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The Speaking Clock

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THE SPEAKING CLOCK

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PRÉCIS

The Speaking Clock provides an accurate time service which is continuously available to telephone subscribers in the London Area. A subscriber connected to an automatic exchange on dialling the code T-I-M, or a subscriber connected to a manual exchange on asking for TIME, is routed to the clock and hears the time announced every ten seconds. Each announcement is followed by three audio-frequency "pips", the last of which indicates within ±0.1 second the exact time spoken.

The announcements are made by photo-electrically reproducing words or phrases which are selected in the correct sequence from recordings made photographically on four glass discs. The mechanism for rotating the discs, for building up the announcement and for changing from one announcement to another is driven by a low speed synchronous motor. The frequency of the A.C. supply to this motor is directly controlled by a seconds-beating free pendulum. Every hour the clock is checked automatically against a signal transmitted from Greenwich Observatory and any small error is corrected. Should the error exceed the prescribed limits the service is transferred to a duplicate stand-by clock.

Facilities are provided to connect up to 100 simultaneous calls to the installation.

REPORT

Introduction

For a variety of reasons the public demand for an accurate time service has increased very considerably in recent years. For example, although the accurate B.B.C. Time Signals and synchronous motor clocks are now available, there has been a steady increase in the use of the service by which telephone subscribers could learn the "Time by the exchange clock". There appeared to be little doubt, therefore, that a large potential demand existed for the type of service now provided by the Speaking Clock.

This opinion was confirmed by the success of similar services in/

in certain continental towns. For example, 10-12,000 calls daily are made to the Paris speaking clock.

From the Departmental point of view there was the added attraction that the peak demand for time was expected to occur outside the normal busy hours. The experience of some months' operation of the service has amply confirmed these expectations.

Requirements of the Service

Admitting the need for the new service, the conditions which it should meet may be considered.

In the first place, the accuracy of the announcements should not suffer from adverse criticism when compared with existing public services. It was therefore decided that the time announced by the clock should not be more than ±0.1 second in error. This accuracy is believed to satisfy the needs of the majority of probable users of the service.

To reduce the quantity of apparatus required for distributing the service without diminishing its availability, the announcements should be made frequently. This condition is met by providing six complete announcements per minute.

In deciding upon the wording of the announcement prior consideration was given to simplicity, clarity and naturalness. Secondly, the wording chosen should not cause avoidable engineering complications in its reproduction. For example, certain short pauses are necessary for switching purposes. It is desirable that these should occur naturally as if an actual person were speaking.

To facilitate making the final choice gramophone records were prepared of several possible forms of announcement by several speakers including both men and women. These records were reproduced electrically through telephone receivers to simulate normal listening conditions. It was decided that a woman's voice should be used and that the announcements should take the form illustrated by the following typical examples.

(1) At an exact hour:

"At the third stroke it will be ten o'clock precisely"

(2)/

(2) At (say) 10 seconds past the hour:

"At the third stroke it will be ten o'clock and ten seconds"

(3) At an exact minute past the hour:

"At the third stroke it will be ten, twenty-five precisely"

(4) At other intermediate times:

"At the third stroke it will be ten, twenty-five and twenty seconds".

Each phrase is followed by three 1000 ∿ "pips" of 0.1 second duration, the last of which indicates the time as announced.

Preparation of Sound Records

Choice of Recording System

Most recording systems may be classified as mechanical, magnetic, or photographic in principle. It is possible by all these processes to produce records which are initially satisfactory. On the other hand, records of the first two types are subjected to mechanical wear in reproduction, and deterioration in the quality of the reproduced speech is inevitable.

The photographic system involves a rather more complicated recording technique than the other two systems, but this is more than outweighed by its advantages for the present purpose. The initial quality of reproduction is good and the noise level low. Moreover, the form of record actually used in the clock is not subjected to any mechanical wear and is, therefore, for all practical purposes permanent.

Form of Record

The form and basis material of the records depend not only upon acoustic requirements but also upon the mechanical features of the reproducing device.

Sound track printed on paper strip, wound on an opaque drum and reproduced by reflected light is used in the Paris speaking clock. (Revue Générale de l'Électricité, 1932, Vol.32, p.315). At the outset of this investigation little was known of the behaviour of such records/

records in service. It was felt, however, that dust and surface scattering of light and distortion of the record due to changes in atmospheric humidity might cause deterioration of the speech quality. A transparent record reproduced by transmitted light was therefore preferred.

Another continental speaking clock does in fact use flat discs of celluloid film carrying circular sound tracks and sandwiched between glass plates (Ericsson Review, 1934, Vol.2, p.85). This construction, although probably superior to paper strip, is not entirely free from objection on grounds of instability. Normal cinema film is open to similar objections and, further, is difficult to employ in a manner which will avoid mechanical wear.

For these reasons, and owing to the fact that suitable recording technique had been evolved, it was decided to use glass as the basis material for the records.

Preparation of Sound discs

Good reproduction of frequencies up to at least 10,000 cycles per sec. can be obtained from ordinary sound film travelling at the normal speed of 18 in. per second relative to the reproducing head. At this speed approximately 9 feet of sound track would be required for the spoken part of the announcement which lasts about 6 seconds. To record separately each different announcement in the 12-hour period would therefore require nearly 8 miles of sound track. This is obviously impracticable. Furthermore, it would be almost a physical impossibility for any speaker to maintain uniformity of volume, intonation and rate of speaking for the recording time required, and the cost of such lengthy records would be prohibitive.

It is necessary, therefore, to divide the announcement into words or short phrases and, by switching from one record to another, to make each serve for as many announcements as possible. For example, the same record of "At the third stroke" is used for every announcement. The sub-division must be such that these switching operations introduce no unnatural pauses.

At this stage it appeared that the best form of record was that of concentric circular tracks on flat glass discs, reproduced by

rotating/

rotating the discs in front of stationary optical systems.

The overall diameter of the discs was fixed at 12 in. since it would be difficult to obtain larger sheets of glass which would be truly plane and remain so after processing. Further, any inaccuracy in the mounting of the discs on the shaft or inherent in the discs would be more pronounced at larger diameters and would lead to loss of articulation by de-focussing the optical system. The diameter of the outermost sound track is 11 in. In order to accommodate as many tracks per disc as possible without unduly restricting the speech output the radial width of the tracks was fixed at 2 mm.

By trial it was found that the time required for speaking the longest of the "minutes" words was 0.9 second. To allow for switching, a speed of 1 revolution per second was chosen. Without loss of quality in reproduction it would therefore be possible for the length of the innermost track to be 18 in. This just permitted the use of two discs only for the 60 "minutes" records.

It is unnecessary to discuss in detail the reasons for the allocation of particular phrases to particular discs, and a brief description of these in their final form will suffice.

Although the complete announcement is divided into five parts, four discs only are required, since two of the discs each perform two functions. Thus, one disc carries the following records:-

Outermost track - "At the third stroke"
Six inner tracks - "Precisely"
"and ten seconds"
etc.

The time taken to speak the longest of these is only 1.7 seconds. To simplify the mechanical arrangements, however, a speed of 1 revolution in 2 seconds was chosen. This disc is shown as item (55) in Fig.2.

Another disc serves for the "hours" portion of the announcement and carries the records:

"it will be one"
"it will be two"
etc.

The/

The actual sequence of the tracks on the disc differs, however, from the simple numerical order since this would entail the necessity for the reproducing system to make a large movement in returning from "it will be twelve" to "it will be one". The order used is shown in Table 1.

Table 1 Order of tracks on "hours" disc

Track No.	Phrase	Track No.	Phrase	Track No.	Phrase
(1) (outside)	It will be 6	(10)	It will be 11	(18)	It will be 15
(2)	" " " 7	(11)	" " " 1	(19)	" " " 22
(3)	" " " 5	(12)	" " " 12	(20)	" " " 16
(4)	" " " 8	(13)	" " " zero	(21)	" " " 21
(5)	" " " 4	(14)	" " " 13	(22)	" " " 17
(6)	" " " 9	(15)	" " " 24	(23)	" " " 20
(7)	" " " 3	(16)	" " " 14	(24)	" " " 18
(8)	" " " 10	(17)	" " " 23	(25) (inside)	" " " 19
(9)	" " " 2				

In this order the passage from one hour to the next normally involves a movement of two track-widths, i.e. 4 mm, but at each end of the half-cycle of operations a single 2 mm movement is required. This principle greatly simplifies the mechanical design.

In general, there is no fundamental reason for the choice of any particular record as the outermost or as the innermost track. In this case, however, an important point is that, with the arrangement chosen, should the 24-hour time system be required later, the change could be accomplished without need for further recordings.

The slow speed of this disc causes a slight attenuation of the highest speech frequencies of the inner tracks but, even in the worst case, the loss is negligible up to 6000 cycles per second.

The next disc is used for the "even minutes" records, the place of "zero minutes" being taken by the words "o'clock".

The remaining disc carries the "odd minutes" records as well as a short recording, lasting 0.1 second of a 1000 ∿ note. The three "pips"

"pips" are obtained by reproducing this note three times in succession. (Actually two such "pips" were recorded in slightly different positions on adjacent tracks to provide a choice of the best overall arrangement.)

The placing of the tracks on these discs is carried out in accordance with the principle underlying the arrangement of the "hours" disc. The actual order is, therefore, as shown in Tables 2, 3 and 4.

Table 2 Order of tracks on "even minutes" disc

Track No.	Phrase	Track No.	Phrase	Track No.	Phrase
1 (outside)	Thirty-two	11	Forty-two	21	Fifty-two
2	Thirty	12	Twenty	22	Ten
3	Thirty-four	13	Forty-four	23	Fifty-four
4	Twenty-eight	14	Eighteen	24	Eight
5	Thirty-six	15	Forty-six	25	Fifty-six
6	Twenty-six	16	Sixteen	26	Six
7	Thirty-eight	17	Forty-eight	27	Fifty-eight
8	Twenty-four	18	Fourteen	28	Four
9	Forty	19	Fifty	29	O'clock
10	Twenty-two	20	Twelve	30	Two

Table 3 Order of tracks on "odd minutes" disc

Track No.	Phrase	Track No.	Phrase	Track No.	Phrase
0 (outside)	Pip signal	10	Twenty-three	21	Fifty-three
0.0	" "	11	Forty-three	22	Eleven
1	Thirty-three	12	Twenty-one	23	Fifty-five
2	Thirty-one	13	Forty-five	24	Nine
3	Thirty-five	14	Nineteen	25	Fifty-seven
4	Twenty-nine	15	Forty-seven	26	Seven
5	Thirty-seven	16	Seventeen	27	Fifty-nine
6	Twenty-seven	17	Forty-nine	28	Five
7	Thirty-nine	18	Fifteen	29	One
8	Twenty-five	19	Fifty-one	30	Three
9	Forty-one	20	Thirteen		

Table 4/

Table 4 Order of tracks on "seconds" disc

Track No.	Phrase	Track No.	Phrase
1 (outside)	At the third stroke	5	and fifty seconds
2	and thirty seconds	6	and ten seconds
3	and forty seconds	7	precisely
4	and twenty seconds		

Recording process

To build up the complete announcement satisfactorily requires close control of the duration of each word and accurate placing of each record on the disc. The early trials soon showed that it was not possible to produce satisfactory discs by direct recording. The speech required was therefore first recorded on standard sound film and subsequently transferred to the discs.

A difficulty experienced by the speaker in accurately controlling the duration of each word and in maintaining uniform intonation was overcome in the following manner.

From many repetitions a satisfactory film recording of "At the third stroke" was selected. This was reproduced from a loudspeaker in the recording studio and, after each playing, the announcer spoke one of the phrases "it will be one", "it will be two", etc. In order to avoid wear of the film the reproducing apparatus used was that which was developed for substituting spoken phrases, e.g. "Line engaged" for signalling tones. (See Research Report No.7640). In this apparatus the film is firmly clamped to the periphery of an aluminium drum, so that the sound track projects beyond the edge.

After some practice it became comparatively easy to match the spoken phrases closely to the standard phrase both in intonation and in duration. Similar means were adopted in recording the remainder of the words and phrases required.

The master disc negatives were made on flat glass plates suitably sensitized. The plate was held in a mounting and rotated at constant speed about a central axis at right angles to the face. The slit of a sound-recording oscillograph was focussed as a short radial line on the/

the plate. Arrangements were made to adjust the diameter of the track so formed exactly to a predetermined figure. Each selected film record was reproduced in turn by means of the drum apparatus just described, and the output from the amplifier of this apparatus was fed to the oscillograph element. By this means the word or phrase recorded on the film was re-recorded on the plate. Great care was necessary in this process to ensure that the speeds of the drum and of the plate carrier were correctly related and that the phrases were recorded so as to begin or end in the correct relative positions on the plate. This is necessary in order to avoid awkward pauses or overlapping when reproduced by the clock.

Early practical trials made with announcements built up from strips of film showed that it was particularly necessary for the interval between the end of the "hours" phrase and the beginning of the "minutes" to be constant and fairly short. For this reason all the former end and all the latter begin on radial lines on the respective discs. The relative positions of the two sets of tracks on the dual purpose discs were determined by the positions, in time, of the various words in the announcement, due regard being paid to the location of the two reproducing systems associated with each of these particular discs.

In all cases the sound tracks are of the so-called "Variable Area" type.

Simultaneously with the speech currents fed to the recording oscillograph a D.C. bias was automatically applied, so that the width of the sound track tapered to zero both at the beginning and at the end. A black area was thus produced on the positive prints which avoids noise due to shuttering, whilst the gradual build-up and die-away avoid noise as the track enters and leaves the reproducing beam of light.

Reproduction of the Speech

The method of speech reproduction follows standard practice. For this purpose the optical unit shown in Fig.1 is used. The exciter lamp is mounted within the ventilated shield (15) and can be rotated slightly in its holder, which also is adjustable for height, in order to/

to bring the (horizontal) filament at right angles to and in the same plane as the optical axis. The optical system itself (16) is of normal design and is provided with adjustments for focussing (17), setting the length of the slit (18) and for setting the slit radial to and centrally over the sound track. The photocell is contained within the tubular shield (19) which is perforated so as just to pass the reproducing beam of light. With this arrangement no trouble has been experienced due to stray light, in spite of the use of A.C. for the room lighting.

The circuit of the speech amplifier (Ex.22018) shows little departure from standard practice. For simplicity the cathodes of all six photocells are connected together and to terminal (7) of the amplifier. The photocells used are of the gas-filled caesium type. Since individual cells may differ considerably in sensitivity, the outputs are equalized by the use of variable potentiometers controlling the voltage applied to the anode of each cell. The overall gain is controlled by means of the variable potentiometer between the first and second stages.

Even with the use of special low-capacity screened cable for the photocell leads some loss of the upper audio frequencies occurs. The input impedance of the amplifier is therefore kept low, and a tone correcting circuit is included between the first and second stages. The frequency characteristic of the amplifier with photocells connected is shown in Ex.33721.

The connecting cables between the speech amplifier and the distributing relay sets are of considerable length. To avoid loss of the higher speech frequencies due to the capacity of the leads and loss of volume due to their resistance the main secondary winding of the speech output transformer in the amplifier gives a step-down ratio of 4:1 which, with the output valves used, requires a matching load of 400 ohms. A second output transformer, mounted on the relay set rack, gives a further step down of 20:1 and, in conjunction with a 1 ohm resistance connected directly across the secondary winding, provides the correct load.

The impedance of the shortest subscriber's line is not much less than 600 ohms, so that even with 100 lines simultaneously connected the/

the total output load impedance falls only to about 0.9 ohm. Practical listening trials showed no detectable difference in volume whether 1 or 100 subscribers were connected. As a check on the speech voltage applied to the relay sets a rectifier type voltmeter is joined across a tertiary winding on the main output transformer.

Alarms

To safeguard the continuity of the service an alarm is necessary should the speech output fall below a predetermined level. For this purpose, speech currents derived from a fourth winding on the main output transformer are rectified by a bridge-connected metal rectifier and charge the condenser (K) (Ex.22018). The circuit values are such that, in consequence, the associated valve (PX4) operates at substantially zero bias. Anode current flows holding relay D in the operated condition. Should the speech output fall, negative bias is applied to the valve by a suitable resistance network, whereupon the anode current falls and relay D drops out. If the valve itself fails D again drops out. Between the end of the "seconds" phrase and the beginning of the next announcement only the "pips" occur and these are too short to maintain the charge on the condenser (K). To hold the relay operated during this period the grid of the valve is brought to zero bias by means of contacts closed by a cam - the "Alarm Suppressor" cam (No.7 Ex.22135; Fig.3) - on the clock mechanism and connected to terminals (8) and (9). A contact D3 of relay D is included in this circuit, so that the relay cannot be operated initially or brought in again after a speech failure, except by the correct speech output. Unless relay D is operated terminal (16) is earthed via contact D1 and, as will be seen later, an alarm bell is sounded and subscribers cannot be connected to the amplifier.

Failure of one of the early valves would be indicated in this way, but failure of one only of the output valves would not necessarily be shown, although the reproduced speech would become distorted. The separate anode feeds to the output valves are therefore taken through the differentially wound relay C. If the output stage becomes unbalanced this relay operates and earths terminal (16). To prevent loss of the higher speech frequencies the windings of this relay are shunted/

shunted by a condenser.

To expedite the diagnosis and clearing of possible faults various meters and miliammeter jacks are provided in the anode circuits and a pilot lamp glows as long as a satisfactory output is being given.

The shortest-lived components in the reproducing systems are the exciter lamps, failure of one of which would cause an incomplete sentence to be sent out. To obviate this the filaments are series-connected so that a partial failure is impossible. The lamps are rated at 10 V but, to increase their life and to reduce the possibility of hum, the six are run from a 50 V, A.C. supply given by a transformer on the clock mechanism base. Each lamp is shunted by a 50 V low power switchboard lamp which glows if the corresponding exciter lamp fails.

The Clock Mechanism

The most essential features of the clock mechanism are accuracy and reliability. To this end the mechanical parts are as few as possible in number and were designed with a large margin of safety.

