265 622 new	x		"	009	432	69.5	.660	
268 230 new		x	1-3/32	003	378	53.3	.525	
267 389 new		x	1	005	376	52.1	.499	
201 177		x	"	007	369	51.7	.492	
245 286		x	15/16	007	354	48.5	.468	
268 148 new		x	13/16	002	298	33.0	.339	
265 565 new		x	¾	002	268	28.4	.280	
265 721 new		x	"	001	268	28.2	"	
243 781		x	"	002	267	27.2	"	
268 269 new		x	"	000	268	27.3	.273	
220 816	x		"	001	274	28.6	.270	x
220 817	x		"	002	275	29.4	"	

Because of the direct relationship between steel area and magnetic flux, it was thought that better correlation would be obtained if this area was drawn as a function of X. It is found difficult, however, to measure the area. For a new rope it can be calculated from the specifications. It is assumed that the area is equal to the sum of the areas of the individual wires divided by the cosine of the angle of lay of the strands and the cosine of the angle of lay of the rope. This means that the sum of the areas of the individual wires is increased by a factor of 9 per cent for compound triangular ropes and by 8% for simple triangular ropes. This calculation has been carried out for the ropes in Table II and the result plotted in Figure 14b. As expected there is some spread, but in at least one case a sample was known to have considerable corrosion. The area of this sample, marked A in the diagram, will therefore be considerably less. Two methods for the determination of the area of such samples have been tried. In the first a length of the sample is cast in white metal or a plastic, cut perpendicular to its axis, polished and photographed. The photograph is enlarged and the area may be measured. In the second a length of the rope is cut using a carborundum cutting wheel. It is then accurately measured as to length and weight; the results allow the area to be calculated. Examples will be given in later sections.



B.L. VERSUS X FOR ROPES
SHOWING CORROSIVE WEAR

FIGURE 15

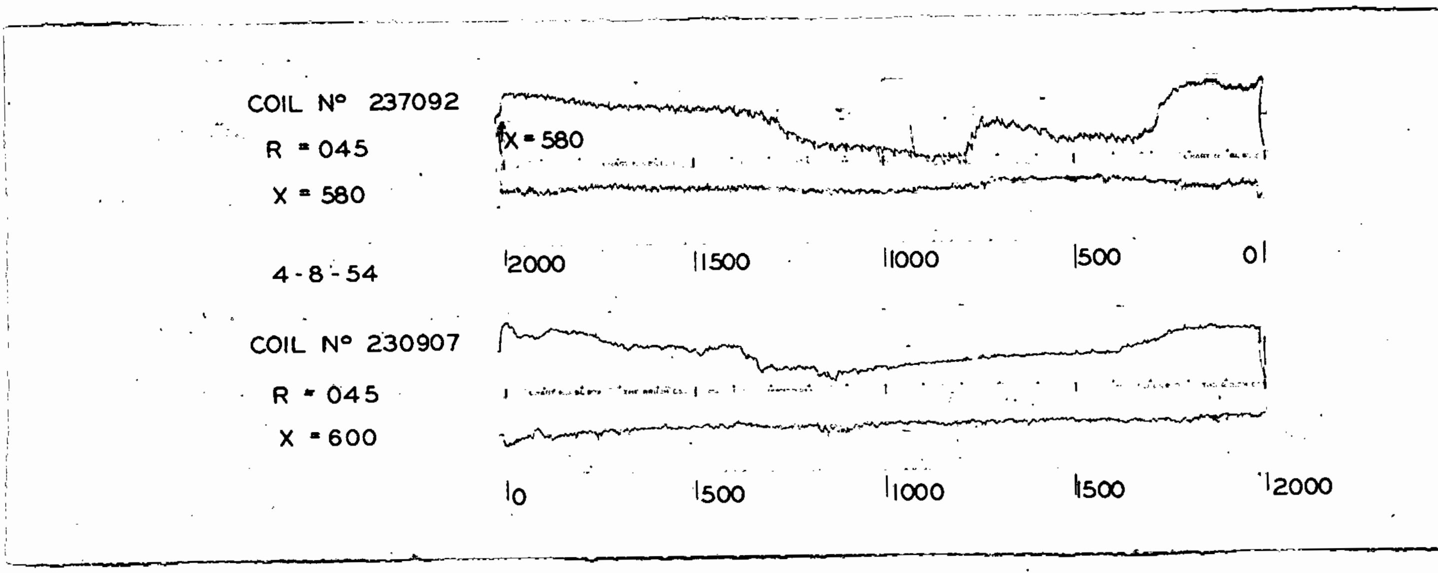


Figure 15b.

It will be noticed that the graph of Figure 14b curves upwards. This is due to the demagnetizing effect mentioned in Section 2.1. In the absence of the demagnetization the graph would be a straight line, the slope of which depends on the dimensions of the coil and the permeability of the steel. The dotted line in Figure 14b has been calculated for a permeability of 44, as measured for the steel used in the manufacture of the ropes used in the tests.

If it should be required to diminish the demagnetizing effect, this can be simply done by using larger coils or a long solenoid.

3.22 Magnetic tests on samples showing corrosive wear.

While the work described in the previous section was in progress, some samples of a rope showing excessive external corrosive wear were received and tested. The results of this test are shown in Table III and Figure 15.

Table III

Coil No.	Specimen No.	Distance from splice	Readings		Breaking load tons(2000 lb)	Original B.L.
			R	X		
237 092	1	at splice	017	604	111.0	115.5
	2	377'	013	581	88.1	
	3	493'	015	581'	86.0	
	4	862'	016	565	69.5	
	5	895'	017	562'	68.0	
	6	933'	016	561	68.0	
230 907	7	797'	016	590	106.3	117.3
	8	drum end	016	620	117.3	

In Figure 15 a line A-C has been drawn. This corresponds to a section of the line drawn through the points of Figure 13. The vertical distance between A-C and the horizontal line A-B should give the approximate reduction in B.L., but only three samples showed B.L. in agreement with this expectation. To find the explanation for the different behaviour of the other samples, specimen 5 was cast in plastic, cut, polished and photographed (Figure 16). These ropes had originally six strands of ten out wires, .126" dia, twelve inner wires, .060" dia, six core wires, .052" dia, and three filler wires .038". It may be seen from Figure 16 that most of the reduction in area has taken place in the three or four outer wires at the surface of the rope. If we assume that in each strand three outer wires have lost half their area, then the total loss will be 1/2 x 3/10 x 75% = 11.25%, as the ten outer wires represent 75% of the

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Figure 16. Cross-section of specimen 5, Coil No 237 092.

total area. The corresponding loss in B.L. would be 11.25% of 117 tons = 13 tons. The actual loss in B.L. is much more and can be explained by the fact that each of the outer wires comes to the surface of the rope approximately every eight inches and will, at that point, be reduced in area by approximately 50%. The loss in B.L. will therefore be 1/2 x 75% x 117 tons = 44 tons, giving a breaking load of 73 tons. In Figure 15 a line A-D is drawn, such that BD = 10/3 BC. Five of the samples have breaking loads which are near to the line A-D.

Records of these ropes are shown in Figure 15b. The first record, Coil No. 237 092, was taken with the conveyance coming up, the other going down. In both cases only 2000 feet of rope was tested.

Two samples of Coil No. 237 092 were used to determine the steel area by measuring the length and weight of short sections, this was compared with similar measurements on a length of new rope of the same specifications. The results are shown in Table IV.

Table IV

Coil No.	Distance from splice	Area sq. in.	X Reading	Length of lay, cms.
237 092	(956'	1.015	562	23.8
	(drum end	1.120	614	25.5
286 429	new rope	1.120	625	26.6

The calculated area for this rope is 1.145 sq. in. as shown in Table II.

The drum end sample has the same area as the new rope, but the sample subjected to corrosive wear shows a reduction of 9.4% in area.

Determination of the area of the wires in Figure 16 using a planimeter gave an average reduction of 12% for the outer wires, which is 9% for the rope. In addition some of the inner wires show some corrosion, giving a total reduction of over 9%.

3.23 Length of lay as an indication of deterioration.

At this stage the author's attention was drawn to work done at the Ontario Research Foundation in Canada (ref. 10). There it was found, first on mathematical grounds and later proved in laboratory tests, that "Lay length decreases with deterioration". It was decided to measure lay length whenever the magnetic

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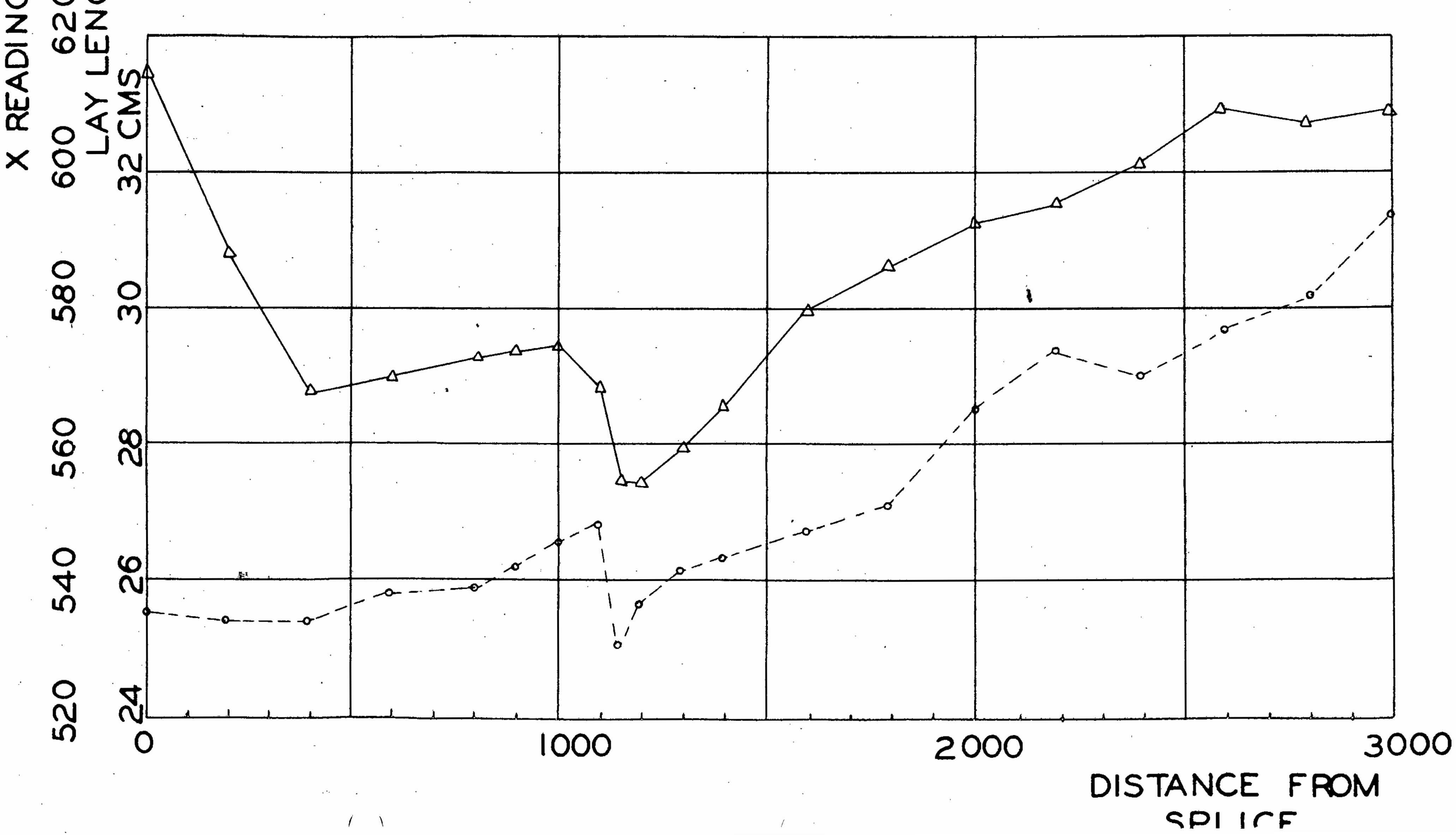
X READING AND LENGTH OF LAY AGAINST DISTANCE FROM SPLICE.

