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MINISTRY OF SUPPLY

ARMAMENT RESEARCH ESTABLISHMENT

REPORT No. 18/50

WEAPONS RESEARCH DIVISION

The Development of a Closed Vessel Piezo-Electric Recording Equipment

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Fort Halstead,
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Ministry of Supply

ARMAMENT RESEARCH ESTABLISHMENT

REPORT No. 18/50

(Weapons Research Report No. 1/50)

The Development of a Closed Vessel Piezo-Electric Recording Equipment.

Summary

An account is given of the development of a Piezo-Electric recording equipment for use, in conjunction with Closed Vessel apparatus, in the assessment of the ballistic characteristics of propellants. Special attention was given to possible use of the recorder in routine testing of propellants, and this consideration, together with that of accuracy, led to the decision that recording should be in terms of rate of pressure rise against pressure. For the same reason, various devices have been incorporated to make the apparatus almost completely automatic in action, apart from the initial adjustment, and to minimize the computations which follow.

After a note on the main design considerations, a description of the general arrangement of the final design is given, followed by an account of special features of this final design.

The various faults which were detected following the installation of the equipment at the A.R.E., and the steps taken to overcome them, are then described.

In conclusion, there are various appendices devoted to such matters as operating instructions, routine adjustments, the rapid assessment of maximum rate of change of pressure, maximum pressure, C.R.T. beam current and calibration writing speeds so that the appropriate adjustments may be made for any particular recording, calibration of the Piezo-Electric Crystal, suggested minor improvements in the design, and the measurement of the recorded curve.

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INTRODUCTION

For the assessment of the ballistic characteristics of a propellant, a sample of the propellant is ignited inside a "Closed Vessel" from which the products of combustion are not permitted to escape until after burning is completed, and the build-up of pressure during the period of burning is examined. By a suitable choice of pressure-recording system, it is then possible to express the results of such a firing in terms of the propellant "force-constant", and the relationship between rate of burning and pressure, i.e. the propellant "rate of burning constant".

The essential features of a Closed Vessel are:-

(a) A steel tube threaded (usually internally) at both ends.

(b) Two closing-blocks, each incorporating an obturating device, to fit the screw threads at the ends of the steel tube.

(c) Means for igniting the propellant charge contained in the steel tube between the inner end surfaces of the two closing blocks.

(d) A guage for recording the build-up of pressure in the chamber during the burning of the propellant charge, and

(e) A valve for evacuating the vessel after the completion of propellant burning.

The earliest design of pressure-recording gauge was based on the principle of the well-known copper crusher gauge employed for the measurement of maximum pressure in the gun, the main difference being that, in the present application, compression of the copper was amplified mechanically and caused a stylus to draw a trace on a blackened plate moving under gravity.

An advance in Closed Vessel recording technique came with the introduction of the Petavel spring gauge, which made use of the elastic properties of steel. In this design of gauge, the spring element consists of a steel tube, one end of which is closed and the other end is fixed to the body of the vessel or closing block. Gas pressure on the closed end compresses the tube, and this axial elastic deformation is caused to rock a small mirror, which sweeps the image of a light source across a rotating drum camera. In this way, a pressure-time curve is recorded on the length of photographic film wrapped round the camera drum. This same basic design of gauge was in use in the A.R.E. for Closed Vessel recording up to 1942, the original design having been improved in the interim period. These improvements were mainly in the means for supporting the fixed end of the tubular spring member, and in the mirror suspension.

In 1942, the spring-gauge recording facilities were interfered with by enemy action, and it was at this stage that the Piezo-Electric method came into use for routine Closed Vessel recording in the A.R.E. Advantage was taken of the experience acquired by the Gun Experimental Section in the use of tourmaline for this purpose, and recordings were carried out on the pressure-time equipment which had recently been installed by this Section for experimental work on guns. As the programme of the Gun Experimental Section increased, opportunities for using these facilities for Closed Vessel recordings necessarily diminished until finally it became necessary to make alternative arrangements. This became possible when the rebuilding of the Closed Vessel laboratory was completed and a Piezo-Electric pressure-time recording apparatus was obtained on loan. From the accuracy point of view, this was a retrograde step, as the error involved in reading the record obtained with this particular apparatus was greater than that obtained with the design of spring gauge in recent use.

At this time, due to the conditions then prevailing, there was an increasing demand for Closed Vessel work, and the possibility of employing Closed Vessel methods in the routine testing of gun propellants was becoming very attractive on grounds of financial economy. Authority was therefore sought, and obtained, for the development of a special recording equipment for this purpose. It was appreciated that, for the main purpose envisaged, viz. that of routine propellant proof, a high degree of recording accuracy would be necessary. Also, the routine of firing the vessels, recording the experimental results and performing the necessary computations must be simplified as much as possible in view of the high rate of fire that routine work of this nature would entail. In satisfaction of the relevant requirements, the choice of recording in terms of rate of pressure rise (i.e. dP/dt) against pressure was obvious. With pressure-time recording it is necessary to differentiate the curve for rates of burning to be deduced, and the measurement, from the record, of small time intervals corresponding to small pressure increments is both tedious and inaccurate, so that the advantages of recording dP/dt directly are immediately apparent.

A Ministry of Supply Extra-Mural Research Contract, No. 294/2/684/CF.9A, was negotiated with the firm of Messrs. Cinema Television Ltd., for the design, development and construction of the new recording equipment, which forms the subject of the present report. As much of the work involved in the development of the equipment was of a somewhat exploratory nature, it was possible to define the requirements in general terms only, and it was necessary to maintain close contact with the firm during the course of the contract.

Final tests of the equipment, in conjunction with Closed Vessel firings, could not be carried out until it was installed in the A.R.E. Such tests soon disclosed serious faults in the apparatus, and it became necessary to take further contract action, in Contract No. 6/Insts./930/CB.16(a), with the same firm, for the elimination of these faults. Extensions to this second contract became necessary as the correction of the major faults enabled minor ones to be detected, and progress continued in step fashion until late 1948, since which time the apparatus has been in constant use without giving any major trouble.

In addition to its possible future application in routine inspection and proof of propellant, this recorder is a valuable research tool, having many advantages over the pressure-time method. Although rates of burning at various stages during the combustion process may be deduced from the pressure-time curve, the plot of rate of burning against pressure is not continuous, as the necessity for differentiating the curve tends to smooth out any genuine irregularities in burning. Also, the errors introduced in measuring the small pressure and time increments, although tending to become smoothed out when the results are reduced to burning-law form, result in a considerable measure of uncertainty in individual values of rate of burning. With dP/dt - pressure recording, irregular burning of the propellant is immediately apparent from the recorded curve, and a continuous plot of rate of burning against pressure can be made. This enables irregularities in burning to be investigated. Over most of the recorded curve, the reading error is so small as to be negligible, and this makes it possible to measure small differences in ballistic characteristics between propellant samples. Thus, the new recorder opens up a wide field of research.

Much of the material contained in the body of this report was prepared by Messrs. Cinema Television Ltd., and is contained in the firm's Handbook No. 158. These remarks apply, in particular, to Sections 1 to 4 inclusive. Section 5 may be considered as being a joint Cinema Television - A.R.E. effort; in particular, nearly all the work on "hash" removal was done by A.R.E. staff. Appendices I and II are due to Messrs. Cinema Television Ltd., and the remaining Appendices were prepared by A.R.E. staff. All the diagrams were prepared in the A.R.E., in some cases from circuit diagrams supplied by Messrs. Cinema Television Ltd., under the Contract.

A Closed Vessel (No.21) for use, in conjunction with the new recorder, in routine investigations, was specially designed, and will form the subject of a separate report.

1. SPECIFICATION

The original requirements were set out in a provisional specification in September 1942, and were for the development and construction of a cathode ray tube recorder for the purpose of obtaining accurate records of the rate of change of pressure in relation to the pressure in a closed vessel in which a propellant charge is fired.

The specification states:-

(a) The input signal will be obtained from a Piezo-Electric Crystal Gauge, feeding into a standard condenser. Circuits will be provided for producing signals proportional to pressure and to rate of change of pressure. Switching will be provided for selecting the output from any one of six gauges.

(b) The gauges will have similar polarity and sensitivities varying between 0.004 and 0.005 microcoulombs per ton per square inch. The maximum pressure obtained will vary between 10 and 20 tons per square inch. The rate of change will vary between 500 and 20,000 tons per square inch per second. The event will be completed in from 1 to 10 milliseconds.

(c) A calibration signal is to be applied automatically at the completion of the event, and will take the form of a grid of lines, the ordinates representing equal steps of pressure, and the abscissae equal rates of change of pressure.

(d) The records are required to be read to an accuracy of 2 parts in 1,000. An instrumental accuracy of this order is to be aimed at, 5 parts in 1,000 being the lowest acceptable. Adequate definition, freedom from interfering signals, good high frequency characteristics and zero constancy are asked for in this section. The calibrating potentials are to be obtained from a standard cell and potentiometer.

(e) The oscillogram will normally occupy a circular area of 60 mm. diameter on the C.R. tube, but this could be reduced to a square of about 2" side. The record is to be full size on Ilford oscillograph paper 70 mm. wide. The records are to be numbered serially and a number is to appear showing which input is connected.

(f) The C.R. tube should be brightened and all further operations required to complete the record should occur automatically on the receipt of a signal by the apparatus. A manually operated shutter should be provided.

(g) For purposes of observation a second C.R. tube having a long afterglow screen is to be provided in parallel with the recording tube.

(h) The apparatus will be used in a normally lighted room and light-tight cassettes should be provided for the sensitive material.

(i) The apparatus will operate on normal 240 V 50 c.p.s. A.C. supply mains.

(j) The apparatus will be constructed in rack form, and attention should be paid to the fact that it will be used by semi-skilled operators for routine testing.

2. DESIGN CONSIDERATIONS

Considering the specification and how it could be met, various requirements stood out as new or specially difficult problems.

Dealing with the display and recording aspects first, it seemed probable from past experience (especially with the pressure/time recorder already in use at A.R.E. Woolwich) that the CINTEL cathode-ray tube type 3 EB2 would provide a trace of the necessary brightness and definition. A suitable lens and camera were available, so that the recording aspect did not appear to present any difficulties.

One thing that seemed likely to complicate matters, in order to maintain reading accuracy at all points on the curve, was the desirability of modulating the spot brightness according to the writing speed so as to avoid extreme variations in the thickness of the recorded line.

Some typical pressure v. time records were examined with a view to ascertaining the writing speed ratio likely to be encountered.

It was felt desirable to work the C.R. tube with its anode and screen earthy. Under these conditions any modulating signal applied to the grid would have to bridge a 10 KV. potential difference.

It can be shown that for the curve dP/dt v.P., the writing speed is proportional to the normal intercept between the curve and the P axis. This intercept did not appear to vary by more than 50 to 1 over that part of the curve which was of interest, the beginning being of small significance. Since the apparatus was to be operated by the incidence of a signal, some time would reasonably be lost and the beginning of the curve would not appear on the C.R. tube.

Photographic tests showed that a writing speed variation of this order could be recorded without undue spread in the photographic image and hence without impairing the reading accuracy to any great extent. It was therefore decided not to continue with the development of a brightness modulating system.

In this recorder it is necessary to deflect the cathode ray beam in two directions at right angles, corresponding to pressure and to the first time differential of pressure.

The cathode ray tube 3EB2 is fitted with only one pair of deflection plates, so that it is necessary to provide one deflection by magnetic means. Some previous experience had been gained in the use of deflection coils with this type of tube and, in fact, a modified tube had already been made in which the plates were spaced away from the gun so that they were not directly in the field of a pair of coils situated in a convenient position on the neck of the tube.

It is convenient if the voltage from the standard cell (about 1 volt), used as a reference potential for the calibration grid, is equivalent to the largest signal from the gauge. If this is the case for a gauge of maximum sensitivity, i.e. 0.005 microcoulombs per ton per square inch, then for a gauge of minimum sensitivity, i.e. 0.004, a pressure of 10 tons per square inch must correspond with 0.4 volts, and 500 tons per square inch per second must correspond with 0.02 volts. These are the minimum input voltages for which the amplifiers have to be designed, and would be produced by the charge from the gauge operating on a capacitor and resistor in series of 0.1 microfarads and 10,000 ohms. The maxima of 20 tons per square inch and 20,000 tons per square inch per second, then each give rise to a potential of 1 volt.

Some 70,000 milliampere turns are required for the magnetic deflection, so that the idea of a d.c. amplifier with 0.4 volts input providing a current change of 50 milliamps in a pair of deflection coils having 700 turns each seemed quite reasonable. On the other hand, a directly coupled amplifier to provide 300 volts (± 150) from 0.02 volts input must have an amplification of 15,000 which is on the high side compatible with the great degree of stability desired, but it was not thought to be beyond the scope of known techniques. The amplifier circuits are described in Section 4.2.

It was at once evident that the first valve in the pressure amplifier would be connected across a capacitor of 0.1 microfarad and that there would be no conducting path to supply bias to its grid. It would therefore be necessary to arrange for this grid to have its potential adjusted to that of the uncharged input capacitor, i.e. to earth potential. This problem is dealt with more fully in Section 4.1, which also describes the cricuit used for achieving the desired result.

It was hoped that it would be possible to use standard H.T. supply vibrators in this circuit. It was required to change over two circuits in synchronism, and a pair of vibrators were driven by a suitable transformer from the 50 cycle supply. A number of problems presented themselves, such as inadequate insulation, contact bounce and the difficulty of maintaining correct phase relationship between the two vibrators. The use of one drive operating all the contacts was tried out but rejected owing to insulation and other difficulties. When it became apparent that for the correct operation of the circuit, it would be necessary to use three changeover circuits, it became very difficult to set up and impossible to maintain the vibrators in adjustment except for short periods.

It was then decided to abandon this type of switching device and some experiments were conducted with relays of the Post Office type, but these proved too difficult to adjust with precision, and a completely new type of vibrator was designed. In this design special attention was paid to features which had previously been troublesome. The three-stage vibrator was large enough to have adequate insulation, all the contacts were separately adjustable, the contact points were of silver and the constants of the cibrating springs were such as to ensure that contact was made at zero velocity so that bounce was eliminated. The technique of making the initial adjustments had to be learned and proved to be somewhat laborious. Operation showed it to be worth while, however, and, except for re-adjustment when the apparatus was moved for installation, none has been found necessary.

A standard method of blacking out the trace on the recording tube is to deflect the cathode ray so that it does not pass through the anode aperture but is collected in a "bucket" situated behind the anode and which is an integral part of the construction of the tube. Two coils are accommodated on the neck of the tube behind the anode for this purpose. It was proposed to use this method provided the coil system could be made to respond sufficiently quickly. A unit containing suitable trigger circuits could then be operated from the pressure or differential signal so as to expose or brighten the trace for the required time. These same circuits could later be operated by the calibrating signals, which would be applied when the pressure had reached its final value and the differential had fallen to zero.

For the purpose of applying the calibration grid, the C.R. tube had to be scanned in a number of single lines in the two deflection directions spaced apart by intervals corresponding to known input potentials. The spacing potentials could readily be obtained from a divider incorporated as part of a standardising potentiometer. Scanning could be done by using half cycles of the normal alternating current supply. Since the writing speed of a sine scan is a cosine function, the spot velocity, and hence the brightness, will not vary by more than 10 to 1 over 90% of the half-cycle, the velocity being greatest in the centre and reducing towards the ends of the scan.

Considerably more volts may be applied than are required to just scan the tube so that the portion of the cycle actually appearing on the screen may have substantially constant writing speed. A multi-bank uniselector might be made to operate from the supply mains, thus producing 50 steps per second, which would be sufficient to provide twenty calibration steps in each direction in less than one second. The uniselector would be started automatically at the conclusion of the event so that the whole trace including calibration grid would be recorded in about one second.

It was felt at the outset to be desirable, if not necessary, to have available a generator capable of giving a signal similar to that expected from the gauge in a closed vessel. In order to ascertain the shape of this curve, a number of pressure-time records were examined and the P.v.dP/dt curves drawn. With this information and the results of some discussions with A.R.E. staff, a signal generator was designed whose output simulated the pressure wave-form over the dP/dt range of 500 to 20,000 tons per square inch per second to a maximum pressure of about 15 tons per square inch. The maximum rate of rise was adjustable by a six step switch, whilst another switch enabled this maximum to be attained in 70%, 80% or 90% of the time taken for the pressure to rise to its maximum value. The circuit is fully described in Section 4.6. As a check on the design and construction, the output from this signal generator was "recorded" on a time-pressure oscillograph which had also been used to record C.V. firings. Comparison of the records showed good agreement, and the signal generator was henceforth used as a standard of test for the apparatus under construction. It has since been found necessary to have this generator constantly available, and it has become incorporated in the recorder and is used frequently when setting up the apparatus prior to firing.

Some tests on stabilising the E.H.T. supply with a conventional saturated core type of transformer showed that, although the output voltage from the transformer appeared constant when measured by a meter normally indicating r.m.s. values, there was serious wave-form distortion. This was of such a nature that the E.H.T. volts dropped when the input volts rose. A mixing circuit was arranged to provide the correct ratio of mains voltage and "stabilised" voltage to give zero change in E.H.T. for quite substantial changes in mains volts. It was, however, felt that the advantage was not sufficient to compensate for the complication involved, and the arrangement was not included in the final design.

During the early testing period of various units and the complete assembly, considerable time was spent on eliminating various faults such as hum and other spurious signal pick-up, unwanted feedback and cross talk. In particular, part of the automatic exposing unit was very sensitive to transient effects apparently transmitted via the mains supply. In order to prevent the C.R. tube being exposed by these unwanted signals, a special circuit was inserted to render this part of the unit less sensitive until a true or wanted signal arrived. The operation of this device is described in Section 4.3.

3. GENERAL ARRANGEMENT OF FINAL DESIGN

A front view of the complete apparatus is given in Plate 1. Plate 2 is a close-up, with the doors open to expose the cathode ray tubes to view.

The apparatus is incorporated on three standard instrument racks, each eight feet high. The general aim in laying out the position for the various units has been to keep the cathode ray tubes as far as possible from disturbing fields such as are produced by transformers and chokes in power supply units. By arranging the tubes high up and the power supplies low down, negligible unwanted deflection was experienced. The cathode ray tubes are situated at the top of the centre rack, the various supplies and control panel being at the bottom of the same rack. The control knobs are within comfortable reach of the operator who has a convenient view of the cathode ray tube screens at about normal eye level, through the rectangular windows.

A mirror at 45° is provided in conjunction with the monitor tube whose screen faces downwards. The recording tube also faces downwards and the screen is focussed on to the recording paper by a Ross 5" lens working at a maximum aperture of f/4.5 giving a picture on the record about 65 mm. square. Situated between the lens and the paper and also focussed on to the paper by a small lens and prism, is the numbering device. A small portion of the top left-hand corner of the calibration grid is obscured to allow the illuminated serial number counter and gauge number indicator to be photographed. A six-way gauge selector switch and a visual serial number indicator are fitted below the monitor cathode ray tube. The whole recording and monitoring system is enclosed by light-tight doors, observation being made through windows.

The camera is fitted with a handle, one turn of which winds the recording paper on 70 mm., thus bringing an unexposed piece into the recording position. A stop is fitted which prevents the handle being rotated for more than one revolution at a time.

The working anode currents of the cathode ray tubes for low speed records are rather small to read directly on a normal microammeter, and current multipliers with a factor of 10 are provided on the cathode ray tube control panel.

Since two cathode ray tubes are incorporated in the apparatus, the focus coils and regulating rheostats are connected to their power supply in the form of a bridge circuit, so that operation of the focus control on one tube has no effect on the current in the other focus coil, even though both coils are supplied from the same power pack.

Since the supply unit for the cathode ray tubes was designed and constructed, a modification has been made to the cathode ray tube heater which is now rated to run at 4 volts with an approximate current of 1.2 amperes. The regulating rheostats fitted have very little effect on the current, but the above condition is usually obtained by turning the controls completely in a clock-wise direction.

On the left-hand rack near the top is situated the differential amplifier, so arranged that its output is connected to the cathode ray tubes by short lengths of screened low capacity cable. Below this are the galvanometer and potential divider units of the special potentiometer supplying the calibrating voltages. The calibrator is immediately under the potential divider and contains a uniselector for applying the appropriate signals sequentially for tracing the calibrating grid on the cathode ray tube.

Lastly, on this rack is the Zero Adjuster, which automatically corrects for currents in the input circuit which tend to set the pressure amplifier off its true zero condition. The necessary power supplies for the above units are housed at the bottom of the rack.

The right-hand rack contains the pressure amplifier also connected to the cathode ray tubes by low capacity cable and the exposing unit. The latter contains the circuits for brightening the cathode ray tube traces on receipt of the signal and for initiating the calibration on the completion of a successful event. The power supplies for these two units are accommodated at the bottom of the rack.

Beneath the exposing unit is fitted the signal generator incorporating its own power supply unit. This unit is permanently connected to position 6 of the guage selector switch.

4. SPECIAL FEATURES OF FINAL DESIGN

4.1 The Gauge Circuit.

4.1.1. The Problem of Zero Drift.

The Piezo-Electric Gauge is essentially an electrostatic device in which a change of pressure on the gauge results in a displacement of charge through the crystal. If this charge is passed through a substantially capacitive load, the potential difference developed across the capacity will be proportional to pressure change. However, the gauge does not deliver any current when the pressure is steady, and the maintenance of a potential difference with a sustained pressure is entirely conditional on the absence of any appreciable leakage across the capacity. If, for example, the potential difference must be maintained for 10 milliseconds within an accuracy of 2 parts per 1000 the time constant must exceed 5 seconds, which, with the capacity of 0.1µF, implies a resistance of greater than 50 megohms. Insulation resistances of the order of hundreds of megohms can be obtained without difficulty, but such circuits are susceptible to interference from stray leakage currents from various sources.

Unfortunately the gauge is not the only possible source of current in the gauge circuit. The circuit must be connected to at least one grid of a thermionic valve for purposes of amplification, and this grid is liable to lose electrons by thermionic emission and to collect positive ions present in the valve due to imperfect vacuum. There are other possible sources of stray leakage current, but the grid current of the valve is, in itself, of sufficient magnitude to require counter-measures if drift of the zero is to be kept within tolerable limits. The magnitudes of leakage currents are necessarily very uncertain, but, for protection against zero drift, it would appear reasonable to specify that a current of .01µ amp should not give rise to more than 1 mV change of potential, which would correspond to a D.C. resistance of not more than 100,000 ohms.

The problem arises, then, of devising a shunt, to close the gauge circuit, having a D.C. resistance of less than 100,000 ohms, but with an impedance of the order of hundreds of megohms for the duration of the desired signal.

4.1.2. The Ideal Solution

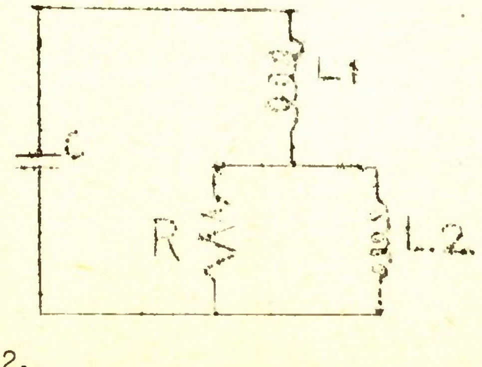
If we ignore, for the moment, the difficulties of obtaining the required component values, an ideal solution is to be found in the use of an inductive shunt having a very high inductance and low D.C. resistance. Using a single inductance L1 in shunt with the gauge capacitor C, the fractional loss of a unit-step signal after time t would be $\frac{1}{2}t^2/L1C$. For a loss of two parts per thousand in ten milliseconds and C = 0.1µF the required inductance is 250,000 H. Provision must be made for damping this circuit which would otherwise continue to oscillate (at about one cycle per second) for a long time after any transient disturbance. By the terms of the problem we are not allowed to use either a simple shunt resistance or a simple series resistance. We can, however, use a series resistance which in turn is shunted by a second inductance to short circuit the D.C. resistance. For the circuit to be non-oscillatory it can be shown that L2 must be at least eight times L1. Suitable values in the present case would be:-

C = 0.1µF

L1 = 250,000 H

L2 = 2,500,000 H

R = 2.5 megohms.



4.1.3. The Practical Solution

The manufacture of inductances of the order of a million henries is not considered to be a practical proposition, so that an alternative method has been devised which makes use of valve circuits and feedback. Although this method appears so very different, it should be emphasised that it gives a result very closely equivalent to the passive circuit already discussed.

The essential property of an inductance is that it draws a current proportional to the time integral of the applied voltage. To simulate inductance we must use D.C. voltage amplification, integration and current feedback. The D.C. amplifier must have its zero stable to a fraction of a millivolt and this has been achieved by the use of a vibrator with metallic contacts which converts the D.C. to A.C., which is then amplified and rectified by a synchronous contact.

4.1.4. The Vibrator

As no vibrator of suitable characteristics was commercially available a vibrator was designed for this purpose. Three change-over contacts are used, and the contacts are required to have different change-over durations so that their closings and openings occur in a definite sequence. An important design feature concerns the tuning of the moving contact springs to definite frequencies. While a contact spring is in transit from one fixed contact to the other it is in a state of free vibration. If it is arranged that exactly one cycle of vibration occurs during the transit time the moving contact will alight on the fixed contact with zero velocity so that no bounce occurs. The three springs are tuned to different frequencies corresponding to the required transit times and all fixed contacts are adjustable to give the correct timings. The stiffness of the contact springs causes the natural frequency of the vibrator to rise with amplitude of vibration, and this detuning effect plays an important part in stabilising the amplitude of vibration. The vibrator is polarised and is driven at 50 cycles per second from the mains supply.

4.1.5. Operation of the Circuit
(Refer to Circuit Diagram, Fig.1)

The changeover contact with the shortest transit time is used to connect the grid of valve 27 alternately to the two sides of the gauge circuit. To minimise disturbance of the gauge circuit by this operation, the impedance of the moving contact must be as high as possible. To this end, valve 27 is a pentode arranged as a cathode follower, and all screening of the grid lead is returned to the cathode to eliminate most of the capacitance of the grid lead.

Any potential difference across the gauge circuit results in an A.C. signal on the grid of valve 27. This signal is cathode-followed by valve 27 and is then amplified by A.C. - coupled valves 18 and 30. The high impedance of the grid circuit of valve 27 renders this circuit liable to spurious signal pick-up during the time that the moving contact is in transit, and so open circuited. To prevent over-load of valve 30 by these spurious signals the connection between valves 18 and 30 is broken by the second contact of the vibrator. This second contact has a transit time which is longer and which overlaps the transit time of the first. The transit time of the third contact is longer still and overlaps the others.

The output of valve 30 is applied across capacitor 35 in series with the third contact of the vibrator, and rectified pulses charge capacitor 39. The cathode follower 43 causes the potential of the one fixed contact to follow the potential of the other. There being thus a negligible potential difference across the fixed contacts, capacitor 35 is feeding into an A.C. short circuit so that the current pulses in capacitor 35 are almost independent of any potential already present on capacitor 39.