Maintenance of efficient operation needs only a minimum of attention over long periods, and the general layout permits ready replacement or adjustment of any of the few parts which might conceivably become defective in service.

The main functions which have to be performed by the mechanism are determined by the manner in which the announcements are made on the one hand and by the necessity for accurate timekeeping on the other. These functions may be considered in greater detail under four main headings:

(1) Driving the sound discs
(2) Building up each announcement
(3) Changing from one announcement to the next
(4) Operating contacts for checking and controlling the timekeeping.

Rotation of the Discs

Since the pip signal which indicates the exact time is recorded on and reproduced from the "odd minutes" disc the speed of this, and hence of all the discs must be accurately controlled. Further, for good/

good speech reproduction the speed must be uniform throughout each revolution. A special motor running at 60 r.p.m. was therefore developed for this purpose. This motor is shown at (51) on Fig.2 which depicts the general layout of the clock mechanism.

Since the "odd" and "even" minutes discs - (52) and (53) respectively - also rotate at 60 r.p.m. a direct drive is used. The "hours" and "seconds" discs - (54) and (55) respectively - rotate on a separate shaft coaxially with the "minutes" discs, but a 2:1 reduction gear (22) is interposed to give the speed required - 30 r.p.m. Helical gears of fine pitch are used to avoid "flutter" due to backlash. Lubrication is by means of oil into which the countershaft gears dip. It was found necessary to devise a special form of oil retaining washer to prevent leakage past the main bearings. Ball bearings are used throughout the mechanism to reduce friction.

The main bearing housings and gearbox are split along a horizontal plane through the axis of the main shafts to facilitate removal of the latter, if necessary.

Smooth running and maintenance of accurate focussing of the discs with absence of whip or vibration are essential to good sound reproduction. The main shafts are therefore made of 1 in. diameter precision-ground mild steel. The discs themselves are mounted on flanged gunmetal hubs, one of which is seen (21) in Fig.1. The tapered ends of the hubs are split and contracted on to the shaft by means of nuts. Rings of filter paper are inserted between the sides of the discs and the flanges of the hubs to improve the grip and avoid breakage. The central holes drilled in the discs are slightly larger than the central portions of the hubs to allow the discs to be accurately centred and lines are scribed on the shafts, hubs and discs to facilitate correct reassembly should the necessity arise for any replacement.

Building up the announcement

From the foregoing it is apparent that the discs are rotating and the exciter lamps are energized at all times. Some form of switching is therefore necessary in order that speech shall be reproduced from only one disc at a time and in the correct order for building up the proper/

proper announcement. Since the first valve of the amplifier is common to all the photocells such switching must occur before this valve is reached. In view of the high gain of the speech amplifier no attempt was made to devise a switching device for the photocell circuits. Switching the exciter lamps would necessitate the use of special heavy-current contacts and, further, would not be completely successful owing to the appreciable time of heating up and cooling down of the filaments.

For these reasons it was decided to perform the switching by optical means. This was accomplished by the use of electromagnetically-operated shutters interposed between the optical systems and the sound discs. These shutters normally prevent the passage of the beam of light to the disc and no output is produced by the corresponding photocell. The announcement is built up by causing the discs to "speak" in turn by opening the corresponding shutters in the correct sequence. This is done by means of a series of contacts operated by cams which are rotated by means of a reduction gear from the main shaft. The cross-shaft (27) Fig.3, is driven from the main shaft (28) by the 2:1 reduction skew-gear (29). By means of a further 5:1 reduction gear (30) the main contact cam assembly (31) is driven at 1 revolution per 10 seconds. The contacts operated in this way are Nos. 1, 2, 3, 4, 5, 6, 7, 8, 10 in Ex.22135.

The manufacture of the cams had to be undertaken before the preparation of the discs was completed. When the mechanism was first put under test it was found necessary slightly to alter the relative positions of certain words in the announcement in order to produce a natural effect. This was, of course, done by slight alterations in the angular relationships of the various discs on their shafts, and the necessity for it was foreseen in the early stages of the design. It was therefore decided to make the individual cams adjustable, so that the shutters could be set to open just prior to the commencement of the sound tracks and close just after the end of these. In this way noise is avoided by opening and closing the shutters when the black area of the disc lies before the optical system. The necessary adjustment is provided by using split cams, the two halves of which can be rotated separately through small arcs to give the setting

required./

required. These cams are made of bakelite clamped between the faces of flanged steel bushes keyed to the cam shaft. For the reproduction of the "pips" the track passes the optical system three times and the associated shutter therefore remains open for just over two revolutions of the main disc shaft.

The method of mounting the shutters in relation to the optical system is shown in Fig.1 (20) and the mechanism is shown in greater detail in Fig.4. The blade (32) of the shutter is shaped so that its movement varies the amount of light passing as smoothly as possible in order to reduce still further any remaining possibility of "clicks" being caused by the operation. The magnet system consists of a small soft iron armature (33) carrying the shutter blade, suspended on hardened steel pivots between the poles of an electromagnet (34). The shutter is normally held in the closed position by a light spring with the armature displaced angularly in relation to the axis of the pole pieces. When the magnet is energized the armature is drawn more nearly into the magnetic axis thereby opening the shutter. The travel of the shutter blade - about $\frac{1}{4}$ in. - is regulated by suitable fixed stops. An oscillogram showing the times of opening and closing the shutter is shown in the lower part of Fig.4. To avoid the production of noise in the speech circuits it was found necessary to shunt the contacts controlling the switching operations by suitable resistance-condenser spark-quench circuits. (See Ex.22135).

Change from one announcement to the next

Simply expressed, the change from one announcement to the next merely involves moving one or more optical systems so as to reproduce different sound tracks. In actual fact, however, the evolution of a truly satisfactory design for this vital part of the mechanism involved many major difficulties. This will be apparent from a consideration of the more important requirements to be fulfilled:

The plane of movement of the optical system must be accurately parallel to the face of the disc to avoid imperfect focussing with consequent loss in articulation.

The extent of each movement of the optical system must be exact, since there is no radial spacing between adjacent sound tracks other than/

than that which arises from the fact that the maximum modulation of the track-width is 80%.

The movement must take place smoothly in order to avoid undue mechanical wear yet must be completed during the short silent period between the end of one announcement and the beginning of the next.

In the final design each of the four movable optical units is mounted on a carriage which runs on ball-bearing rollers on two horizontal cross-guides situated below and at right angles to the disc shafts. The carriages are moved by means of steel cams working on rollers mounted on the carriages. Contact between the cam faces and the followers is maintained by spring pressure.

This principle has the advantage that the steps of each cam are at equal angular spacings and the magnitude of each step is equal to the required mov ement of the optical system. Nevertheless, the manufacture of the cams presented several problems. The asymmetry of contour necessitated a considerable amount of hand work. To avoid the development of inaccuracy through wear the cams must be hardened and freedom from distortion during hardening is therefore essential.

In the first stage of the shaping operation the blanks, consisting of "Nitralloy" steel, were "roughed-out" by hand to approximately the contour required then each step was milled to the correct radial distance from the centre. A radius was then milled leading from each step to the next and the intermediate contour was finally blended in by hand filing and polishing. After hardening by the special treatment required by this material no measurable distortion could be detected.

In the case of the "minutes" cams the circle swept out by the cam proved to be inconveniently large. Accordingly, each of these cams is split into two portions using a smaller radial scale for the outer portion of the travel but keeping the lift of the steps the same. These cams can be seen (35) in Fig.5. Each of the two "minutes" carriages is fitted with two separate followers one of which runs on an eccentrically mounted spindle. This is necessary in order to match the followers accurately to the respective halves of the cam and give a smooth take-over. One of the additional followers is seen at (36). The two composite cams are mounted on a single camshaft so that/

that the central radii of the steps of one lie midway between the steps of the other. The 60 positions required to cover the minutes are thus obtained by the use of 30 steps only on each complete double cam.

The method of imparting the correct angular movement to the "minutes" cams can also be seen in Fig.5. The shaft (37) is driven continuously at 60 r.p.m. by skew gearing from the cross shaft previously mentioned. (See also Fig.3). Mounted freely on this shaft is an eccentric (38), the sheave of which is integral with a special clutch (39). A connecting rod couples the strap of the eccentric to a swinging arm which is freely mounted on the cam shaft. A pawl carried on this arm engages with a 60-tooth ratchet wheel (40) which is pinned to the cam shaft, and the throw of the eccentric is such that, when the clutch makes one complete revolution, this wheel advances one tooth and the cams move the carriages the appropriate distance. The time of movement is $\frac{1}{2}$ second, which is slow enough to avoid damage due to rebound.

A light aluminium drum (41) suitably engraved and pinned to the cam shaft, in conjunction with a fixed pointer, indicates visually the track being reproduced at each setting of the cams. The bakelite cam (11) operates a change-over contact which permits the operation of either the "odd minutes" or the "even minutes" shutter according to the setting at any instant.

The clutch (39) which turns the eccentric sheave through exactly one revolution as required is shown more clearly in Ex.22287. Before incorporation in the final design a sample unit was subjected to a severe accelerated life test in the laboratory and found to function reliably. The main body of the clutch (39) is freely mounted on the shaft (37) to which is pinned the ratchet wheel (42). The pawl (43) carried on the body of the clutch is normally held out of engagement with the ratchet wheel by the armature (44) of the electromagnet (25). On passing a momentary current through the coil the armature is withdrawn from the projecting end of the pawl which is then thrown by the spring (45) into engagement with the ratchet wheel. The whole assembly is thus locked to and rotates with the shaft. When the current ceases the armature is returned to normal by the spring (46).

On/

On the completion of one revolution, the projecting end of the pawl (43) strikes the armature, is thrown out of engagement with the ratchet wheel and the whole assembly comes to rest. A spring-loaded lever (47) bearing on a roller (48) holds the clutch in this position in readiness for the next operation.

The carriages associated with the "hours" and the "seconds" discs are moved similarly. The mechanism is seen in the foreground in Fig.2.

The sequence of operations of this mechanism is as follows:-

Immediately after the third pip of each announcement, a contact operated by a cam on the shaft (23) is momentarily closed. This energizes the electromagnet (24) and the "seconds" portion of the announcement is changed in the manner just described. When the "seconds" carriage moves into the position to reproduce "and 50 seconds" a contact (9) associated with the "seconds" cam shaft closes and connects the magnet (25) in parallel with (24). After the third pip of this particular announcement, both magnets are momentarily energized and simultaneously the "minutes" carriage moves to its next position and the "seconds" carriage to the "precisely" position. Similarly at "59 (minutes) and 50 seconds" the magnet (26) is paralleled with the other two. Following this announcement, the "hour" changes to the next, the "minutes" to "o'clock" and the "seconds" to "precisely" as before.

The introductory phrase "At the third stroke" and the three pip signals are common to all announcements. The optical systems used to reproduce these are shown at (49) and (50) respectively, Fig.2.

The bed-plate, on which the whole of the mechanism is carried, is a single casting in cast iron containing nickel 5 ft. 9 in. long by 2 ft. 9 in. wide. Machined surfaces are provided for all components, and all vital parts are dowelled in order to ensure accurate refitting in the event of removal being necessary. Suitable weathering periods were allowed to elapse before taking the final cuts in the machining operations to avoid risk of distortion.

<u>Method of Drive</u>

For a mechanism of this size and complexity the requirements of the/

the method of drive are unusually stringent. It is obviously desirable to use one driving motor for the whole mechanism if possible. The power required to drive the discs only is small, but the peak requirement, which occurs once per hour, i.e. when all three cam-shafts move simultaneously, is relatively large. An adequate margin of power above this peak is necessary, and the whole rotating system must possess sufficient inertia to prevent noticeable speed fluctuations with change of load.

It has already been seen that the speed of rotation must be accurately controlled. Since the maximum error permissible is ±0.1 second, the gain or loss per hour, assuming hourly correction, should not exceed 0.05 second. This necessitates some form of continuously operating control, in spite of which, however, an error exceeding 0.1 second could ultimately accumulate. A periodical over-riding check is therefore required to correct this error. This operation should be automatic and the whole scheme should not need constant or skilled attention for its efficient working. In view of the novelty of the scheme ultimately used a short account of the experiments leading up to its adoption is given.

Methods available

Greenwich Mean Time is naturally the standard against which the clock is compared. The periodical check therefore employs the signal transmitted exactly at each hour from the Observatory.

For the continuous control, however, various possible methods are available. One of the simplest would be to use a synchronous motor running on time-controlled A.C. mains for the main drive. At present, however, the required accuracy cannot be attained by this means, and there is no simple way of providing an effective stand-by drive in the event of mains failure. Two other possibilities are a motor whose speed is under the control of an accurate tuning fork or a pendulum.

At the outset of these investigations little was known of the behaviour of low-frequency tuning forks. A few experiments were actually carried out in which a 50 ∿ fork was used to control the frequency generated by an inverter circuit using gas-filled relays,

but/

but it appeared doubtful whether the required frequency stability and reliability could be attained.

The properties of higher frequency, e.g. 1000 ~ forks are better known and, with close temperature control, the required accuracy could undoubtedly be reached. It would be necessary to follow such a fork with a frequency divider or to use a very high-speed motor with a high-ratio reduction gear in order to obtain the slow speed of the clock mechanism. The disadvantages of such schemes are apparent and, in view of the success attained in early experiments using a pendulum, further work on forks was ab-ndoned.

Pendulum speed control

For the early experiments on pendulum control a Clock No.36 was used. This has a seconds-beating pendulum employing an Invar rod. The swing of the pendulum is maintained by means of the Hipp toggle contact and electromagnet. The count wheels etc. which close contacts at intervals of 6 and 30 seconds were removed for the present investigation. The 1-second contacts were used to operate a secondary dial (Clock No.28) by the aid of which the daily rate of the pendulum was measured. It was found possible to maintain a rate of ±1 second per day without difficulty. This is of the right order.

For the present purpose the hourly rate throughout the 24 hour period was of greater importance. This was measured in the following manner:-

The 1-second contact was removed and the length of the arc of swing measured with reduced energy input to the driving magnet, so that the difference between maximum and minimum amplitude was small. A photographic transparency shaped as shown in Fig.6 was mounted at the bottom of the pendulum. The image of a vertical narrow illuminated slit was focussed centrally on the transparency when the latter was at rest. The base of the transparent area was equal to the arc of swing and the shape was such that when the pendulum was swinging normally the amount of light passing through the trace and falling on a photocell varied sinusoidally at 4 cycles per second. (The transparency was prepared by photographic reduction from a drawing 10 times the linear dimensions of the trace required). Despite the very low frequency/

frequency it was found possible to amplify the output of the photocell by means of an amplifier of straightforward design. A small two-pole synchronous motor was constructed which was driven at 4 revolutions per second by the A.C. output of the amplifier. The motor, with the aid of suitable gearing, operated contacts by means of which the error of the pendulum was recorded at each hour. Ex.22305 shows the circuit employed. Contacts 1, 2, 3, 4 and 5 were operated by cams rotating at the speeds shown. 30 seconds before each hour contact 1 closed and relay A operated and locked via contacts 2 and A1. 15 seconds later contact 1 restored and contact 3 closed. Relay C then operated and locked via contacts A2 and C1. By the closing of contact C2 relay D operated and started the motor of a syphon recorder via mercury contact D1 Hg. During the period for which relay C was operated relay B was impulsed momentarily every second via contact C3. Contact 4 was closed at 3.5 seconds before the hour and opened 7 seconds later. By means of contact B1 seven momentary impulses were thus applied each hour to the coil X of the recorder. The central impulse was taken to represent the exact hour and the others afforded a means of accurately determining the speed of the recorder tape. The other pen (7) of the recorder recorded the signal transmitted from Greenwich at each hour. 15 seconds after the hour contact 2 opened and reset the apparatus in readiness for the next hour. By simple measurement the rate of the pendulum during each hour could readily be computed. The records obtained in typical day's run are shown in Figs. 7A and 7B.

The results, over a period of some months, showed that this pendulum could be adjusted to run true to time with an error of ±0.05 to 0.1 second per hour. This was nearly good enough.

The success of these experiments suggested that if the pendulum could be arranged to swing perfectly freely (in the horological sense of the word) by eliminating the Hipp escapement still better timekeeping could be secured.

At this stage various ways of employing such a pendulum were examined in order to determine whether any further increase in accuracy could profitably be utilized. There are several known methods of employing/

employing a pendulum for the purpose of speed control.

In most of these a D.C. motor is used and, in addition to driving some mechanism, operates contacts at regular intervals. By means of relays the operation of these contacts is compared with the operation of other contacts by the pendulum. The speed of the motor in relation to the time of swing of the pendulum is thus determined and corrections made as required by automatic control of the field excitation.

There are several disadvantages of such schemes. The operation of contacts adversely affects the accuracy of the pendulum. These contacts are called upon to operate frequently and, at the last stage, to control appreciable power in an inductive circuit. Frequent maintenance attention would therefore probably be necessary and difficulties were expected in avoiding the introduction of noise into the speech circuits. Appreciable variations of speed from moment to moment are inevitable although the mean speed over a period may be correct. There is a definite risk that this might cause noticeable changes in the pitch of the reproduced speech. Finally, the use of a relatively high-speed motor and gearing introduces maintenance problems which are largely absent in a purely low-speed mechanism.

For these reasons attention was concentrated on direct utilization of the 4 ~ current generated in the manner just described. The first problem was naturally that of securing efficient amplification at this low frequency. Resistance-capacity intervalve couplings with a large enough time constant are straightforward. Even transformer couplings are perfectly practicable if the windings are designed to have enough inductance. In this case, however, an alternative path for any direct current in the circuit must be provided in order to avoid saturation of the core. This last point is particularly important in the design of the output transformer, the windings of which must carry the mean D.C. flowing in the valve anode circuits. This problem was solved by using cores of relatively large cross-section, and a balanced output stage in which these D.C. components cancelled out. Apart from these considerations the transformer design was carried out in the normal manner.