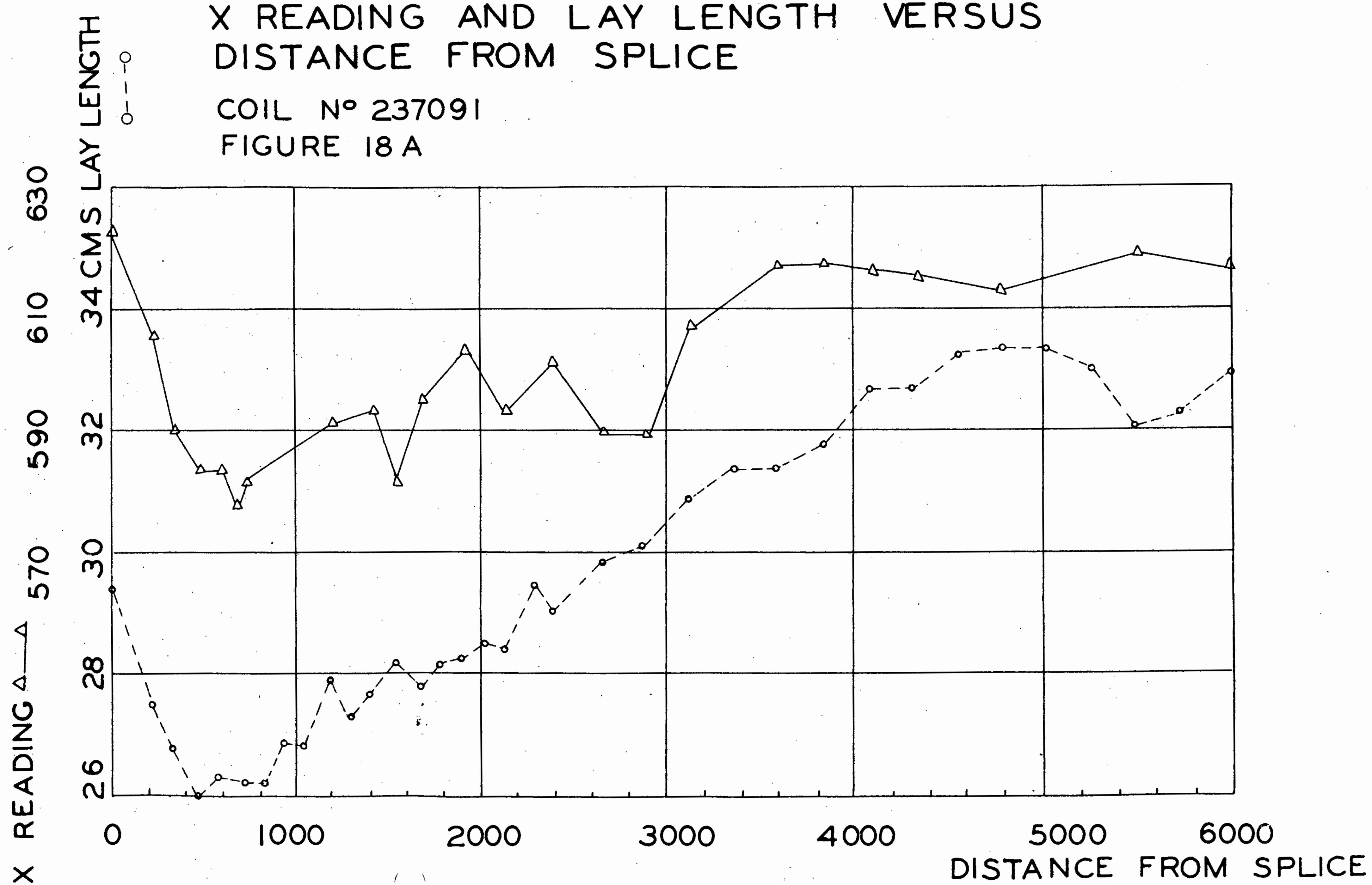
COIL Nº 234553
FIGURE 17.

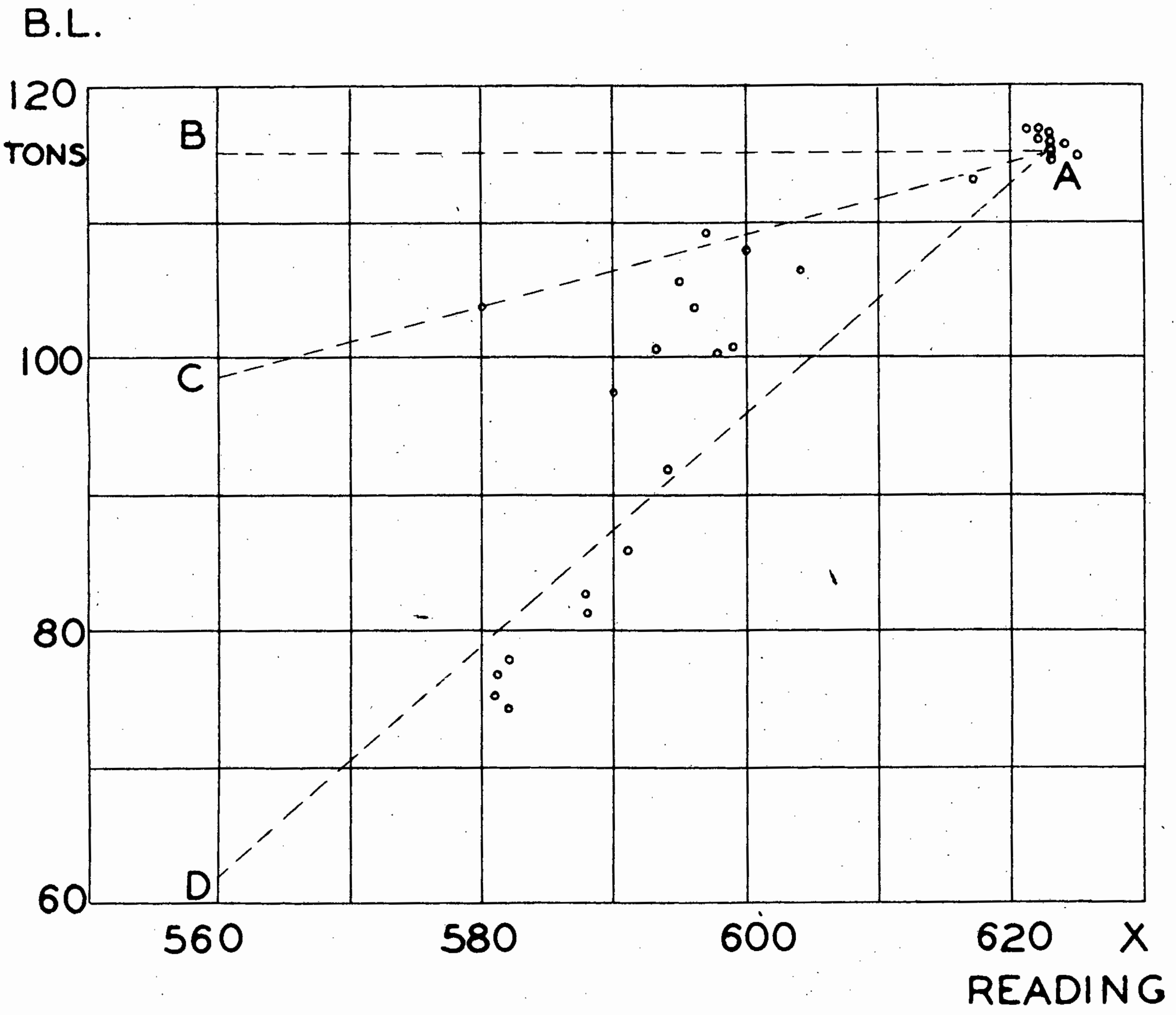


X READING AND LAY LENGTH VERSUS DISTANCE FROM SPLICE

COIL Nº 237091

FIGURE 18 A





B.L. AGAINST X

COIL N° 23709~~2~~1

28 SAMPLES

FIGURE 18 B

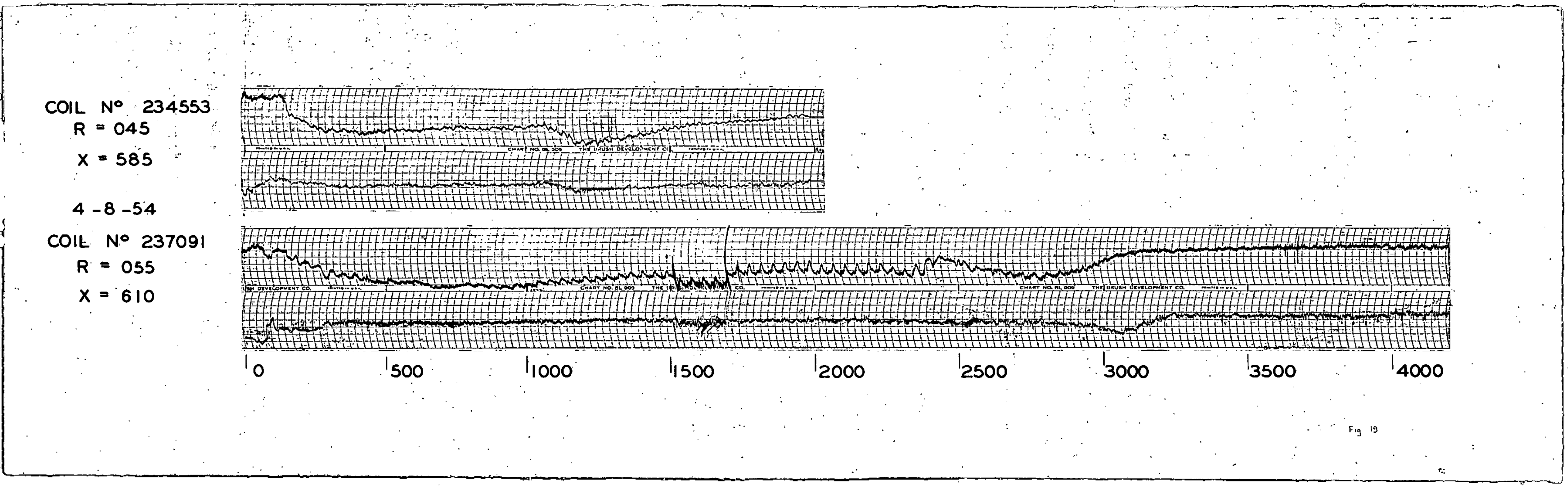


Figure 19, Charts.

test indicated corrosion, as an additional check. Some samples will be shown.