The mean charging current of capacitor 39 is therefore proportional to the potential difference across the gauge circuit, and the potential across this capacitor will be proportional to the time integral of the potential across the gauge. The integrated potential is applied via cathode follower 43 and a 100 megohm resistor 6 to the gauge circuit. The current through resistor 6 will therefore be proportional to the time integral of the voltage across the gauge circuit, thus simulating the action of the inductance L1 in the ideal case considered above.

Resistor 6 does not, as might be supposed, shunt the gauge circuit with 100 megohms. Any signal on the gauge circuit is transmitted directly through cathode followers 15 and 43, and over 90% of the signal will be applied to the other end of resistor 6. Thus the equivalent shunt resistance will be over ten times the actual resistance of 6.

So far, only capacitor 39 has been described as an integrating element in the circuit. Capacitor 39 corresponds, by simple inversion, to inductance L1 of the ideal passive circuit considered above. By the same inversion, capacitor 41 and resistor 40 correspond respectively to L2 and R of the passive circuit. These circuit elements are necessary to ensure that after any transient disturbance the zero will be restored without oscillations and in a reasonably short time

Some trouble was experienced with small interfering signals picked up in the gauge circuit from the pulse waveforms necessarily present in the circuits of the zero adjuster. Break through was found to be occurring along several paths, and the additional elements 51 - 55 were included to effect a cure without materially affecting the normal operation of the circuit.

The meter 7 is included to monitor the operation of the circuit. The meter reading is, in effect, a much magnified indication of the correcting current through resistor 6, full scale readings corresponding to ± 0.1uA.

4.2. The Amplifier Circuits

4.2.1. The Effect of Gauge Lead Capacitance

The gauge has to produce a signal representing pressure and a signal representing the time differential of pressure. These signals would be developed in pure capacitance and pure resistance loads, respectively. These loads would still operate correctly, connected in series, if the gauge had infinite impedance, but the finite capacitance of the gauge lead modifies the response at high frequencies. Gauge leads may vary in length but it was assumed that in every case the capacitance would be made up to a standard value of 500 pF., which, with the load resistance of 10 K gives a high frequency droop corresponding to a time constant of 5 microseconds. Both amplifiers were then arranged to produce a compensating high frequency boost.

The load circuit was split into two capacitors and two resistors to permit each amplifier working with one terminal grounded. (See Fig.2 for block diagram).

4.2.2. Choice of Deflection Methods.

The recording cathode ray tube had only one pair of deflection plates, so that deflection in the other direction had to be effected magnetically. The rise in impedance of the deflecting coils with frequency severely limits the deflection which can be obtained at high frequencies. The magnetic deflection was used therefore for the pressure signal, leaving the electrostatic deflection plates available for the differential signal with its much greater high-frequency content.

4.2.3. The Pressure Amplifier.
(Refer to Circuit Diagram. Fig. 3)

The output of the pressure amplifier is a current which passes through the deflecting coils, and the main complication in the amplifier, which is otherwise fairly simple, is the rise of impedance of the coils with frequency. Both the inductance and the resistance of the coils are rather uncertain quantities, so that it is desirable to use an amplifier output circuit of sufficiently high impedance that the current will be substantially independent of the coils and equal to the current on short circuit.

The frequency characteristic of the short circuit current is affected only by C2, which, shunting the cathode feedback resistors R16 and R22, produces the required 5 microsecond high frequency boost.

The output impedance of the amplifier is raised to a high value by positive feedback from R14 and R20 via R1 and R5 to the grids of V4 and V3. The rising frequency characteristic caused by C2 is offset, round the feedback loop, by the shunt consisting of C1, R17 and VR6. Some compensation for the effects of deflector coil capacitance is provided by VC1 and VC2.

A push pull amplifier can be operated from a single input signal if sufficient degeneration of the un-balanced component is provided by the use of common cathode resistance. R2 and R4 in parallel form a resistance in the common cathode circuit of V1 and V2, while R18 is common to the cathode circuits of V3 and V4. These resistances cause the signal, which is completely unbalanced as it is applied to the grid of V1, to become almost balanced as it appears in V3 and V4 and, in addition, they help to fix and stabilise the mean operating currents of the valves. A further stabilisation results from the use of the volt drop across R19 as the source of voltage for the grid-cathode circuit of V1 and V2. The current in R19 consists mainly of the sum of the currents of V3 and V4. Any tendency to change in this current is opposed by feedback from R19 into the grid-cathode circuit of V1 and V2 and thence from the anodes of V1 and V2 back to the grids of V3 and V4.

4.2.4. The Differential Amplifier
(Refer to Circuit Diagram. Fig. 4)

The differential amplifier has three D.C. coupled push-pull stages. The unbalanced input signal becomes substantially balanced by degeneration of the unbalanced component by common cathode resistances. Further stabilisation of operating conditions in the first two stages is obtained by feeding from the common cathode circuit of the second stage through a cathode follower to the grid-cathode circuit of the first stage. The resulting degenerative D.C. loop opposes any tendency to drift in the operating conditions.

A considerable range of gain control is required and is effected by adjusting the amount of negative feedback which is applied across the last two stages. The required overall frequency characteristic is imparted to the amplifier by including the inverse characteristic in the feedback circuit. Capacitors 52 and 53 in conjunction with resistors 45, 58, 46 and 59 produce a 5 microsecond time constant droop in the feedback loop. Additional small capacitors 44, 47, 57, and 60 and small resistors 51 and 54 are required to control the phase characteristic of the loop gain in the vicinity of cut-off to avoid instability.

An adjustable D.C. shift is applied to the point where the end of the feedback network feeds into the anode circuit of the first stage. The shift signal, just as any other signal, will be opposed by a signal amplified and returned through the feedback network, so that at some point in the feedback network the direct and returned signals will cancel.

Resistors 14 and 17 have such a value that this null point occurs where the gain control is shunted across the feedback network, so that the gain control can be varied without affecting the shift.

The small capacitors (18, 24, 50 and 55) shunting the anode-grid coupling networks serve to balance the grid capacitances of the valves and give the amplifier an approximately level frequency characteristic. At maximum gain with no feedback, the characteristic is level, but as the gain is reduced by the application of feedback the characteristic approximates to the inverse of the feedback characteristic, thus producing the desired 5 microsecond boost. The variation of frequency characteristic with gain is not objectionable, as the high gain settings are used only for slowly changing signals where the 5 microsecond correction would have no significance.

4.3. The Exposing Unit
(Refer to Circuit Diagram. Fig.5)

The function of this unit is to ensure that the C.R. Tubes are brightened as soon as the signal arrives from the gauge, to maintain the brightness during the event and to restore the blacked-out condition as soon as the pressure has reached its maximum value. By this time the differential which, of course, starts from zero, will have fallen to zero again. It would be possible to use the differential signal to operate the exposing circuit, switching on when the signal reached some fraction of its maximum value and switching off again on falling below the same fraction. Unfortunately, this would mean that the end of the trace was not recorded and the point of maximum pressure would be lost. In order to extend the exposure time, the differential signal is again differentiated and the resulting signal is inverted and added to the original. The combined value of these two signals remains sufficiently high until the point of maximum pressure is reached.

The valve V10 is normally conducting so that current flows through the C.R. Tube black-out coils which are connected between the anodes of V10 and V9. The current is supplied from the HT line through the choke in the anode of V9. These two valves have a common cathode resistor so that the cathode current must be shared between them. A trigger pair V7 and V8 coupled to the grids of V9 and V10 determines which of these valves shall take current, and on the relative grid potentials of V9 and V10 being suddenly reversed V10 ceases to conduct, the current previously flowing in the coils now flowing in V9.

Valves V1 and V2 accept the positive and negative going balanced differential signals from the deflection plates of the C.R. Tubes. The points X and Y being connected together are driven negative as the differential signal increases, the grid of V7 follows, the trigger pair flip over and the tubes are exposed. The precise amplitude at which this takes place is determined by the bias on the grid of V1 and is controlled by the potential divider VR.1.

The differential signals are also fed via differentiating networks to the valves V3 and V4, the resulting d^2P/dt^2 signals being amplified and inverted by V5 and V6. The anode of V5 is also connected to the point X so that the signal from V5 is added to that from V1. The amplitude to which this signal can fall without blacking out is determined by the adjustment of VR.3. Owing to the additional amplification in this part of the circuit, spurious or interfering signals with steep wavefronts appearing on the C.R. Tube plates may have sufficient amplitude at X to operate the exposing circuit. Since the second differential signal is used to maintain the exposure only at the end of the event, arrangements are included to hold it off until the pressure has attained a reasonable value.

The potential divider VR7 connected to the trigger valve V8 holds the grid of V13 positive while the tube is blacked out. Since V13 has the same cathode resistor as V5 and V6 the current flows in V13, thus preventing any signal from being delivered by V5 to the point X. As soon as the tubes are exposed the grid of V13 goes negative, allowing the current to flow in V5 and its signal to be added at X.

Another function of the circuits in this unit is to start the calibration grid uniselector when the record has been completed. A relay in the anode of V15 is used to close the uniselector starting circuit. The relative grid potentials of the common cathode pair V14 and V15 are such that V14 normally takes the current. As the pressure rises, the potential of V14 grid falls by virtue of its connection to the pressure amplifier output valve cathodes through V11 and V12. This is delayed, however, by the bias supplied from the potential divider VR2 until the pressure has risen to between one third and one half of the maximum value. In the meantime, the exposing circuit having operated, the grid of V15 is taken even more negative so that V14 is still conducting. As soon as the exposing circuit returns to normal and the tubes are blacked out, V15 grid reverts to its initial potential whereas V14 grid is now negative. V15 therefore takes the current, the relay is energised and the calibration is initiated.

The points X and Y are connected together during the recording of the event, but are then disconnected so that appropriate signals from the calibration unit may be applied to the exposing circuits at the point Y. From this point onwards the circuit works exactly as before, negative signal being required to expose the C.R. Tubes.

4.4. The Calibrating Unit.

(Refer to Circuit Diagram. Fig. 6)

The calibrating lines have to be drawn with the same value of beam current used for the actual record. Hence the rate of sweep used in the calibration must bear some relation to the speed of the record in order to produce an appropriate recorded density.

The slowest records are made on the calibration grid having the highest P and the smallest dP/dt. The writing speed on the recording is proportional to the length of the normal to the curve, the scale being such that the length of one side of the record represents a velocity of full scan in 20/500 = 40 milliseconds.

As for simplicity a 50 cycle wave is used for the sweep, full scan can be effected in about 6 milliseconds, which provides sufficient density.

The exposing circuits are readily operated by a 50 cycle wave in quadrature. As a shift is applied to the amplifiers to bring the zero lines to the edges of the screen, a D.C. bias is used to neutralise the shift and to centralise the sine wave scan.

A 25 position 8 bank uniselector has alternate half wipers removed, the remaining halves being connected together in pairs, so that for a complete revolution the uniselector has 4 banks each with 50 positions. One of these banks is used for stepping the uniselector along 50 times per second, the driving current being obtained by a half wave rectifier from the mains supply transformed down to a suitable voltage. The second bank supplies the quadrature wave to the exposing unit at the point Y during the calibration, but connects the points X and Y during the recording time. The amplitude is adjusted so that the tubes are brightened for nearly half a cycle. The two remaining banks have their wipers connected to the two amplifiers which are connected, in the reset position of the uniselector, to the input capacitor and resistor.

When the uniselector is operated, the amplifiers are connected sequentially to the various calibrating potentials and scanning sine wave so that at each calibrating step one line is drawn across the screen. The horizontal lines (dP/dt calibration) are traced first, followed by the vertical lines (P calibration). The first line to be drawn in each case is the zero line, the amplifier inputs being at earth potential.

At the conclusion of the calibration the amplifiers are returned to zero input by way of the check switch (in position 0). Operation of the check switch now, through the positions 1, 2, 3 and 4, after reducing the beam currents to avoid burning the C.R. Tube screens, exposes the spot and enables its position to be observed at the corners of a square determined by the maximum calibration values recorded.

The switches marked PRESSURE DIVISIONS and DIFFERENTIAL DIVISIONS enable the number of steps recorded to be selected. These can be varied between 9 and 20, the choice being determined by the expected maximum pressure, and by the maximum rate of rise. In the pressure direction each step represents one ton per square inch, but in the differential direction the value of each step depends on the setting of a control knob on the potentiometer Resistance Unit (183 - S12). This is variable in 5 steps from 50 to 1000 tons per square inch per second. Whatever selection is made, of course, the whole range of potentials are applied during calibration. The lines not required merely overscan the C.R. Tube and are masked off in the camera gate.

In order that the rate of sweep may be varied in accordance with the record speed, potential dividers are fitted in the form of Kelvin Varley slides enabling the scale to be read from 0 to 100. It can be shown that the amplitude required for the pressure amplifier is proportional to the maximum dP/dt, whilst for the differential amplifier it is proportional to $(dP/dt)^2$ divided by P. For convenience, since the maximum variation in P is only two to one, this has been ignored in computing the graph showing the settings of the writing speed controls which are therefore related to dP/dt and its square. Controls are also fitted in the form of log law potential dividers for supplying the required D.C. shifts.

A push button S2 enables the uniselector to be returned to its initial position in readiness for the next recording. Once it has been reset it is not possible to observe the spot in other than the initial position since it is advisable to avoid the complication of switches in the input circuits. It was found impossible to provide this facility and keep the amplifiers free from unwanted pick-up such as hum. The push botton S1 enables the uniselector to be operated independently either for checking or for setting up gains etc., in the operated position. Neon lamps show which position the uniselector is in. A switch S8 enables the drive to be switched off so that adjustments may be made to other parts of the apparatus, e.g. when using the signal generator and setting amplifier gains, without the uniselector being operated by each signal.

Connected in series with the drive is a lamp which illuminates the gauge and serial number indicator so that the figures are photographed on the record. At the end of each operation the serial number counter is stepped up one digit and the switch S4 enables the supply to be cut off from this counter when not required.

4.5. The Potentiometer.

(Refer to Circuit Diagrams. Figs. 7 and 8)

The potentiometer for providing standard voltage steps is in two parts. A conventional circuit balances the potential difference across a load resistance against the potential of a standard Weston cadmium cell (Fig.7).

The load resistance comprises two potential dividing networks with constant resistance attenuaters (Fig. 8). The first pair of attenuators have positions marked from .60 to .69 and from .000 to .009 respectively, the two figures taken together representing the mantissa of the common logarithm of the gauge sensitivity. The values are so arranged that these figures also represent the logarithm of the voltage per step on the potential divider R5 which provides the pressure calibrating steps. It will be seen that for a gauge with a sensitivity of .005 microcoulombs per ton per square inch (common logarithm .6990) the voltage per step on R5 is .05, which is the voltage produced by such a gauge across a capacity of 0.1 microfarads for a pressure of 1 ton per square inch. The calibrating pressure scale is therefore read directly in tons per square inch, provided the attenuators are set to the gauge sensitivity used.

Similarly, the third attenuator determines the value of the steps on R8, these being indicated on the control knob scale and varying between 50 and 1000 tons per square inch per second. The galvanometer used for determining balance has a sensitivity such that the error is not more than 0.1% if the deviation is within 5 mm. of zero.

4.6. The Test Signal Generator.

(Refer to Circuit Diagram. Fig.9)

It would clearly have been very inconvenient, if not impracticable, to have relied on firings in the closed vessel as the sole source of signals for testing the apparatus, especially during the development period, and the test signal generator was therefore devised as a convenient artificial source. The generator has proved so useful that it is now retained as a permanent accessory.

The generator is required to produce a transient signal whose waveform corresponds closely to the signal picked up by the gauge when a charge of propellant is fired in the closed vessel. The waveform should be adjustable to simulate the effects characteristic of propellants of differing geometrical form and size.

A feature common to all the waveforms is that for a considerable fraction of the total range of pressure the rate of build-up is proportional to the pressure, which results in most of the waveform having the form of a growing exponential curve. In the electrical circuit this can be simulated by the charging of a capacitance with a negative resistance. Two valves regeneratively coupled can supply the negative resistance, and the shunt capacitance can be adjusted to vary the time constant.

The proportionality between the differential and the pressure is not maintained all the way up to the final pressure, and the maximum differential may occur at from 70 to 90% of the final pressure depending on the geometry of the propellant. This effect may be simulated in the electrical circuit by making use of the non-linear characteristics of the valves. The non-linearity may be controlled by a suitable combination of negative and positive feedback.

Referring now to the actual circuit details, (Fig. 9), the output signal is fed through capacitor C1 which represents the standard capacitance of the gauge and its lead. The signal applied to C1 represents pressure, at the rate of 10 volts for 1 ton per square inch. C2 and R1 serve to improve the D.C. isolation of the gauge circuit, and the time constant can be regarded as representing the cooling of the closed vessel, though in view of its relative unimportance no serious attempt has been made to provide the correct value of time constant. The signal is produced by reducing the anode current of V1 from about 10 mA to zero, representing a pressure rise of about 15 tons per square inch.

The cathode of V1 is coupled to the cathode of V2, and the anode of V2 is coupled back to the grid of V1. This forms a regenerative loop providing a negative resistance effect which, with the capacitance shunting the anode of V2, is responsible for the shape of the greater part of the waveform.

As the changeover of current from V1 to V2 approaches completion, the fall of mutual conductance on the bottom bend of the V1 characteristic reduces the rate of change of current. This non-linear effect can be reduced in two steps by adding R9 and R8 between the cathodes, the resulting loss of gain being made good by adding R11 and R12 in the coupling from V2 anode to V1 grid. R4 and R5 are compensating resistances to maintain constant D.C. starting conditions on the grid of V1. The values have been chosen so that the maximum differential occurs at approximately 70, 80 or 90% of the final pressure, according to the setting of switch S1, corresponding to signals produced by multi-tube.

The bottom bend of V2 affects the shape of the start of the signal, as the development of the regenerative effect is then dependent on the mutual conductance of V2. If the signal was to be initiated by bringing V2 into operation (by raising its grid potential from below cut-off) very slowly, the resulting waveform would start with a portion which would be hyperbolic (differential proportional to square of pressure) rather than exponential. To produce an approximation to the desired exponential shape, the grid potential of V2 must be raised at a definite rate. This is achieved by a simple resistance-capacitance combination in the grid circuit. The required rate is modified slightly by the proportions of negative and positive feedbacks in use, and is corrected by resistors R14 and R13 controlled by switch S1.

When the "Firing" switch, S3, is closed the grid of V2 jumps to a potential, determined by the slider of VR1, a few volts below cut-off and then rises, as determined by the capacitor charging, to bring V2 into operation at the required rate. Test switch S4 is provided for checking the setting of VR1. When S4 is operated the capacitor is shunted by R16. If VR1 is adjusted so that the circuit can only just be fired by S4, it follows that the potential supplied from the slider of VR1 is below the firing point of V2 by an amount equal to the volt drop across R16, which has been chosen to provide a suitable value.

To change the time scale of the complete waveform without changing its shape involves changing only two capacitances. Switch S2 changes the time scale in this way over a range of 40 to 1 in six steps.

5. FAULTS DETECTED AND CORRECTED DURING TESTS.

5.1. The Phenomenon of "Hash"

When the apparatus was installed and tried out at the A.R.E., Woolwich, various faults immediately became apparent. The most serious of these was the phenomenon generally known as "hash".

In the first tests, a range of propellant shapes and sizes selected to provide a wide range of test conditions was fired in the Closed Vessel. In most cases the recorded curves were rendered extremely difficult, if not impossible, to read with any reasonable accuracy by the occurrence of high-frequency oscillations of large amplitude, frequently referred to as "hash", superimposed on the main trace. In addition, signals corresponding in frequency to pressure waves in the Closed Vessel were recorded in some cases, but these could usually be eliminated by a suitable choice of ignition system.

The main requirement, then, was to eliminate the unwanted "hash", and the logical approach to this problem appeared to be to discover its origin, if possible. Various possible explanations, such as mechanical vibration of various components of the vessel, were examined, but in most cases they could be discarded because the natural frequencies involved were very much lower than the "hash" frequency. Vibration of the gauge crystal itself, however, is not precluded. An entirely different design of gauge, employing quartz instead of the usual tourmaline, was tried out, but did not effect any improvement in this direction, as can be seen in Fig.11. Records Nos. 380, 303 and 377 are for the same charge weight of cordite WM 017 fired in the Closed Vessel. For rounds 380 and 303 the normal design of tourmaline gauge was used, but for round 377 a piston and quartz crystal arrangement was employed. The quartz crystal was of the same dimensions as the tourmaline crystal, but gives a smaller size of record because of its smaller Piezo-Electric sensitivity. However, the ratio of "hash" amplitude to the amplitude of the main trace is approximately the same in the two cases.

In the absence of a more satisfactory explanation, "hash" is tentatively presumed to be a genuine phenomenon of propellant combustion, and as such would merit further study. However, in the present connection it is regarded as interference which prevents legible recording of the main event occurring in the Closed Vessel. It is surmised that, during the burning of the propellant, there occur high-frequency irregularities in the development of the pressure, which, although of small amplitude, produce large signals when differentiated.

A Closed Vessel charge of a large propellant size will have a comparatively small burning surface, and will give a slow build-up of pressure. To record such a signal, the differential amplifier must be set at high gain, and this, of course, results in considerable amplification in the signals producing "hash". The ratio of "hash" amplitude to the amplitude of the main signal is then very large, and the record is illegible. On the other hand, a charge of small-sized propellant produces a large dP/dt signal, which requires little amplification, with the result that the ratio of hash to main signal amplitudes is small. This can be seen from the records for three different cord sizes in Fig.10.

Some filtering circuits were tried with a view to reducing the amplitude of the "hash", but it became apparent that this could not be done without introducing distortion of the curve. Owing to the unknown precise nature of the curve it is not possible to calculate exactly what this distortion will be, and absolute accuracy cannot be obtained. The relative accuracy between rounds will not, however, be affected.

From the experience obtained with various filter arrangements it was found possible to select a small number which would cover the required range of record speeds. A plug and socket arrangement was fitted in the input lead to the apparatus, enabling suitable filters to be inserted as required.

A preliminary examination of the problem of removing "hash" without excessive distortion of the recorded curve indicated that a filter circuit containing resistance and capacity offered the best solution. At first sight, the development of suitable circuits appeared to be a somewhat formidable undertaking, in view of the wide dP/dt range of the apparatus and the diversity of the signals, corresponding to different propellant shapes and sizes, which were required to be recorded. For the direct assessment of the distorting effect of the filter, Closed Vessel signals were obviously unsuitable, due to "hash"; also, such a method would have been very laborious, in view of the large number of firings involved. There was a requirement, then, for a means of applying to the recorder a smooth signal of the type produced by the Closed Vessel so that the amount of distortion caused by any filter combination could be measured directly. Fortunately, such a device was available, in the form of the signal generator (Section 4.6) developed as a means of applying test signals during the development of the recorder.

A limited number of Closed Vessel firings, covering the complete dP/dt range of the recorder, was carried out with various combinations of filter resistance and capacity introduced in the input lead to the apparatus, and the recorded curves showed that, in most cases, the "hash" could be removed without reducing the maximum dP/dt by more than 1%.

Some examples of the effect of the filter on the shape of the recorded curve are shown in Fig.12. In all these cases, the signal was provided by the simulator. In record No. 271, the curve with the higher maximum is for an unfiltered signal, but for the lower curve a filter consisting of capacity only was employed, the signal generator and recorder settings being the same in the two cases. It will be seen that the filter condenser has reduced the maximum pressure and the maximum dP/dt by the same fraction. Thus, this reduction in record size is equivalent in effect to a decrease in sensitivity of the Piezo-Electric crystal, and may be allowed for in the gauge sensitivity setting on the recorder. The addition of resistance to the filter, however, causes the maximum dP/dt and maximum pressure to be reduced by unequal amounts, as can be seen from records 772, 774a and 777b of Fig.12. In all three cases, the trace with the higher maximum is an unfiltered signal from the simulator, and the lower trace is the same signal after filtering. Nos. 772 and 774a correspond to the tubular propellant shape, and 777b to the cord shape. In each case, the gauge sensitivity setting on the recorder was adjusted to allow for the capacity of the filter condenser. For convenience, the reduction in dP/dt max. due to the introduction of resistance into the filter circuit is henceforth referred to as distortion.

In record No. 772 an excessive amount of filter resistance (830KΩ) was used, causing 12.5% distortion (i.e. a 12.5% reduction in dP/dt max.). A much smaller resistance (only 45KΩ) was used for record No. 774a, and this reduced the distortion to only 2.9%. It will be noticed that, in both cases, distortion does not commence until dP/dt max. is approached, and there is no detectable difference between the filtered and unfiltered traces over the straight portion when dP/dt is increasing. It is precisely this portion of the curve which is of interest in the determination of the propellant burning law from this type of record, for the following reason. It will be remembered that these two records correspond to the tubular shape of propellant, which has the property that its surface area remains constant during burning, if parallel layer burning is assumed, and the area of the ends of the sticks (a very small fraction of the total area) is ignored. If instantaneous ignition is effected over the whole charge surface and the dimensional accuracy of the sticks is of a high order, when burning is completed the charge surface area will decrease instantaneously from its constant value to zero i.e. dP/dt will decrease from dP/dt max. to zero at constant pressure. In practice, these ideal conditions are impossible to achieve, and the decay of dP/dt to zero takes a finite time. Even without such complications as so-called erosive burning, (i.e. non-parallel layer burning due to gas flow tangential to the propellant burning surface), the result is that, due to dimensional differences, some of the propellant sticks begin to burn through before others. Also, individual sticks may burn through unevenly, due to non-uniform ignition and eccentricity of the perforation with respect to the outer surface. These factors lead to a rounding-off of the recorded curve in the region of maximum dP/dt when the burning surface, in fact, commences to decrease as, at this stage, there is still an appreciable fraction of the charge available for increasing the pressure.

Methods for deducing rates of burning from the recorded curve must involve knowledge of the area of the burning surface of the charge. This is known, with some degree of certainty, only up to the stage at which it begins to decrease, in the above case, with the result that rate of burning calculations can not be made for the rounded portion of the curve and its continuation to the maximum pressure. It is precisely this part of the curve which is distorted by the filter, and it follows that, for propellants of such shape that the surface area remains sensibly constant during burning, the distorting effect of the filter may be ignored.

For the present purpose tube, slotted tube, multitube and strip propellant may be considered to burn with constant surface area, and distortion by the filter of the Closed Vessel signal presents no difficulty in the computations. The cord shape, however, is in a different category in this respect, as its surface area decreases continuously as burning proceeds. For the calculation of rate of burning, the curve of dP/dt v. P for cord propellant is of interest up to at least 90% of the maximum pressure, i.e. well beyond the maximum dP/dt stage, which occurs in the region of two-thirds of the maximum pressure. Record No. 777b of Fig.12. shows the type of distortion caused by the filter in the case of a cord round. In this particular case, distortion commences at a pressure of about 8 tons per sq. in., but the curve would be measured up to about 14 tons per sq. in. However, it has been found that, for the same maximum dP/dt in the two cases, the same combination of filter capacity and resistance causes approximately the same percentage reduction in dP/dt at 90% of the maximum pressure for a cord signal as at maximum dP/dt for a tube signal. In some cases, therefore, filter distortion may be ignored even for cord propellant, as the maximum error at any point of the measured curve is 1%, with no error over half this range. For more precise work, however, it is necessary to apply corrections for the effect of the filter, and these may be obtained directly by recording similar filtered and unfiltered signals from the signal generator.