Convenience and the relatively large output power required made almost/

almost inevitable the choice of A.C. mains for the energy supply to the amplifier. The overall gain of the amplifier is very high, and particular care was therefore necessary in order to prevent unwanted interaction. For the sake of their low impedance mercury vapour rectifying valves are used in the H.T. supply unit and the actual circuit used (Ex.22071) incorporates the suggestions made by Dunham (Journal of the Institution of Electrical Engineers, 1934, Vol25, p.278) to give good voltage regulation. Very thorough decoupling is used in the individual anode feeds. As a further precaution the second stage of the 4 ∿ photocell amplifier is connected in push-pull in order to reduce circulating alternating currents in the power unit. (As will be apparent later, the same result is incidentally achieved in the later stages of the final amplifier).

The first form of output stage employed two triodes in push-pull. Valves dissipating 75 W at an anode voltage of 1000 were used and delivered a 4 ∿ output of 36 W into the load.

This output was used to drive an experimental synchronous motor at 60 r.p.m. Since it was ultimately superseded, it is unnecessary to describe this motor in detail, except to state that its measured characteristics were very close to the calculated figures and that its efficiency at full load was over 80%. The mechanical power output was adequate, but the speed under load showed a slight periodic fluctuation due to the inherently pulsating nature of the torque produced. When using the motor for driving a sound disc this speed fluctuation was manifest by a slight but detectable "wobble" in the reproduced speech. Although in this precise form the method of drive was not entirely satisfactory the experience gained in its development suggested that complete success was probable if the scheme could be modified to polyphase working.

Fortunately this proved to be comparatively simple. The basis of the modification was the 3-phase sinusoidal oscillating circuit devised by Van der Pol (Physica, 1934, Vol.1, p.437). As this circuit does not appear to be widely known, it may be considered briefly. The basic circuit is shown schematically in Ex.22285. The three unit-stages are identical. Any disturbance originating at the/

the grid of the first valve will reappear in the anode circuit with a phase change of 180°. In passing to the grid of the second valve a further phase change will be sustained in the condenser-resistance network and so on. At one definite frequency the interstage phase change will be 60° and the disturbance will return to the first grid in phase with the initial disturbance. Under suitable conditions sustained sinusoidal oscillations will therefore occur at a frequency determined simply by the value of the coupling components. Further, the alternating e.m.f's appearing at the 3 anodes or at the 3 grids will be in a balanced 3-phase relationship. In practice the unavoidable stray capacities may produce oscillations in a different mode, usually at a very high frequency. These can be suppressed by shunting one or more of the anode resistances by small condensers which do not affect the oscillations at the lower frequency.

A practical trial of this circuit showed that with suitable values it functioned satisfactorily at approximately 4 cycles per second, but that the actual frequency varied somewhat with changes in anode voltage. This variation was eliminated by the addition of a neon-tube voltage stabiliser, but even with this addition the natural frequency was insufficiently constant for the present purpose. The frequency was, however, successfully stabilized by injecting into one of the grid circuits a small e.m.f. derived from the 4 ∿ photocell amplifier even when the natural (uncontrolled) frequency of the oscillator differed from 4 ∿ by as much as 10%. Under these extreme conditions, slight wave-form distortion was apparent. In the final circuit (Ex.22070) the oscillator frequency is stabilized in this manner by injecting the true 4 ∿ e.m.f. between terminals (2) and earth after setting the natural frequency as near to 4 cycles per second as possible. As a further precaution the voltage stabiliser (Ex.22301) is retained. Terminal (6) of the latter is connected to terminal (6) of the power unit (Ex.22071) and the H.T. supply to the oscillator is taken from terminal (1) (Ex.22301).

Mention may be made of a key (see Ex.22070) which, when thrown to one side or the other of its normal position, cuts out the pendulum control and alters the resistance values in the oscillator circuit so that/

that the speed of the clock mechanism is increased or decreased by approximately 10%. Additional contacts on the key prevent the clock being brought into service except in the normal (i.e. controlled) position. This feature is very useful when starting or restarting a clock which has been stopped either by the occurrence of a fault or for general overhaul.

The output stage consists of three 75 W triodes coupled to the oscillator by three special transformers which employ mu-metal cores to obtain the necessary inductance without undue bulk. A single output transformer is used in order to avoid D.C. magnetisation of the core. Variable potentiometers are included between the oscillator valves and the output valves for balancing the currents in the three secondary windings. The latter are star-connected with the neutral point earthed. Under normal conditions the 4 ∿ component in the main H.T. supply to the whole amplifier is negligible and no undesirable feed-back effects have been detected.

The total maximum undistorted output of the amplifier is over 50 W. The actual consumption of the motor is, however, only about 20 W. The wave form of the current in a resistive load at full output is shown in Ex.22286.

Pendulum Maintaining Circuit

It is now evident that the speed of the 3-phase motor and, therefore, the accuracy attained by the whole clock depend entirely upon the time-keeping of the pendulum. It has been seen that, even using the Hipp escapement, this is good, but could be further improved by allowing the pendulum to swing completely freely.

The manner in which this ideal was attained will be apparent from Fig.8 which is a purely schematic diagram of the whole method of drive. (Batteries are shown for the sake of clearness although the actual equipment is entirely A.C. operated). So long as the arc of swing is correct, i.e. equal to the length of base line of the wave-trace (56) the output wave-form of the photocell amplifier (57) will be sinusoidal.

If the amplitude of swing is slightly too small, theoretical considerations show that the wave form obtained should be similar to

(B),/

(B), whereas if the amplitude of swing is too great the shape shown in (C) should be produced. Due to unavoidable slight imperfections in the amplifier the actual wave forms obtained differ from these slightly though not seriously. For example, the upper oscillogram in Fig.9 shows the actual output when the amplitude is too small and the lower oscillogram shows the output obtained with too great an amplitude. (In each case the departure from normal amplitude was small.) The output from the amplifier (57)(Fig.8) is applied to a transformer (58), one secondary winding (59) of which has a centre tap. By means of rectifiers (60) and (61) the condensers (62) and (63) receive charges due respectively to the positive and the negative half cycles of the current. The difference in potential between the two condensers, after smoothing is applied to the resistance (64). When the amplitude of swing of the pendulum is correct and the wave form symmetrical (A) the charges on the condensers are equal, there is no p.d. between points (65) and (66) and the potential of the point (66) relative to the earth line, i.e. the effective bias applied to the grid of the gas filled relay (67), is simply that due to the battery (68). As the amplitude of swing falls the wave form becomes unsymmetrical (B) and the charges on the condensers become unequal. In consequence, a difference of potential appears between points (65) and (66) of such sign that the effective negative bias on the gas-filled relay is reduced. This change of bias is utilized to permit application of a driving impulse to the pendulum as required and at the correct point in the swing.

At the mid point in each left-to-right swing of the pendulum a shutter (69) allows a narrow beam of light from the source (70) to fall on the photocell (71). An increase then occurs in the photoelectric current flowing through the resistance (72) as a result of which there is a momentary rise in the potential of the grid of the gas-filled relay (67). When the amplitude of swing of the pendulum is correct this rise in potential is insufficient to make the relay conducting. When, however, the amplitude has fallen by a predetermined permissible amount the reduction in effective steady bias produced by the p.d. appearing across the resistance (64) is such that the relay becomes conducting at the instant of application of

the/

the impulse from the photocell (71). The condenser (73), which is charged through a high resistance (74), then discharges through the energizing coils of the magnet (75) which, attracting the armature (76), applies a driving impulse to the pendulum and restores normal amplitude of swing.

The small 4 ∿ e.m.f. required for stabilizing the frequency of the 3 phase oscillator (77) is derived from a tertiary winding (78) on the output transformer of the photocell amplifier.

It will be apparent that this form of pendulum drive, depending as it does upon slight distortion mainly of the cycles generated at the extremities of the swing, will be more positive in action at low frequencies. The frequency employed - 4 ∿ per second - is therefore a compromise between this factor and the comparatively greater ease of designing the remainder of the apparatus to work at a higher frequency.

The full circuit diagram of the photocell amplifier is shown in Ex.22069.

A practical trial of this scheme extending over several months demonstrated a considerable increase in accuracy. On the whole the hourly error rarely exceeded ±0.05 second. Such larger errors as did arise were ultimately traced to variations in ambient temperature. By maintaining the pendulum cabinet at constant temperature, the departures from the mean rate of the pendulum did not exceed 0.05 second and rarely exceeded 0.02 second per hour over long periods.

The method of generating the 4-cycle current and maintaining the pendulum has been protected by British Patent Specification No.455441.

Construction of Pendulum Unit

The pendulum unit in its final form, but with cover removed, is shown in Fig.10. The iron casting (81) carrying the pendulum (82) and impulsing magnet (75) is mounted within an aluminium box (83) built up on a steel framing. The box is supported on substantial rag bolts let into a main foundation wall of the basement of the Holborn Telephone Exchange building. The effects of vibration are thereby minimized. The pendulum for the second clock is mounted similarly on an adjacent wall at right angles to the first. The method/

method of fixing was designed to give a rigid mounting and allow for accurate levelling.

The optical system (84) is carried directly on the front of the box. The source of light is a 75 W exciter lamp similar to those used in the speech optical systems and is mounted in an adjustable holder (85). This lamp in conjunction with a condensing lens, uniformly illuminates a narrow slit 0.0025 in. wide between two steel knife-edges. The slit-mounting can be rotated through a small angle by means of the lever (86) to bring its image into a vertical position. A short-focus projection lens is used to form the image of the slit on the wave trace and can be focussed by means of the lever (87). Provision is made for a slight sideways movement of the whole system by rotating the milled head (88) to bring the image of the slit over the vertical centre line of the wave trace when the latter is stationary. To simplify making these adjustments the image formed can be inspected closely through the low power microscope (89).

The second beam of light required by the pendulum maintaining circuit is obtained by forming an image of the exciter lamp filament on the end of the shutter by means of an inclined mirror and a suitable lens system. This is focussed by moving the lever (90). Fig.11 is a view of the lower portion of the pendulum unit with the optical system removed showing the wave trace (56) fixed in its holder (69). The horizontal extension of the latter serves as the shutter which controls the illumination of the impulsing photocell. The two photocells are mounted within the tubular screens (71) and (91).

The pendulum box is contained within a wooden cabinet fixed to the wall. The atmosphere within the cabinet is maintained at substantially constant temperature by means of heaters and thermo-regulator, a fan being provided for securing uniform temperature distribution.

The wiring diagram of the pendulum unit is shown in Ex.22139.

Four-cycle three-phase synchronous motor

In view of the low frequency employed it appeared very attractive to/

dispense with gearing and to design the motor to run at the same speed as the main disc shaft, i.e. 60 r.p.m. An 8-pole rotor was therefore required.

At this low speed the major problem, with a rotor of reasonable diameter, is that of obtaining adequate back e.m.f. The pole shoes were made detachable for convenience in winding, but apart from these the rotor was milled from a single solid billet of "Armco" iron. To reduce slot-ripple and improve the wave form of the back e.m.f. the pole shoes are skewed.

The stator is wound with one coil of 90 turns per pole per phase each coil occupying two of the 48 slots. The neutral point is not earthed. When driven as a generator at 60 r.p.m. with normal excitation the measured and calculated characteristic curves of open-circuit voltage against rotor excitation are as shown in Ex.33722. The agreement between these two curves and also between similar curves taken under load conditions is good.

Time Control

The necessity for a periodic check of the time-keeping of the clock has been mentioned. The operations of this check are two-fold viz: (a) detection and (b) correction of the error. The maximum permissible error having been settled as ±0.1 second it was decided that in order to provide a margin of safety a correction should be applied for any error exceeding ±0.05 second, but that smaller errors should be ignored. For any error exceeding 0.05 second the ideal would be to apply an equal correction, but there is little doubt that this would be very difficult to realize. Further, experience both in the laboratory and in the actual running of the complete installation has shown that such refinement is unnecessary. Accordingly, for errors between 0.05 and 0.1 second, it was decided to apply a correction of 0.1 second. Similarly for errors between 0.1 and 0.2 second a corection of 0.2 second is applied. This represents an abnormal condition and an alarm is given. Errors exceeding 0.2 second represent definite faults for which an alarm is given but no automatic correction is applied.

The most important part of the correcting equipment incorporated in/

in the clock mechanism is a distributor shown in Fig.12, mounted on the motor bearing pedestal. The rotating brush (92) bridges across from the continuous ring (93) in turn to each of several short segments (94) which are connected to relays in the correcting equipment. In addition there are four cam-operated contacts the functions of which are described below. These contacts are Nos.8, 10, 13 and 14 in Ex.22135 which is a wiring diagram of the clock base. Contact 8 is closed by means of a cam (8) on the 6 r.p.m. cam shaft (23, Figs.2 and 3) from 0.4 second before to 0.4 second after the beginning of the third pip of each announcement but only that operation which occurs at the exact hour is of importance. Contact 10 is operated by another cam (10) on the same shaft but the only significant operation is the opening of this contact for 0.5 second five seconds after the hour. Contact 13 is opened at 56 minutes past the hour and closed at 59 minutes past the hour by a cam (13, Fig.5) on the "minutes" cam shaft. Another cam (14, Fig.5) on the same shaft opens contact 14 at 5 minutes before the hour, makes on the back spring 1 minute before the hour and restores at 1 minute past the hour. The correcting circuit proper is shown in Ex.22121. (For clearness the cam-contacts and the distributor wiring are repeated in this diagram). The apparent complexity of the circuit arises from two main causes. In the first place, the duration of the Greenwich signal is about 1 second, as a result of which precautions are necessary to prevent the operation of more than one of the low resistance relays F, G, M, L, N, K, J and H. In the second place, these relays must be rapid in operation and as many contacts as possible must therefore be operated by relief relays. The time signal is received on terminals (77) and (78) (one of these is earthed in practice and an earth return circuit is used).

The operation of the circuit is as follows:- Providing that the error, if any, of the clock does not exceed 0.4 second the contact operated by Cam 8 will previously have closed, relay FF will have operated and contact FF_1 changed over. Terminal 73 will also be earthed via cam-contact 14. On the arrival of the time signal relay E operates and contact E1 closes. The particular contact segment over which the rotating brush is passing at this moment will therefore also be connected to earth and the corresponding one of the relays F to N will/

will operate. If, for the sake of argument, the clock should be between 0.05 and 0.1 second slow this will be relay K. By means of its first contact it will lock in and by means of the second contact operate the low resistance relay Z. The Z1 contact of the latter removes the earth from the rotating brush and so prevents operation of any other relay connected to the contact segments.

The closing of the third contact of the relay E operates the corresponding high resistance relay P which then locks in via its own first contact. To avoid overheating of the low-resistance relays, each of which absorbs 12.5 W, they are released 5 seconds after the hour by the opening of cam-contact 10.

The second contact of P lights a lamp which gives a visual indication of the error and the third contact applies the necessary correction in a manner shortly to be described. The remaining contact appears in the chain of series-connected contacts associated with cam-contact 14. If no time signal should arrive at any hour none of these contacts will have operated. On the restoration of contact 14 an earth connection will thereby be extended to terminal 85 and thence to the alarm bell which will then ring.

The operation of relay Q if the error is between 0.05 and 0.1 second fast is similar as also is that of relay U if the error does not exceed ±0.05 second with the exception that the latter relay does not apply a correction.

An error between 0.1 and 0.2 second will lead to the operation of relay O if slow or R if fast. This is an abnormal, but not necessarily a serious condition. The fourth contact of these relays makes the alarm connection. This draws the attention of the attendant, but does not automatically remove the clock from service.

The operation of relays Y or X, if the error is between 0.2 and 0.4 second, or of relay W if the error exceeds 0.4 second represents a definite fault condition which is indicated by an alarm. No automatic correction is applied for such errors, but the third contact of these relays is used to remove the clock from service. By the closing of one of these contacts relay T operates and this in turn extends an earth to the change-over panel. T locks in via one of/

of its own contacts and the second contact of relay Z. By this means the service cannot be re-connected to this clock until some subsequent time signal has shown the clock to be within the permissible range of error, i.e. until Z2 has released T and the latter has not again been operated by W, X, or Y. The alarm bell can, however, be silenced by throwing a key which operates relay S.

Five minutes before the hour the cam-contact 14 opens (to avoid giving the "no time signal" alarm) and one minute later cam-contact 13 opens and restores all the relays (except T) to normal in readiness for the next check.

Method of Correction

In applying the necessary corrections it is essential to avoid sudden changes of speed which might affect the pitch of the voice. The correction is therefore applied gradually.

Various possible methods were considered of which the most attractive and the one ultimately used is control of the rate of swing of the pendulum. This, again, can be accomplished in various ways.

In a simple free pendulum, of which the dimensions are fixed the rate of swing is determined by the gravitational force acting on the pendulum. By applying also a vertical magnetic force, a variation in the effective gravitational force and hence in the rate of swing can be produced. A practical trial showed that by varying the current in the coils of a suitably placed electromagnet adequate control could be obtained without any apparent disturbance of the normal operation of the pendulum.

In the actual arrangement a certain current normally flows in the coils of the correcting magnet. If the clock should tend to run slow the closing of contact O3 or P3 (Ex.22121) increases the current in the magnet and slightly accelerates the rate of swing. Conversely, if the clock tends to run fast the opening of contact Q3 or R3 reduces the current and retards the rate. In each case the alteration in rate is effective during the succeeding hour and produces the necessary correction.

This method has the additional advantage that by altering the setting/

setting of the potentiometer R3 the current in a second winding on the magnet can be varied in order to make fine adjustments to the mean rate. The effect of such adjustments may be observed by throwing the Key No.73. This renders the automatic correction ineffective and earths terminal 40, so that the clock cannot be brought into service until normal conditions are restored. Fig.10 shows the actual arrangement of the magnet system, (79) being the soft iron armature fixed to the pendulum rod and (80) the two magnets.

The effectiveness of the time control as a whole may be judged from Ex.33723 which shows the errors recorded on both clocks during the second week of public operation of the service. (Later adjustments made after the pendulum had settled down to a steady rate have resulted in still better timekeeping, and Ex.33723 is of interest mainly from the aspect of showing the actual effects produced by the method of pendulum control).