In Figure 17 length of lay and X reading have been plotted against distance from splice for a Free State rope, Coil No. 234 553, known to have excessive corrosive wear. Two samples of this rope, cut between 200' and 300' had B.L's of 108.8 and 107.7 tons, and two samples cut between 1200' and 1300' broke at 71.3 and 76.4 tons. The minimum lay length of 25.1 cm coincides with the minimum X reading of 555 at ~~1500~~ 1150 feet. The points in Figure 17 represent measurements on the rope in the shaft some weeks before the rope was discarded. These measurements were taken every 200 feet, except for a section from 800 to 1400 feet where they were taken more frequently. For the sake of clarity the points have been connected by straight lines, this does not mean that there is no change of lay length or X reading between the points.

Figure 18a shows a similar diagram for another rope, Coil No. 237 091; X reading and lay length were measured while the rope was run through a rope making machine at the rope factory. This was done with the purpose of obtaining constant tension in the rope while the measurements were carried out, in addition it was thought that better sampling of the rope could be done this way. Unfortunately a number of labels became detached during transport to the Government Mechanical Laboratory and were then attached to the wrong samples. Because of this mishap, values of B.L. have not been plotted in Figure 18a, but against X readings taken at the Government Mechanical Laboratory in Figure 18b. Lines A-B, A-C and A-D have been drawn as in Figure 15, except for a small displacement to the right to allow for the higher X reading obtained for the unworn portion of the rope and a displacement downwards to allow for the lower original B.L. of 115.2 tons. Of the 28 samples, 9 are near point A, i.e. the B.L. differs little from the original B.L., 5 points are near line A-C, for these the reduction of B.L. is proportional to the reduction in area, 8 points are near A-D, indicating external ~~ex~~ corrosive wear, while the remaining 6 samples show an intermediate condition.

The lay length diagram of Figure 18a shows a minimum from approximately 400 to 1000 feet, this coincides with a minimum on the X diagram. However other minima of the X reading do not coincide with minima of lay length.

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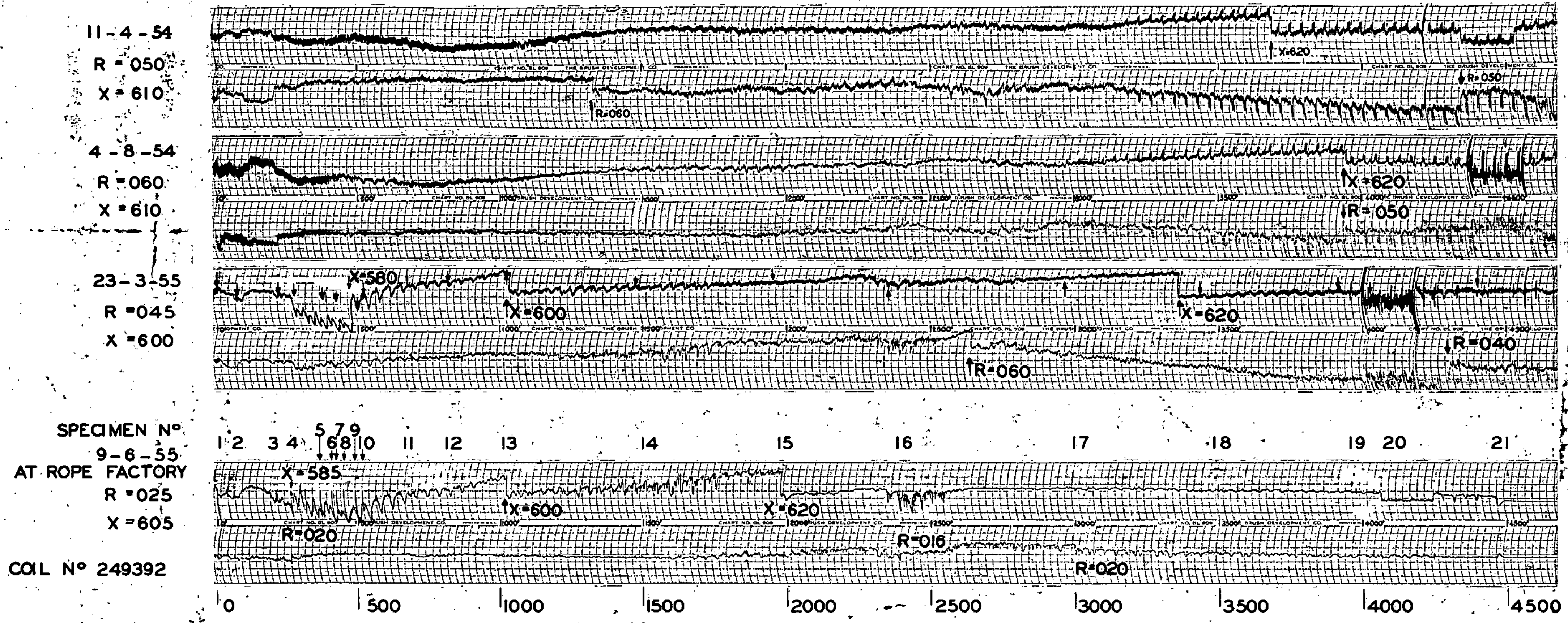

Fig 20a.

Figure 20a, Charts.

One possible reason may be seen from Figure 18b, where 5 points are near the line X = 580, of these one lies on the line A-C, but the other four are below A-D; for these the lay length would be shorter as for the first.

Records of these ropes are shown in Figure 19. Of the first rope only 2000 feet was recorded.

3.24 A rope with corrosive wear.

Figure 20a is a reproduction of four records of the same rope, Coil No. 249 392, which had the same specifications as the ropes in section 3.22. It was taken into service on the 13th September 1953 and discarded on the 3rd April 1955. The first record was made after seven months' service and shows a decrease of 3% on the X trace at 800'; beyond 3000' peaks typical of condition (i), section 3.2, occur at turn intervals. As the peaks are in pairs, the rope must have been pulled in at the drum end at least once. The decrease on the X trace over nearly 200' from 4350' from the splice is caused by a permeability change and will be discussed in section 3.4, it occurs again in the other three records. Due to slip between rope and the pulley of our apparatus, as well as test lengths being cut at the splice end of the rope, this decrease is not shown on the records at the same position. In the second record, taken 4 months later, the decrease of 3% ox X has affected the rope from 300' to 800'; at 500' small peaks indicative of internal corrosion may be seen at intervals corresponding to the circumference of the drum. The double peaks from 3000' onwards are nearly the same. The R trace is slightly lower on the second record up to about 3000'. The third record, taken shortly before the rope was discarded, shows a marked general decrease of X of at least 5% from 280' with several peaks at turn intervals indicating additional internal corrosion. The double peaks have disappeared, which shows that the slight opening up of the rope has gone.

The R trace is considerably lower up to 1500' compared with the previous records. After the record was made the rope was inspected visually at a point near 500' from the splice and excessive corrosive wear of the external wires was found. This coupled with the X reading of X - 570 and taking into account the results of section 3.22 as shown in Fig. 15, suggested a breaking load at this point of 70 tons. The original B.L. being 119.2 tons, this would represent a

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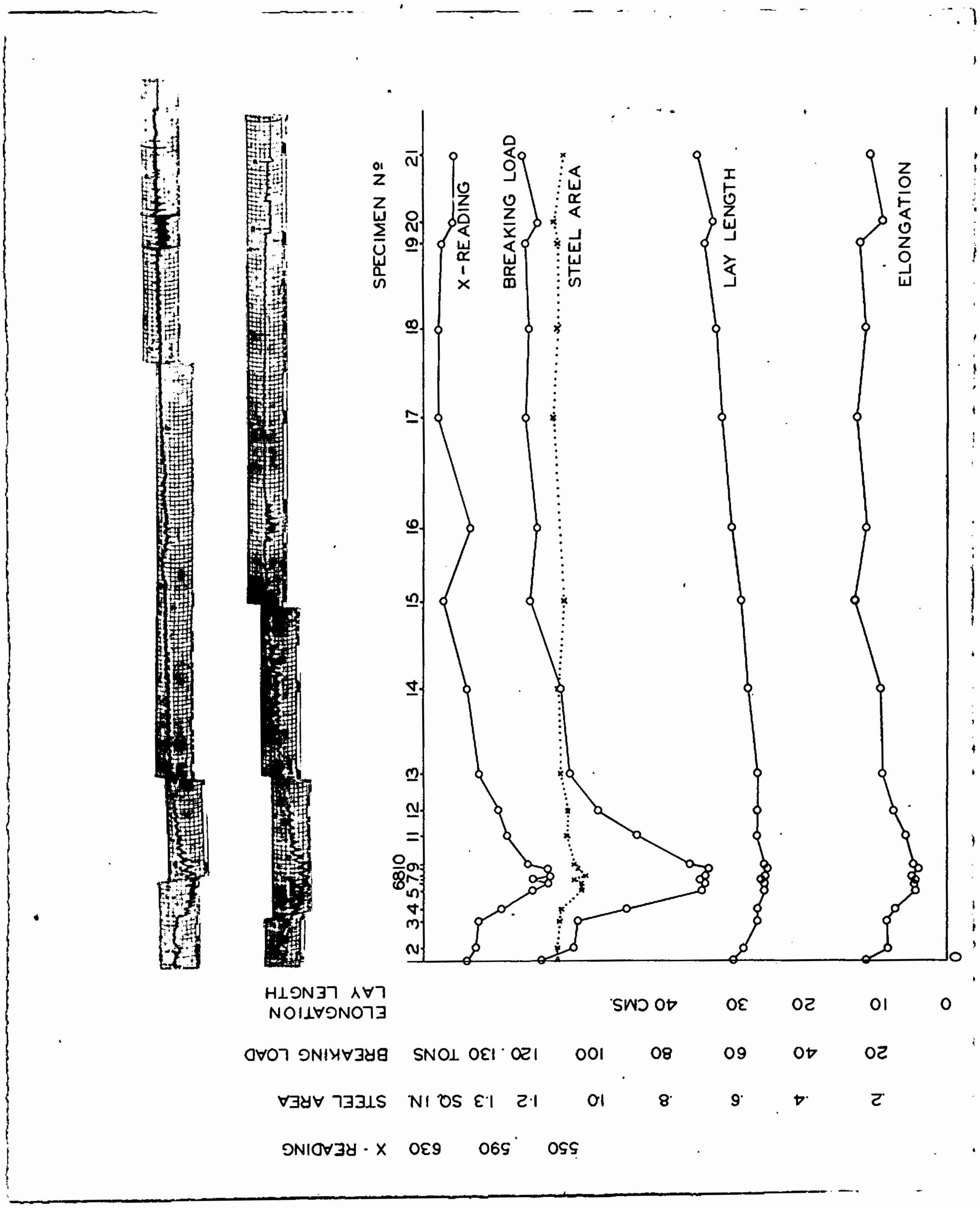


Figure 20b, X reading, steel area, breaking load, lay length and elongation against distance from splice.