For the rapid design of filters appropriate for specified dP/dt levels, curves of maximum recorded dP/dt against filter resistance for various filter capacities have been developed, using the previously-mentioned criterion of 1% distortion at dP/dt max. for a tube round. These curves are reproduced in Fig.13, from which it can be seen that, for example, if the maximum dP/dt expected in a particular firing is 3,000 tons per sq. in. per sec., a filter with capacity 0.0005uF and resistance 220 KΩ could be used, and such a filter would be expected to remove all hash and distort a tube signal by 1% at maximum dP/dt.

The curves of Fig.13 were obtained, basically, by recording filtered and unfiltered signals supplied by the simulator, and measuring the distortion caused by the filter. It has previously been explained (in Section 4.6) that dP/dt amplitude variation is provided for in the simulator, through a six-position switch. By this means, the full dP/dt range of the recorder could be covered. With the switch in position 1, the simulator set to generate "tube" signals, and no filter in the circuit, a signal was recorded. Further signals were then recorded, firstly with a filter condenser of 0.0005uF capacity, and then with the same filter condenser and increasing amounts of filter resistance until there was an appreciable amount (approximately 5%) of signal distortion. Finally, a second unfiltered signal was recirded to provide a check on signal generator drift during the series of recordings. A selection of records from such a series is shown in Fig.14. The records were then accurately measured, using a travelling microscope, and the percentage distortion caused by each of the values of filter resistance was calculated. These values of distortion were plotted against resistance, and the resistance causing 1% distortion in these particular circumstances was determined by extrapolation. It was felt that this method, as compared with one involving repeated determinations at or near the 1% level, would give accurate results with a minimum expenditure of time.

The above procedure was repeated for each of the remaining five dP/dt settings of the signal generator. In this way was obtained a series of values of resistance which, associated with a condenser of 0.0005uF capacity, distort the signal by 1% at specified dP/dt levels. These figures were employed to plot one of the curves of Fig.2, and the remaining curves, for filter capacities of 0.0006, 0.001, 0.0015 and 0.002uF respectively, were obtained in a similar manner.

The filter network is built up inside a frame of insulating material fitted with plugs for insertion in the socket provided in the input lead to the apparatus. Twelve such frames have been provided for carrying filters to cover the whole dP/dt range. Filters for the following maximum dP/dt values are suggested:- 900, 1200, 1500, 2000, 3000, 4000, 5000, 7000, 10,000, 15,000 and 20,000 tons per sq. in. The remaining frame can then be used as a short-circuiting device for firings in which a filter is not required.

In practice, it is convenient to use a standard filter capacity of 0.0005μF which reduces both maximum dP/dt and maximum pressure by 1%. This is equivalent to a reduction in gauge sensitivity, and it is possible to adjust the gauge sensitivity setting on the recorder to take this into account so that the differential and pressure calibration steps on the record retain the desired whole numbers. The use of a standard filter capacity thus has the advantage that such adjustment to the gauge sensitivity setting is the same for all filters used.

A typical example of the removal of hash from a Closed Vessel signal is given in Fig. 15. The charge consisted of Cordite N, in multitubular form, the mean web thickness being 0.060 in. and the density of loading 0.2 grams per c.c. For record No. 45 no filter was used, and the hash amplitude was very large. As the size of the filter is increased the record becomes progressively smoother, but it is seen that the hash occurring in the early stages of burning is the most difficult to remove. Ultimately, however, all hash was removed (see record No. 227) by using a filter made up of five 100 KΩ resistors and five 0.0001μF condensers. (The resistors were, of course, in series with the gauge, and the condensers in parallel). Fig. 13 shows that, at this particular dP/dt level (1600 tons/sq.in./sec) a filter with a total resistance of 420 KΩ and a total capacity of 0.0005μF would cause 1% distortion. Thus, in this particular case, distortion is little more than 1%, but if the resistance values are increased to, say, 470 KΩ each, as for record No. 111, there is a serious reduction in dP/dt max.: also, dP/dt max. is displaced in the direction of the pressure zero.

It is interesting to note that, in contrast to the above example, the maximum hash amplitude occurs in the region of dP/dt max., as for cordite WM 017 (see Fig. 11). It would appear that further study of hash formation might furnish evidence on the mechanism of propellant burning.

Some typical filtered records for various propellant shapes are shown in Fig. 16. Record No. 760 was for the cord shape of propellant, the maximum dP/dt occurring at about 2/3 of the maximum pressure. This is characteristic of the cord shape for which this figure of 2/3 is exact if the relationship between rate of burning and pressure is linear. The second record, No. 745, is for the tubular (i.e. constant burning surface) shape. In this case, it is necessary merely to multiply the values of dP/dt by a constant in order to deduce rates of burning. Thus, the recorded curve is of the same shape as the curve of rate of burning against pressure. It can be seen at a glance that, over the range from 2 to 12 tons per sq. in., the law of burning is of the form:- Rate of burning = βP^{α}, where α is a little greater than unity. In record No. 749 there is the complication that burning surface of the propellant shape, slotted tube, decreases as the burning proceeds, and this fact makes a considerable contribution to the shape of the curve. The remaining records, Nos. 896, 899 and 725, for the multitube propellant shape, indicate the burning - through of the web, at which stage the charge burning surface, and therefore dP/dt also, commences to decrease rapidly. A point of interest here is the hump which occurs in the early part of the curve, which is thought to be due to erosive burning of the propellant inside the perforations. The hump becomes increasingly pronounced in the order NH - FNH/P - N/2P/M, and this is probably connected with the fact that propellant adiabatic flame temperatures decrease in this order. Elementary theory of erosive burning predicts that propellants become more susceptible to erosive burning as the adiabatic flame temperature is reduced.

5.2. Fault in Zero Adjuster

Some of the early Closed Vessel recordings were sufficiently well defined, even without the use of a hash filter, to disclose a hump which occurred in such a random manner and with such variable amplitude that there was a strong suspicion that it did not emanate from the Closed Vessel, but was due to a fault in the recorder itself. Simultaneous recordings with the old pressure-time recorder and the new apparatus proved conclusively that the fault was in the new recorder. It was eventually traced to the zero adjuster circuit, and was due to an interfering signal being fed back to the input circuit. Suitable filter networks were fitted to attenuate the interfering signals. The effect of these filters was to cause a time constant of 10 seconds to appear temporarily across the input capacitor. The input signal would thereby be reduced by one thousandth of its value in 10 milliseconds. The filter time constant was 2 milli-seconds, so that the error introduced could amount to only 0.02%.

5.3. Screen Charging of the C.R.T.

When the above two difficulties had been overcome, it became possible to make a direct comparison between the new recorder and the pressure-time apparatus formerly employed by simultaneous recording of the same Closed Vessel firing. For this purpose, two tourmaline gauges were fitted to the Closed Vessel gauge block; one gauge was connected to the new recorder, and the other was connected to the pressure-time apparatus.

From a comparison of curves of rate of burning against pressure deduced from the simultaneous recordings, it soon became apparent that there was some wandering of the spot on the screen of the recording cathode ray tube in the new equipment. For the cord shape of propellant, in particular, the rate of burning deduced from the dP/dt - P curve was in very close agreement with that deduced from the P - t curve up to the stage of maximum dP/dt, but beyond this stage the rate of burning calculated from the new type of curve became increasingly greater than that indicated by the P - t record. This effect was equivalent to over-shooting of the spot on the recording tube, and was deduced to be due to collection by the screen of the beam current giving rise to electrostatic charges of sufficient magnitude to affect the deflection of the beam at or near the screen. The screen was only one crystal thick, and the resistance was therefore high and would prevent the rapid disposal of such charges. While the spot is travelling in a straight line there will be overshoot in the direction of motion, but at dP/dt max. there is a change in sign of the velocity component in the dP/dt direction. Beyond this stage, the velocity component in the direction of zero dP/dt is increasing rapidly, but the component in the pressure direction is decreasing, and there is opportunity for the over-deflected spot to drift back in the zero pressure direction. This will lead to fictitiously high dP/dt deflections, mainly over that part of the curve in which dP/dt is decreasing.

To eliminate screen charging effects, advantage was taken of recent advances in technique to put an aluminium backing on the screen, sufficiently thin for the electrons to penetrate to the luminescent material but thick enough to provide a low resistance surface much less prone to establish areas of unequal charge.

The same effect was observed on the monitor tube in spite of the lower resistance of its double screen, but this was not considered to be of sufficient importance to warrant correction, as this tube is used as an indicator only, and no measurements are made of the trace appearing on it.

5.4. Microphony in Differential Amplifier

Microphony at full gain in the differential amplifier was due to shocks transmitted from the uniselector switch. Although precautions had been taken to absorb these shocks at their source, a small amount of vibration reached the input pair of valves. This was greatly reduced by mounting them resiliently.

5.5. Differential Amplifier Power Supply

With the differential amplifier power supply provided, stabilisation is confined to certain sensitive parts of the circuit. This has proved to be insufficient, and there is a certain amount of "hum" present at high gain. In this respect it is unfortunate that this is the most useful part of the range for the study of gun propellants, and it has therefore been necessary to make provision for the whole H.T. supply to the differential amplifier to be stabilised.

5.6. Instability of Pressure Amplifier.

An occasional slight instability in the pressure amplifier was cured by a slight modification to the feedback circuit.

5.7. Photographic Problems.

At one time during the early tests a photographic effect became apparent which caused some anxiety. On some records a general fogging occurred accompanied by thickening of the trace. It was observed that this thickening was bad at the beginning of the record, becoming progressively better during the calibration until the last few lines were frequently normal. Sometimes, the early part of the trace was reversed in density, appearing as a white line on a grey background or as a double black line.

Observation of the recording tube during one of these recordings showed that during the calibration period the whole screen was luminous with a suffused glow which was evidently the cause of the fogging exposure. This glow was apparently due to scattered electrons from the beam during the time when it was deflected off the screen and was hitting either the edge of the deflecting plate or more likely the aquadag coating on the inside of the glass tube.

The observations and results seemed to fit in well with the photographic "CLAYDEN" effect, in which an image due to a short high intensity exposure followed by a long low intensity one may be partially or completely reversed, depending on the relative values of the two exposures.

Some thought was given to the problem of eliminating the fogging exposure, and a circuit was devised for limiting the scanning whilst retaining the fast writing speed.

It transpired, however, that by suitable adjustment of the exposure variables, beam current, lens aperture and calibration writing speed, the effect could be eliminated under normal conditions of operation without modification to the circuits.

Acknowledgments.

In a report of this type, it is difficult to make suitable acknowledgment to all individuals concerned. The broad requirements were specified by the Closed Vessel Section of the Ballistics Branch. Many of the units were designed by Mr. Nuttall of Messrs. Cinema Television Ltd; the firm's Engineer in charge of development was Mr. Phelp, who was assisted by Mr. Tappenden as Wireman. Throughout the course of the contract, technical liaison with the firm was maintained by Mr. J. B. Goode, now Superintendent of Ballistics Research, and administrative questions were dealt with by Mr. A. J. Milne-Smith. Following the installation of the recorder in the Closed Vessel Section of the Ballistics Branch, the staff of this Section collaborated with the firm's Engineer and Wireman in the tracing and rectification of faults.

In view of the remarks in the introduction regarding the sources of the information contained in this report, it seems undesirable that the report should appear under the name of any particular individual. Matters concerning the apparatus should be referred to the Closed Vessel Section, S.B.R., A.R.E., Woolwich, S.E.18.

APPENDIX I

OPERATING INSTRUCTIONS

(a) Switching on and setting up

See that all switches are OFF except C.R. tube heaters.

Switch on mains supply. WAIT 15 MINUTES.

Turn BRIGHTNESS controls fully anticlockwise.

Switch on POWER SUPPLIES in following order:-

E.H.T.

FOCUS

DIFFERENTIAL AMPLIFIER

CALIBRATION UNIT

ZERO ADJUSTERS

POTENTIOMETER (BATTERY SWITCH)

PRESSURE AMPLIFIER

EXPOSING UNIT

Operate UNISELECTOR (put UNISELECTOR SWITCH ON and PUSH BUTTON).

Set DIFFERENTIAL DIVISIONS AND DIFFERENTIAL SENSITIVITY so that their product exceeds the maximum differential expected. (See Appendix III for assessment of maximum dP/dt).

Select and plug in FILTER appropriate to expected maximum differential (see Fig. 13).

Set PRESSURE DIVISIONS to exceed expected pressure. (See Appendix IV for assessment of maximum pressure).

STANDARDISE POTENTIOMETER.

Set GAUGE SENSITIVITY to the MANTISSA of the COMMON LOGARITHM of the gauge sensitivity in microcoulombs per ton per square inch.

Turn Recording Tube BRIGHTNESS Control to give one or two microamps beam current. Operate CHECK switch and adjust amplifier gain and shift controls so that spot proceeds to corners of camera gate. Note that the spot is masked by the serial number printer in the top left-hand corner.

RESET UNISELECTOR and return CHECK switch to position one.

PUSH UNISELECTOR button and switch OFF when horizontal calibration line is about half way across the screen. Reduce PRESSURE WRITING SPEED to zero and adjust D.C. BIAS until the spot is in the centre of the C.R. Tube screen. Set WRITING SPEED controls according to the graph provided. (See Appendix VI). Check C.R. TUBE FOCUS.

Switch ON the UNISELECTOR until vertical line is halfway across screen, then switch OFF.

Set DIFFERENTIAL D.C. bias for central spot and DIFFERENTIAL WRITING SPEED controls according to the graph. (See Appendix V). Switch ON the UNISELECTOR which will proceed to its fully operated position.

Turn CHECK switch OFF.

The recording tube BRIGHTNESS and LENS APERTURE may be set by the following rule:-

$\frac{dP/dt \text{ max.}}{25 \times P \text{ max.}}$ gives the beam current in microamps at a lens aperture of f/8.

If the figure obtained exceeds 20, increase the lens aperture to f/5.6 and divide beam current by 2. If this still exceeds 20, increase lens to f/4.5 and divide current again by 1.5. (See, however, Appendix V for direct assessment of beam current and lens aperture.)

NOTE The beam current meter reads 10 times the actual value.

The monitor tube current may be set to about 10 microamps. (100 microamps on the meter).

(b) Application of Test Signal

RESET UNISELECTOR.

A test signal may now be offered from the signal generator (connected to line 6 switch position) and any necessary adjustments made to the exposing unit controls to ensure the end of the event being recorded. The Uniselector may be switched OFF if desired whilst making these tests, which can however only be made with the Uniselector in the RESET position.

(c) Routine Before Firing

Set GAUGE SELECTOR SWITCH to the required channel. On opening the inspection door the spot position may be observed by operating the CHECK switch to position 1. Make any necessary adjustments to the SHIFT controls. Return CHECK switch to OFF position.

See that the COVER DOORS are securely CLOSED.

Switch on SERIAL NUMBER relay and the UNISELECTOR.

Check POTENTIOMETER and WIND ON PAPER ONE TURN.

The apparatus is now ready for firing, but if for any reason it is necessary to check the spot position, or make any other adjustment which might fog the sensitised paper, remember to wind on the paper ONE TURN before firing.

(d) Routine After Firing

Immediately it is observed that a record has been obtained REDUCE THE BEAM CURRENTS TO ZERO, SWITCH OFF SERIAL NO. RELAY.

WIND ON PAPER TWO TURNS and cut off. Remove the R.H. Cassette to the dark-room for processing.

Should it be desired to record a number of events in succession, the paper should be wound on one turn only.

After resetting the uniselector and restoring the beam currents, the apparatus is ready for the next record.

(e) Switching Off

Switch off the supplies in the following order:-

FOCUS

E.H.T.

PRESSURE AMPLIFIER

EXPOSING UNIT

DIFFERENTIAL AMPLIFIER

CALIBRATOR

ZERO ADJUSTER

POTENTIOMETER

GENERAL MAINS SUPPLY

APPENDIX II

ROUTINE ADJUSTMENTS

(a) Differential Amplifier

When the gain controls have been set to the approximate value required, the amplifier balance should be checked. With the shift control about the middle of its travel, adjustment of the screen balance (9 in circuit S.3) will bring the spot to the required position. This control is operated by the centre spindle behind the valve cover. The fine gain control should now be turned fully clockwise and the spot should be returned to its position by means of the screen balance control. Reducing the fine gain control will now displace the spot, which should be returned by operating the cathode balance (7 in circuit S.3). This is the left-hand spindle behind the valve cover. The spot position should now be independent of the position of the fine gain control, and the amplifier balanced.

The balancing control 42 only needs adjustment when either of the valves 35, 37 are changed, and should be adjusted to give zero hum deflection on the C.R. Tube.

(b) Pressure Amplifier

The pressure amplifier may be balanced in a similar manner using the controls VR1 in circuit S.5 (screen balance) VR2 (gain) and VR4 (cathode balance). The latter is situated on the left-hand side; the screen balance is the top one of the two right-hand spindles behind the valve cover.

Owing to the limited range of the gain control in this amplifier it is unlikely that any out of balance will occur during normal operating.

The control VR5 in circuit S5 is used for balancing the hum appearing on the grid of V2 and is adjusted on installation. Should it be necessary to readjust, some additional hum should be introduced across the H.T. line by disconnecting the two smoothing condensers in the power supply. Set the gain to maximum and observe the hum deflection on the C.R. Tube. The control VR5 may now be adjusted until the deflection is a minimum.

(c) Zero Adjuster

The Zero Adjuster is provided with a control knob for varying the current through the vibrator driving coil. This is set by hand to the position of minimum contact noise, on either side of which the noise level rises steeply. The vibrator has proved to be a very reliable component and it is unlikely that any other adjustment will have to be made.

(d) Exposing Unit

The trigger circuit formed by the pair of valves V7 and V8 (in circuit S7) is adjusted by the resistors VR4 and VR5 so that V7 is normally taking current but flips over sharply when the grid of V7 is taken negative, i.e., when VR5 is reduced.

VR1 determines the amplitude of the dP/dt signal required to operate the unit and hence the point at which the curve is first exposed. If set too low the unit may be triggered by interfering signals. Since, however, the beginning of the trace is not usually of special importance, it is not necessary for the control to be set too finely.

VR3 determines the amplitude of the derived $d^2P/_{dt}{}^2$ signal at which the unit blacks out. This control must be set with some care if the end of the trace is to appear and is not at the same time to be confused owing to the slowing down of the writing speed. The use of the signal generator on an appropriate range is a great help in setting the control.

Some types of interfering signal, although of small amplitude may, owing to their frequency characteristic, give rise to derived signals sufficient to operate momentarily the exposing trigger circuit. The control VR7 may be used to hold off the effect of the derived signals until the event takes place and the C.R. Tube is exposed by the normal signal. The correct setting for this control can be ascertained by observing that the C.R. Tube remains blacked out before an event takes place. The resistor VR6 controls the operation of the calibration relay, and may be turned completely anticlockwise when it is desired to withhold the operation of the uniselector, e.g., when adjusting other sections of this unit in conjunction with the signal generator. The normal operating position may be easily found by trial. In addition, VR2 should be adjusted so that a pressure signal of at least half the normal amplitude is required before the calibrating relay operates. The position for this is easily determined by reducing the pressure amplifier gain and supplying a signal from the test generator.

APPENDIX III

ASSESSMENT OF MAXIMUM dP/dt.

Before carrying out a firing in the Closed Vessel, it is necessary to make an assessment of the maximum value of dP/dt to be expected, so that the appropriate controls on the recorder may be set to give the maximum practicable size of record. For rapid assessment, this quantity has been graphed against propellant size for various propellant compositions and shapes. Thus, in Fig. 17, dP/dt max. is plotted against propellant size for cord propellants ranging in adiabatic flame temperature from 1,700°K to 3,600°K. Similarly, Fig. 18 is for the tube shape, and Fig.19 is for multitube and slotted tube. In all cases, the propellant loading density in the vessel, which is of 700 c.cs. capacity, is 0.2 grams per c.c., which is standard for propellants with flame temperatures of 2,200°K or greater. For propellants cooler than this, the loading density is increased to 0.25 grams per c.c..to bring the maximum pressure up to a reasonable level. Fig. 20 is intended to meet such cases.

For the present purpose, it is sufficiently accurate to assume that, for any particular shape and size of propellant, dP/dt max. is related to adiabatic flame temperature T_o. In other words, it is assumed that all propellants with the same T_o follow the same law of burning. In Figs. 17, 18 and 19, values of T_o, where associated with propellant nomenclature, are included merely to indicate the order of temperature level, and in some cases do not correspond exactly to T_o for the composition specified.

Logarithmic scales were chosen for these graphs because the main interest, so far as gun propellants are concerned, is in the size range from about 0.02 in. to 0.06 in., and the corresponding dP/dt max. range from about 800 to 5,000 tons per sq. in. per sec. This method of plotting spreads out that part of the scale in which the main interest lies, and at the same time leads to straight line graphs which are, of course, much easier to draw than the curves which would be obtained by plotting to even scales.

It should be mentioned that some of these graphs are based on rather scanty data. In Fig.17, for example, only two propellant samples with a T_o of 1,700°K have so far been fired in the Closed Vessel, and these were very nearly equal in size. Thus, in effect, only one point on this curve is known with any degree of certainty. The method adopted in drawing these sets of curves was first to establish curves for those compositions which had been explored in the past over the greatest range of size (e.g., cordite S.C. and W.M. in the case of the cord shape), and to assume that the corresponding curves for the remaining compositions are parallel to these.

It is well known that, for various reasons, the relationship between rates of burning and pressure for any particular propellant composition and size is not invariable. In practice, the products from different factories differ slightly in this respect, and, in fact, the product of individual factories is found to vary also. Such variations cause differences in the maximum recorded dP/dt, and it will be appreciated, therefore, that the plotted curves referred to above can give merely a general indication of the order of maximum dP/dt in any particular case. In addition, there are various other factors which contribute to the uncertainty of the dP/dt max. estimate.

For example, in the case of cordite N, it has been established that the granulation of the picrite used in the manufacture of this propellant has an appreciable effect on rate of burning, which increases as the picrite crystal is reduced in size. For this reason, it is suspected that a colloidal propellant burns somewhat faster than one containing an appreciable proportion of crystalline ingredients, for the same adiabatic flame temperature.

The plotted curves, then, permit dP/dt max. to be estimated to a degree of accuracy which is sufficiently high for the purpose of adjusting the various settings on the recorder . Having estimated dP/dt max., the number of differential divisions and the differential sensitivity on the recorder are then set so that their product is slightly in excess of this figure.

APPENDIX IV

ASSESSMENT OF MAXIMUM PRESSURE

In order to select the appropriate number of pressure calibration lines for any particular Closed Vessel firing, it is necessary to make an estimate of the maximum pressure to be expected. For this purpose, maximum pressure has been graphed against propellant size, for propellants with various levels of adiabatic flame temperature. These graphs are reproduced in Fig. 21, in which the continuous lines refer to a propellant loading density of 0.2 grams per c.c., and the dotted lines to a loading density of 0.25 grams per c.c. As explained in Appendix III, a loading density of 0.2 is used for propellants with adiabatic flame temperatures of 2,200°K and above, but this is increased to 0.25 for propellants cooler than this.

The curves plotted in Fig. 21 were drawn up from calculated maximum pressures. First, the theoretical (i.e. uncooled) force constants for the various compositions were calculated, and hence the uncooled maximum pressures for the appropriate densities of loading were deduced. Allowance was then made for heat losses for a range of propellant sizes. The heat loss corrections were determined from Closed Vessel firings of five sizes of each of four propellant compositions with flame temperatures ranging from about 2,400 to 3,600°K, from which it was possible to express heat loss as a linear function of propellant size for any particular level of flame temperature. Other conditions being the same, the energy losses during the burning of a charge in the Closed Vessel are related to the geometry of the combustion chamber. If this is scaled down in size, then the wall surface area per unit of charge is increased, and the heat lost by conduction to the vessel walls during the burning of the charge is increased also. In addition, energy losses due to expansion of the vessel under pressure and compression of the obturating system depend on the vessel design. Fig. 21 must therefore be considered to refer only to the particular design of Closed Vessel (viz. No.21) in common use in the A.R.E. This vessel has a nominal chamber capacity of 700 c.cs.

In Fig. 21 the quoted values of adiabatic flame temperature (T_0) indicate merely the temperature levels, and not the exact flame temperatures of the various propellant compositions listed with them.

APPENDIX V

BEAM CURRENT ADJUSTMENT

In Appendix I, under the heading of "Operating Instructions", an expression is given for calculating the C.R.T. beam current appropriate for the recording of specified conditions of dP/dt max. and P max., for a lens aperture of f8. This was recommended by the manufacturers and was designed to ensure a high degree of photographic contrast even in the most unfavourable circumstances. The greatest variation in spot writing speed occurs during the recording of a Closed Vessel signal corresponding to the burning of a propellant with constant surface area, (e.g., tubular propellant). With such a propellant shape, if ideal ignition and manufacturing perfection could be achieved, at the end of burning the area of the burning surface, and hence dP/dt also, would fall to zero instantaneously, and the spot writing speed would be infinite. In practice this stage takes a finite time, but even so the writing speed can reach a very high value. The expression given in Appendix I for calculating beam current ensures that, even with such high writing speeds, there is sufficient brilliance of the spot for this part of the event to be recorded on the photographic paper with a high degree of contrast. Such an amount of beam current, however, leads to considerable thickening of the trace, due to the low writing speed at the commencement of the recording. It has already been mentioned that, in such recordings, only that part of the curve up to the region of dP/dt max. is of interest for the calculation of rates of burning. If the beam current is reduced below that calculated from the given expression, the recording of the important part of the curve is improved, and contrast is lost over the comparatively unimportant part, without affecting the measurement of maximum pressure which is required for the assessment of the propellant force constant. The spot, having passed through its phase of very high writing speed, slows down as the maximum pressure is approached, giving adequate contrast for the required measurement.

By recording curves of various shapes, it was found that a suitable degree of photographic contrast could be obtained by operating with the beam current calculated from the given expression, but with the recording lens stopped down from f8 to f16. This is, of course, equivalent to using the recommended aperture of f8, with a quarter of the calculated beam current.

It will have been observed from the given expression that the recommended beam current is inversely proportional to the maximum pressure of the recording. As, however, the range of pressures to be recorded is not very great, this is an unnecessary complication in practice. The curves of beam current meter reading against dP/dt max. for various lens apertures, reproduced in Fig. 22, were, in fact, deduced by assuming a uniform maximum pressure of 16 tons per sq. in., and have given satisfactory results in practice. These curves incorporate the reductions in beam current referred to in the previous paragraph. Logarithmic scales were employed in order to expand the more commonly used lower part of the dP/dt range.

The full-scale reading of the beam current meter is 500, corresponding to 50 microamps. In practice, settings greater than 100 are avoided, to prevent fogging of the photographic paper. On the other hand it is undesirable to operate with a very low beam current because of the consequent loss of relative accuracy in making the adjustment. As a general rule, therefore, the lens aperture is adjusted to permit the use of a beam current of from 4 to 8 microamps (I.e., a meter reading of between 50 and 80).