Alarm and Stand-by Arrangements

One of the main aims in the design of the clock equipment has been to preserve the continuity of the service. For this reason stand-by equipment, which can be brought into service in an emergency, is provided wherever possible. To avoid unduly complicating the individual mechanism the scheme adopted includes the installation of two duplicate complete clocks.

It is not possible to start up an idle clock, adjust it to give correct time and bring it into service by any simple and rapid means of automatic changeover, since if the running clock should stop there would be no local accurate standard of time. Hence to avoid lengthy interruptions of the service both clock mechanisms are always running and in correct adjustment except when one is temporarily shut down for maintenance. Only one speech amplifier, however, is in operation supplying the service.

The faults which may occur fall into one or other of two broad classes - speech faults or timing faults. The manner in which these are dealt with may be seen from the circuit shown in Ex.22095.

It may be assumed that No.I is the working clock and the functions of relays V and VV and their contacts may be ignored for the/

the moment. Under normal conditions the output to the subscribers' relay sets (terminals (17) and (18)) is taken from terminals (10) and (11) of the Speech Amplifier No.1 via the changeover switch and A1 contact. On the appearance of a fault in the speech amplifier terminal (16) is earthed causing operation of the relays A and AA. Contact AA2 closes operating the alarm bell and A2 connects the mains to the stand-by speech amplifier and to the corresponding indicator lamp. Until the stand-by amplifier warms up no output is available and terminal (16) of this amplifier is also earthed. Since AA1 has closed, the relay B also operates. Contact B1 earths terminal (35) which is connected to the relay sets and causes "Number Unobtainable" tone to be sent out to subscribers. Contact B2 causes the corresponding indicator lamp to light. In the unlikely event of the stand-by amplifier also being faulty or out of service, this condition persists until the prime fault has been cleared. In general, however, as soon as the stand-by amplifier is hot and giving output the earth is removed from its terminal (16), relay B restores and the stand-by takes over the service via the changeover contact A1 which remains operated. Upon manual operation of the changeover switch No.2 becomes the working clock, relays A and AA restore and attention may be directed to clearing the fault on No.1. For adjustment purposes a tumbler switch shunting the mercury contact A2 can be closed to switch on the stand-by speech amplifier if required. Switches are provided to connect loud speakers across the output of either or both clocks for monitoring purposes.

In the event of the working clock developing an excessive time-error a similar series of operations occurs except that terminal 40 receives the earth connection. Under "No time signal" conditions the alarm is given by the earthing of terminal (85), but there is no changeover since, if the indication is genuine and not due to a cause such as a dirty contact, the actual fault will probably be external to and will affect both clocks simultaneously.

It will be apparent that the operations just described can deal only with the small errors registered at the hourly checks. Under abnormal conditions, however, a large error might arise and go undetected until the next check. Thus failure of the pendulum exciter/

exciter lamp or of a valve in the photocell amplifier would permit the oscillator to run uncontrolled, or faulty operation of a clutch mechanism might immediately produce a large error. To deal with this kind of fault advantage is taken of the fact that it is extremely unlikely that such errors would arise in both clocks simultaneously. Thus the fault condition would be indicated by the clocks running out of step. Arrangements are made to maintain a continuous circuit from earth to terminal 30, whereby the slow to release relay VV is held operated, as long as the two clocks are in step. In the out-of-step condition this relay drops out followed, if the circuit interruption is long enough, by the similar relay V which is not self-resetting. The second contact of V rings the alarm bell, the third lights an alarm lamp and the fourth causes relay B to operate whereby the service is discontinued and "Number Unobtainable" tone is sent out. There is no changeover since there is no automatic means of telling which clock is at fault. An out-of-step alarm cut-out key is provided for resetting after clearing the fault and also to prevent an alarm condition arising if the stand-by clock is deliberately stopped for any reason. This facility is provided with the aid of distributors associated with each cam shaft, two of which are shown (95) in Fig. 5. The number of contacts on each is the same as the number of teeth on the corresponding ratchet wheel. As shown in Ex.22119, corresponding contacts on the two sets of distributors are wired together and the rotating brushes are connected so that a continuous circuit involving all these distributors exists as long as the two clocks are in step. The use of two slow-release relays in tandem in the alarm circuit is necessary to avoid false operation due to the unavoidable momentary interruptions in the circuit when the cam-shafts move from one step to the next.

General Layout of Installation

The whole of the equipment so far described is installed in a special room adjoining the Power Room at Holborn Exchange. On one side of the room are the amplifiers and control racks and the pendulum associated with No.1 clock. On the other side of the room are the two clock mechanisms and monitoring loudspeakers and on the end wall is mounted the pendulum associated with No.2 clock.

The/

The amplifier and control racks are shown in Fig.13. From left to right of the photograph the first two bays are the two 4 ~ equipments. From top to bottom the separate units are, respectively: Photocell amplifier, Rotor current and valve anode current meter panel, Three-phase oscillator and power amplifier, Power unit and, finally, Voltage stabiliser unit. The third bay contains at the top, the two timing relay sets, below these the D.C. distribution panel then the A.C. distribution panel and, finally, the main switches. At the top of the right-hand rack are the two speech amplifiers, below these the changeover and main alarm panel and at the bottom the two power units for the speech amplifiers. Apart from the power leads all connections to points external to the clock room are made to a tag strip mounted on top of the third rack.

Fig.14 shows the apparatus racks on the left and the two clock mechanisms on the right. In the background can be seen one of the monitoring loudspeakers and the pendulum cabinet for No.2 clock. The clock mechanisms are carried on substantial tables and protected from dirt by glass-panelled covers. Leads from the racks to the mechanism are taken via chases cut in the floor.

It has been found from experience that the gas-filled relays in the pendulum drive circuit function erratically at extremes of ambient temperature. For this reason the artificial ventilation and heating arrangements are arranged to permit thermostatic control of the room temperature at a few degrees below the temperature within the pendulum cabinets.

Power Supplies

The main requirements of the power supplies are simplicity and reliability. All the D.C. equipment, i.e. the rotors of the synchronous motors, the relays, the pendulum control, shutter and clutch magnets and the alarm lamps and bells are worked from the 50 V exchange battery. No stand-by is provided since a failure of this supply is most unlikely and, in any case, would prevent any calls being made to the clock. The total consumption is about 250 W.

The amplifiers, exciter lamps and pendulum heaters are worked from the A.C. public supply mains and together consume about 1800 W

under/

under normal conditions. In this case a stand-by supply is necessary and is provided by two motor generator sets of 2.5 K.V.A. capacity. One of these is always running light on the exchange battery. In the event of the mains voltage - normally 200 - falling below 170 the generator takes over the load. The load automatically returns to the mains when the voltage of the latter exceeds 190. The control gear is normal and is connected according to diagram Ex.22306. The operation of the equipment was checked by taking oscillograms of the voltage across one of the mains transformers when the normal supply was artificially interrupted and then restored. Two such oscillograms are shown in Fig.15. Repeated tests under artificial fault conditions have shown that changeover and restoration of the power supply occurs smoothly and without introducing errors of timekeeping.

Distribution of the Service

Access to the clock is obtained at the normal rates applying to calls from the subscriber's exchange to exchanges within the London 5 mile circle.

Few features of the distribution of the service call for special comment. The relay sets at present permanently installed can cater for 100 simultaneous calls. Individual calls are routed to these sets in the normal manner.

The speech output is taken across the 1 ohm resistance connected across the secondary winding of the second output transformer. Although incorporated primarily in order to maintain a constant volume level this resistance also introduces sufficient attenuation between subscribers who happen to be simultaneously connected to frustrate attempts at conversation.

To avoid difficulties in switching, whether carried out by means of D.C. or voice-frequency currents, a 2 mF condenser and a 200 ohms resistance are included in both leads between each relay set and the output transformer.

To avoid congestion it is necessary to limit the time during which a subscriber can remain connected. An automatic forced release is therefore applied which, according to the instant when the connection is established disconnects the call after 90-180 seconds. In the worst/

worst case 8 complete announcements will thus be heard.

The occurrence of a major alarm condition, i.e. one necessitating temporary interruption of the service, causes the operation of relays which disconnect all subscribers from the clock output and send out "Number Unobtainable" tone. During such periods non-metering conditions apply.

It was expected that immediately after the official opening of the service by the Astronomer Royal on 24th July 1936, and particularly after a transmission of the clock in the Second News Bulletin broadcast by the B.B.C. very heavy curiosity traffic would occur. Precautions were taken to deal with this. In the first place, the forced release was set to operate after $\frac{2}{3}$ of the normal period had elapsed. Secondly, calls made through manual exchanges were connected direct to the output transformer via special reserved junctions to avoid using the ordinary relay sets and finally, calls in excess of these provisions were routed to a special number on Mayfair exchange and dealt with by means of temporarily installed amplifiers and relay sets. By this means the maximum number of calls simultaneously connected rose to 280. The introduction of the service in the late afternoon (4.30 p.m.) avoided much of the inconvenience to normal traffic that would otherwise have arisen.

Apart from the first week of public operation of the service when there was a large amount of curiosity traffic the number of calls per week has been about 200,000 with a rising tendency as shown by diagram Ex.33815. Total figures at various dates during the first six months of public service are shown in Table 5.

Table 5/

Table 5 Number of calls made to Speaking Clock in first six months of operation

Date	Time	Total Calls	Date	Time	Total Calls
25. 7.36	10.0 a.m.	36,867	24.10.36	8.0 a.m.	2,919,548
31. 7.36	8.0 a.m.	353,581	31.10.36	" "	3,136,375
"	4.30 p.m.	381,006	7.11.36	" "	3,355,607
1. 8.36	8.0 a.m.	398,158	14.11.36	" "	3,590,749
8. 8.36	" "	597,633	21.11.36	" "	3,812,517
15. 8.36	" "	810,218	28.11.36	" "	4,044,314
22. 8.36	" "	1,020,809	5.12.36	" "	4,269,883
29. 8.36	" "	1,223,289	12.12.36	" "	4,507,165
5. 9.36	" "	1,425,875	19.12.36	" "	4,751,778
12. 9.36	" "	1,629,006	26.12.36	" "	4,957,783
19. 9.36	" "	1,836,740	2. 1.37	" "	5,194,298
26. 9.36	" "	2,049,623	9. 1.37	" "	5,439,780
3.10.36	" "	2,258,422	16. 1.37	" "	5,693,912
10.10.36	" "	2,489,331	23. 1.37	" "	5,951,001
17.10.36	" "	2,705,263			

Attachments

Photographs, oscillograms etc., Figs. 1-15.

Diagrams Ex. Nos. 22018, 22069-71, 22095, 22119, 22121, 22135, 22139, 22285-87, 22301, 22305-6, 33721-23, 33815.

CONCLUSIONS

A Speaking Clock equipment has been designed and constructed by the Research Branch and installed in the Holborn Telephone Exchange building. The installation includes two duplicate mechanisms and driving equipments, with provision for automatic changeover, in order to preserve continuity of the service during maintenance periods or fault conditions.

Announcements/

Announcements of the time are made every ten seconds and each is correct within ± 0.1 second.

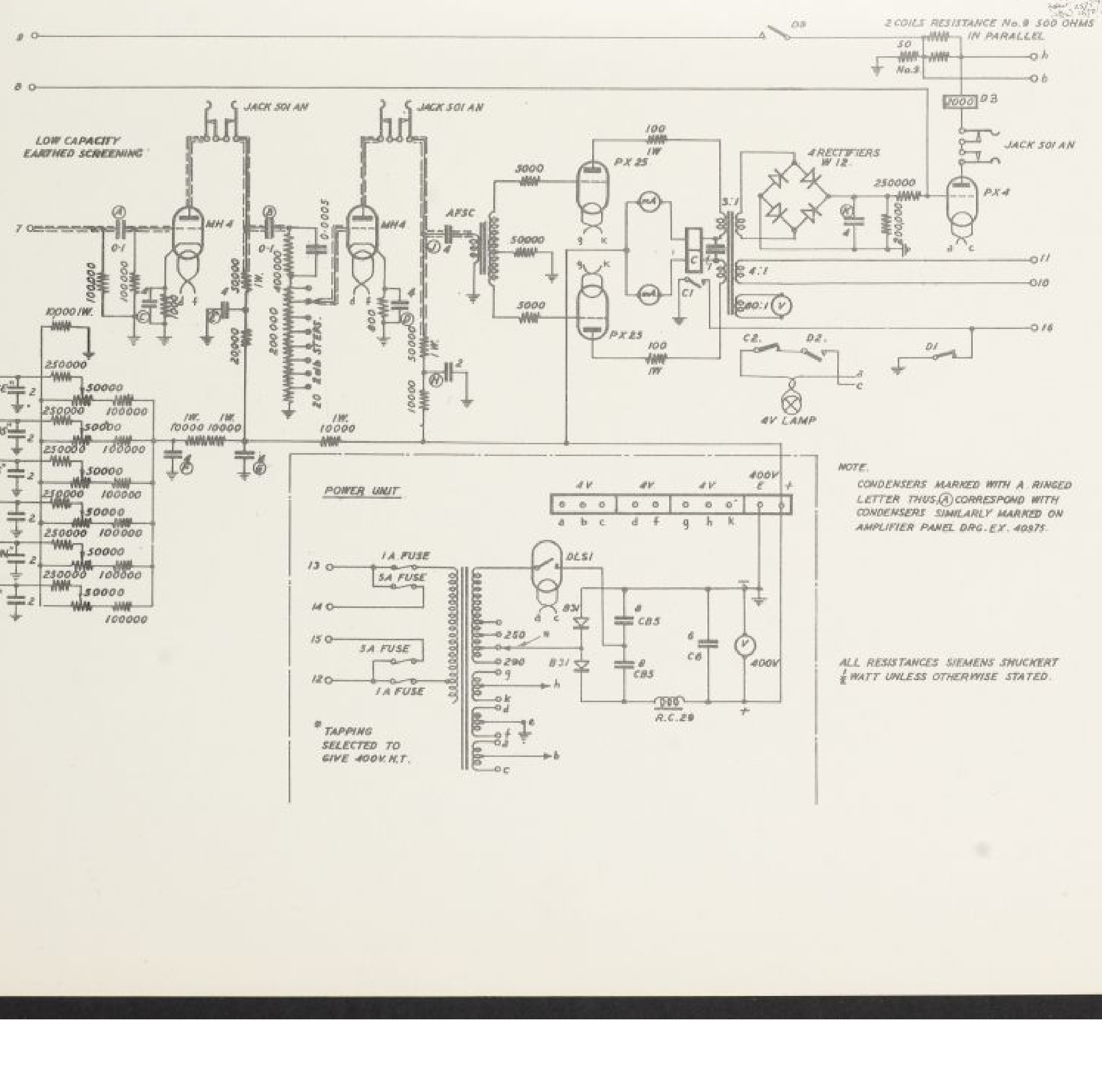
Distribution of the service is by means of relay sets installed in Tandem Exchange which allow up to 100 simultaneous calls to be connected to the clock.

The service was opened by the Astronomer Royal on 24th July 1936 and during the following week nearly 400,000 calls were made to the clock. Subsequent traffic has been at the rate of approximately 200,000 calls per week.

POST OFFICE ENGINEERING RESEARCH STATION DOLLIS HILL LONDON N.W.2 CASE No. — DATE. 24.10.35.

SPEAKING CLOCK SPEECH AMPLIFIER.

EX. 22018 C



NOTE.
CONDENSERS MARKED WITH A RINGED LETTER THUS (A) CORRESPOND WITH CONDENSERS SIMILARLY MARKED ON AMPLIFIER PANEL DRG. EX. 40975.

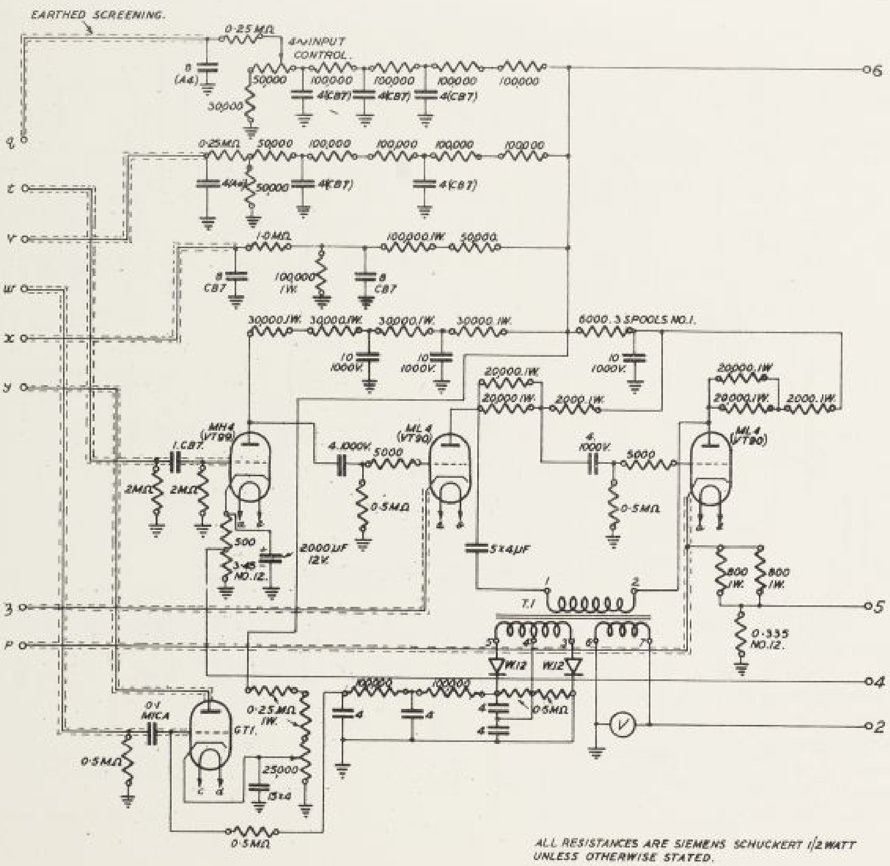
ALL RESISTANCES SIEMENS SHUCKERT ½ WATT UNLESS OTHERWISE STATED.