At the top the X traces of the charts taken on 23/3/55 and on 9/6/55 have been reproduced. At points where the X control has been readjusted, the charts have been cut and put together to give continuous traces.

reduction of over 40%. After being discarded, the rope was despatched to the rope factory, where another record was made, and samples were cut for B.L. test The record made at the factory is similar to the third, except for a considerab lower R trace, caused by the lower tensile stress.

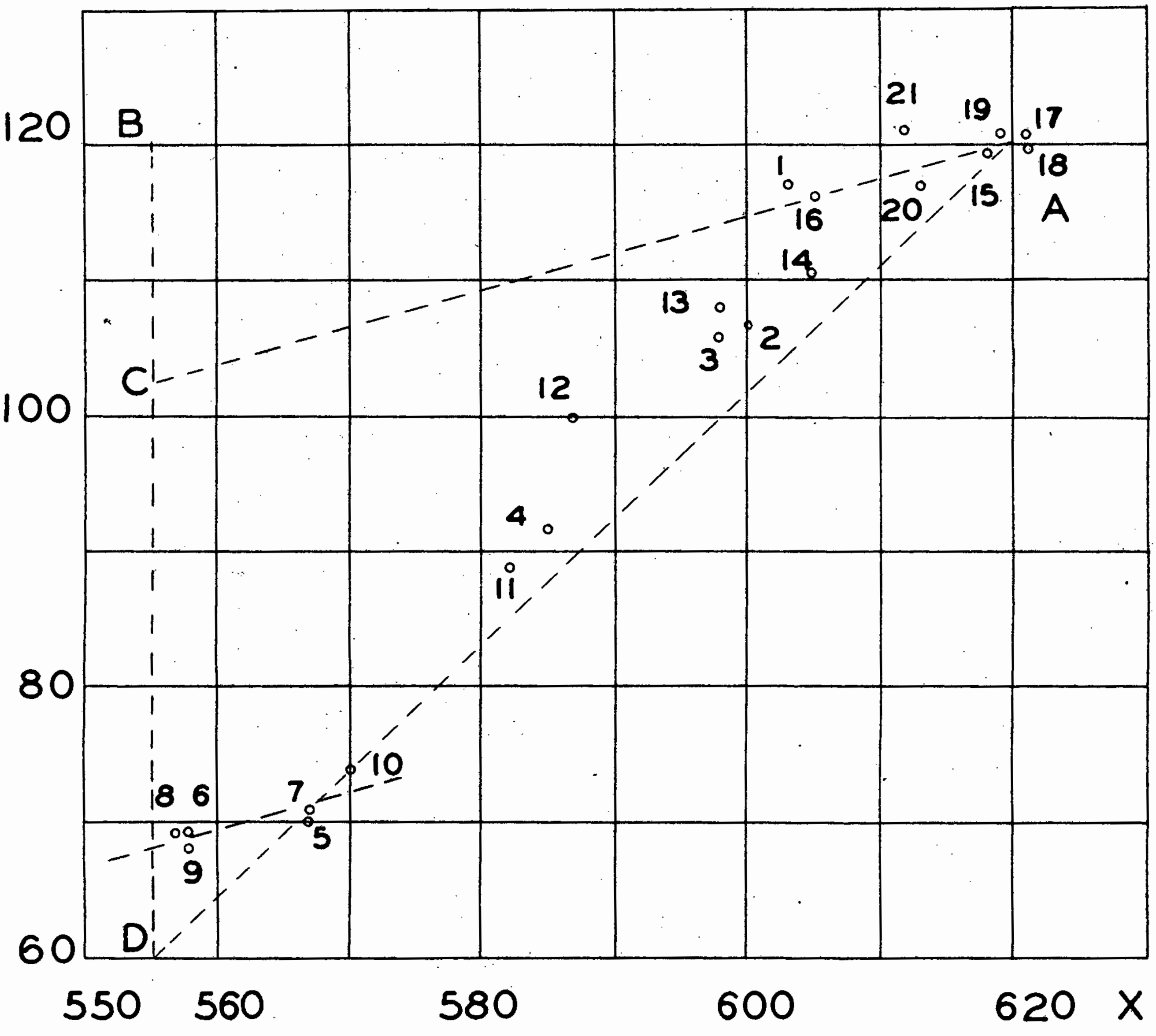
After the B.L. tests, sections of approximately one foot were cut from the samples and their length and weight determined; this enabled us to calculate the cross-sectional area of the samples. Before weighing, the sisal core was removed and each strand - not each wire - was cleaned.

Table V.

Specimen No.	Distance from splice. (feet)	R Readings	X Readings	B.L. (tons)	Area (sq.in.)	Lay length (cms.)	Elongation cms
1	18	025	605	116.0	1.113	30.5	11.6
2	90	022	600	106.8	1.115	29.0	8.4
3	240	020	598	105.7	1.109	27.0	8.5
4	288	018	585	91.5	1.106	27.0	7.4
5	396	022	567	70.0	1,046	26.0	4.4
6	438	020	558	69.0	1,047	26.0	4.6
7	450	020	567	70.5	1.066	26.4	4.5
8	480	020	557	69.0	1.031	26.0	4.8
9	516	020	558	68.0	1.054	25.6	4.1
10	546	020	570	73.5	1.066	26.0	4.7
11	702	020	582	88.7	1.088	27.1	5.9
12	840	020	587	99.8	1.084	27.0	7.6
13	1050	020	598	108.8	1.106	27.0	9.2
14	1580	018	605	110.5	1.111	28.5	9.5
15	2040	020	618	119.2	1.097	29.4	13.0
16	2460	016	603	117.2	-	30.7	11.5
17	3090	018	621	120.5	1.126	32.2	12.9
18	3600	022	621	119.7	1.112	33.0	11.7
19	4080	019	619	120.5	1.113	34.6	12.3
20	4200	018	613	117.0	1.123	33.4	9.1
21	4590	017	612	121.5	1.097	35.7	10.8

Table V shows the result of these tests. In this table the distance from splice was the reading of the distance counter of the rope-making machine, not distance on the records; R and X readings were those taken when the sample were marked at the rope factory, the lay length was measured at the same time; elongation was measured from the load-elongation diagrams as supplied by the Government Mechanical Laboratory after the B.L. tests.

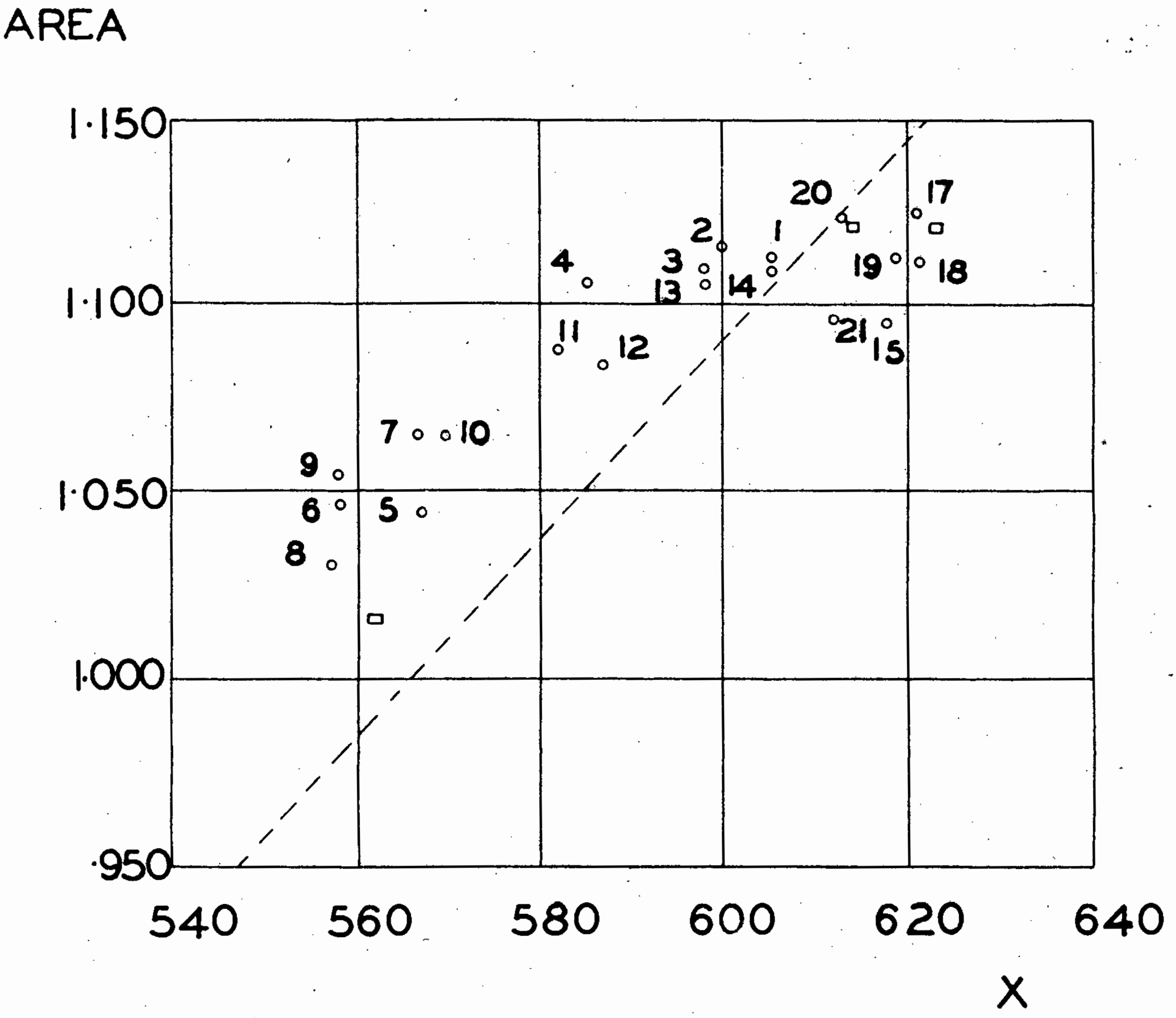
These same results have been plotted against distance in Figure 20b, in Figure 20c values of B.L. are plotted against X readings, in Fig. 20d steel area against X and in Fig. 20e B.L. against steel area.



B.L. VERSUS X

COIL N° 249,392.