APPENDIX VI

CALIBRATION WRITING SPEED ADJUSTMENT

The necessity for making the calibration writing speed adjustment is explained in Section 4.4. Curves of writing-speed control settings plotted against dP/dt max. were supplied with the apparatus. These curves were intended for use in conjunction with the initial instructions regarding beam current adjustment, which, as shown in Appendix V, it has been found necessary to modify. As the calibration lines have to be drawn with the same value of beam current used for the actual record, if the reduced value of beam current recommended in Appendix V is used with calibration writing speed settings read off from the curves as supplied, the calibration writing speeds will be too high and the grid will be too faint. A satisfactory solution is to halve the recommended calibration writing speeds, and new curves of calibration writing-speed setting against the maximum dP/dt of the recording have been drawn up on this basis (see Fig. 23). It will be observed that logarithmic scales have again been used, in order to extend the scale over the most commonly used part of the range. Separate curves are provided for pressure calibration writing speed and differential calibration writing speed.

APPENDIX VII

CALIBRATION OF GAUGE CRYSTAL

The pressure sensitivity of the tourmaline crystal must be determined before it can be used in the Closed Vessel, so that the appropriate setting may be made on the recorder. The method of making this determination is to subject the crystal to an accurately-known pressure in a hydraulic press, and to measure the output from the gauge when this pressure is released. It was the original intention to make special provision in the recorder for the measurement of gauge output for sensitivity determinations, one suggestion being to measure, by means of an electrostatic voltmeter, the difference between the voltage produced by the charge across a condenser, and a backing-off standard voltage. This method would have the advantage of speed of operation, but certain technical difficulties would have to be overcome.

At the moment, it is not possible to record the calibration signal directly, as for a Closed Vessel signal, as the recorder was built to record only a positive signal. In effect, the technique of pressure release used in gauge calibration reverses the polarity of the signal, and the recorder is unable to deal with this. Reversal of the crystal in its mounting would solve this difficulty, but this would involve breaking the cement joint, and this in itself might have some effect on gauge sensitivity which would be undetected. As used in the Closed Vessel, the tourmaline crystal supplies the recorder with only the positive charge, and the negative charge is led to earth. Removal, instead of application, of pressure reverses the polarity of these charges. Experiments are in hand with a special calibrating adapter in which a spring-loaded plunger is used to take off the charge from that face of the crystal which is connected to earth in Closed Vessel firings. On release of pressure, therefore, this charge is of the correct polarity to operate the recorder normally, and in this way it is hoped to record crystal calibration signals in the normal manner.- At the present time, however, it is necessary to use a separate (pressure-time) recording apparatus in the determination of gauge sensitivity.

In the calibration experiments now being carried out, the main difficulties are associated with the type of signal generated by the crystal when the hydrostatic pressure is released. During the release of pressure, with the particular experimental set-up employed there are reversals in sign of dP/dt which are capable of operating the C.R.T. blacking-out unit, with possible non-recording of the remainder of the event. Even with full recording of the complete signal, it is not possible to measure the maximum deflection in the pressure direction to a sufficiently high degree of accuracy, due to the peculiar shape of the recorded curve and thickening of the trace in the region of maximum pressure. A more favourable shape of recorded curve could, no doubt, be obtained by suitable modification to the mechanical part of the set-up. As an alternative to this, it may be possible to use only the pressure signal from the crystal under test, and to apply a triggered sweep in the differential direction instead of the differential signal from the crystal. The latter alternative is probably more feasible than the first, and is being investigated at the moment.

APPENDIX VIII

IMPROVEMENTS

A second model of this recorder is now being built by Messrs.Cinema Television Ltd., for installation at the Defence Research Laboratories, Maribyrnong, Australia. Advantage has been taken of experience gained with the prototype to incorporate various improvements in this second model. These are listed below, together with some minor modifications made mainly to assist in production:-

(a) Differential amplifier power supply - a new design, with improved stability, to be used.

(b) Exposing unit - a sub-panel to be fitted so that adjusting knobs and graduated scales can be fitted to the various knobs, without complicating the removal of the front panel.

(c) C.R.T. baseplate - a more rigid arrangement to be used.

(d) C.R.T. housing - windows (ruby and clear) in doors to be fixed; mirror under monitor tube to be removable instead of collapsible; new design of locking knob to be used for the doors; frame to be of T - section steel; doors to have a flange for lightproofness and additional strength.

(e) C.R.T. heater circuit - original arrangement requires constant current for the heaters; new tubes require constant voltage, a more usual design. This will eliminate two controls and two meters from the C.R.T. power supply panel.

(f) C.R.T. heater and grid leads - to be in polythene cable instead of bakelite tube which is now unavailable.

(g) Camera - Messrs. Cossor Ltd., no longer make a 70 mm. camera as originally used, and it may be necessary for Messrs. Cinema Television Ltd. to design and make this item themselves if an alternative standard model can not be found. Lens to be fixed in position relative to the recording paper; focussing to be adjustable by movement of the C.R.T. mounting, through a micrometer screw; extension tube and additional lens to be supplied for full-size recording of low-pressure firings.

(h) Signal Generator - to have adjustable gain in pressure direction in addition to the differential gain provided in the original equipment.

(N.B Provision for pressure gain has been added to the prototype).

(i) E.H.T. power pack - the condensers in the prototype are now obsolete, the new design is wax impregnated and larger in size. The increase in size has necessitated some re-design of this unit.

(j) Mains voltage - provision for 200,210, 220, 230 and 240 volt tappings.

(k) Cable - lead-covered cable, which had been used for rigidity in the first model, may not be available for the long connections between panels.

(l) Heater transformers - so long as provision is made, where necessary, for switching on the heater of a valve before the H.T. supply, the use of separate heater and H.T. transformers for the ordinary valves is not necessary.

(m) Filter - location of filter assembly with respect to its socket to be improved.

(n) General - all chassis to be cadmium plated. (In the prototype, the chassis are copper plated and painted).

- all components to be suitable for tropical conditions wherever this is possible.
- meters to be sealed types.
- neon type indicator lamps to be employed.
- new type of locating and fixing screw to be used for all cover plates.
- labels on panels will be of aluminium instead of xylonite.

APPENDIX IX

MEASUREMENT OF dP/dt - PRESSURE RECORD

The quantities required to be read off from the recorded curve of dP/dt against pressure are:-

(1) Values of dP/dt at each pressure calibration line (a) up to maximum dP/dt in the case of propellants which burn with constant or nearly constant burning surface (e.g. multitube, single-hole tube, slotted tube, sheet, strip, flake, etc), or (b) up to the maximum pressure for propellants of such shape that there is a considerable variation in surface area during burning (e.g., cord), and

(2) The maximum pressure of the firing.

For these measurements, a standard Universal Measuring Machine, manufactured by Messrs. Cambridge Instrument Company, Ltd., is employed. The photographic record is inserted between a pair of glass plates supported horizontally on a carriage which is capable of movement, with micrometer adjustment, in a transverse (or "y") direction. The record is viewed through a telescope, fitted with cross-wires, supported with its axis vertical on a second carriage, which is adjustable in the longitudinal (or "x") direction. Measurements in the two directions are made by means of fixed figured scales, which are read to the nearest 0.5 mm., and filar micrometers carried on the carriage. In both cases, one revolution of the filar micrometer thimble corresponds to a movement of 0.5 mm., and as it is graduated in 50 divisions it is a simple matter to take measurements to the nearest 0.001 cm.

The record is positioned so that the pressure axis is coincident with the "x" direction of the measuring machine. Measurements at each of the required points are then made as follows. For measurement of dP/dt at a pressure calibration line, the telescope cross-wires are first brought into coincidence with the appropriate pressure line and the dP/dt line immediately below the point where the main trace cuts the pressure line by making appropriate adjustments in position of the two carriages. The view through the telescope eye-piece is then as shown in Fig. 24 (a). The "y" direction scale and filar micrometer are then read. The carriage supporting the record is then adjusted in the "y" direction until the telescope cross-wires coincide with the intersection of trace and pressure-line (see Fig. 24 (b)), and a second "y" reading is taken. This is followed by a third "y" reading with the cross-wires at point C (Fig. 24 (c)). The intercept AB and the height of the dP/dt step are then obtained by subtraction, and the intercept AB is converted into units of dP/dt from the known step sensitivity by simple proportion. This is then added to the value of dP/dt corresponding to the number of whole steps below the intersection.

In the technique employed previous to the installation of this recorder, curves of pressure against time were recorded by a Piezo-Electric method. Calibration of the pressure amplifier was performed automatically for each round by the application of a series of five accurately-known voltages immediately prior to the firing of the round. Thus, at the commencement of each recorded trace there occurred a series of five steps, each step corresponding to the same known pressure increase. The first operation in the measurement of such records was to measure the heights of these steps and to draw a calibration curve of pressure against deflection.

This curve was usually of $\int$ -shape. The next step was to differentiate the recorded pressure-time curve, and as this involved the measurement of very small displacements a high degree of accuracy in the resultant values of dP/dt could not be expected because of reading errors. An average example would be a pressure increment corresponding to 0.3 cm. on the photographic record, and a time increment corresponding to 0.4 cm. If these measurements are in error by + 0.001 cm. and - 0.001 cm. respectively, then the corresponding error in dP/dt is 0.6%. On the curve of dP/dt against pressure, a reading error of 0.001 cm. would, in general, cause dP/dt to be in error by approximately 0.2% at a pressure of 1 ton per sq. in., diminishing to 0.02% at maximum dP/dt.

It is, perhaps, safe to say that, in all types of experimental work, some measure of inaccuracy is inevitable. In some cases, as in the present, the sources of possible error are fairly numerous, but many of them can be kept within reasonable bounds. In the present instance, the change from pressure recording to dP/dt recording has obviously reduced the record reading error very considerably, but it is desirable to know the magnitude of this error in order to determine whether any further improvement may be effected in this direction. Arrangements were made, therefore, for seven observers to read the same pressure-time record and also the same dP/dt - pressure record. The usual routine of dividing the pressure range into 50 equal parts and taking readings at odd integers was adopted for the pressure-time curve, and, in order to make the results comparable on a pressure basis, the same procedure was followed for the dP/dt curve instead of the usual method of taking measurements at each whole ton per sq. in. In both cases, the measurements were converted to units of dP/dt and the individual sets of seven readings for each measured point were averaged. For both types of record, deviations from the mean were calculated for the individual measurements made by the various observers. In all cases, the maximum pressures were read in a similar manner, and the deviations from the mean were calculated for each of these measurements. The results are plotted in Fig. 25 (A) referring to the pressure-time record and (B) to the dP/dt - pressure curve. The improved reading accuracy gained with the new recorder is at once evident from this figure. The corresponding standard deviations of the measurements are graphed in Fig. 26. Over most of that part of the dP/dt range which is employed for the calculation of propellant rate of burning the standard deviation in the measurement of dP/dt is under 0.1%, but the corresponding error for the pressure-time curve averages at 1.5%. The standard deviation in the measurement of maximum pressure is considerably smaller for the dP/dt record than for the pressure-time record, but an even greater improvement in this respect is possible. With the new type of record, maximum pressure reading accuracy is largely a matter of correct black out of the C.R. spot. In the region of maximum pressure, the spot is moving very slowly, and if blacking-out is over-delayed the recorded trace terminates in a large black blob surrounded by considerable fogging, and accurate measurement of maximum pressure becomes impossible. Controls for adjustment of cut-off are provided in the exposing unit, but there is no arrangement for indicating the setting position. In any particular circumstances the appropriate adjustment is made by trial and error on a succession of signals from the simulator, but in the second model now under construction it is proposed to build a sub-panel in the exposing unit so that the controls may be fitted with pointers for reference to graduated dials. (See Appendix VIII).

Referring again to Fig. 26, it is interesting to note that an appreciable proportion of the error in measuring dP/dt in the case of the pressure-time record may be due to the non-linearity of the pressure-deflection calibration curve. As only five points were available for the drawing of this curve, some uncertainty in the shape of the curve between pairs of points inevitably arises in regions where the shape is changing. Provided that the curve is made to pass through the plotted points, those parts of the curve in the immediate vicinity of the plotted points will probably be in least error. Fig. 26 provides some confirmation for this deduction, the standard deviation in dP/dt measurement being a minimum where two of the calibration steps occur.

As the errors of measurement for the dP/dt record are so small, no special action is being taken at the present time to effect further improvement in this direction. Some consideration, however, is being given to the problem of reducing the amount of work involved in the measurement of records, without sacrificing reading accuracy. On an average, 14 measurements of dP/dt and one measurement of pressure are made for each record. This involves setting the measuring machine 45 times and taking this same number of readings. There follows an appreciable amount of arithmetic, consisting of 30 subtractions, 15 divisions, 15 multiplications and 14 additions, with much scope for errors to occur. (Incidentally, the high point in the region of 23% burnt for the dP/dt curve in Fig. 26 was due solely to one bad determination by one observer). Another aspect which merits consideration in the routine measurement of such records is that of operator fatigue. The measuring machine at present in use has a range of 13 cms. x 33 cms. (compared with the dP/dt record size of 7 cms. x 7 cms.), and is therefore somewhat massive. This leads to considerable discomfort of the operator after prolonged use, and this is aggravated by the constant use of the adjusting and measuring telescopes, which causes eye-strain. It was felt that the time required to read records, and fatigue of the operator, could be considerably reduced, without any appreciable sacrifice of reading accuracy, by the development of a special measuring instrument.

Various alternative methods of measuring the record were considered, viz:-

(a) Optical projection, and direct measurement of the enlarged trace using special devices for reducing the amount of arithmetic. Reading accuracy would probably suffer, as it would be difficult to estimate the middle of the enlarged trace, which would be lacking in contrast.

(b) Microscope with micrometer eye-piece. This is a variant of (a) above, in that the special scale would be in the telescope eye-piece. There are two opposing requirements; a high magnification would be necessary for the attainment of the requisite degree of accuracy, but a low magnification is wanted for ease of reading.

(c) Microscope with filar micrometer incorporated in the eye-piece. The field of view of the telescope must cover the largest calibration step. Measurement of intercept and step height would be direct, and arithmetic would be much reduced. The readings would require conversion into fractions of a step, and thus into units of dP/dt.

(d) Combination of mechanical and electrical methods. This would retain the advantage of a microscope, in which fine adjustment (corresponding to step height) would be through thimbles containing rheostats. The associated electric circuit would contain standardising rheostats and would be so designed that, by traversing the telescope cross-wire from one dP/dt line to the next through rotation of the appropriate rheostat thimble, full-scale deflection of a spot galvanometer would result. The scale of the dP/dt spot galvanometer would be graduated in terms of the dP/dt step sensitivities (viz. 50, 100, 200, 500 and 1,000 tons per sq. in. per sec.), and arithmetic would be reduced to the absolute minimum. The main objections to this method are possible difficulties with the rheostat thimbles due to contact potential, and the use of batteries.

Eventually, Messrs. Cambridge Scientific Instrument Company, Ltd., were consulted in this matter, and an entirely mechanical design containing all the advantages of method (d) above is now being evolved. The appearance and size of this instrument will be very similar to that of the usual design of analytical microscope. The telescope will be inclined to the vertical for comfort in reading, and the platform, with provision for adjustment in two directions, is designed round the size of the record to be measured. Displacement of the table is through a combination of screw thread and lever which amounts, in effect, to a variable pitch screw. With the measuring thimble fully rotated in an anticlockwise direction up to a stop, the microscope cross-wires are focussed on the lower of the two dP/dt steps between which a measurement is to be made. The thimble is then rotated one complete revolution in the clockwise direction, again up to a stop, and a lever adjustment is then made so that the telescope cross-wires are focussed on the second of the two dP/dt steps. This operation is equivalent to adjusting the pitch of the operating screw so that one revolution of the thimble is equivalent to the dP/dt step being measured. If the number of graduations on the measuring thimble corresponds to the number of dP/dt units per calibration step, the reading on the thimble when it is rotated back to bring the cross-wires into coincidence with the intersection of trace and pressure is the value of the intercept between this point and the lower dP/dt line, in units of dP/dt. The only remaining calculation is that of simple addition. The graduations on the thimble will be on removable rings, and rings graduated in terms of the various dP/dt sensitivities of the recorder will be supplied.

When optical methods are employed in the measurement of photographic records there is usually some optical magnification of the trace, and this inevitably results in some loss of contrast between the trace and its background. As the magnification is increased, it becomes increasingly difficult to gauge the middle of the trace, until a stage is reached at which further increase in magnification will result in loss of reading accuracy. In the measuring machine used at present, the optical magnification is X18, and this is considered to be too high for the present purpose. A reduction in magnification below this value certainly makes record reading considerably easier. For the special design of instrument which is now under development it is, of course, desirable to employ the degree of magnification best suited to the particular type of record which it is required to measure. Accordingly, a test was made to determine whether a reduction in magnification below the present X18 level could be tolerated on accuracy grounds. For this purpose the machine in present use was employed, and the same dP/dt - pressure record was measured by each of nine observers, with the present X18 magnification and also with the magnification reduced to X8. In each case, measurements of dP/dt were made at pressure intervals of one ton per sq. in., as in the normal method of reading. For each of the two magnifications, the nine measurements of dP/dt at each pressure step were averaged, and standard deviations from the mean were calculated.

These are plotted in Fig. 27, from which it can be seen that there was some slight loss in reading accuracy when the magnification was reduced from X18 to X8, which would affect the accuracy of the propellant rate of burning law deduced from these measurements. In Fig. 28 the ratio between the mean values of dP/dt, using the two magnifications, is plotted against pressure. The equation of this curve is:- Plotted ratio = $0.9992\ P^{0.0004}$. This is equivalent to a difference of 3 parts in 10,000 between the rate of burning constants (reduced to a linear law) deduced from the three sets of readings. It is apparent that, in the present instance, reduction in magnification from X18 to X8 has had no appreciable effect on the accuracy of the final result.

The nine observers were unanimous in the opinion that the reduction in magnification made the record much easier to read, due to improved definition of the trace. It is possible that, for a record less clearly defined than that actually employed in the test, the conclusion regarding the effect of magnification on reading accuracy might have been reversed, due to improved definition at low magnification.

On balance, therefore, X8 magnification is preferred to X18, but provision is to be made in the new instrument for both magnifications.

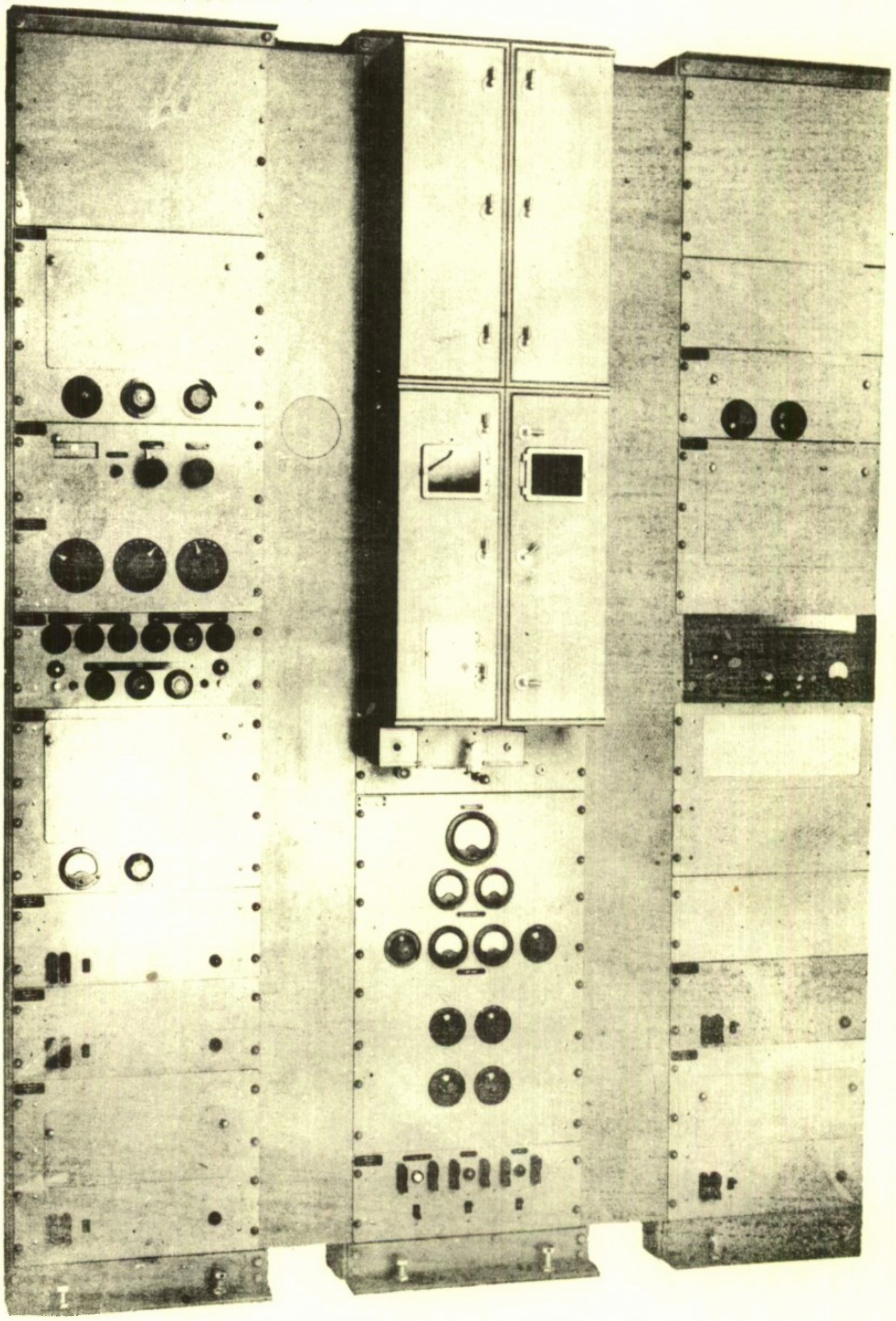


PLATE 1

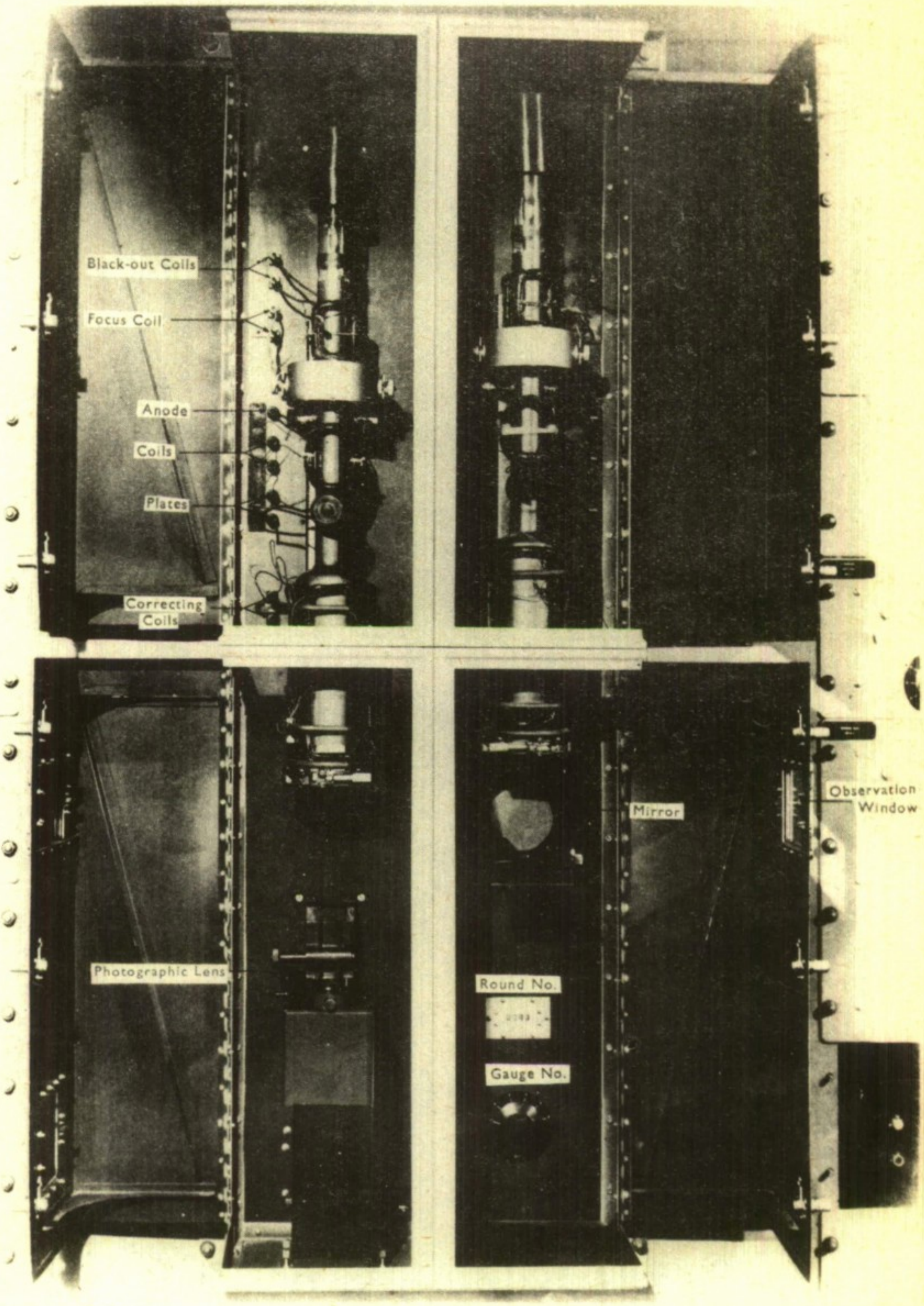
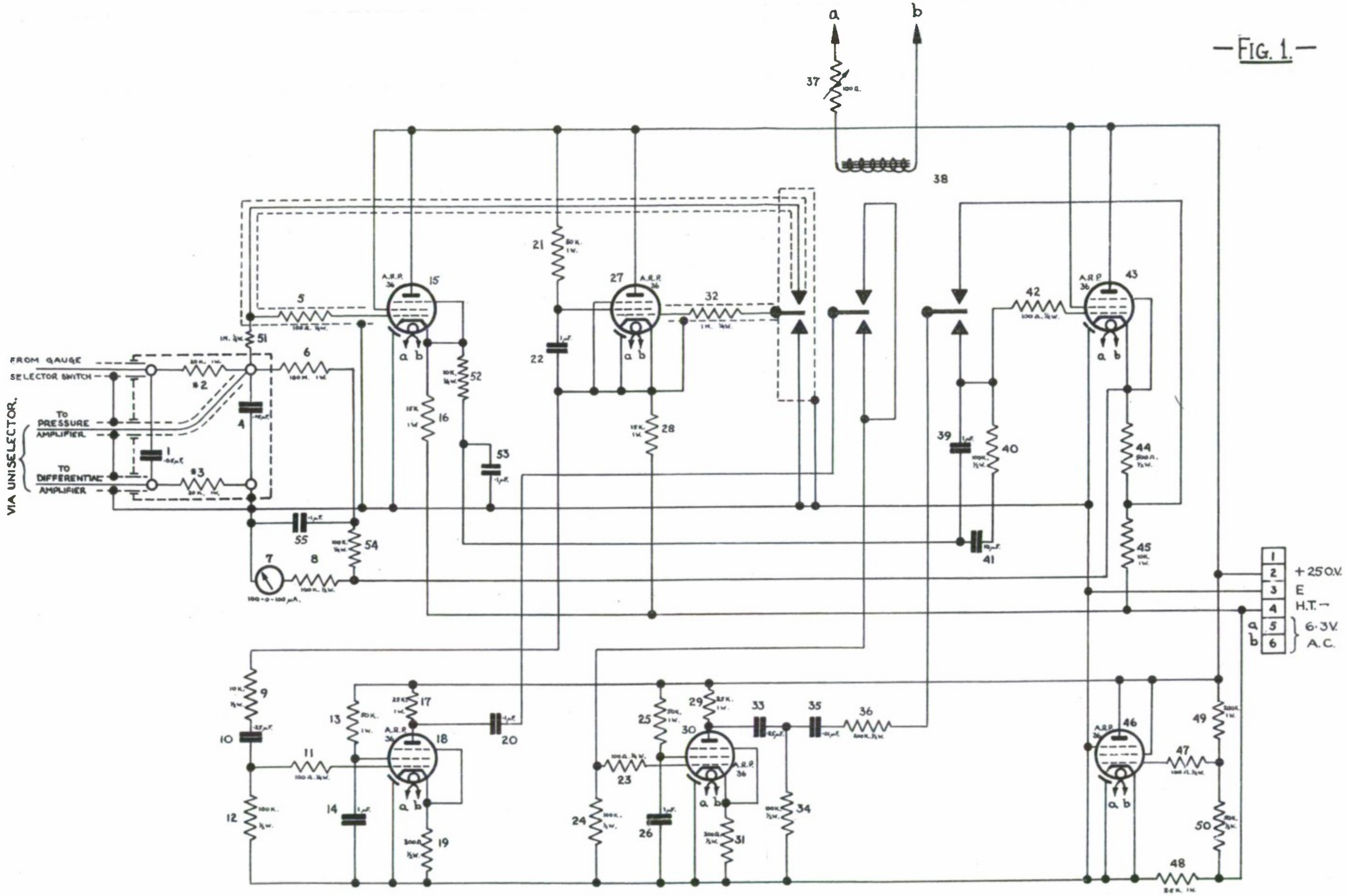

Black-out Coils
Focus Coil
Anode
Coils
Plates
Correcting Coils
Photographic Lens
Mirror
Round No.
Gauge No.
Observation Window

PLATE 2

— FIG. 1. —



* High-stability Resistors
38 Vibrator. 183/SA30
C.T. Ltd.