CLOCK SPEAKING.

PHOTOCELL AMPLIFIER 4 CYCLES PER SEC.

EX. 22069.

INITIALS. J.S.F.



ALL RESISTANCES ARE SIEMENS SCHUCKERT 1/2 WATT UNLESS OTHERWISE STATED.

POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE NO. DATE 27.11.35

A–VALVES ML4 (VT90) WERE AC/P & MH4 (VT99) WAS AC/HL. 2-2-37.

Post Office Engineering Research Station, Dollis Hill, London N.W.2 Case No Date 25.11.35

CLOCK, SPEAKING

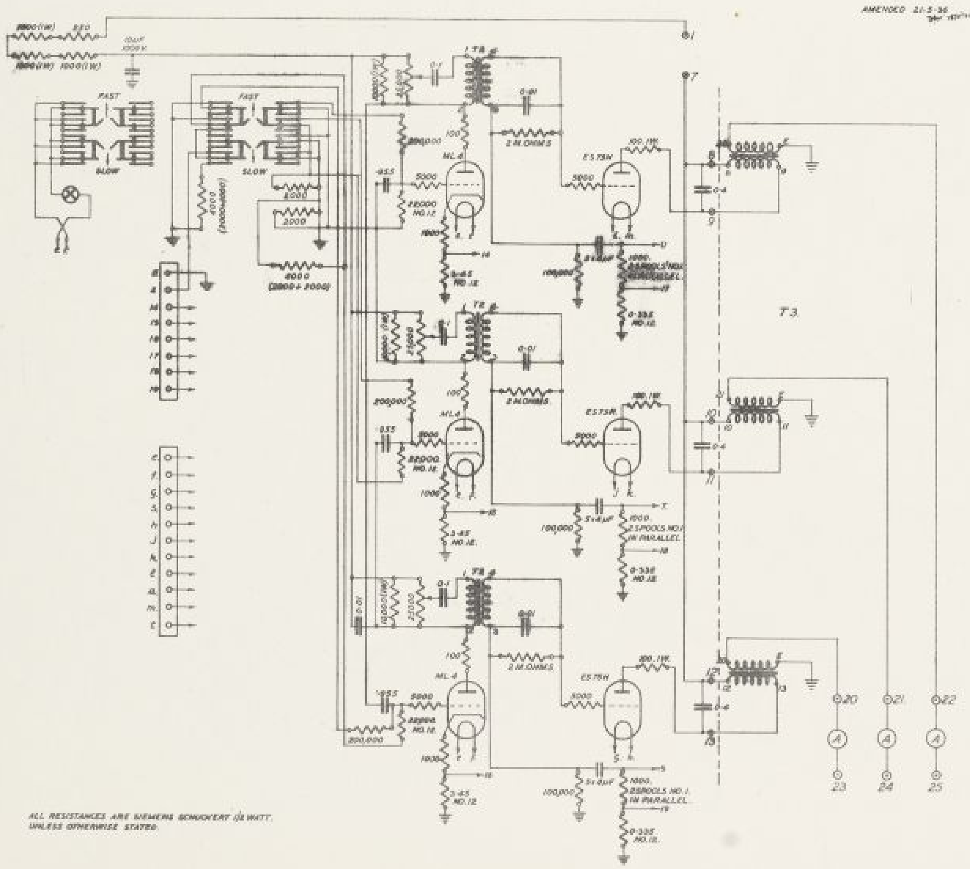
3 PHASE AMPLIFIER

EX.22070.C.

INITIALS J.S.H.

AMENDED 12.12.35.

AMENDED 21.5.36



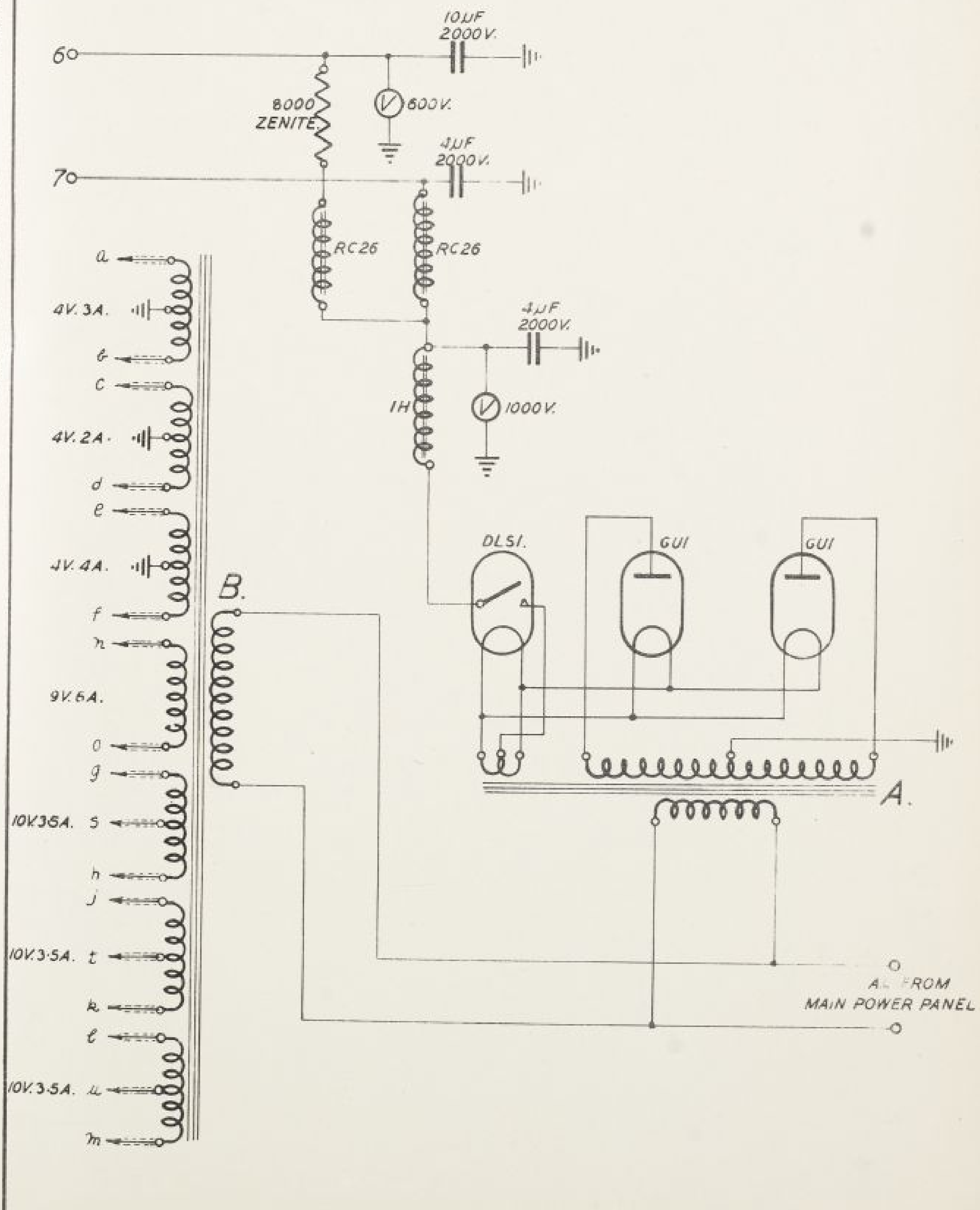
ALL RESISTANCES ARE SIEMENS SCHUCKERT 1/2 WATT. UNLESS OTHERWISE STATED.

CLOCK SPEAKING.

POWER UNIT FOR 4 CYCLE AMPLIFIER.

EX. 22071

INITIALS...J.S.F./ [handwritten initials] 28/11/35



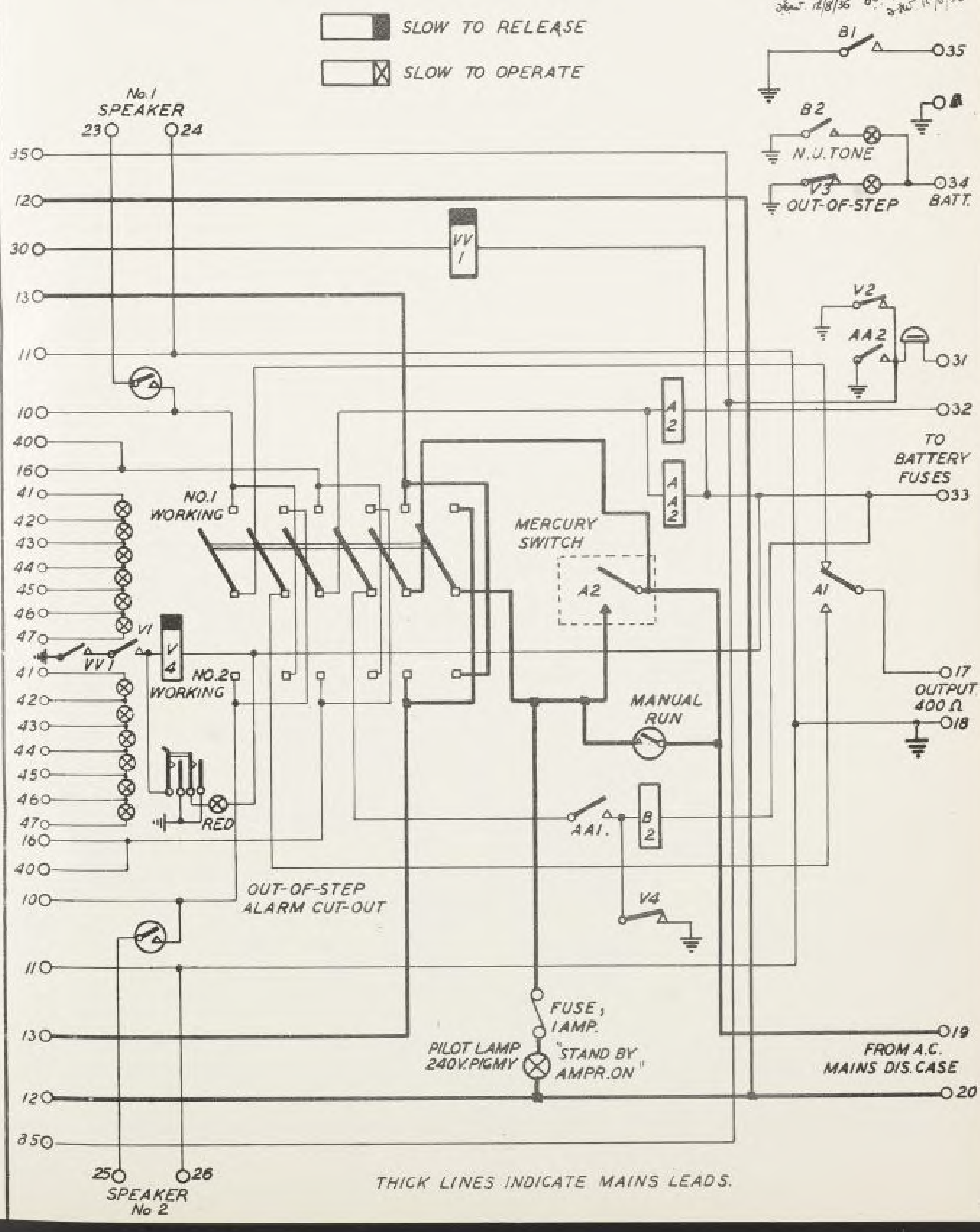
POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE NO. DATE 3.12.35.

EX. 22095.E

INITIALS... J.S.F./
MODIFIED 6-2-36.
" 5.5.36

CLOCK, SPEAKING

SPEECH AMPLIFIER SWITCH PANEL.



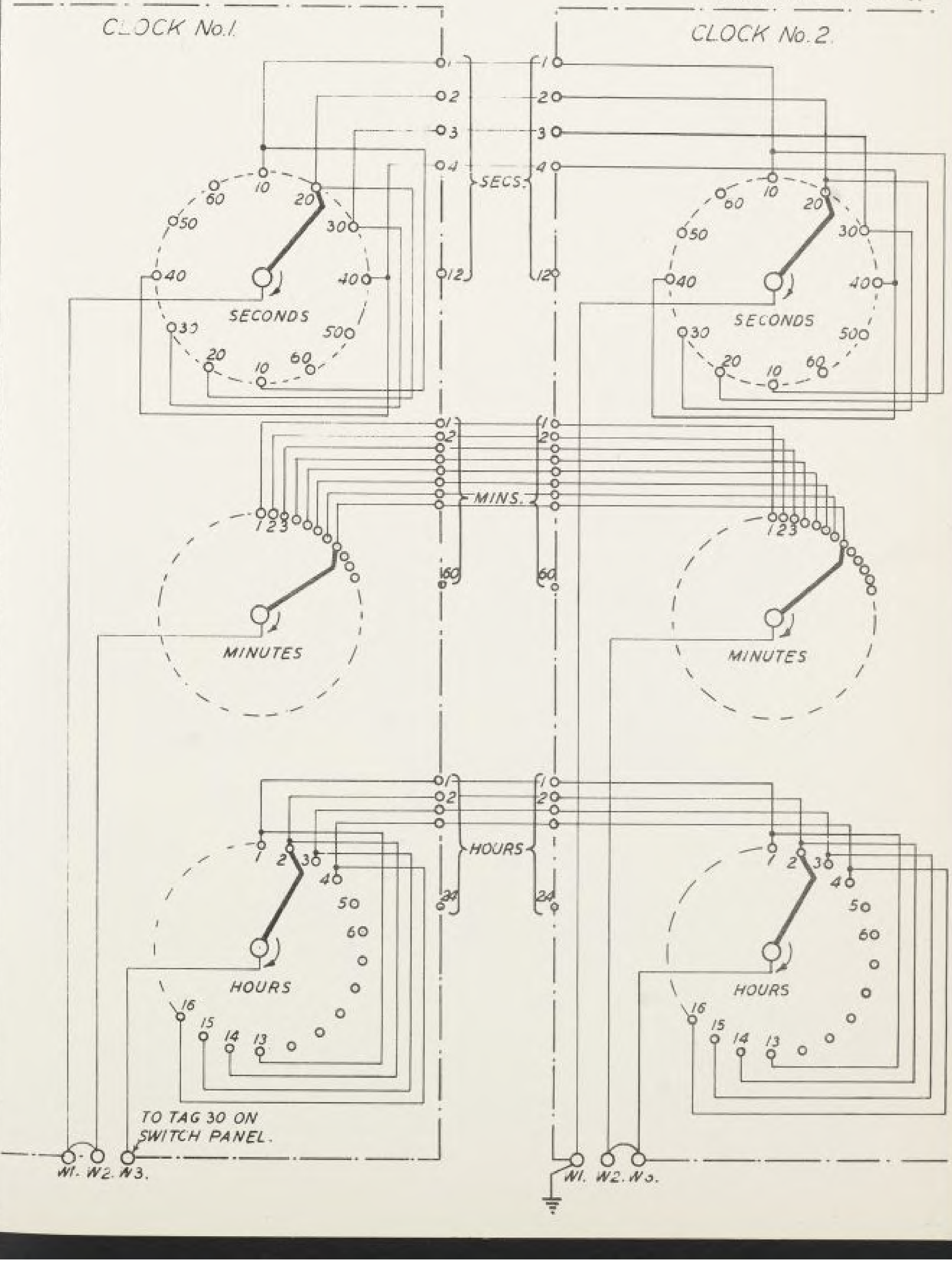
THICK LINES INDICATE MAINS LEADS.

CLOCK SPEAKING.

SYNCHRONISING CIRCUIT

EX. 22119. B.

INITIALS... J.S.F./J.E.W.
MODIFIED 6·5·36 J.E.W. 7/5/36 11/12/36
MODIFIED. 3-12-36. J.E.W.



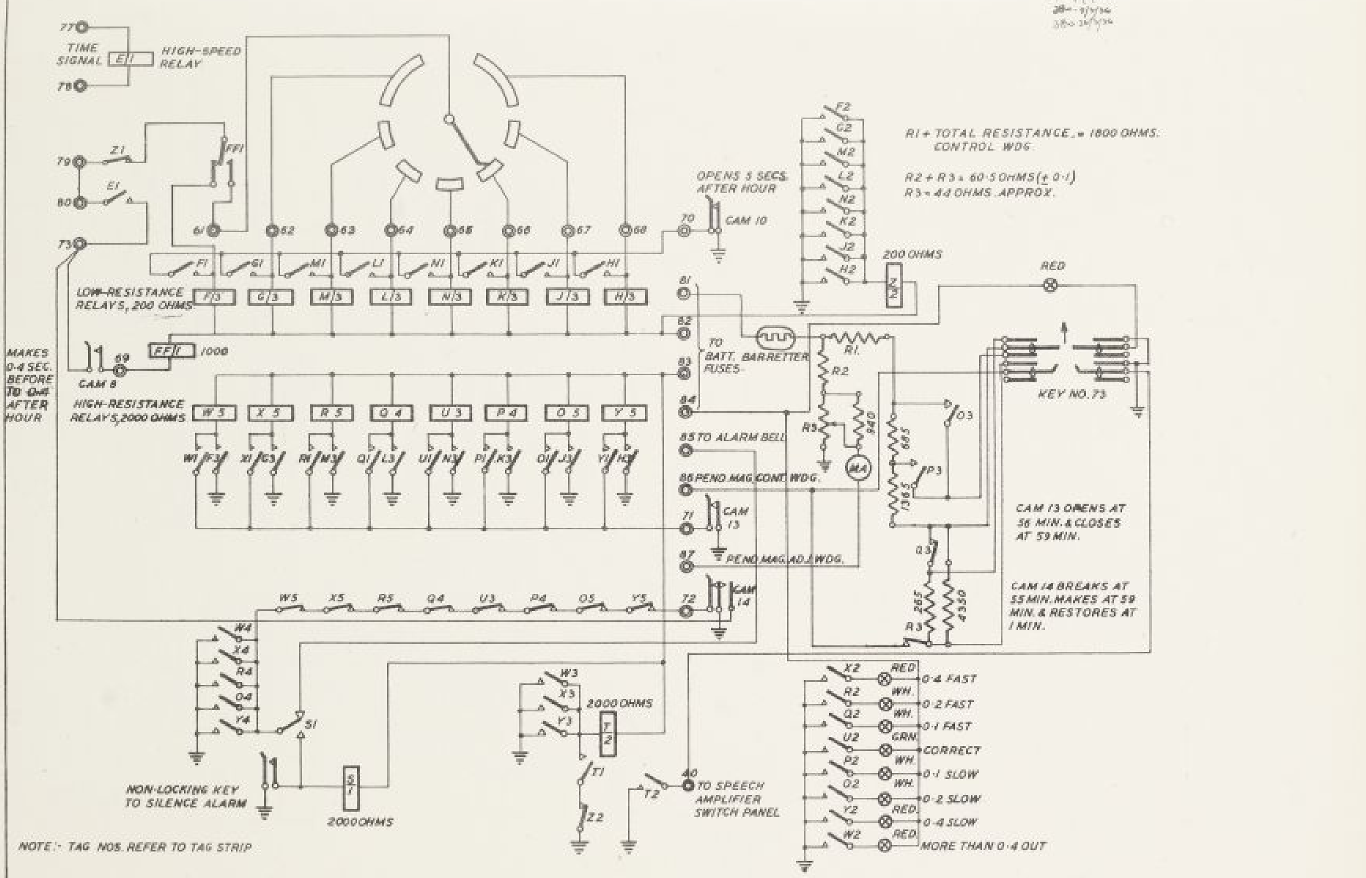
POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE No. — DATE. 7-2-36

POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE NO.— DATE.10.2.36.