FIGURE 20 C

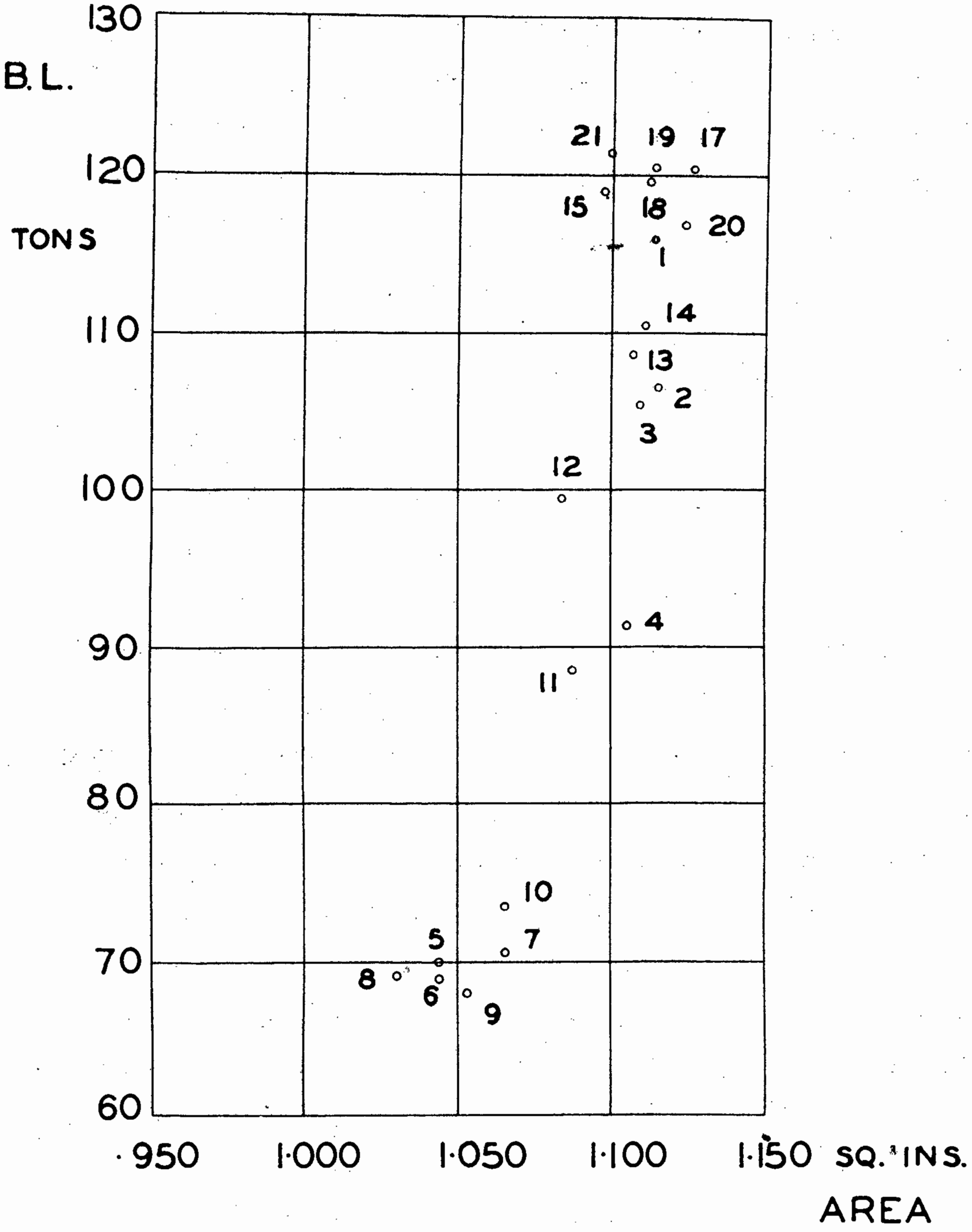


STEEL AREA AGAINST X

FIGURE 20 D

○ = POINTS OF TABLE V

□ = POINTS OF TABLE IV



B. L. VERSUS AREA

FIGURE 20 E

Samples 4 to 12 are all considerably reduced in strength; B.L's of approx. 70 tons being recorded for samples 5 to 10. It is significent that these show little difference in B.L, as 5, 7 and 10 were cut between peaks and 6, 8 and 9 at internal corrosion peaks. The reason for this is shown in Fig. 20c, where points 5, 7, and 10 lie on line A-D, and points 6, 8, and 10 lie on a line parallel to A-C through the centre of 5,7 and 9. This illustrates the assumption that the general decrease is caused by external corrosive wear and the additional peaks by internal corrosion.

In Figure 20d a straight line is drawn through points X = 620, area = 1.145 sq. in. and X = 550, area = .957 sq. in. from Fig. 14b for 1/2" and 1 3/8" dia. ropes. The points for the samples of Table V are at a considerable distance from that line, but show a similar tendency. It is thought that a possible reason is - errors in area determination due to the samples having been subjected to breaking load tests beforehand. As some samples of other ropes were available, the area of these has been measured and the results given in Table IV; Section 3. 22, plotted in Fig. 20d, where they are nearer to the line in Fig. 20d. The main object of the area determination was to prove the statement that the X reading is a function of the area, and that the reduction of B.L. is not always proportional to reduction of area. If we compare samples 8 and 10, it is found that the X reading is reduced by 10.3%, the area by 8.4%, and the B.L. by 42.7% The predicted reduction of area for the same reduction of X reading of 10.3% is approximately 15%, nearly twice the measured reduction. This will partly be due to errors in area determination, but partly to the fact that the demagnetizing factor for a worn rope will be different to that of a new rope, of which the area is the same as that of the worn rope. This means that the slope of the line in Fig. 20d will be somewhat different.

The lay length drops by nearly 5 cms over the first 500' from the splice and is small for samples 5 to 10. Similarly elongation is very small for the same samples.

3.25 Prediction of breaking load for rope with internal corrosion.

Recently a rope was discarded which had shown peaks characteristic of internal corrosion. The rope which was put into service on the 14th February 1954 and taken off on the 27th August 1955 had the following specifications:- nominal diameter 1 3/4", six strands Langs lay, each strand 12 outer wires of .126" over 12 wires of .074" over a triangular coreof 6 wires of .068" and 3

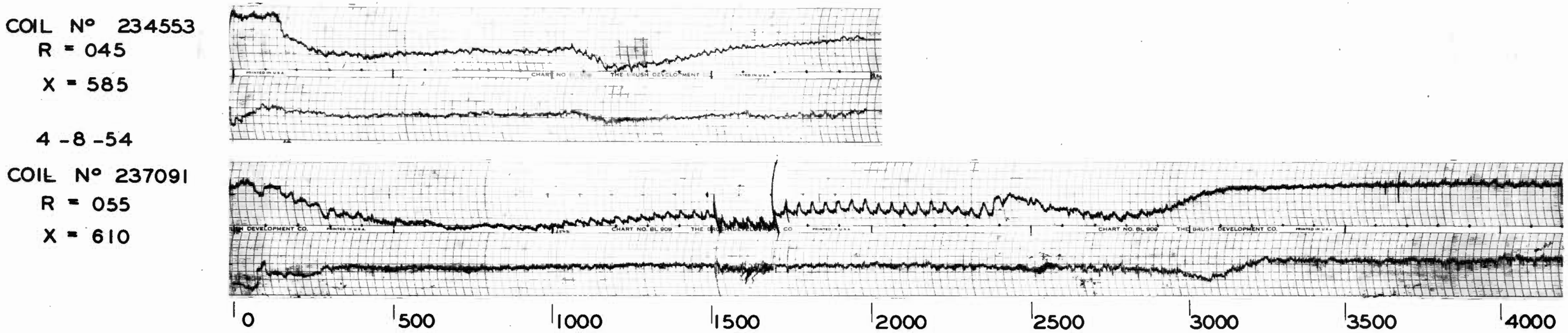


Fig 19

Figure 19, Charts.

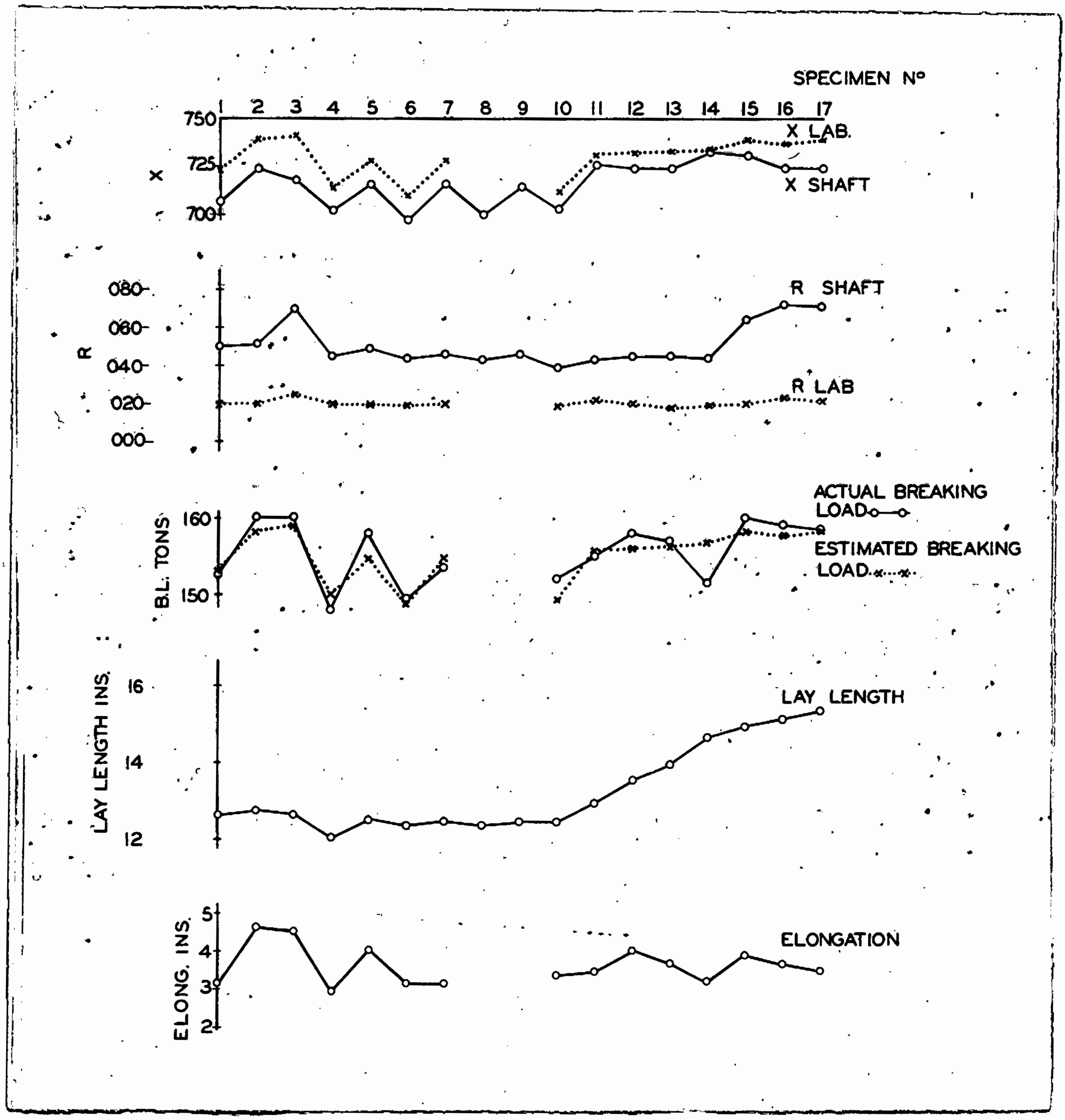


Figure 21b, R and X reading, estimated and actual breaking load, elongation and lay length for rope with internal corrosion.

Figure 21c. Typical breaks in wires from sample 14. The wire on the left broke at 2400 lbs, the other at 3400 lbs. The first wire showed severe plastic deformation near the point of fracture.