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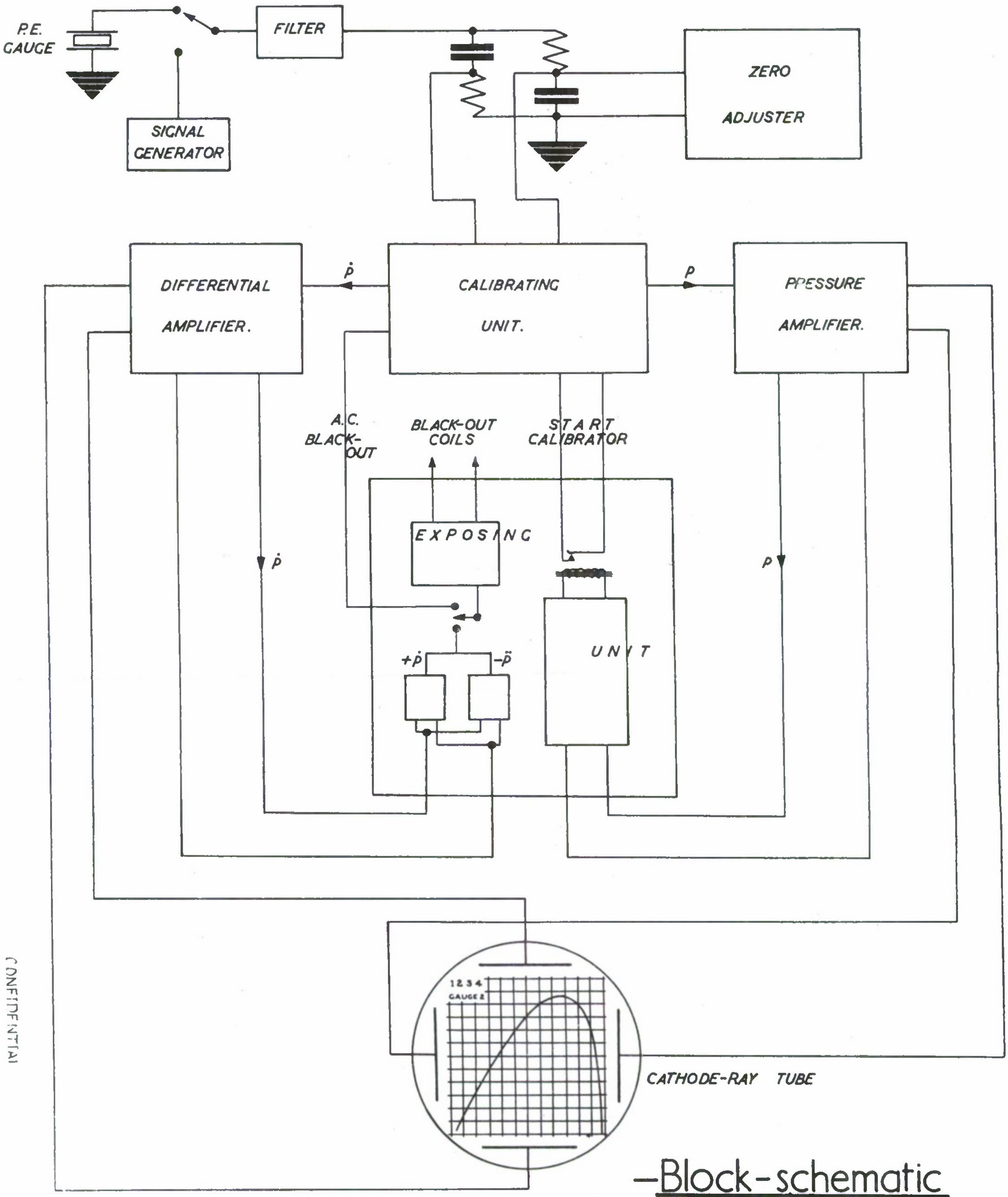
— Zero Adjuster —



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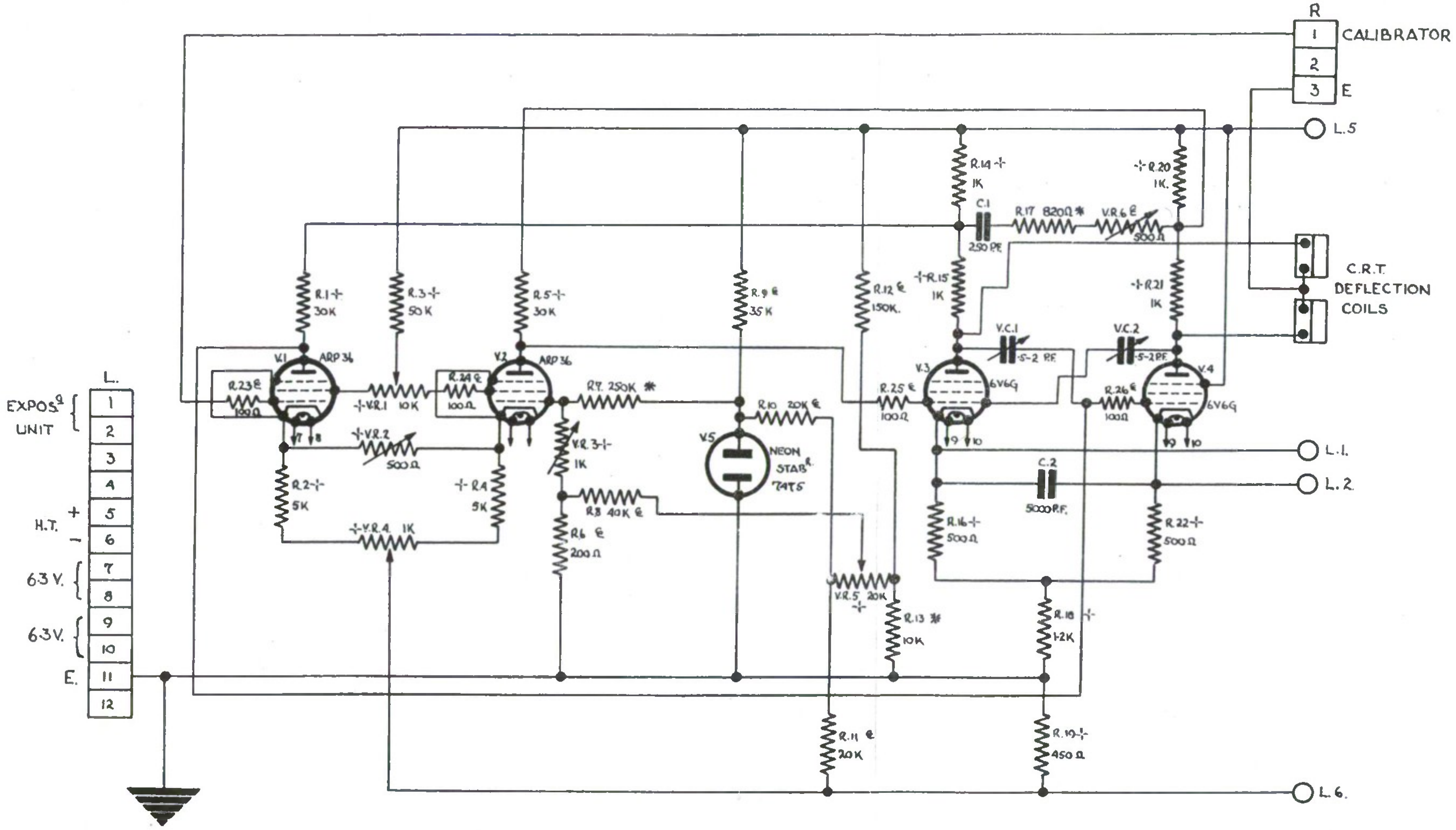
-FIG. 2-

-Block-schematic diagram of C.V. Recorder-

– FIG. 3. –



* High-stability Resistor.
-¦- Wirewound " " "
€ Carbon " " "

— Pressure Amplifier. —

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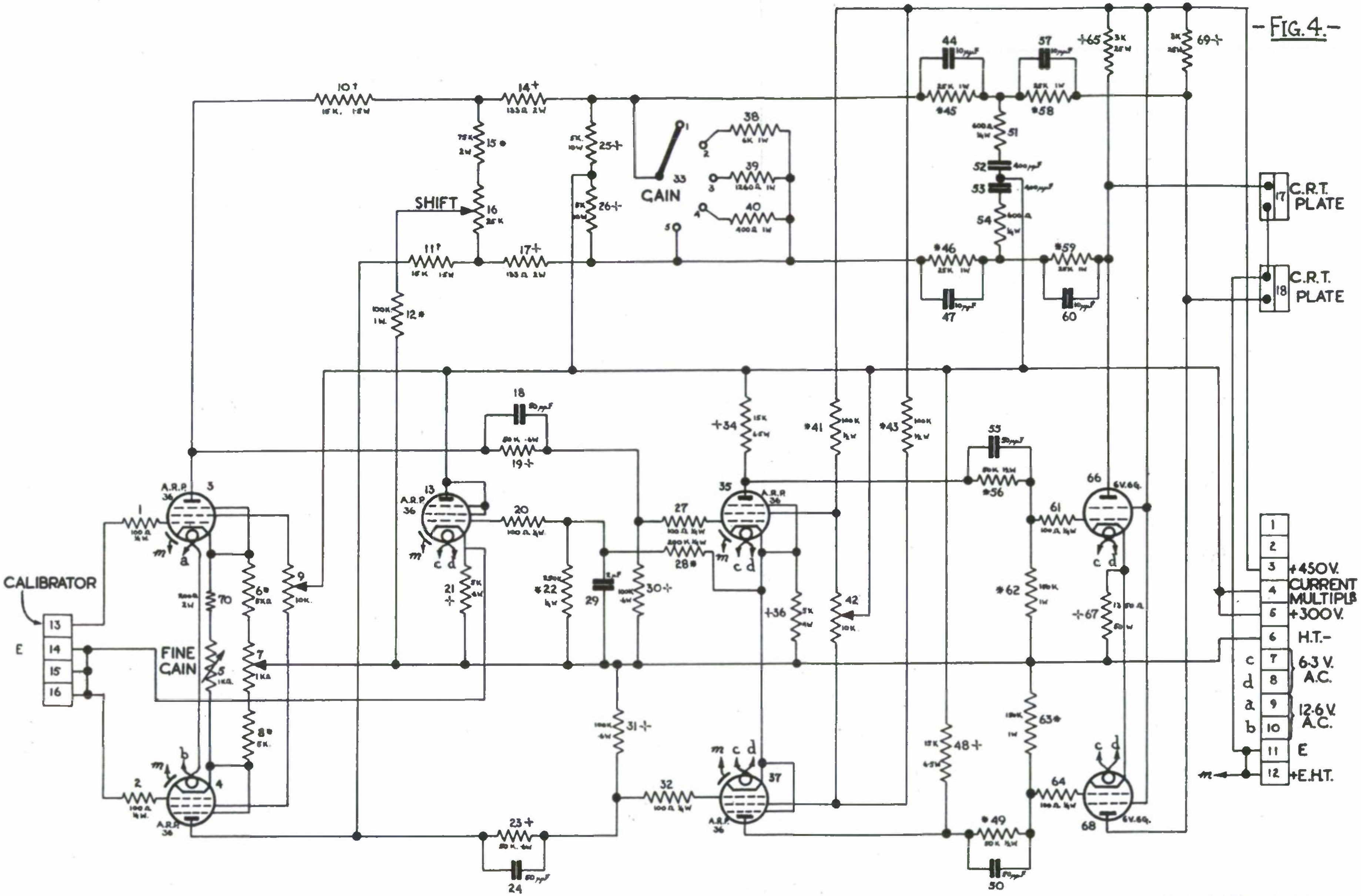
- FIG. 4. -



* High-stability Resistors.
+ Wirewound Resistors.

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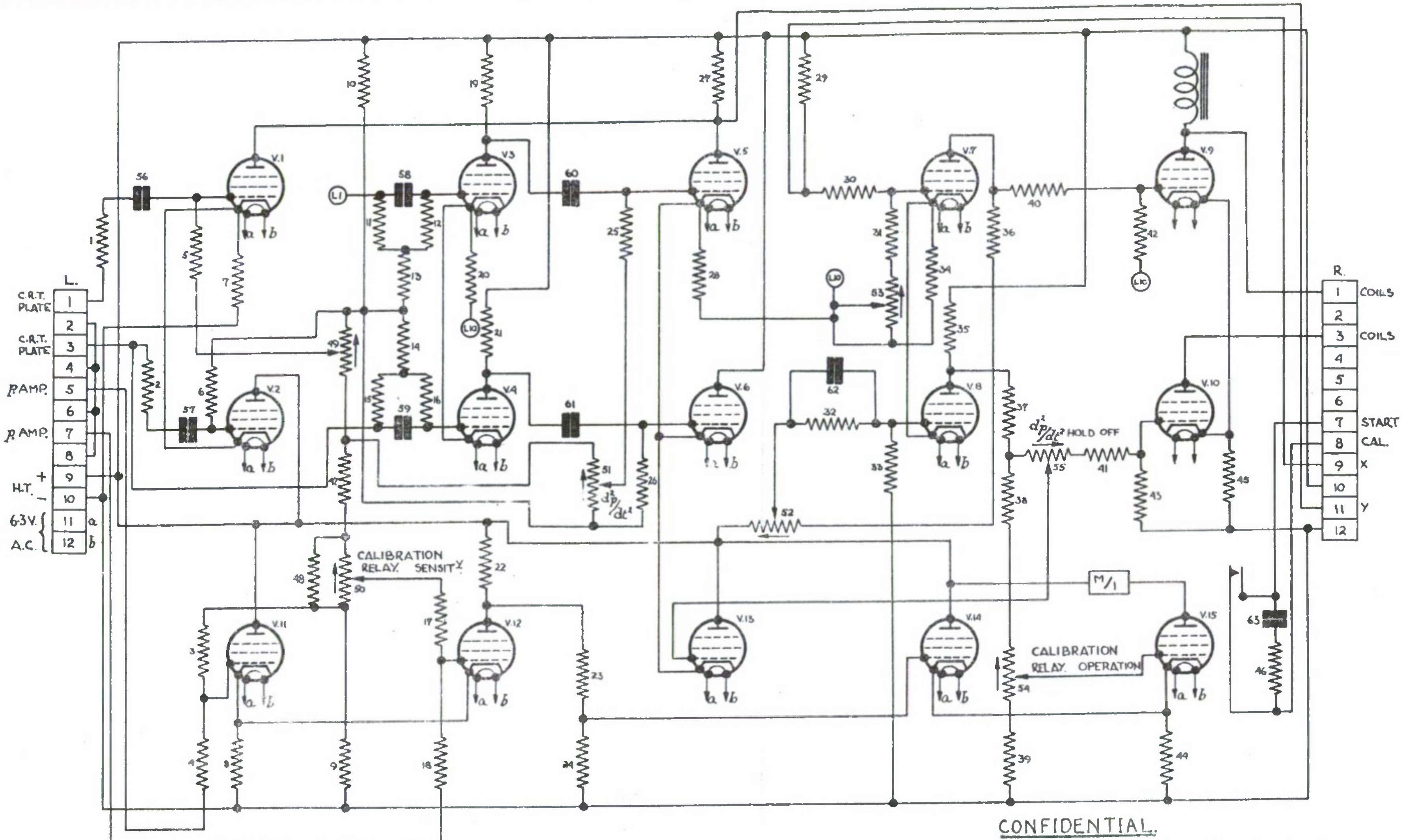
- Differential Amplifier -

FIG. 5.

1.	250 K. 1/4 W. H.S.	5.	100 K. 1/4 W. H.S.	9	50 K. 1/2 W. H.S.	13.	1 K. 1W. Carbon.	17.	100 K. 1/4 W. H.S.	21.	10·5 K. 2 W. H.S.	25	100 K. 1/4 W. H.S.
2.	250 K. 1/4 W. - -	6.	100 K. 1/4 W. - -	10.	200 K. 1/4 W. - -	14.	1 K. 1W. - -	18.	100 K. 1/4 W. - -	22.	25 K. 3 W. Carbon.	26.	100 K. 1/4 W. - -
3.	100 K. 1/4 W. - -	7.	15 K. 2 W. Carbon.	11.	1 M. 1/2 W. - -	15.	1 M. 1/2 W. H.S.	19	10·5 K. 2 W. - -	23.	250 K. 1/4 W. H.S.	27.	50 K. 12 W. W.W.
4.	100 K. 1/4 W. - -	8.	20 K. 2 W. H.S.	12.	100 K. 1/4 W. - -	16.	100 K. 1/4 W. - -	20.	15 K. 2 W. Carbon.	24.	250 K. 1/4 W. ·· -	28.	15 K. 2 W. Carbon.



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29.	20 K. 1/2 W. H.S.	37.	100 K. 1/4 W. H.S.	45.	1·5 K. 20 W. W.W.	49.	10 K. C.V.S. Painton.	53.	20 K. C.V.S. Painton.	56.	·1 μF. 350 V. T.C.C. 343.
30.	200 K. 1/4 W. - -	38.	150 K. 1/2 W. - -	46.	100 Ω. 1/4 W. Carbon	50.	25 K. - - - -	54.	50 K. ·· ·· - ··	57.	·1 μF 350 V. ·· ··
31.	100 K. 1/4 W. ·· -	39.	100 K. 1/4 W. - -	47.	10 K. 1/4 W. - -	51.	10 K. - - - -	55.	50 K. ·· - - ··	58.	100 P.F. T.C.C. CC31Y.
32.	200 K. 1/4 W - -	40.	200 K. 1/4 W. - -	48.	25 K. 1/4 W. - -	52	5 K. T.W. Reliance.			59.	100 P.F. - - ·· -
33.	100 K. 1/4 W. - -	41.	50 K. 1/4 W. - -							60.	·1 μF. 350 V. T.C.C. 343.
34.	10 K. 2 W. - -	42.	100 K. 1/4 W. - -							61.	·1 μF. 350 V. - -
35.	15 K. 2 W. Erle.	43.	100 K. 1/4 W. ·· ··							62.	100 P.F. T.C.C. CC31Y.
36.	10 K. 2 W. H.S.	44.	15 K. 2 W. Carbon.							63.	1 μF T.C.C. 62.

V.1 - V.8 A.R.P. 36.
V.9 & V.10 6V6G.
V.11 - V.15 A.R.P. 36.

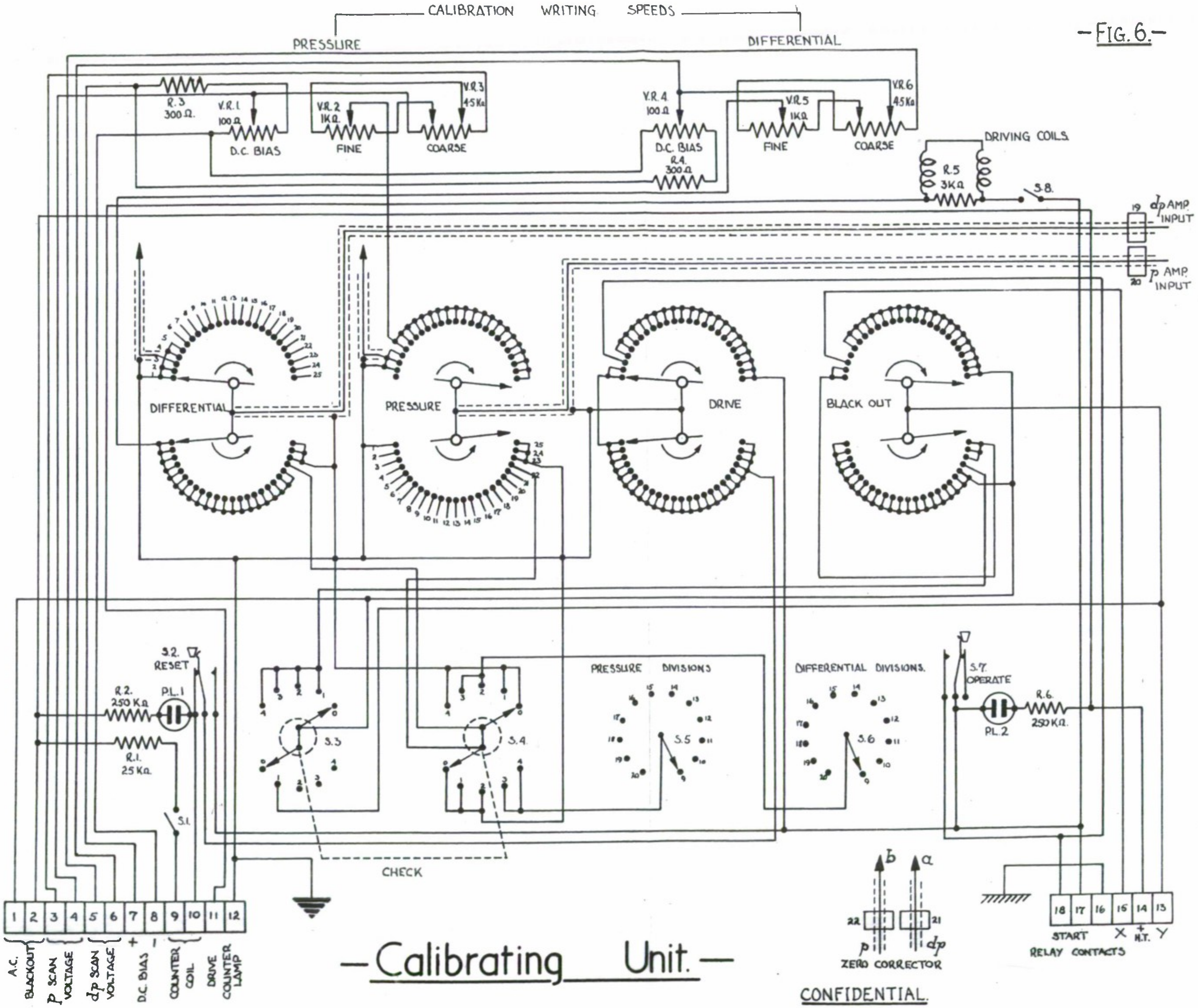
—Exposing Unit—

All Suppressors to H.T.+.

All Screens to Cothodes.

↑ Arrow Indicates clockwise direction.

-FIG. 6.-



-Calibrating Unit.-

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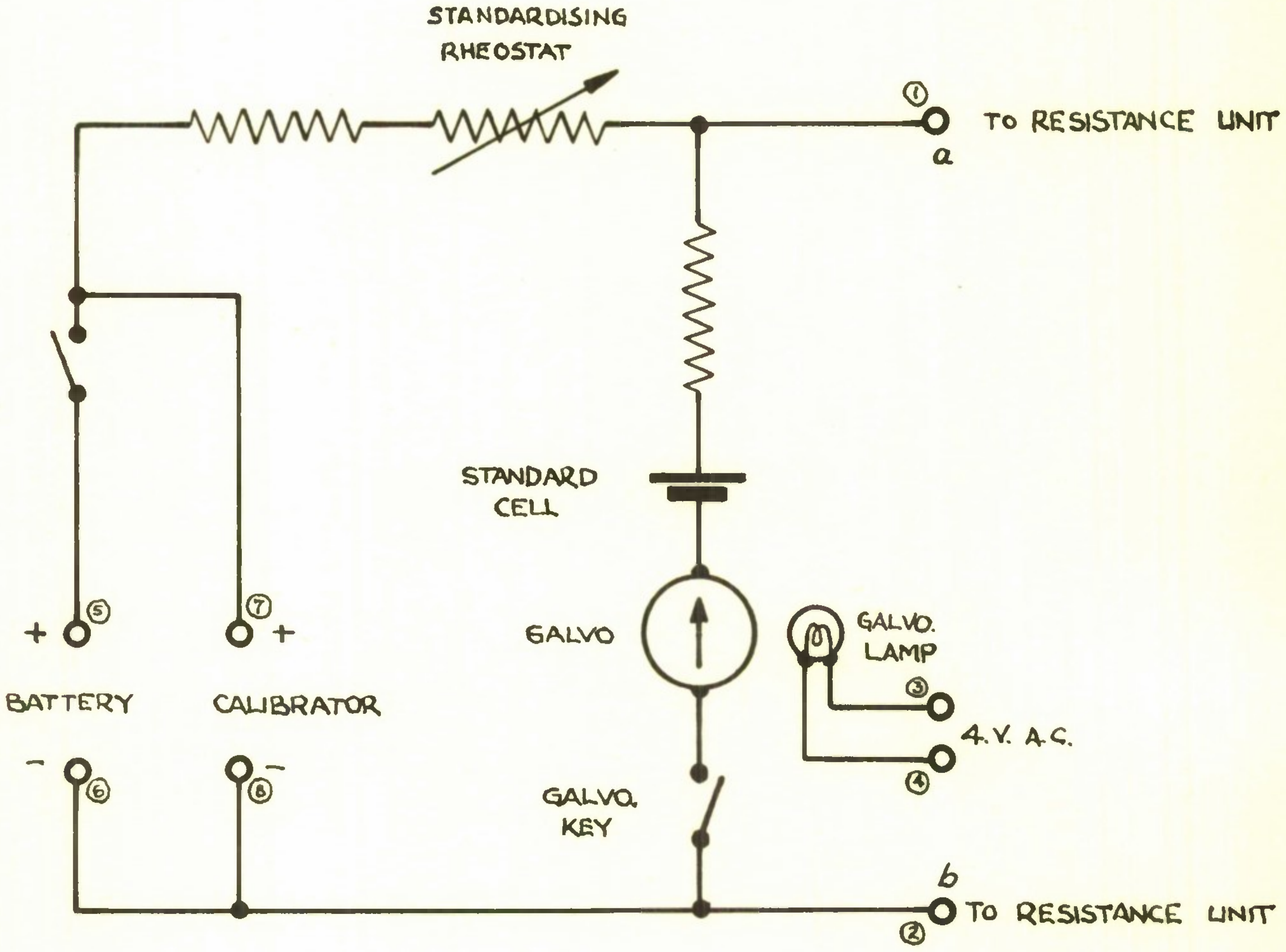
-FIG. 7.-



OUTPUT 1·0186 VOLTS ACROSS 20 OHMS LOAD.