CLOCK SPEAKING.

CORRECTING CIRCUIT.

EX. 22121 C.
INITIALS J.S.F.



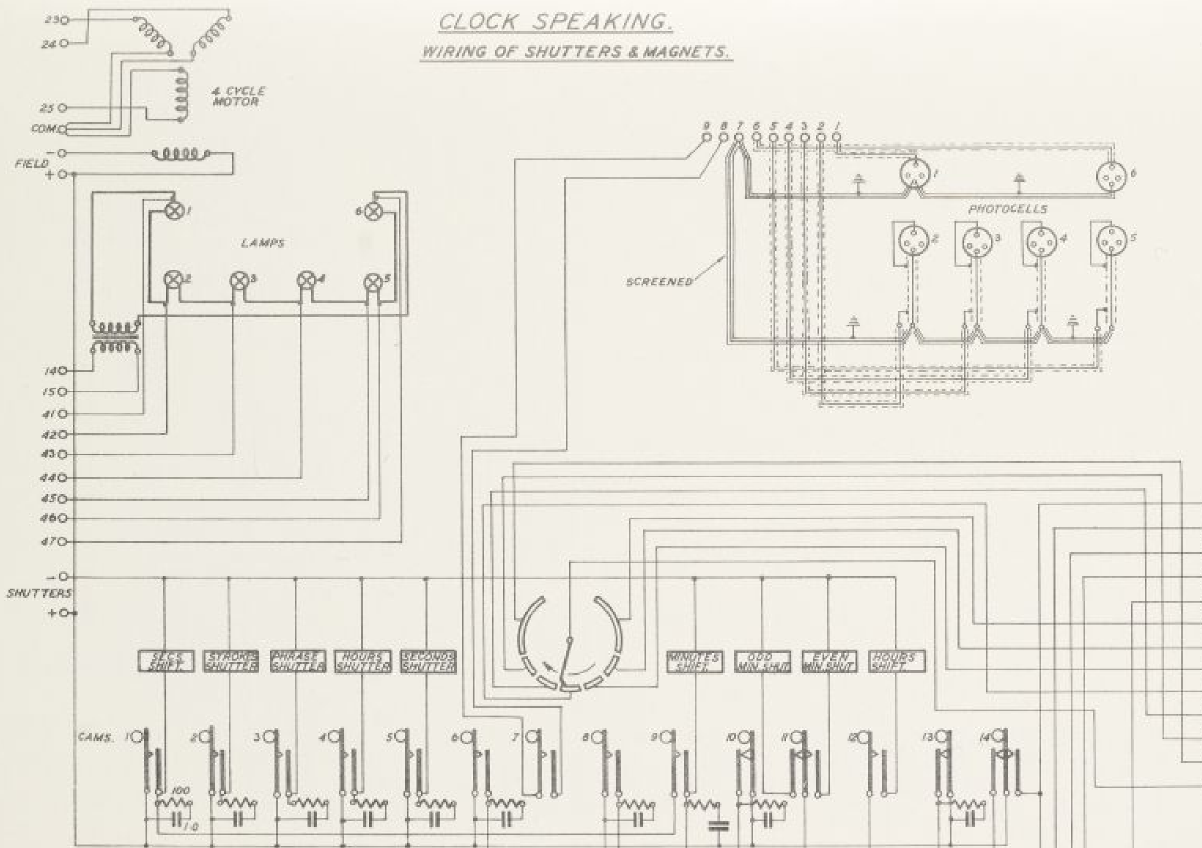
NOTE:- TAG NOS. REFER TO TAG STRIP

CLOCK SPEAKING.

WIRING OF SHUTTERS & MAGNETS.

EX. 22135.A

INITIALS. J.S.F.



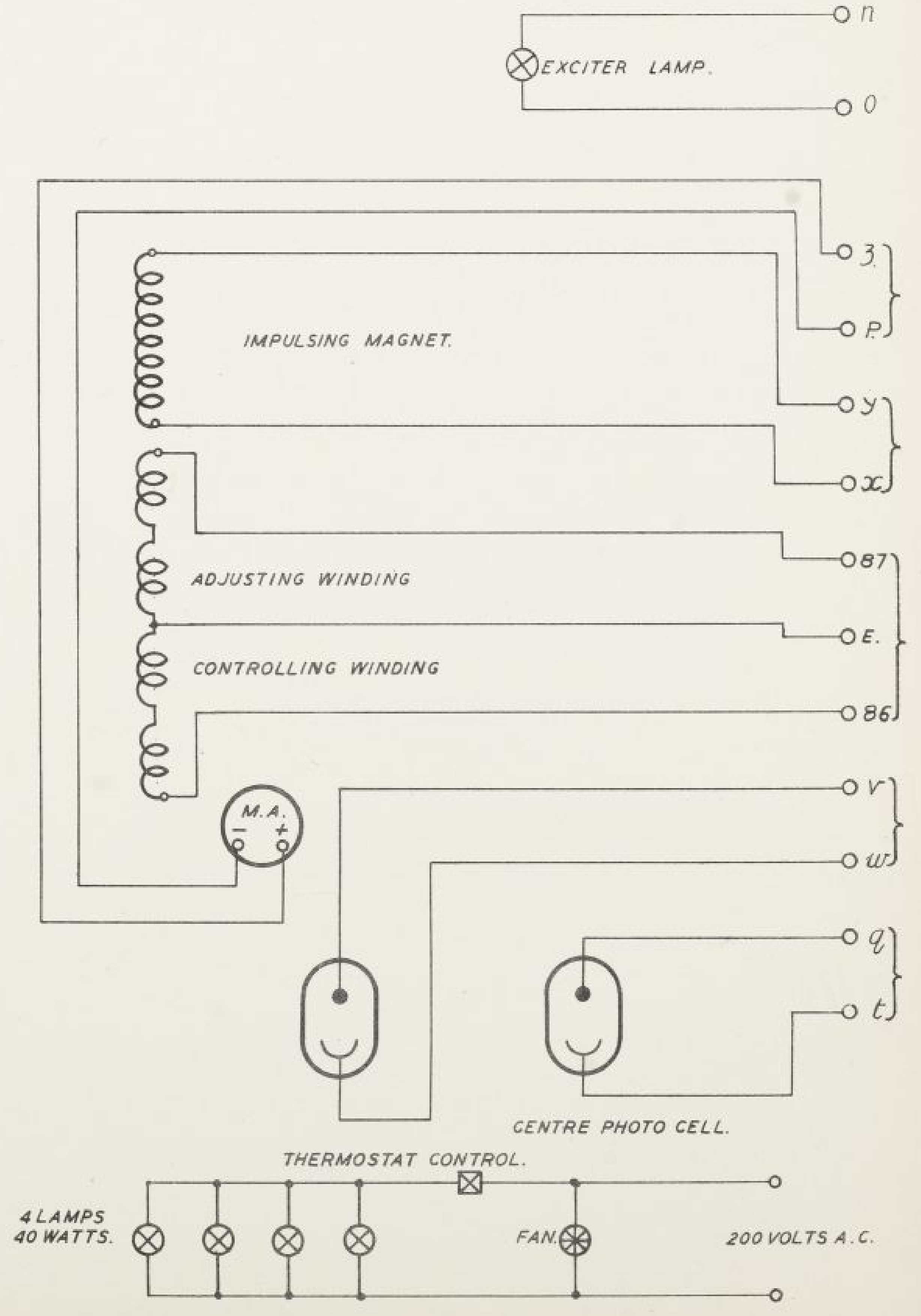
POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE NO.—— DATE 9-4-36

CLOCK SPEAKING.

EX.22139.

INITIALS...J.S.F./

WIRING OF PENDULUM CASE.



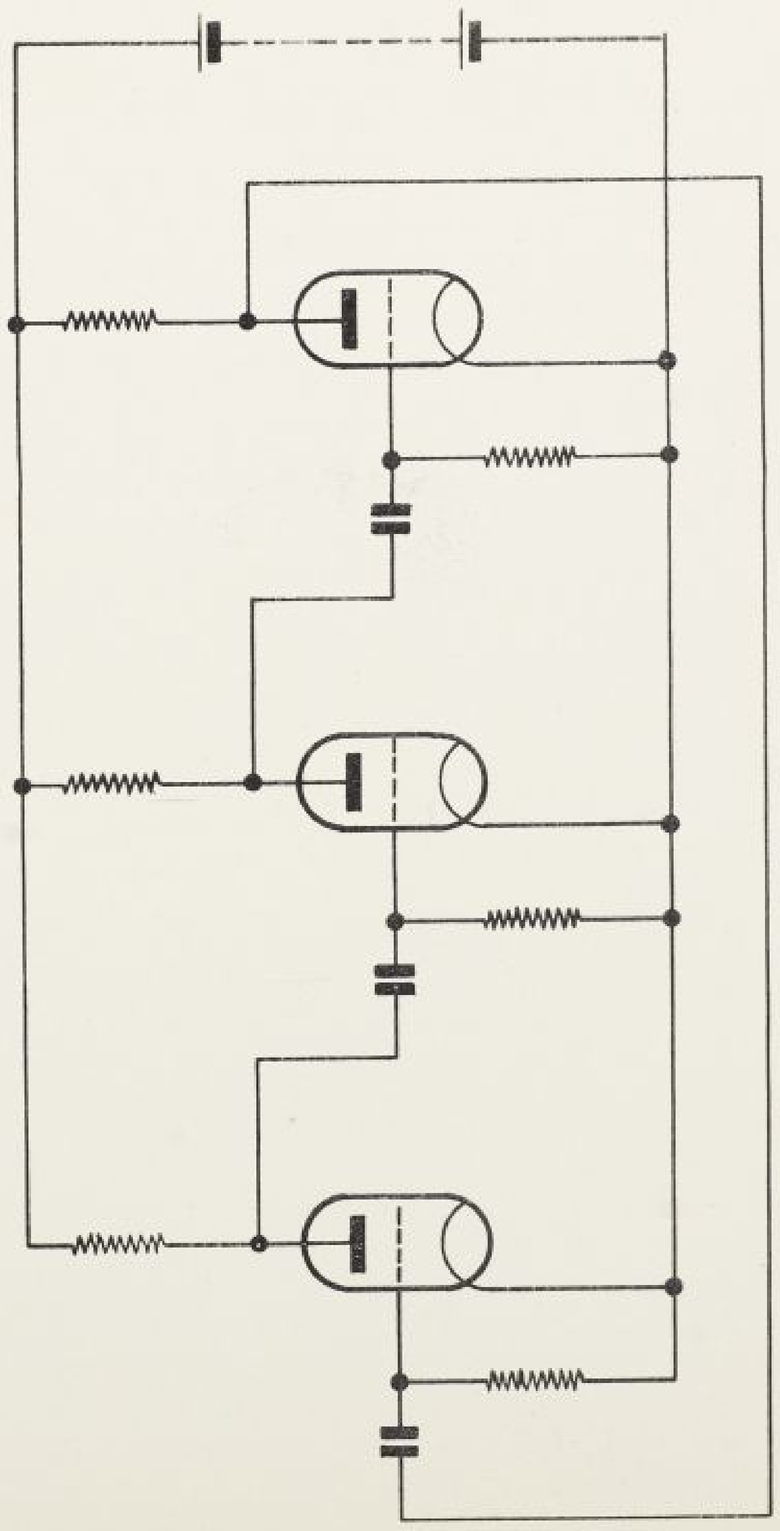
POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE No. — DATE. 26·3·36

ISSUE: A. TEMPERATURE CONTROL ADDED. 14.8.36.
B. EXCITER LAMP ADDED. 17.10.36.

BASIC CIRCUIT OF 3-PHASE OSCILLATOR.

EX. 22285.

INITIALS. gas. / G.A.S.



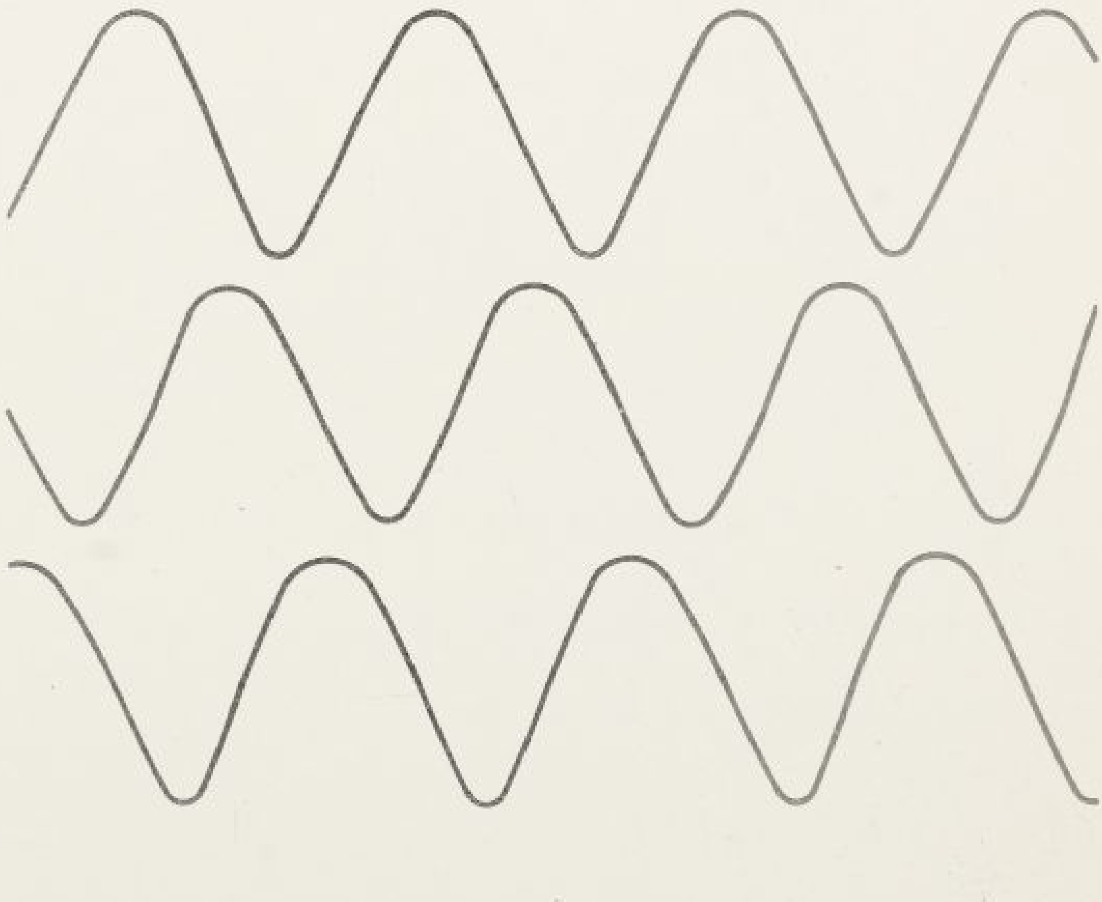
DATE. SEPT. 36.

POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE No.

CLOCK, SPEAKING. 3 PHASE AMPLIFIER. OUTPUT WAVE-FORM.

EX. 22286

INITIALS... [illegible]/E.P.W.