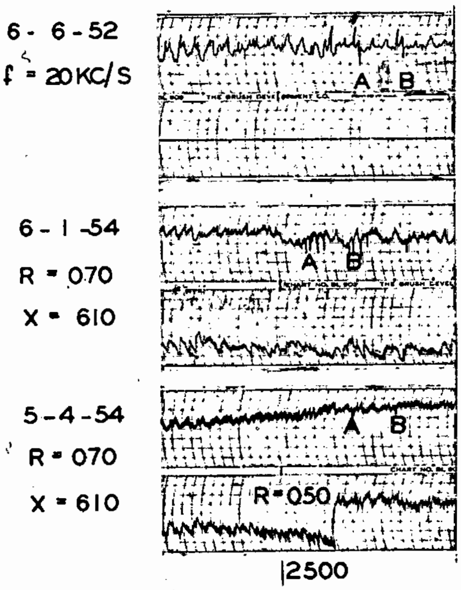


Figure 23. Chart of rope with peaks due to crushing.

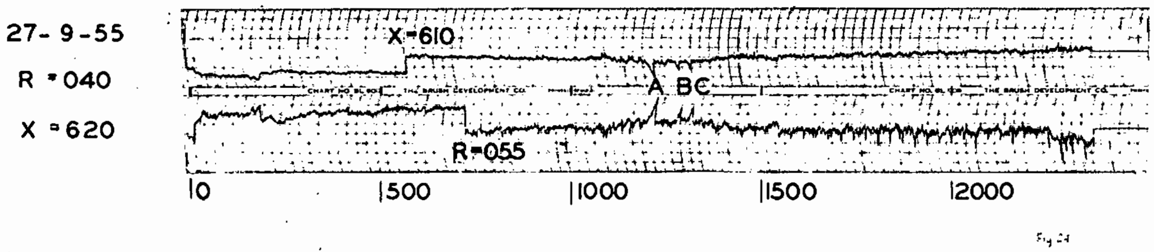


Figure 24. Chart of rope with plastic wear due to crushing.

filler wires of .050", calculated area 1.374 sq. in., class of steel 128/140 tons pe per sq. in., original B.L. 158.7 tons. Five records of this rope are shown in Figure 21a, the first of which shows little variation on the X and R trace, except for some peaks at turn intervals on the R trace from 250' to 700'. As the peaks are a decrease of R reading, it follows from condition (1) Section 3.2, that the rope has opened up or untwisted slightly at these points, which will correspond to crossover points in the top layer on the drum. In the second record only a few of these peaks can be seen, but there is a general reduction of the R trace, which has extended in the last three records from 225' to beyond 2500'. This may indicate that the core lubrication is deficient over this length of rope. The X trace in the last records has a number of peaks at turn intervals, which coupled with the low R reading indicate internal corrosion. Just before the rope was taken off, X and R readings as well as lay length measurements were taken at 17 points in the rope, as indicated on the last record. These points were taken as the centres of samples of which 15 were tested for B.L. Further X and R readings were taken prior to the B.L. tests. These figures were used in conjunction with Figure 14a to predict the B.L. Results are given in Table VI.

Table VI

Spec. No.	Distance from splice.	R shaft	R Lab.	X shaft	X Lab.	B.L. Estim.	B.L. Meas.	Lay length in.	Elon. in
1	10 ft.	050	020	707	723	153.0	152.5	12.62	3.12
2	70	052	020	724	739	158.3	160.2	12.75	4.62
3	200	070	025	718	741	159.0	160.2	12.69	4.5
4	235	045	020	702	714	150.0	148.0	12.06	2.94
5	265	049	020	716	728	154.7	158.0	12.50	4.0
6	285	044	019	697	710	148.7	149.5	12.31	3.12
7	300	046	020	716	728	154.7	153.5	12.44	3.12
8	330	043	-	700	-	-	-	12.37	-
9	360	046	-	715	-	-	-	12.44	-
10	515	039	019	703	712	149.3	152.0	12.44	3.37
11	1000	043	022	726	731	155.7	155.0	12.94	3.44
12	1500	045	020	731	732	156.0	158.0	13.56	4.0
13	2100	045	018	731	733	156.3	157.5	13.94	3.69
14	2500	044	019	733	734	156.7	151.3	14.62	3.19
15	3000	064	020	731	739	158.3	160.0	14.94	3.87
16	3175	072	023	724	737	157.7	159.0	15.12	3.62
17	3500	071	021	724	739	158.3	158.5	15.37	3.44

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The connection between R reading and lubrication may be seen from Table VII, where the R reading in the shaft is compared with the remarks

Table VII

Spec. No.	R reading shaft	Lubrication
1	050	Deficient on heart. Dry under crown.
2	052	Deficient to dry on heart and under crown.
3	070	Fair to deficient on heart. Deficient to dry under crown.
4	045	Deficient to dry on heart.Dry under crown.
5	049	Dry on heart and under crown.
6	044	Dry on heart and inside strands.
7	046	Deficient to dry on heart and under crown.
10	039	Dry on heart. Deficient to dry under crown.
11	043	Dry on heart and under crown.
12	045	Dry on heart. Fair under crown.
13	045	Dry on heart and in places inside strands.
14	044	Dry on heart and in places inside strands.
15	064	Deficient on dry on heart. Good to fair inside strands.
16	072	Good to fair on heart, otherwise good.
17	071	Good.

on lubrication from the test certificates. Sample 3 has higher R reading and better lubrication than 2 abd 4, while 15, 16, and 17 are better than 13 and 14.

In Figure 21b R and X readings, estimated and actual B.L. are plotted against specimen numbers. The X reading in the shaft is always less than that in the laboratory. The largest differences occur where the R readings have the largest differences. This will be further discussed in Section 3.3.

Except for specimen 14, the difference between estimated and actual B.L. does not exceed 2.1% For sample 4 which has the lowest B.L. the error is only 1.2% For this sample the reduction in B.L. is nearly 7% In sample 14 which broke 4.7% below the original B.L., instead of 1.3% as predicted, eight outer wires were found to be split longitudinally after the B.L. test. This sample was further examined at the laboratory of the rope factory, where it was found that split wires had lost approximately 1000 lbs. in tensile strength. The records do not indicate split wires, but as sample 14 was taken at a point of plastic wear, as shown in the last record of Fig. 21a, visual inspection of such points may well reveal split wires.

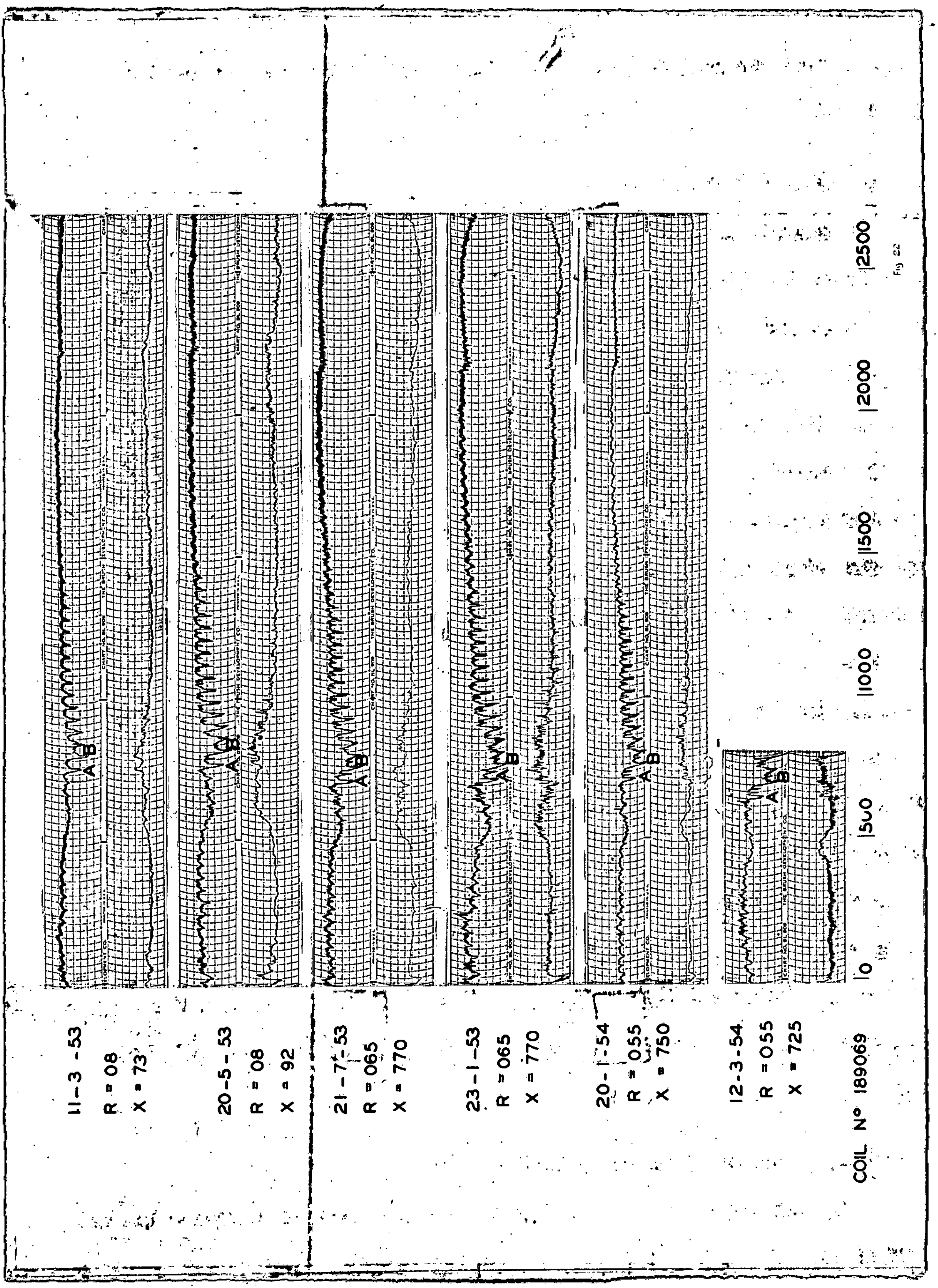


Figure 22. Chart of rope with plastic wear.

Graphs of lay length and elongation are also shown in Fig. 21b. Differences in lay length are small, but the smallest value occurs for the sample with the smallest B.L. Sample 14 does not show a reduction in lay length.

3.26 Rope with severe plastic wear.

An example of plastic wear as indicated by condition (ii), section 3.2, is given in Figure 22, where six charts of a rope, coil No. 189 069 are shown. This rope which was put on on the 4th February 1951 and discarded in April 1954, has the same specifications as the rope in Section 3.25. The records have peaks of decreased X and increased R reading at turn intervals from 770' onwards. The first two marked A and B on the charts correspond to the crossover points between top and second layer. Up to the time the first record was taken, this rope was pulled in at the drum end every six months by approximately six feet. Afterwards it was pulled in by 15 feet in April, June and October 1953. As a result a new smaller peak appears between points A and B in the 2nd, 3rd and 4th records and a second in the last two records. The diameter at point B was 1/8" below normal in April 1953, but after pulling in at the drum had shifted it away from the crossover, further reduction of diameter over the next year was less than 1/64".

Two samples cut near point B broke at 146.0 and 144.8 tons, compared with the original B.L. of 160.0 tons, the X readings prior to breaking were X = 701 and X = 697. Using the same method as in Table VI for estimating B.L., values of 145.7 and 144.3 are obtained. At the time of the test this method was not known.