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-Potentiometer. Galvo. Unit.-

—Potentiometer. Resis. Unit.—

A. CONSTANT RESISTANCE (20 OHM) ATTENUATOR WITH 10 SWITCH POSITIONS.

SWITCH POSITION	·60	·61	·62	·63	·64	·65	·66	·67	·68	·69
R.1 (OHMS)	4·606	4·046	3·498	2·963	2·441	1·930	1·430	·942	·465	·0
R.2 (OHMS)	106·85	118·88	134·35	155·0	183·9	227·3	300	445	879	∞

B. CONSTANT RESISTANCE (200 OHM). ATTENUATOR WITH 10 SWITCH POSITIONS.

SWITCH POSITION	·000	·001	·002	·003	·004	·005	·006	·007	·008	·009
R.3 (OHMS)	·798	·750	·702	·655	·607	·560	·513	·465	·418	·371
R.4 (OHMS)	521	553	589	631	679	734	800	880	976	1098

C. TAPPED RESISTANCE. 20 STEPS OF 2 OHMS EACH, TOTAL 40 OHMS.

D. CONSTANT RESISTANCE (40 OHM) ATTENUATOR WITH 5 SWITCH POSITIONS.

SWITCH POSITION	1/20	1/10	1/5	1/2	1
R.6 (OHMS)	760	360	160	40	0
R.7 (OHMS)	42·105	44·44	50	80	∞

E. TAPPED RESISTANCE. 20 STEPS OF 2 OHMS EACH, TOTAL 40 OHMS.

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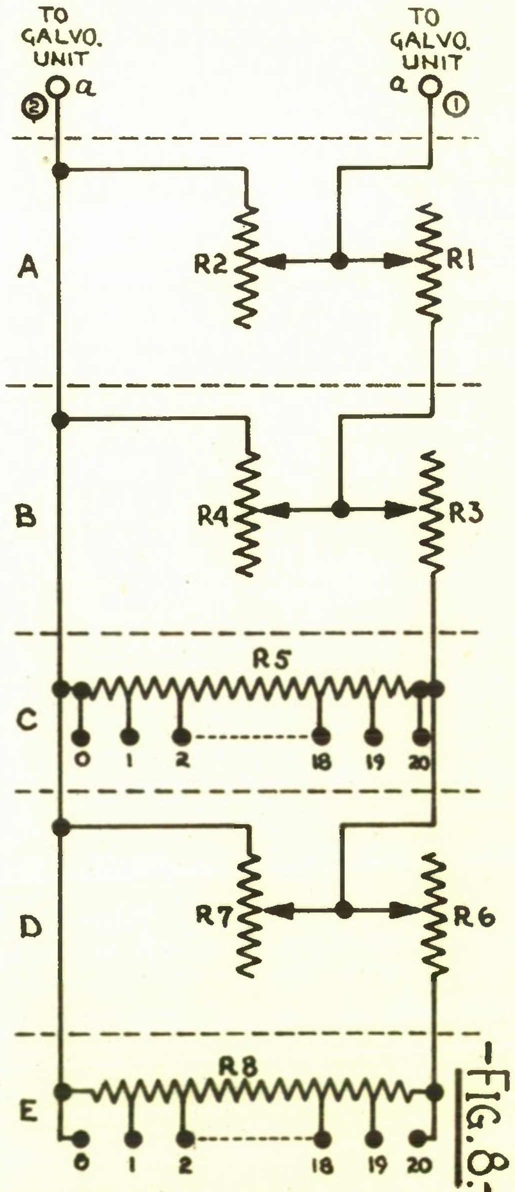
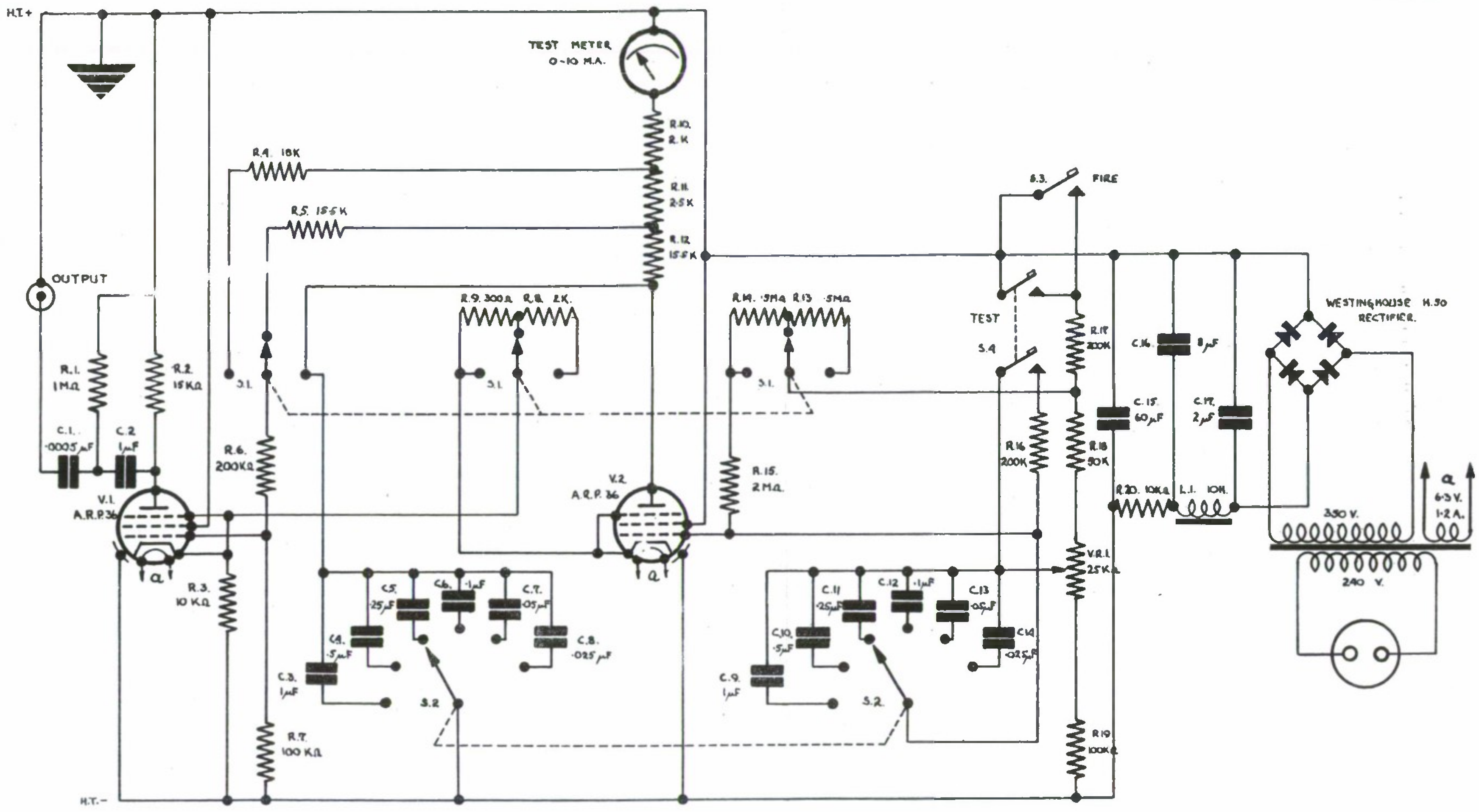


-FIG. 8.-

—FIG. 9.—



—Test Signal Generator.—

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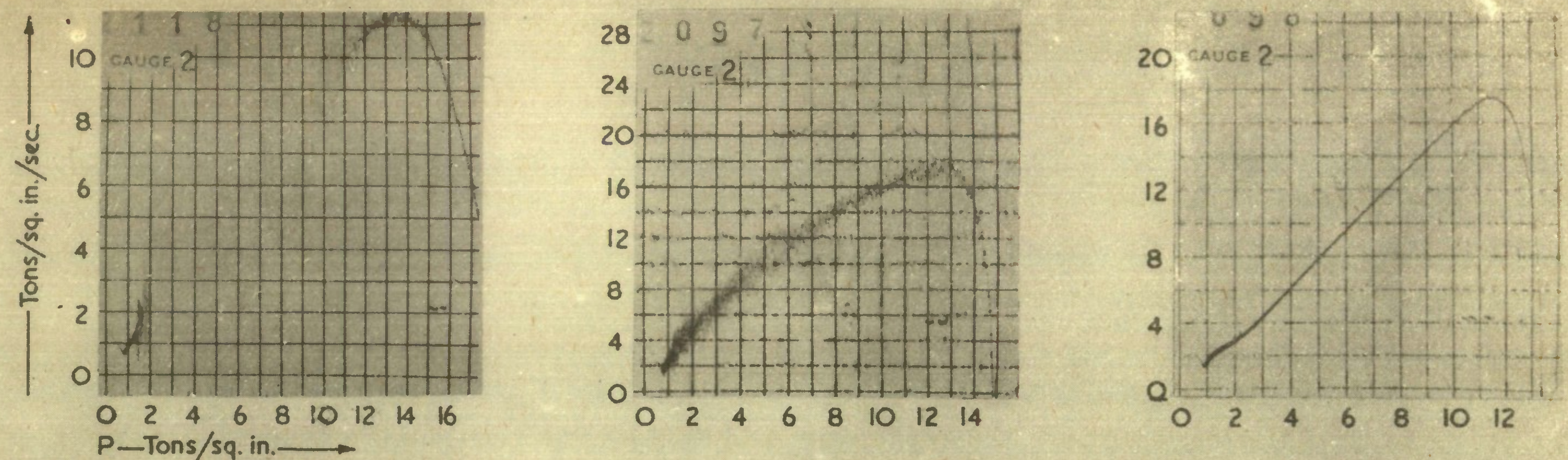
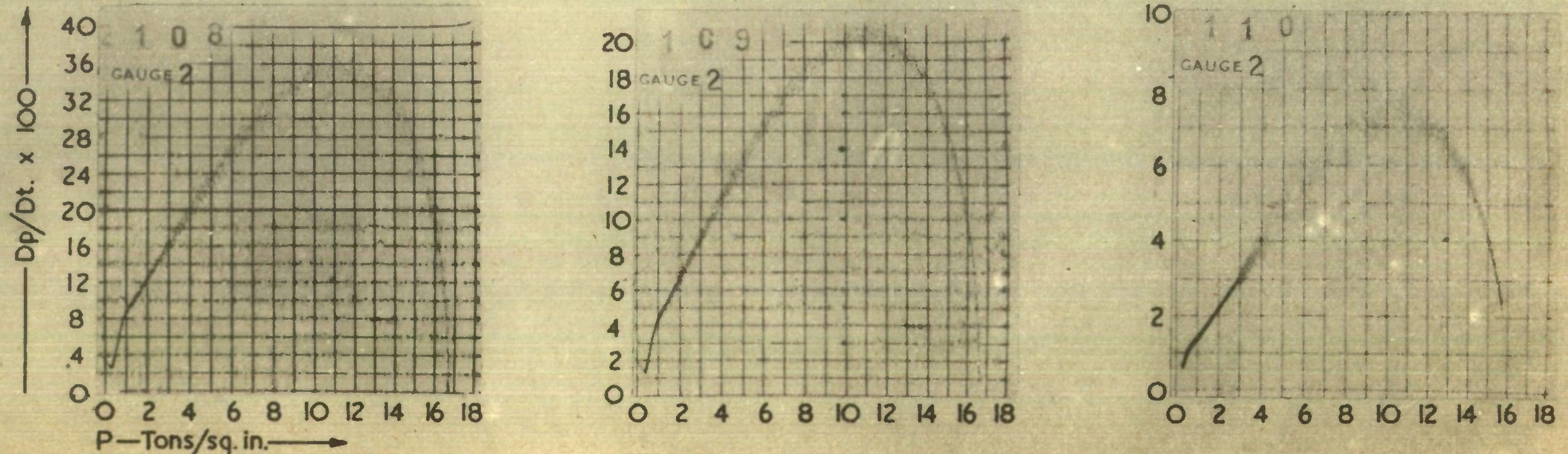
Fig. 10.

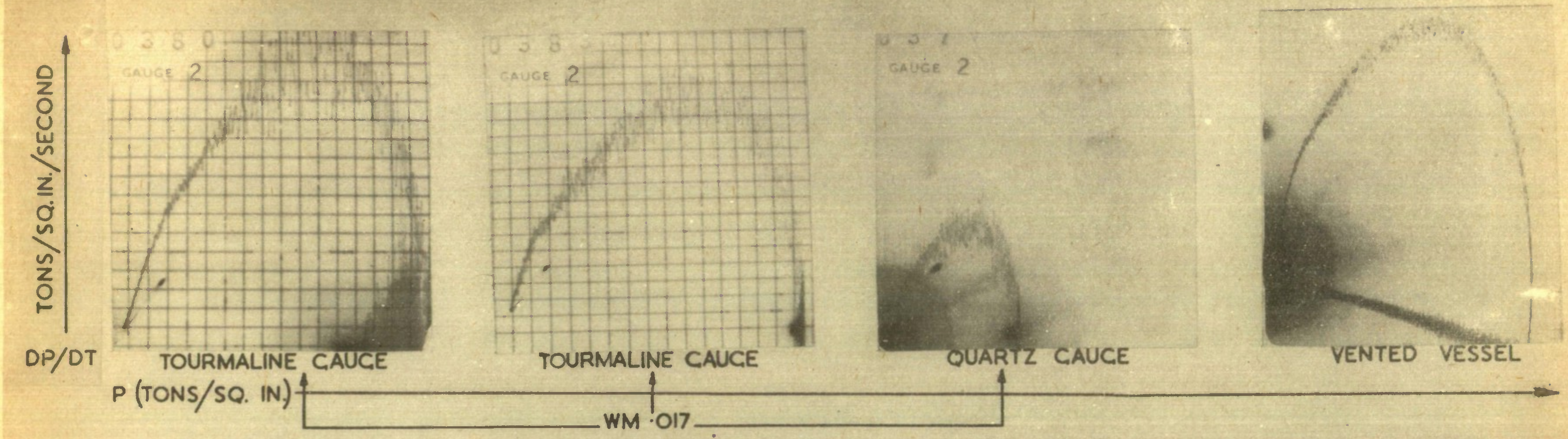
TYPICAL EXAMPLES OF "HASH"



PROPELLANT TYPE:—	F 478/45.	NF.	ASN.
" " SHAPE:—	Multitube.	Slotted Tube.	Tube.



PROPELLANT TYPE:—	SC.	SC.	SC.
" " SHAPE:—	061.	103.	300.



UNFILTERED RECORDS

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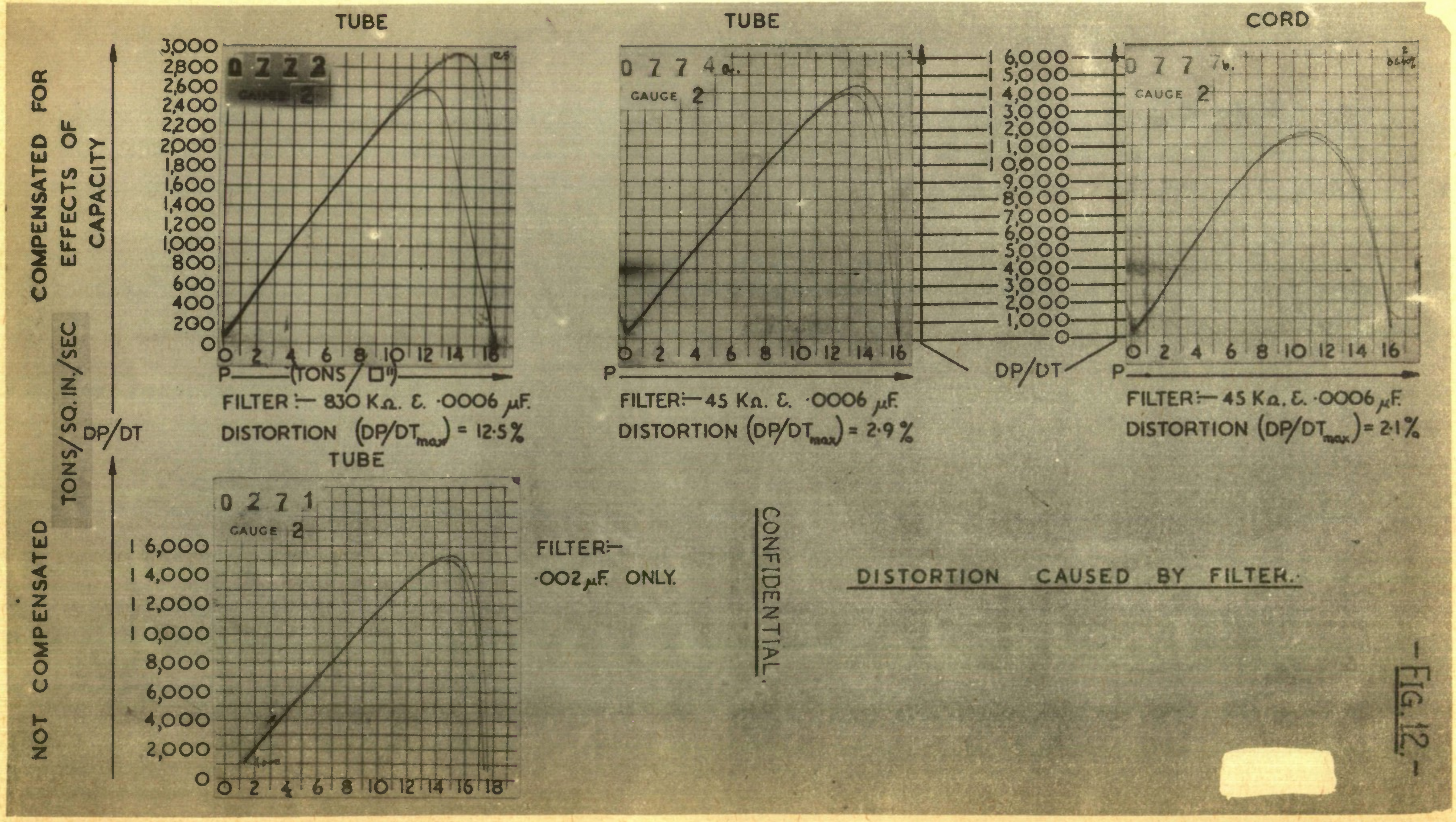
-FIG. 11.-



FILTER:— 830 KΩ. & ·0006 μF.
DISTORTION (DP/DT$_{max}$) = 12·5%

FILTER:—45 KΩ. & ·0006 μF.
DISTORTION (DP/DT$_{max}$) = 2·9%

FILTER:—45 KΩ. & ·0006 μF.
DISTORTION (DP/DT$_{max}$) = 2·1%

FILTER:—
·002 μF. ONLY.

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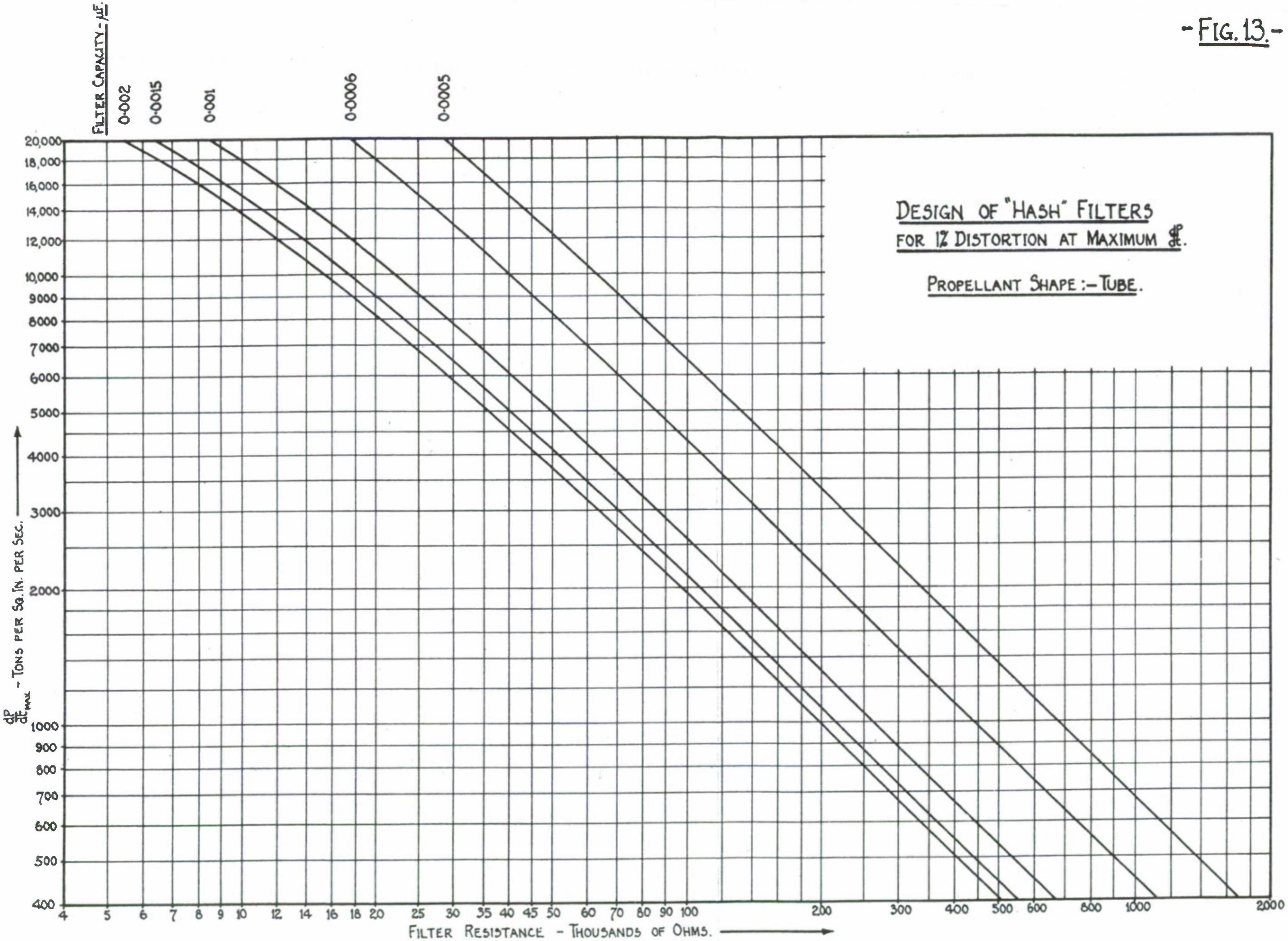
DISTORTION CAUSED BY FILTER.

-FIG. 12.-

- FIG. 13. -



DESIGN OF "HASH" FILTERS FOR 1% DISTORTION AT MAXIMUM $\frac{dP}{dt}$.

PROPELLANT SHAPE :- TUBE.

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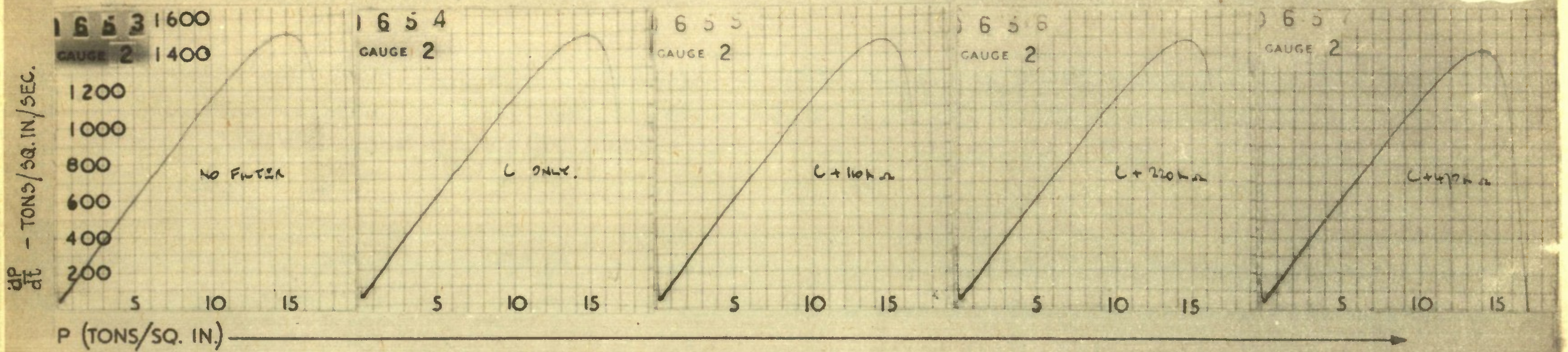

NO FILTER

FILTER :- ·001μF

FILTER :- ·001μF + 110KΩ

FILTER :- ·001μF + 220KΩ

FILTER :- ·001μF + 470KΩ

(TRACE PRODUCED BY SIGNAL GENERATOR)

DISTORTION PRODUCED BY FILTER.