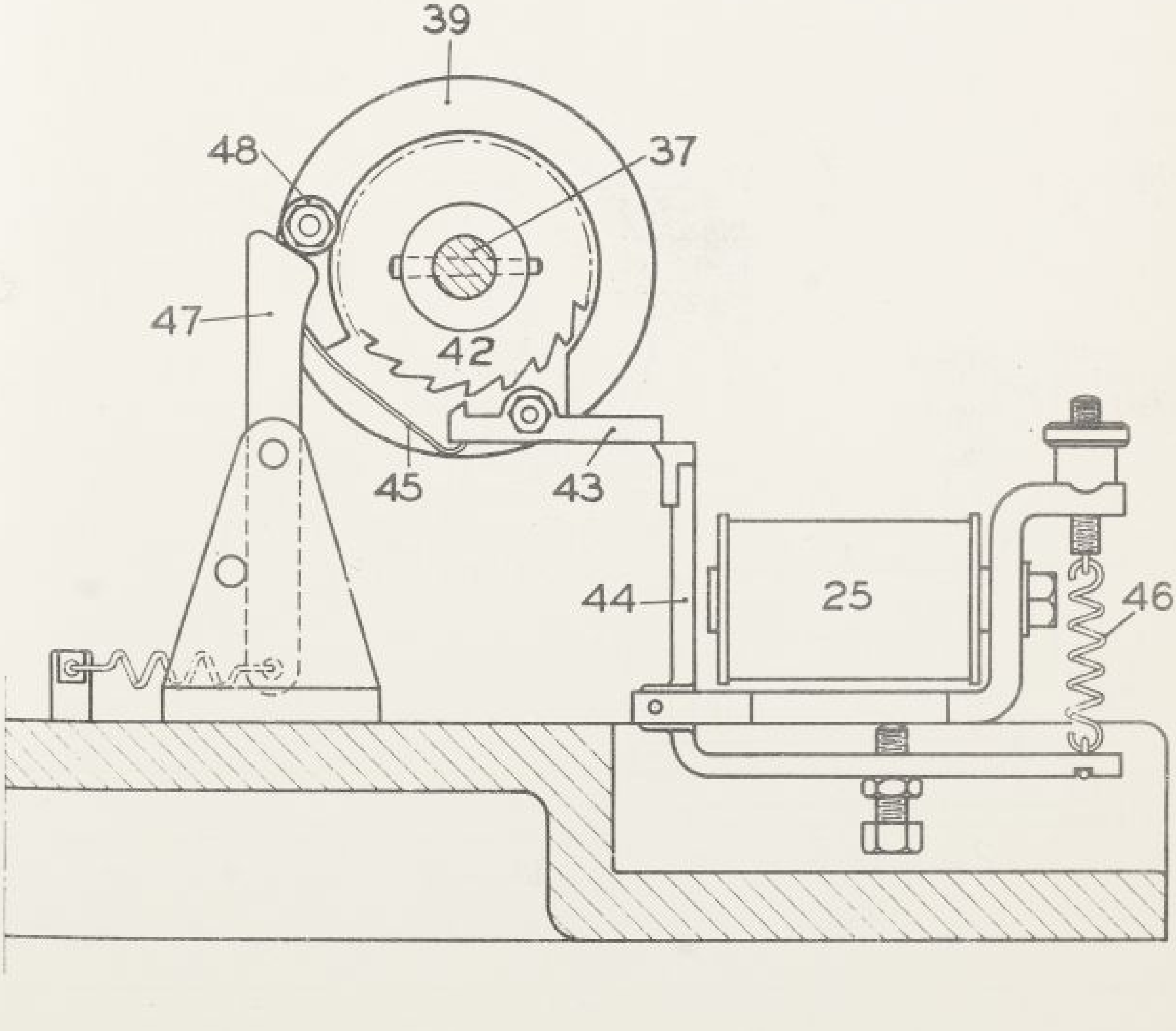


POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE No. DATE: 29-9-36

CLOCK, SPEAKING. CLUTCH MECHANISM. EX. 22287

INITIALS...

[redacted]

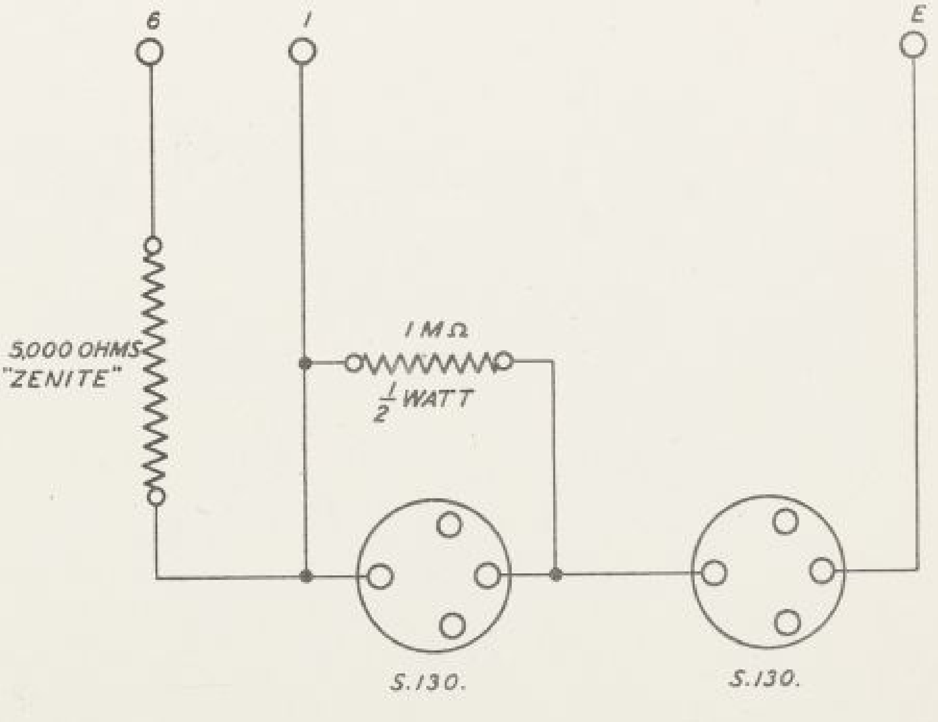


POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE NO. DATE. 29-9-36

CLOCK, SPEAKING
VOLTAGE STABILISER PANEL.
CIRCUIT DIAGRAM.

EX. 22301.

INITIALS... T.G.R. J.B.W.

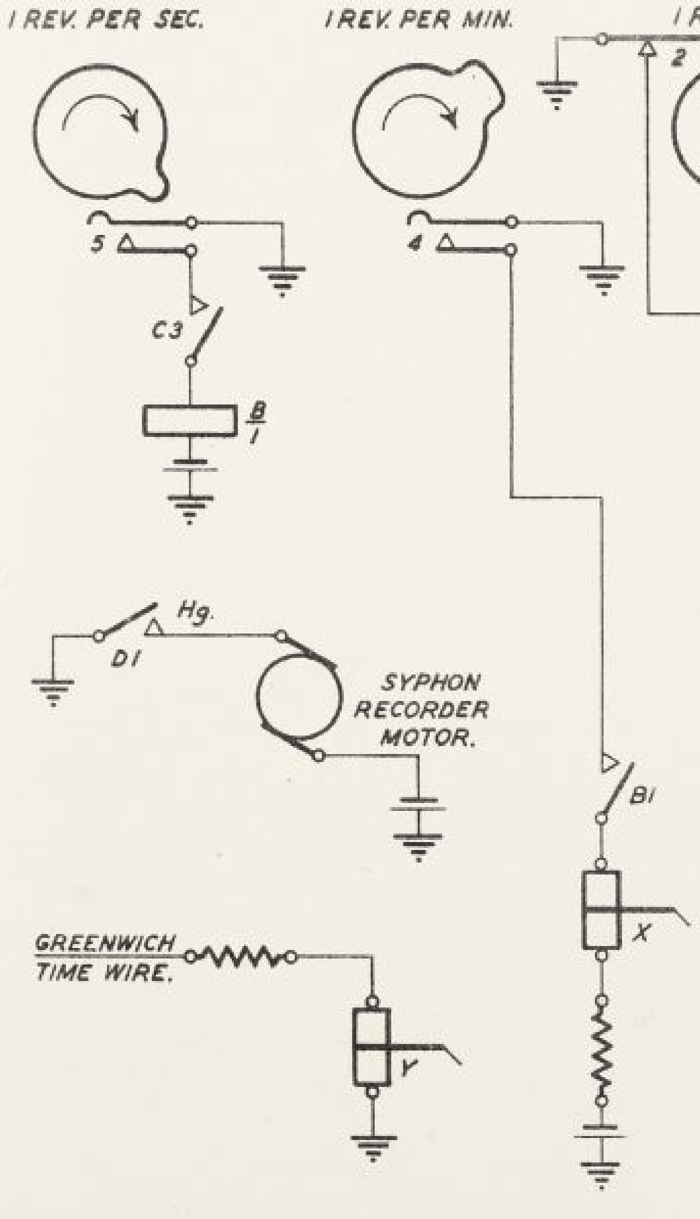


POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE No. DATE. 12·10·36

CLOCK, SPEAKING
PENDULUM TIMING CIRCUIT.

EX. 22305

INITIALS. J.G.D. / E.A.S.



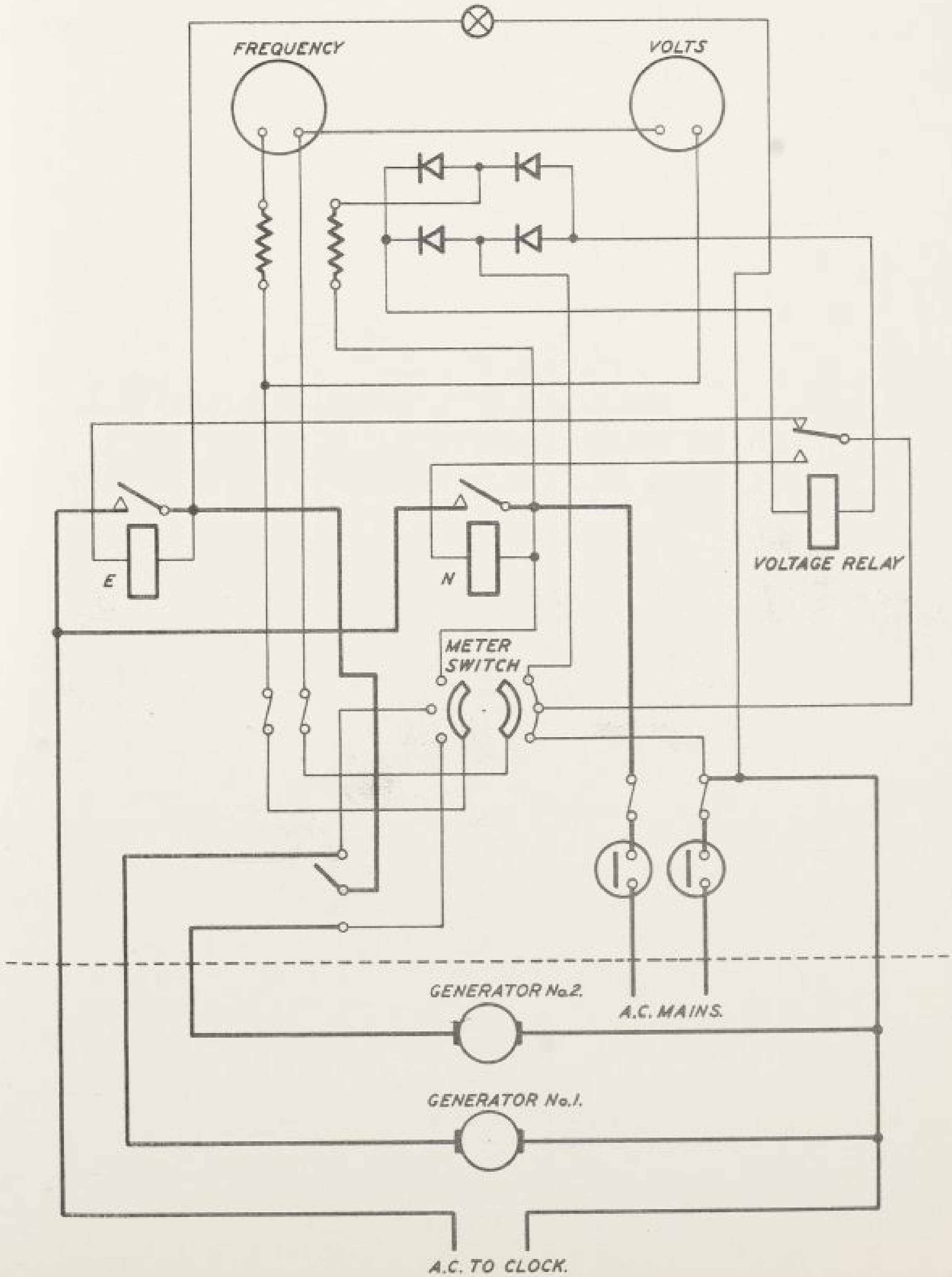
POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE No. 8627. DATE. 12·10·36

POST OFFICE ENGINEERING RESEARCH STATION, DOLLIS HILL, LONDON, N.W.2. CASE NO. DATE. 15.10.36

CLOCK, SPEAKING.
A.C. GENERATOR CONTROL PANEL.

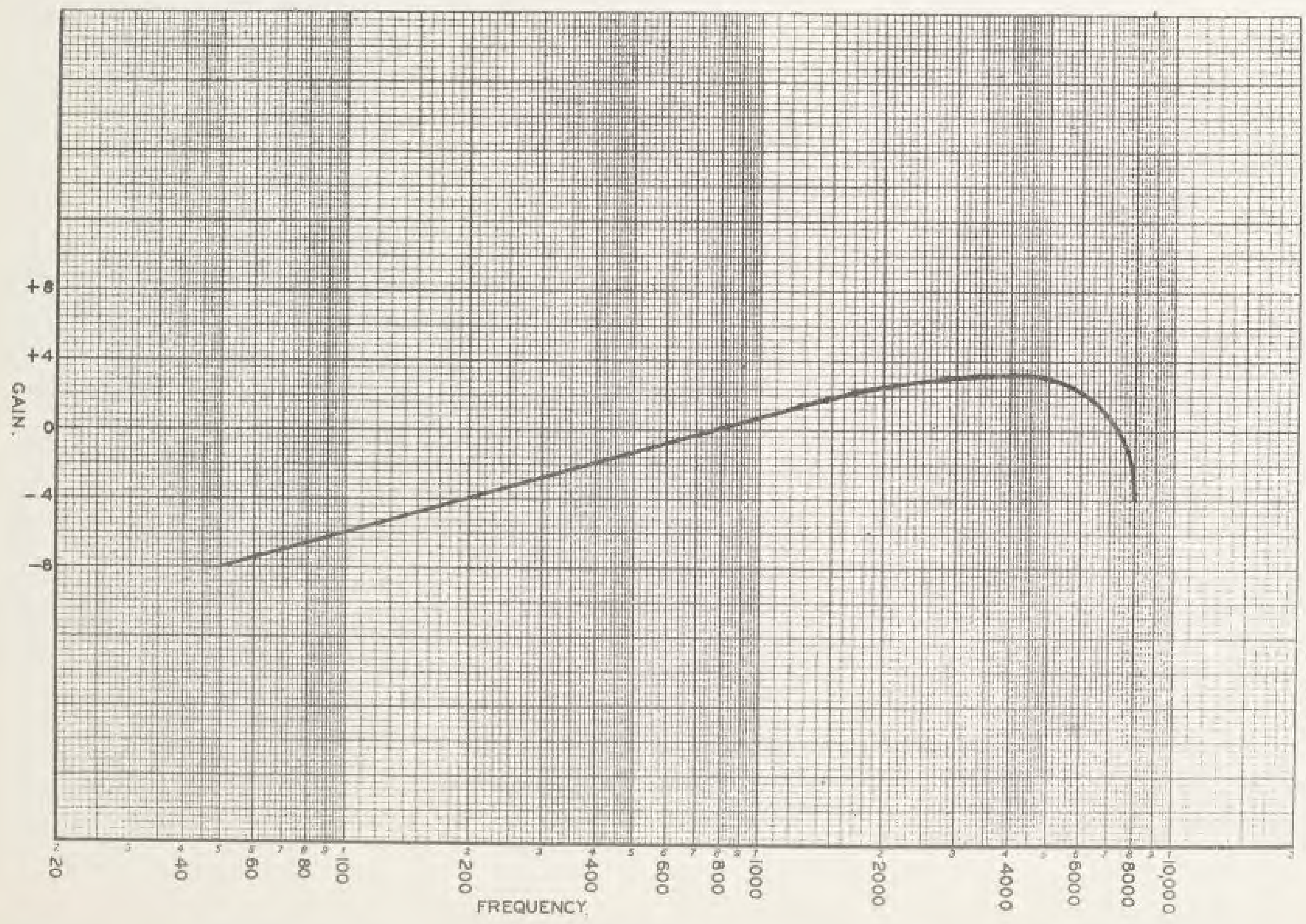
EX. 22306.

INITIALS...