3.27 Other examples of plastic wear.

In June 1952 a request was received for a test on a rope which had been in service for a few months, in which the diameter at one spot had been found to be reduced by 1/16" over a distance of 8". The test was carried out with an early model at a frequency of 20 kc/sec. The first chart of Figure 23 shows part of this record. The point under investigation is marked B and is recorded as a decrease of flux, due to increase of eddy currents. A similar peak A may be seen 115' nearer to the splice, which proved to have a slightly larger reduction of diameter. At the time no reason for this could be found for these peaks, which were believed to be caused by local crushing of the rope. In January 1954 another request for a test was made, as the rope was due to come off and the points had been lost. The second chart in Fig. 23 shows part of the record made at the time. At points A and B four peaks may be seen, one peak in each group is at a distance of 115 feet from a peak in the other group. The distance between the peaks in one group corresponds to the length of rope pulled in at the drum end on three separate occasions. Even now the cause for these peaks was not discovered and at the author's request another test was made on the new rope which was installed some time later. The third chart shows part ofnthe record of the new rope. Two small peaks were found again at a distance of 115 feet, which is equal to three times the circumference of the drum. When these peaks were marked and run back on the drum, two bolt heads protruding slightly through the drum were found at a distance of three turns.

Another use of the records is demonstrated by the chart of Fig. 24. Three months before, the ropes of this hoist had to be taken off rather suddenly after the discovery of numerous broken wires at a number of points in the "dead" turns, which are never unwound except during pulling-in at the drum end. No records of these ropes had been made. As the affected portion of the rope cannot be tested with our equipment in the normal way, an indirect method was used. It was believed that the broken wires were caused by excessive crushing, in which case signs of crushing should be found in the second layer. This proved to be the case and at points A, B, and C, in the chart, plastic deformation was recorded. These points were marked, run back on the drum and in this way the corresponding points in the bottom layer were located. Visual examination at these spots revealed, in the words of the examining engineer "a degree of cold-working of outer wires at the cross-over points, such that any appreciable delay in pulling in might have resulted in broken wires.

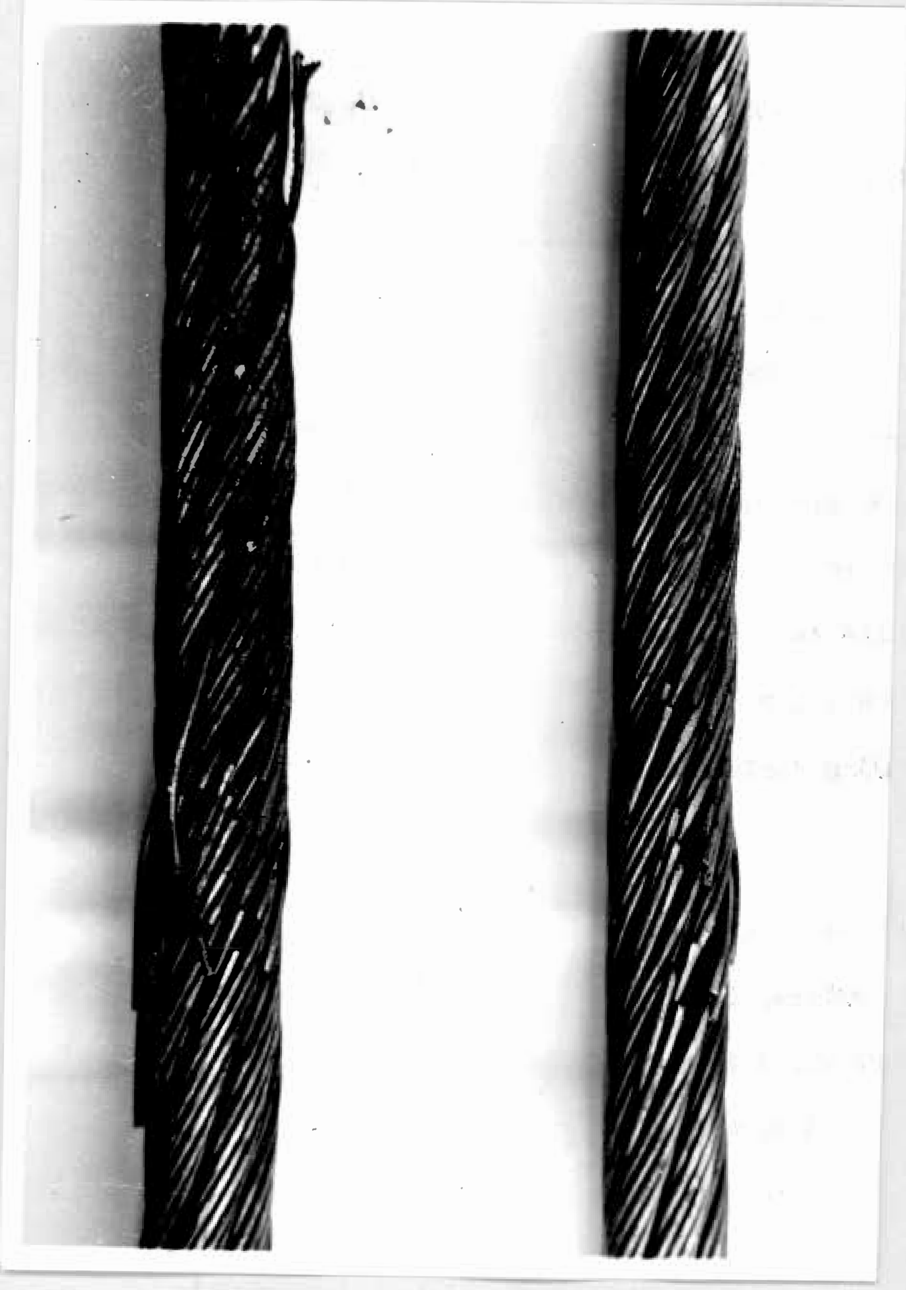


Figure 24b. Broken wires in two sections of a rope, caused by crushing. The sections are taken from the 'dead' turns of the rope.

3.28 Rope records showing little variation after long use.

In Figure 25 two records are reproduced of a pair of ropes used in an underground incline shaft. At the time ~~o~~the test was conducted the ropes had done nearly six years of service. The uniformity of the records is therefore remarkable. Variations of X do not exceed 1% and those of R are less than 1/2% Shortly after the test the rope of No. 2 compartment broke in the splice due to an accident in the shaft. New ropes were installed and the rope which broke was tested on surface. The variations were not larges than before. Thirty samples were cut for test, four next to the splice, the others at 200 feet intervals. The results of the breaking load tests are given in Table IX.

Table IX

Spec. No.	Distance from splice	R	X	Breaking load(tons)	Elongation cms.
		readings			
1	0'	010	405	56.0	4.7
2	12	010	402	60.4	5.8
3	25	010	410	62.3	7.2
4	40	010	402	60.6	5.8
5	200	010	404	61.6	5.7
6	400	011	405	62.0	6.2
7	600	011	405	62.1	6.5
8	800	011	406	62.4	6.4
9	1000	010	405	62.1	6.3
10	1200	011	406	62.1	6.2
11	1400	011	405	62.1	6.3
12	1600	011	405	62.2	6.7
13	1800	011	406	62.3	6.0
14	2000	011	406	62.2	6.5
15	2200	011	406	62.4	6.3
16	2400	011	406	62.4	6.3
17	2600	011	406	61.4	5.9
18	2800	011	406	61.9	6.4
19	3000	011	406	61.0	5.8
20	3200	011	405	61.5~~2~~	6.1
21	3400	011	406	62.0	6.5
22	3600	011	406	61.4	6.3
23	3800	011	406	61.1	6.1
24	4000	010	407	61.0	6.0
25	4200	010	407	60.9	5.9
26	4400	010	409	61.5	6.3
27	4600	010	407	62.7	7.9
28	4800	010	410	62.4	7.8
29	5000	010	409	62.6	7.8
30	5200	010	409	62.5	7.4

The variation of X is slightly larger than those in the chart. The breaking loads, with the exception of the first sample~~s~~ cut next to the point where the rope broke, vary from 60.4 to 62.7 tons. A possible reason for the lower B.L. of the first sample may be that in the accident this part of the rope was stretched beyond the elastic limit. This point will be followed up by a further experiment.

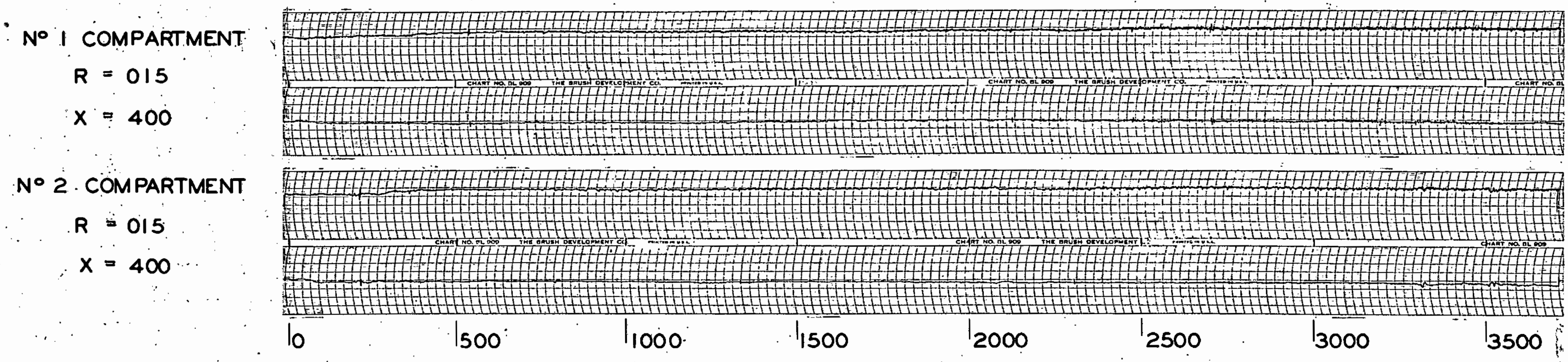


Fig 25

Figure 25. Rope records showing little variation after longuse.