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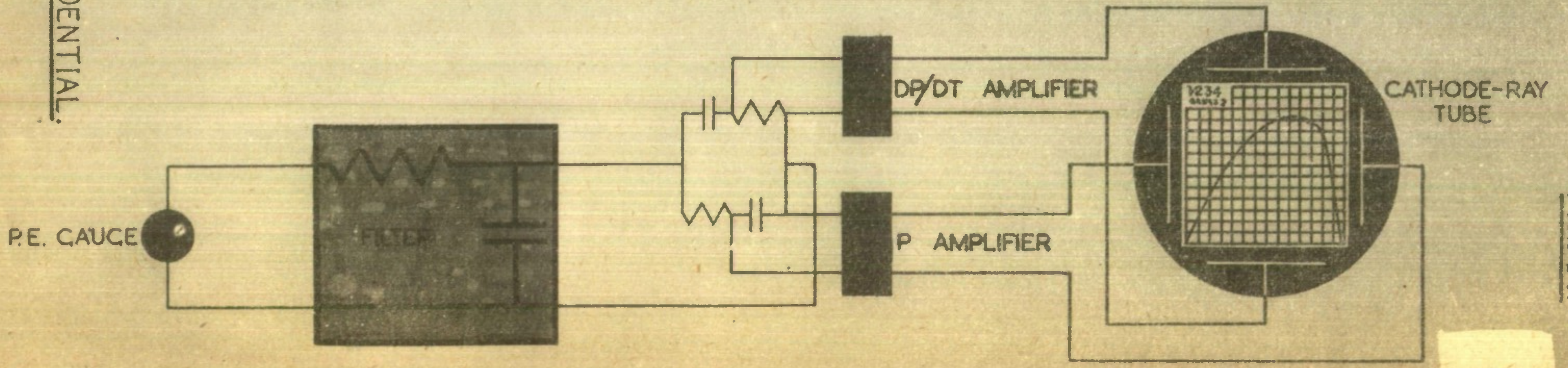
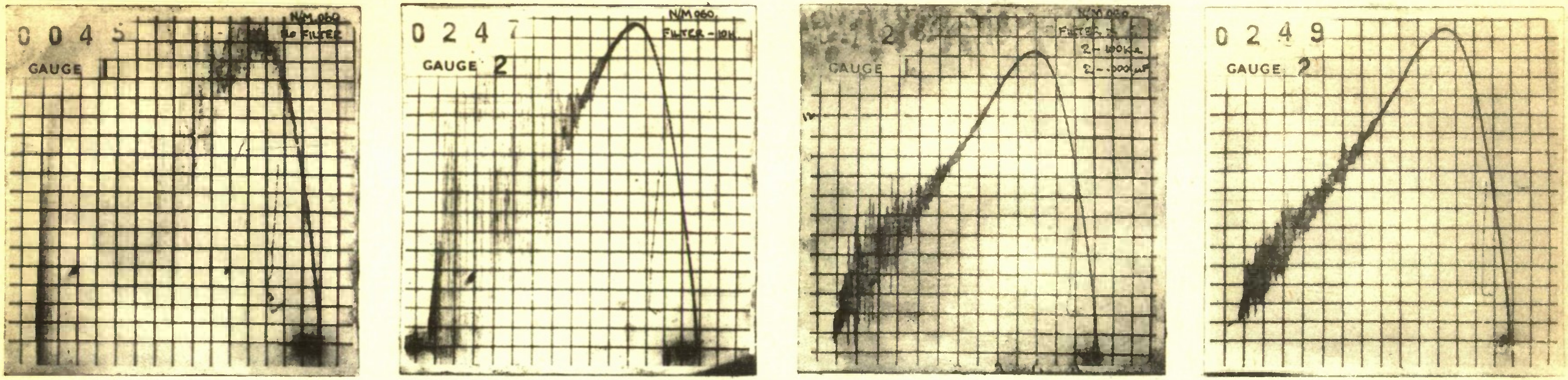
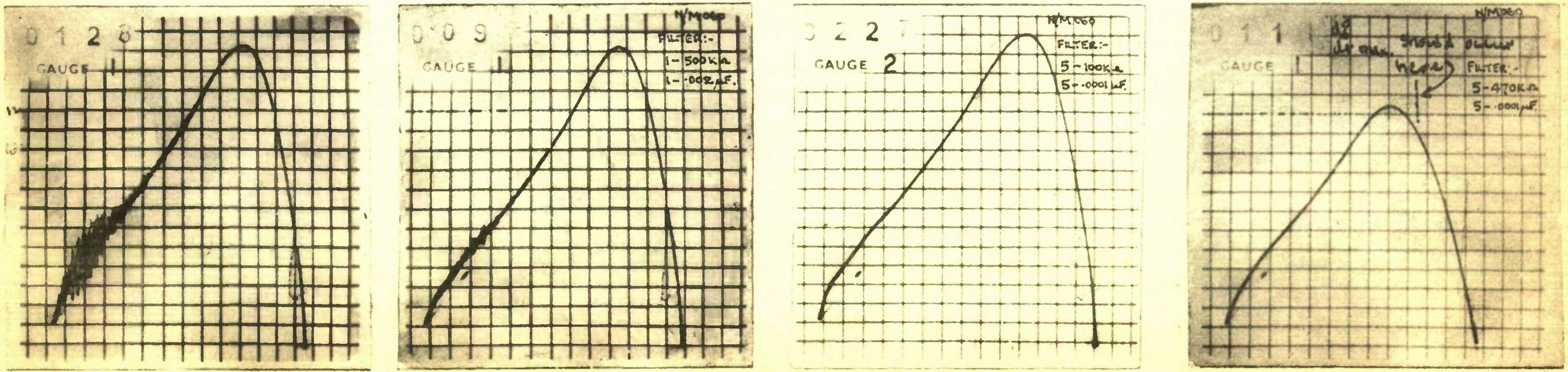


- FIG. 14. -



– STAGES IN HASH REMOVAL. –

PROPELLANT SHAPE: MULTI-TUBE.



A.R.E/C.642.
H.A.F.

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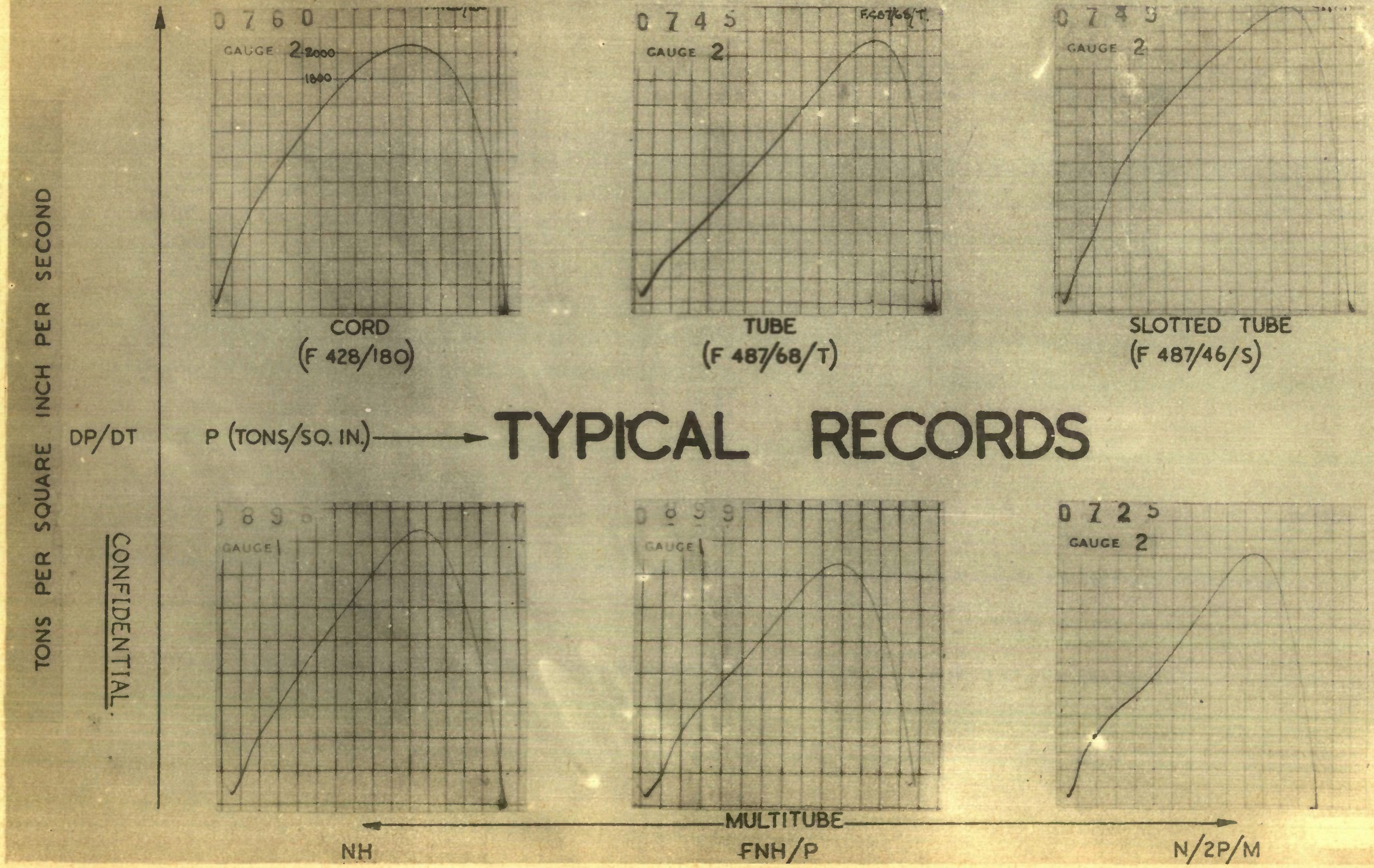
– FIG. 15. –

-FIG. 16.-



TYPICAL RECORDS

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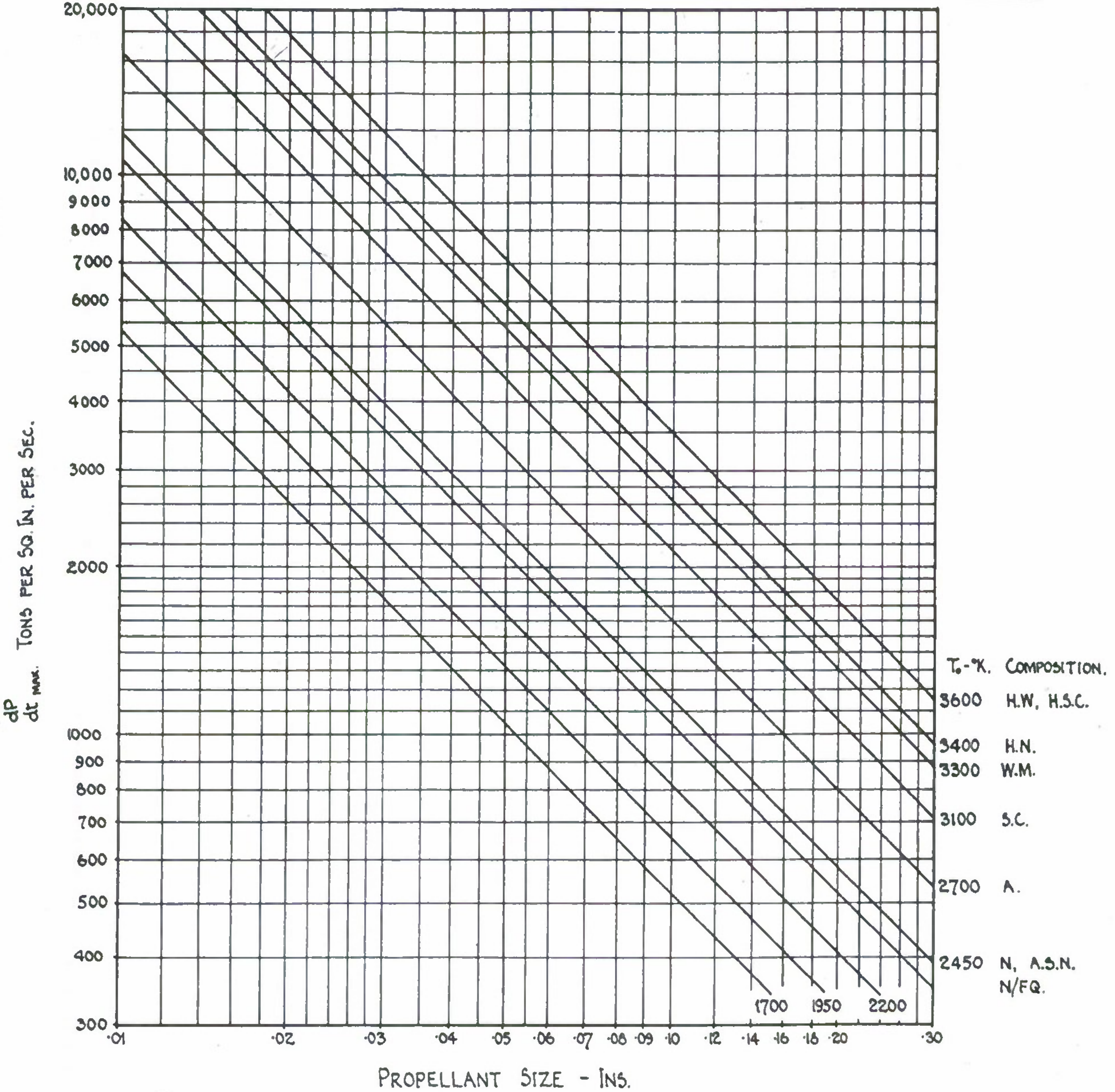
FIG. 17



PROPELLANT SHAPE - CORD.
LOADING DENSITY - 0·2 GMS/C.C.

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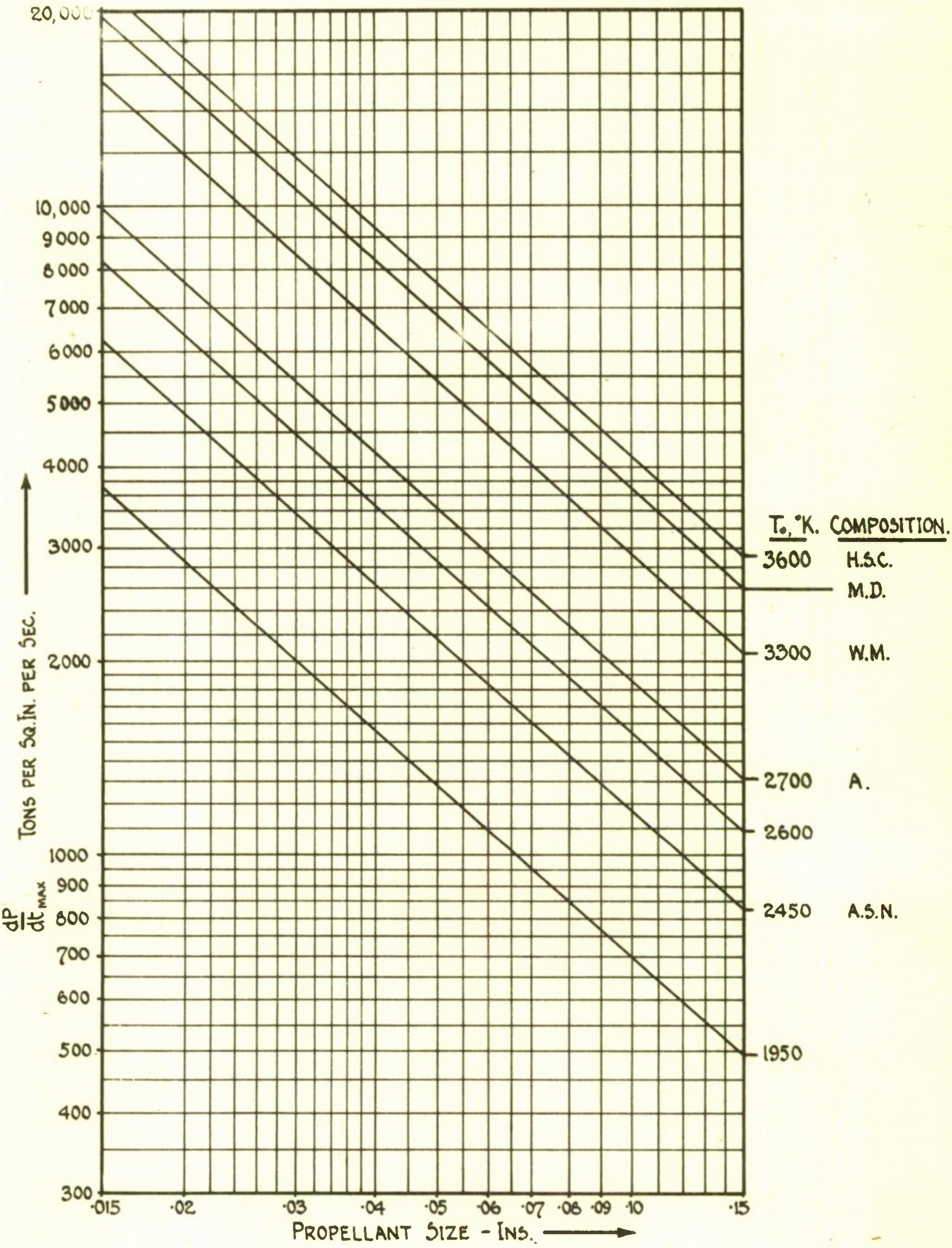
-FIG. 18.-



PROPELLANT SHAPE - TUBE.

LOADING DENSITY - 0·2 GMS PER C.C.

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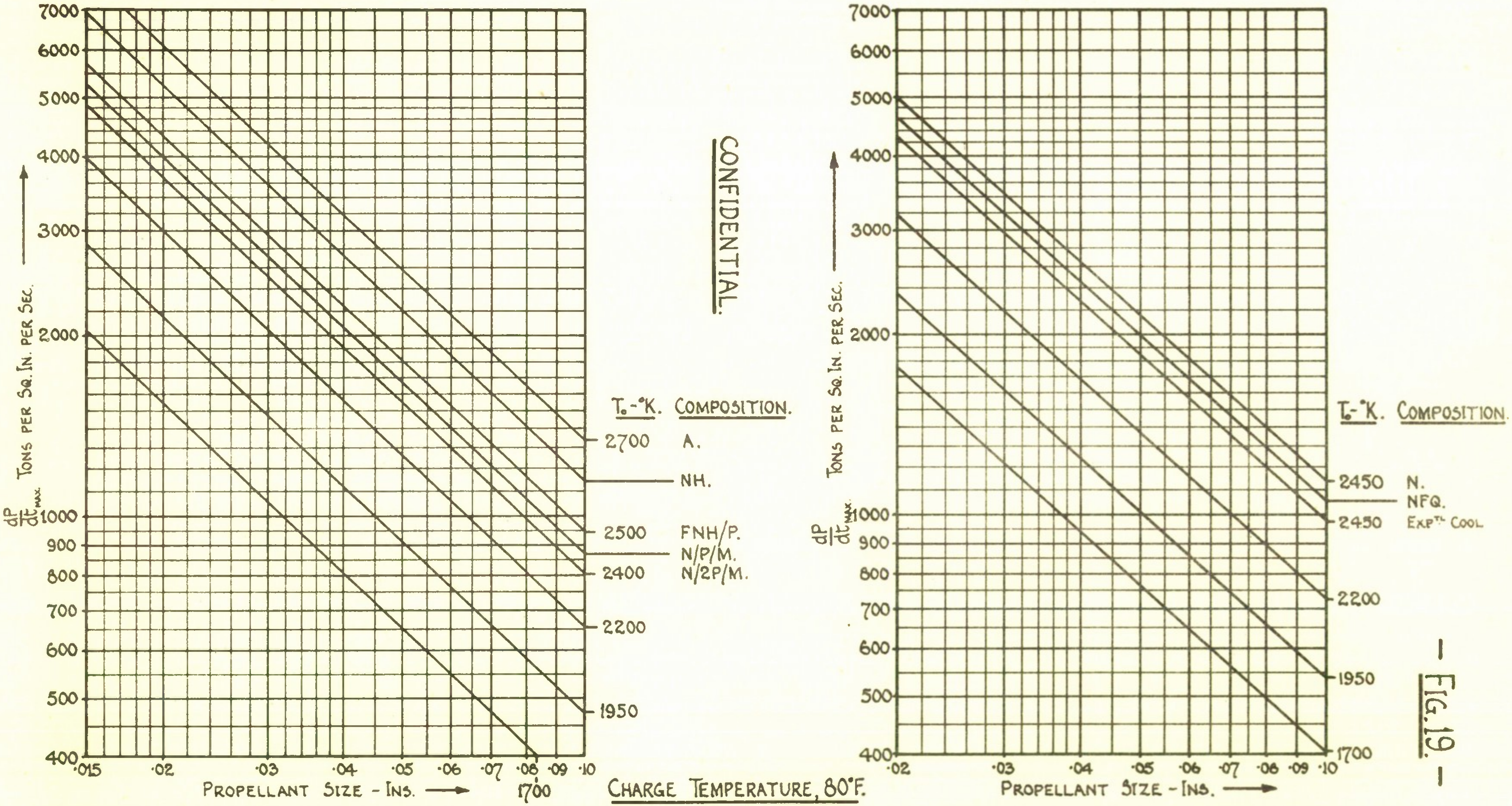
CONFIDENTIAL.



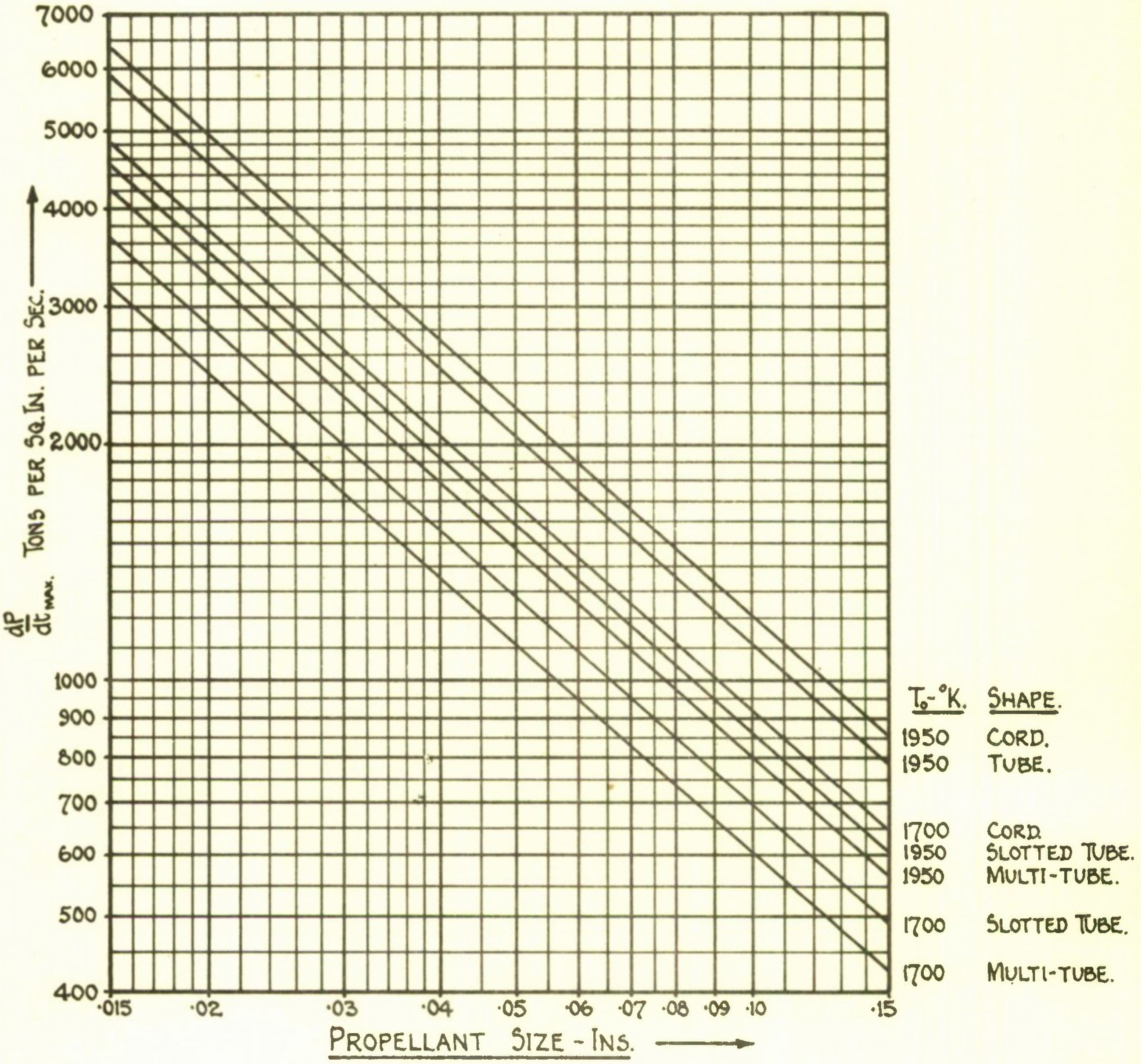
Propellant Shape - Multi-tube.

Charge Temperature, 80°F.

Loading Density - 0·2 gm/c.c.

Propellant Shape - Slotted Tube.

- Fig. 19. -



LOADING DENSITY 0·25 GMS/C.C.
CHARGE TEMPERATURE, 80°F.