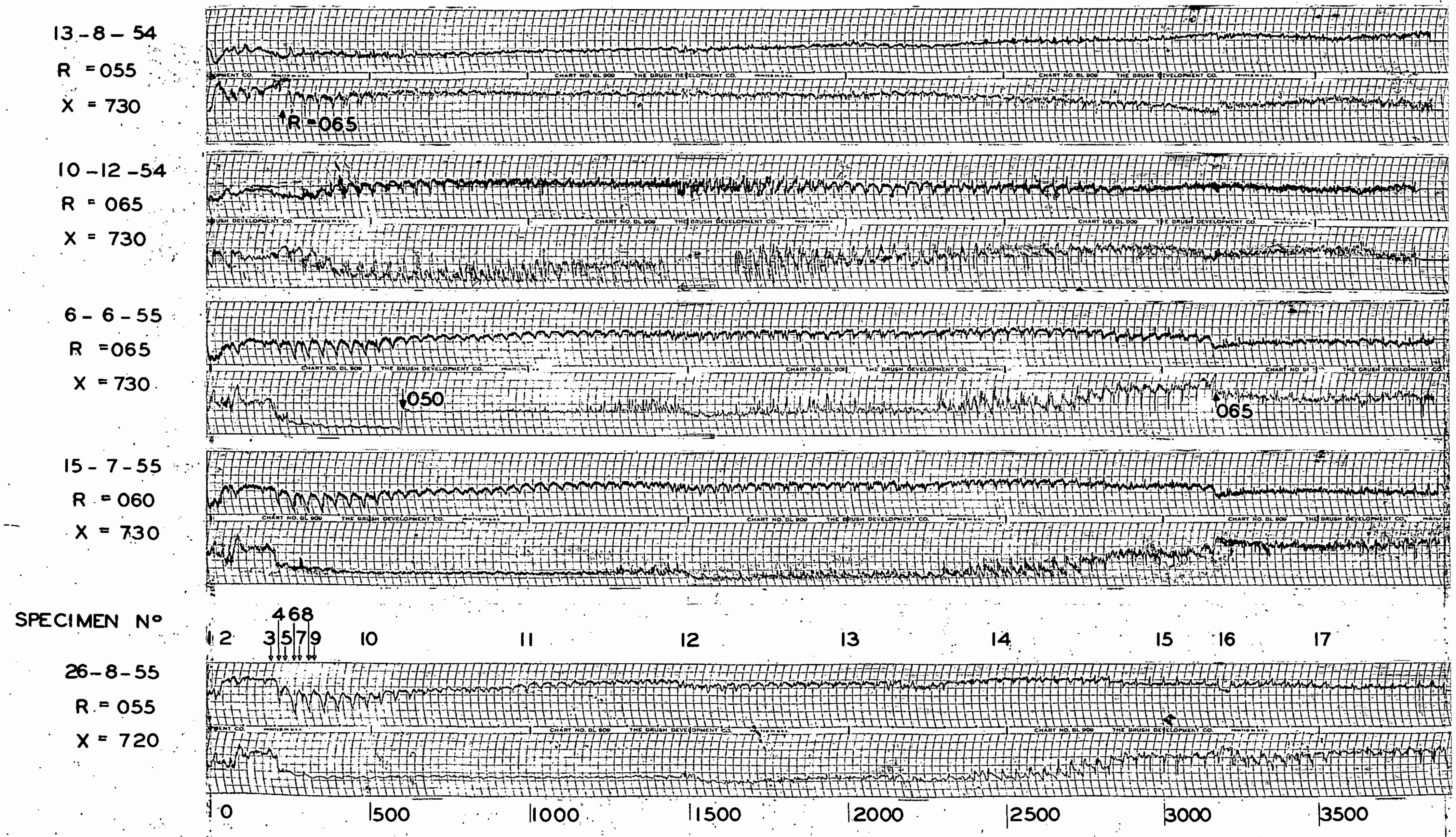


Figure 21a, Charts of rope with internal corrosion.

3.3 Effect of eddy currents.

In Section 3.3 of the first paper it was shown that eddy currents largely determine the phase-angle between magnetizing current and the voltage induced in a search coil in the rope. In the present instrument the ratio between R and X readings is the tangent of that phase-angle and therefore dependent on the eddy currents flowing in the rope as a result of the a.c. magnetisation of the rope. The amplitude of the eddy currents depends on the flux linkage and the resistance of each path. The resistance will vary with the surface condition of the wires and the area of contact between adjacent wires. The surface condition will to a large extent depend on the internal lubrication of the rope and the area of contact on the forces in the rope and on the shape of the wires. Study of charts over a period of time have shown that variations of eddy currents can be used to indicate deficient lubrication, e.g. Section 3.25, or plastic deformation, e.g. Section 3.27.

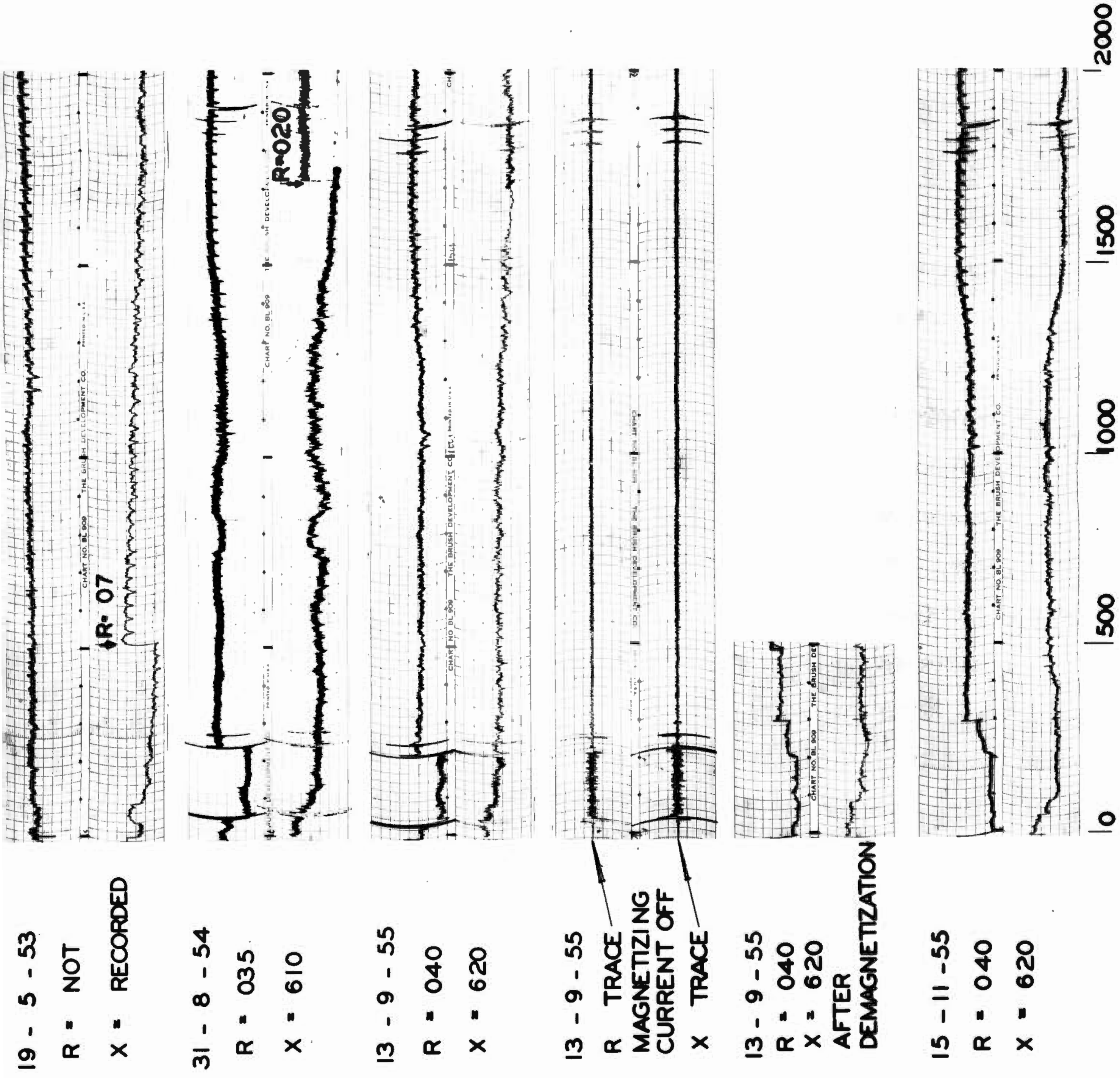
Eddy currents have also an effect on the X reading as may be seen from Figure 21b and Table VI. The X readings in the shaft are usually lower than those in the laboratory and R readings higher. The estimated B.L. figures are based on the X readings in the laboratory and it would therefore be important if these Xreadings could be accurately predicted from the X readings in the shaft. To study the influence of eddy currents on magnetic flux the following experiment was carried out. A rope sample of the same specifications was inserted in the coils and readings were taken with short circuit rings of increasing wire size. The results are given in Table VIII below.

Table VIII

Size of wire in s.c. ring	R readings	X readings	Z	Phase-angle	X/R	X_o-X
None	016	722	722	1°16'	45.0	0
27 s.w.g.	019	721	721	1°31'	37.4	1
21 s.w.g.	028	720	720	2°14'	25.7	2
18 s.w.g.	043	717½	719	3°26'	16.7	4½
16 s.w.g.	068	710	714	5°29'	10.4	12
14 s.w.g.	087	704	709	7° 3'	8.1	18

Z is the vector sum of R and X, except for the last value it never differs by more than ½% from X. But for constant permeability and steel area the X reading will drop when eddy currents rise. The relation between X readingand eddy currents for a rope in the shaft will most probably differ from ~~what~~ that for the rope sample in the experiment as the eddy current path will be considerably different.

Figure 26. Chart showing permeability change due to permanent magnetization.



of less than 50 f.p.m. In a further experiment the first 300 feet of this rope were demagnetised by moving the rope slowly through a coil, one foot long, 3" diameter and having 80 turns. This coil was connected to the 50 c.p.s. mains through a step-down transformer, giving a current of 6 Amperes. A further record was made of the first 300 feet of rope, the result is shown in the fifth chart. It may be seen that the transients have disappeared, but the X trace of the part of the rope which was demagnetised is lower than before. The sixth chart shows a further test on the same rope two months later. The transients have not reappeared and the X trace is still lower over the first 300 feet. These tests show that the original depression was caused by a decrease in permeability, due to the rope being permanently magnetised. This will occur in ropes where part of it is at rest for long periods in line with the earth's magnetic field.

4. CONCLUSION.

The instrument described in this paper is small and simple to use. The interpretation of the charts has progressed to a stage where the breaking load of the rope may be estimated. In all cases where corrosion was predicted as a result of the variations shown on the chart it was found to be present. The theory of the indications recorded on the chart suggests that all cases of corrosion can be detected in the type of rope investigated. When external corrosion is accompanied by abrasive wear (referred to as corrosive wear in this paper) it can cause a very large reduction in breaking load. The variations shown in the chart are similar to the indications of internal corrosion and by visual inspection of the rope at points suggested by variations on the chart, corrosive wear can be immediately confirmed.

Plastic wear of the wires in the rope will also be shown on the chart in all cases.

Loss of area due to abrasive wear or to broken wires will show only when it is of the order of one percent of total area or more.

Fatigue is encountered only on very rare occasions; theory suggests that it will not be shown.

5. ACKNOWLEDGEMENTS.

The author wishes to express his thanks to Prof. R.Guelke, Dean of the Faculty of Engineering of the University of Cape Town, for his advice and encouragement in the work and in the preparation of this paper; to the Management of Union Corporation for permission to publish this paper; to the Consulting Mechanical Engineer and his staff for their assistance in this work, and in the preparation of this paper; to the staff of the mines of the Union Corporation Group, as well as those of other groups, for assistance in carrying out tests and preparing rope samples; to the Chief Inspector of Machinery and the Officer in Charge of the Government Mechanical Laboratory for carrying out the breaking load tests described in this paper; to Mr.I.Haggie of Messrs Haggie, Son and Love for many helpful discussions, for the use of the rope machine, preparation of numerous rope samples by factory personnel and tests in their works laboratory; to Mr.L.G.Archer of the same firm for the preparation of wire samples and for the photograph Figure 16; to his colleagues at the Group Rope Testing Laboratory for their assistance.

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