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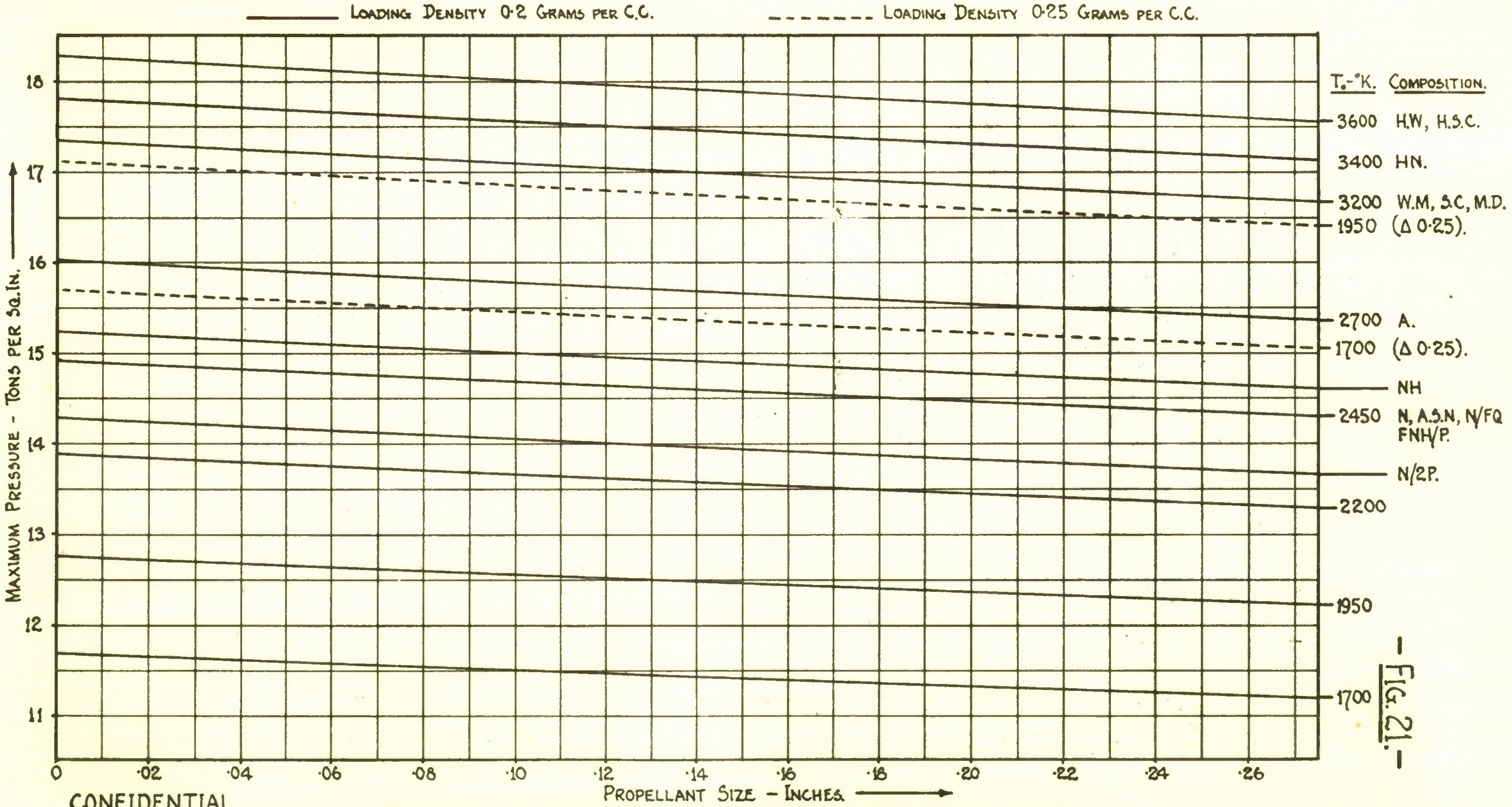

- Fig. 21. -

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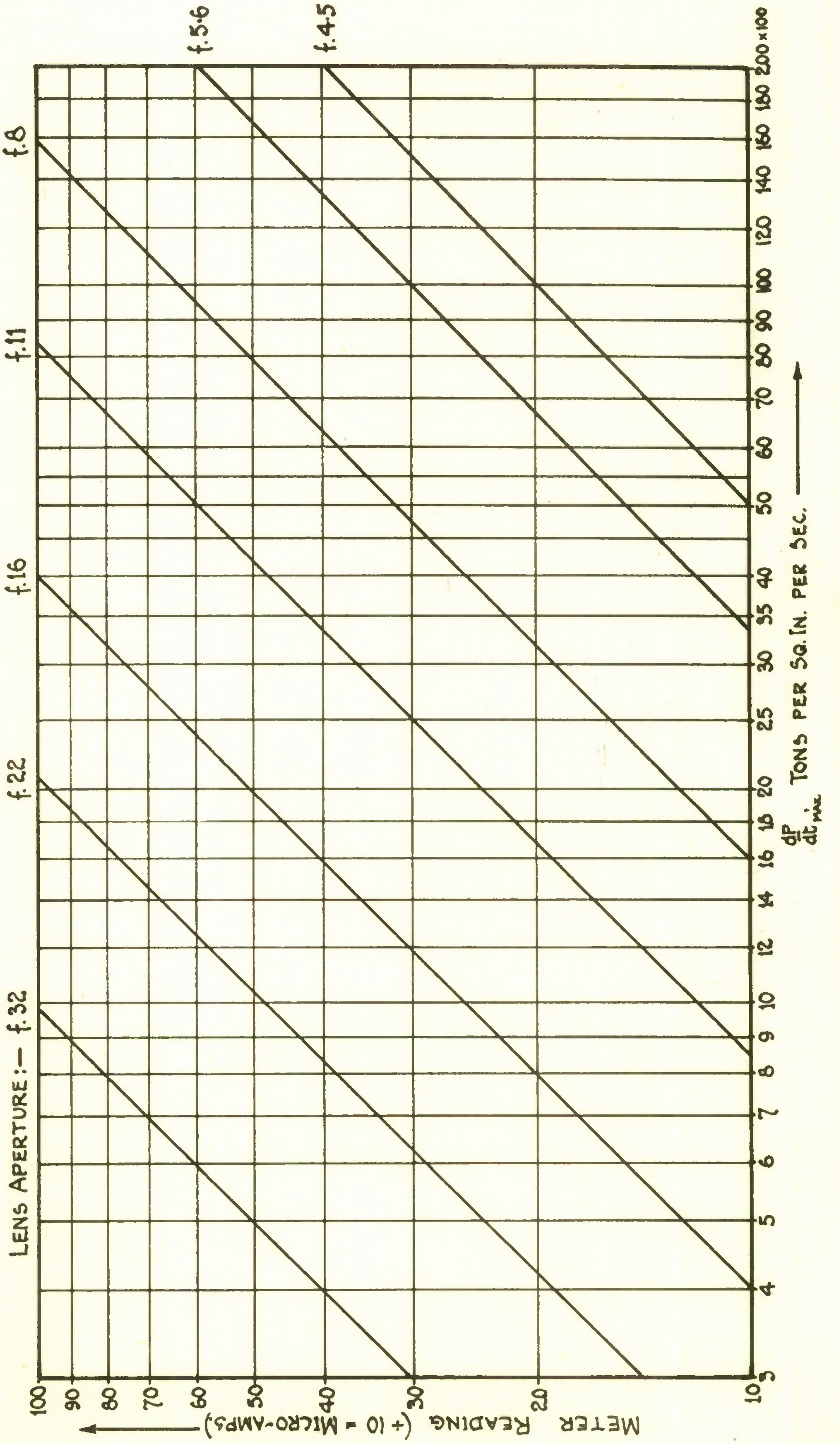
— Pressure produced in Closed Vessel of 700 c.c.s. Capacity. —

- FIG. 22. -



BEAM CURRENT vs. $\frac{dP}{dt_{max.}}$

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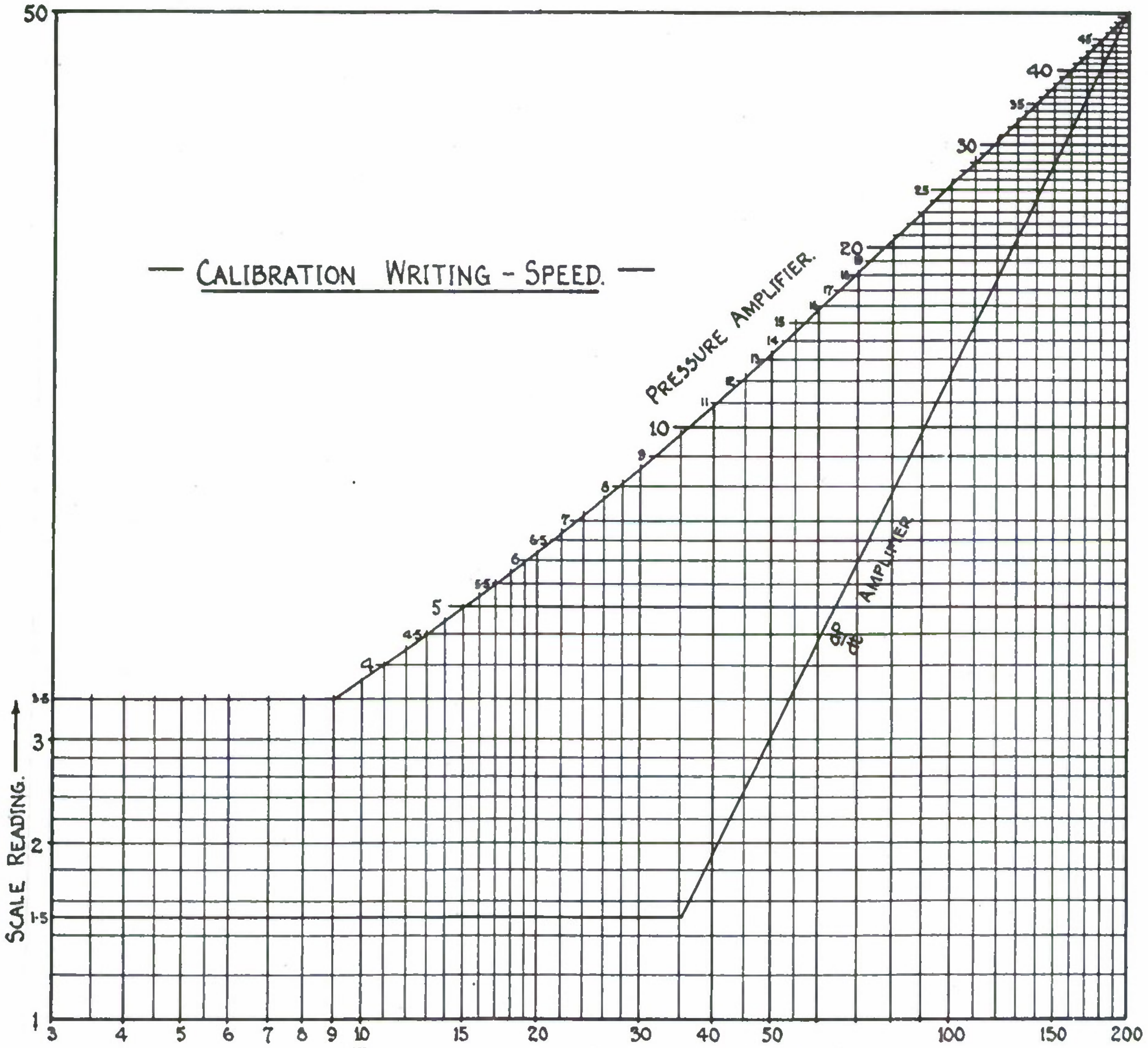
— FIG. 23. —



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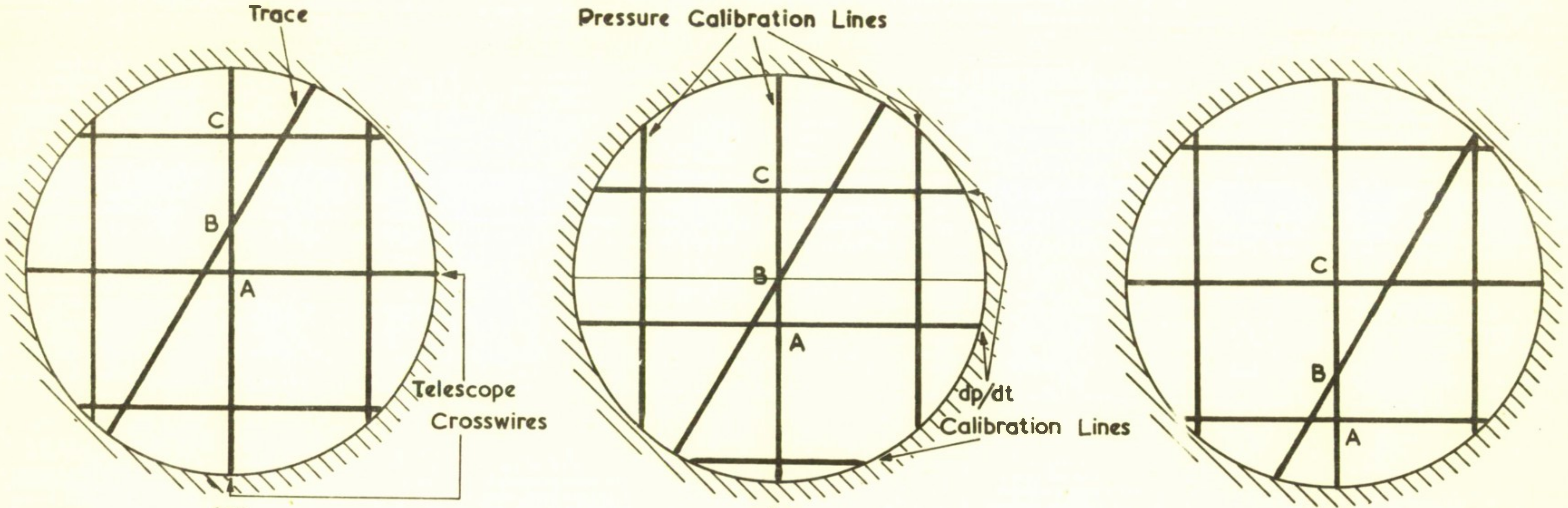

(a). (b). (c).

Measurement of dp/dt v. Pressure Record.

View through telescope of measuring instrument.

FIG. 24.-

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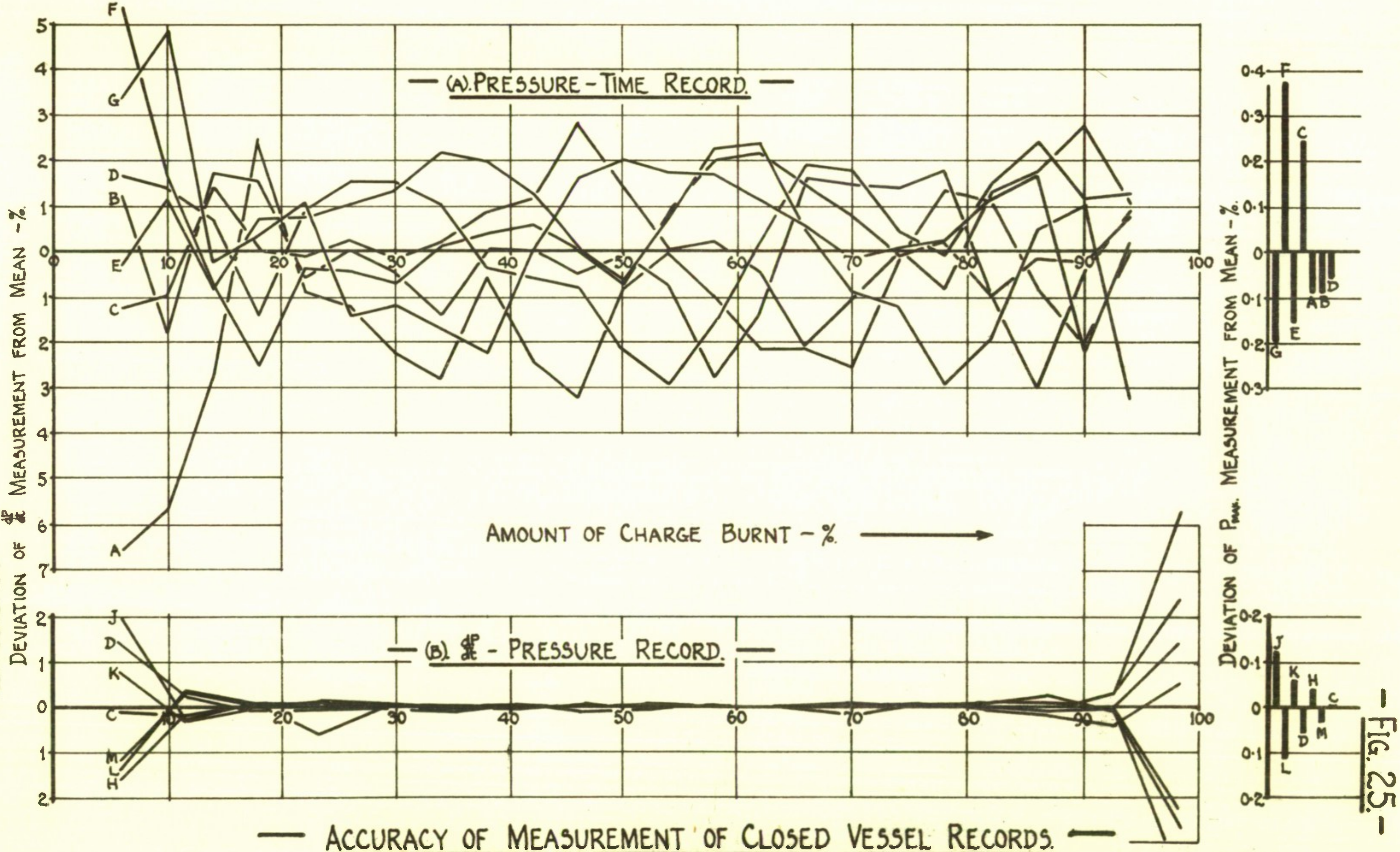

— ACCURACY OF MEASUREMENT OF CLOSED VESSEL RECORDS. —

– FIG. 25. –

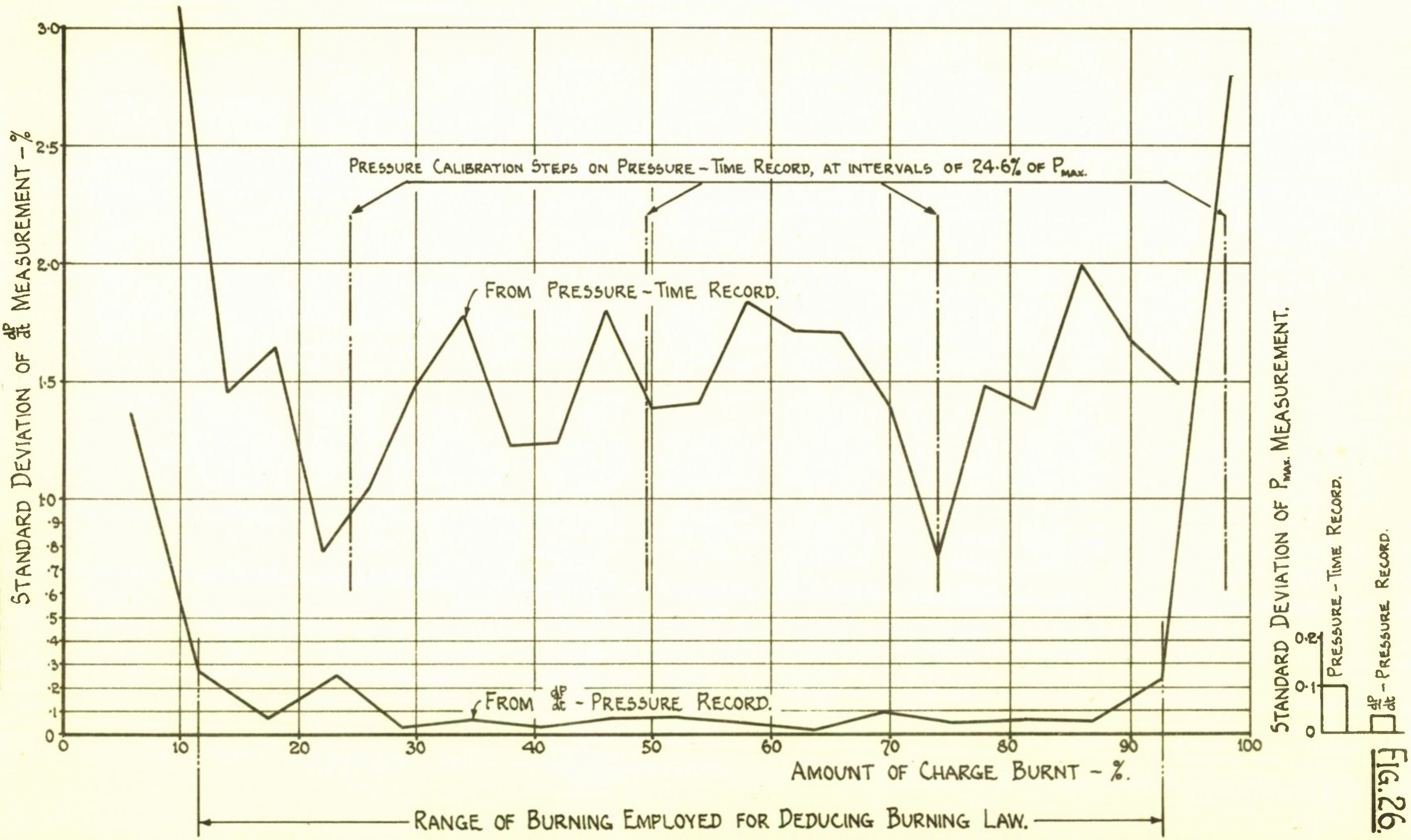

FIG. 26.

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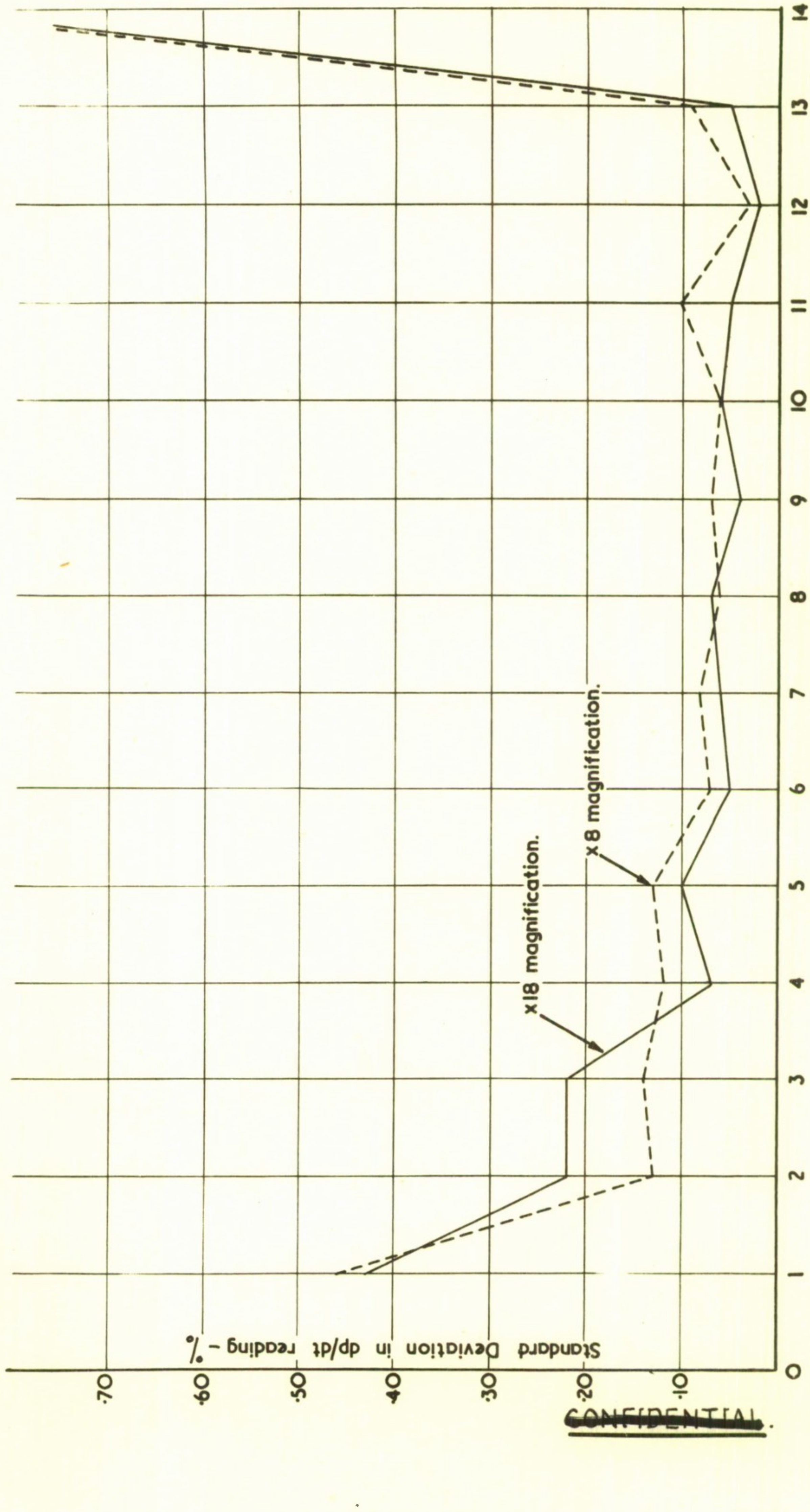
- FIG. 27. -



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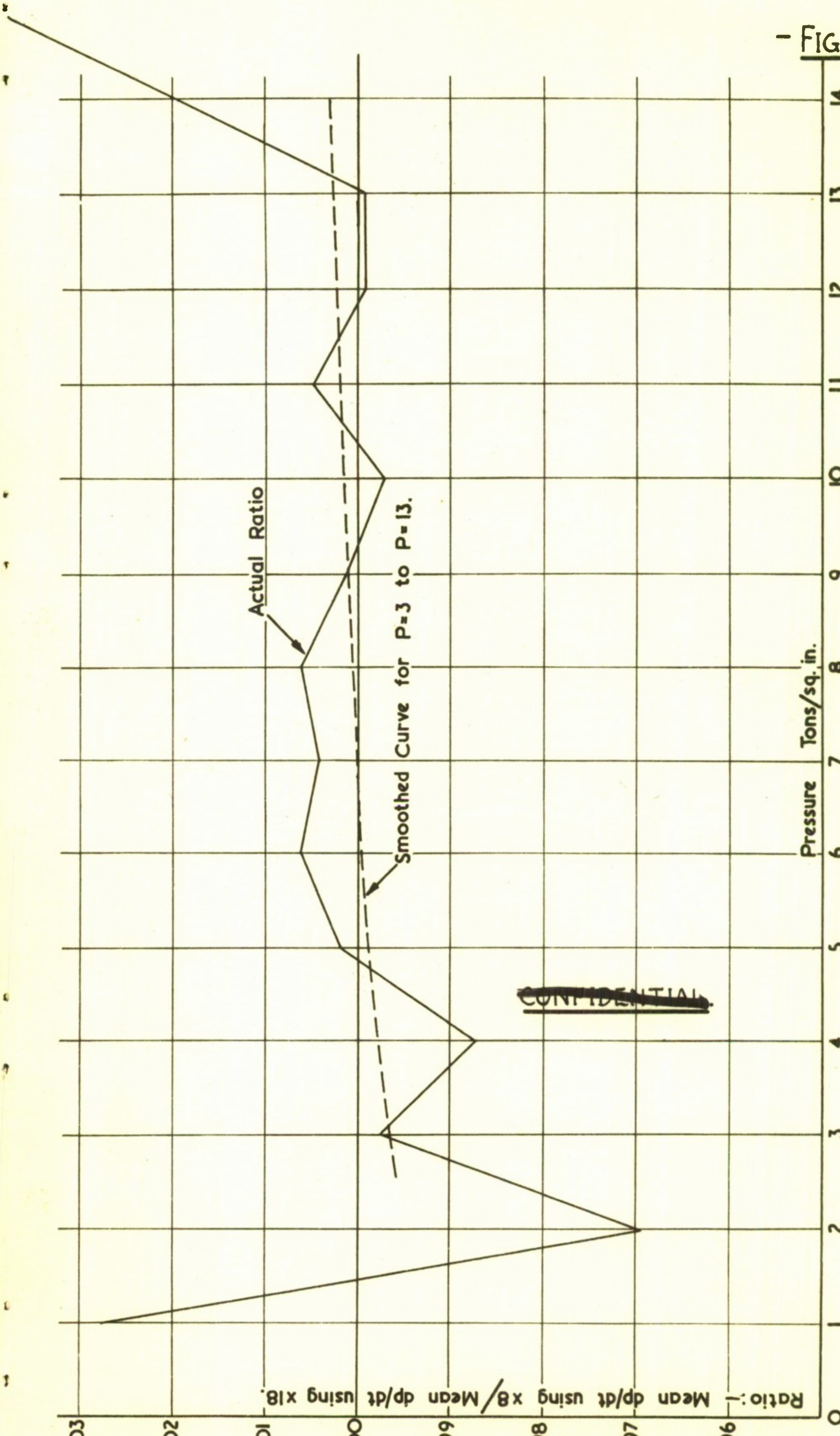
- FIG. 28.-



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