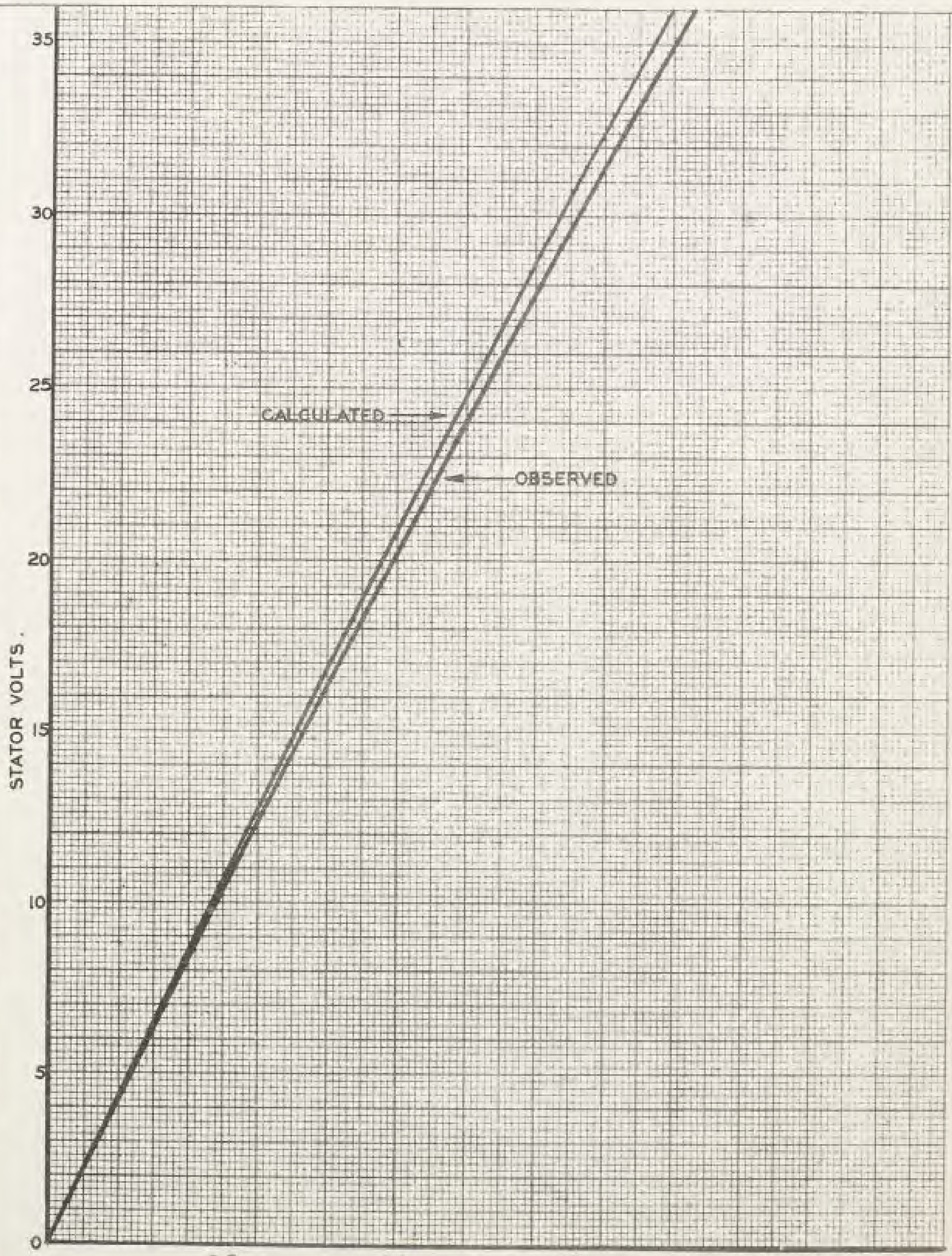
CLOCK, SPEAKING. FREQUENCY
CHARACTERISTIC OF SPEECH AMPLIFIER.

EX. 33721
Initials J.S.F./
Date 29-9-36



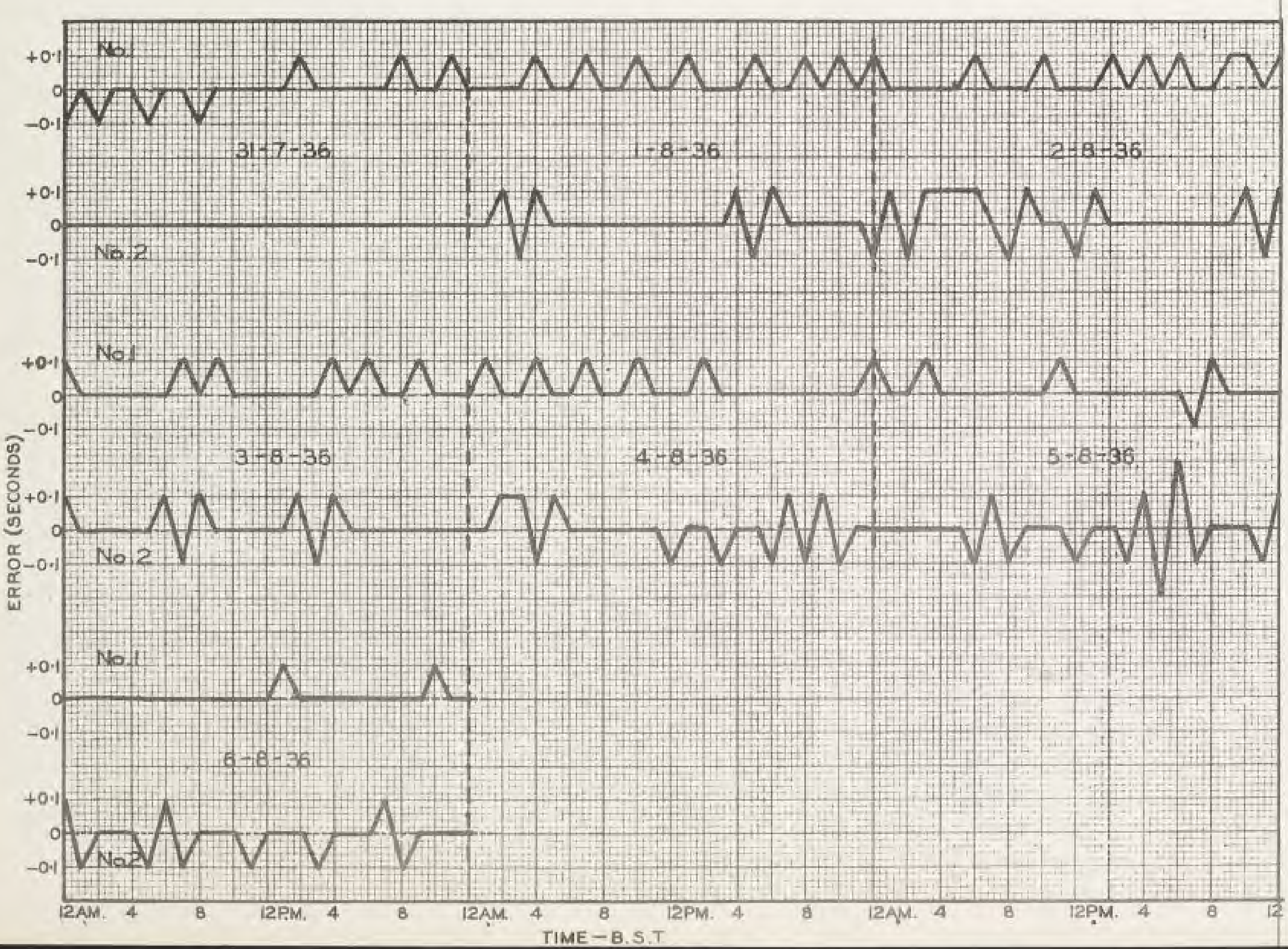
CLOCK, SPEAKING. 4 ~ MOTOR. OPEN CIRCUIT STATOR VOLTS v ROTOR CURRENT.

EX.33722.
Initials J.S.F./ E.B.
Date 29·9·36



P.O. Engineering Research Station, Dollis Hill, LONDON, N.W.2.

CLOCK, SPEAKING HOURLY ERRORS DURING WEEK 31-7-36 TO 6-8-36



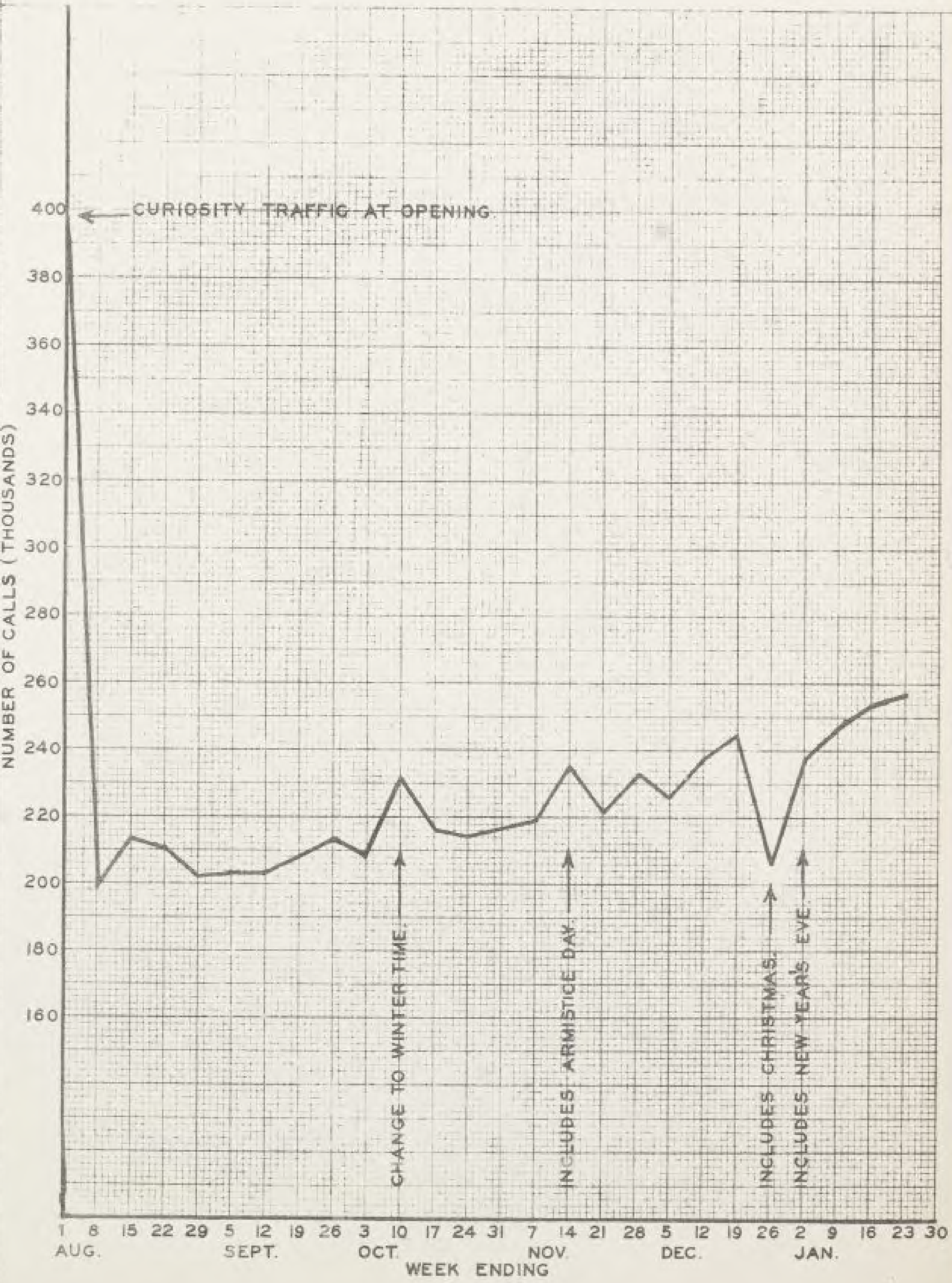
EX. 33723

Initials J.S.F.

Date 29·9·36

CLOCK, SPEAKING.
WEEKLY CALLING RATE.

EX 33815
Initials E.A.S.
Date 26-1-37.



P.O. Engineering Research Station, Dollis Hill, LONDON, N.W.2. Case No. 8627

CLOCK, SPEAKING. "EVEN MINUTES" DISC AND OPTICAL UNIT.

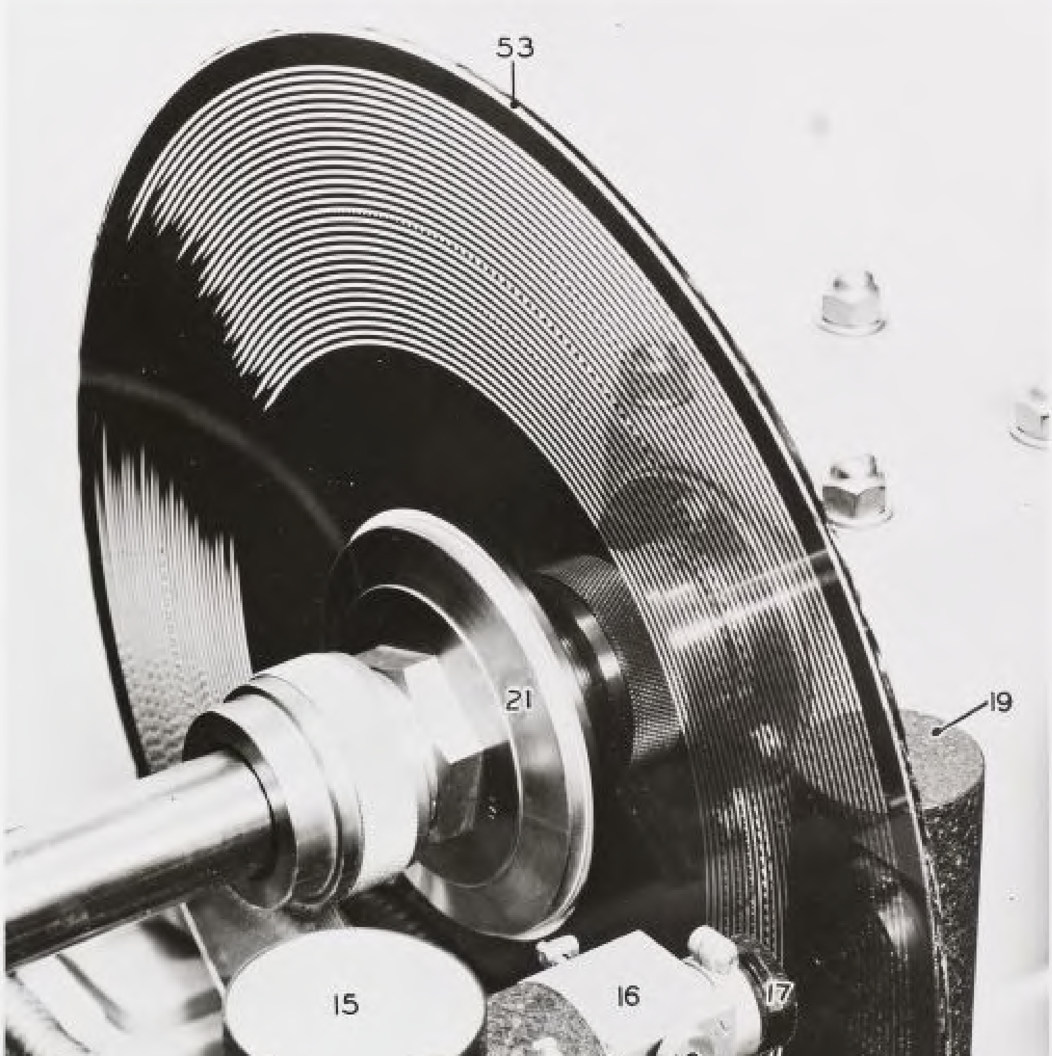
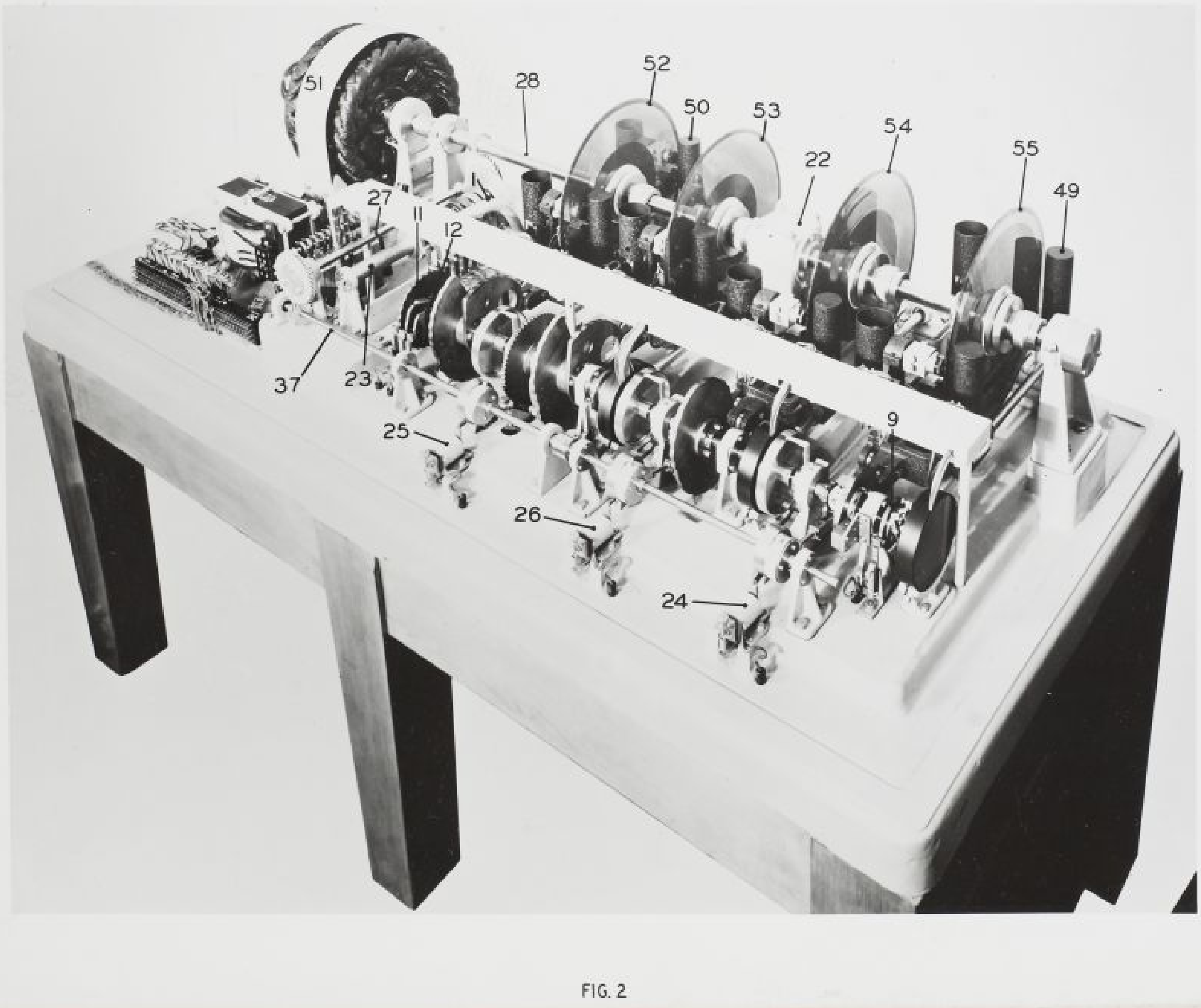


FIG. 1



CLOCK, SPEAKING. CLOCK MECHANISM.

FIG. 2

RESEARCH REPORT No. 8627

CLOCK, SPEAKING. MAIN CONTACT CAM SHAFT.

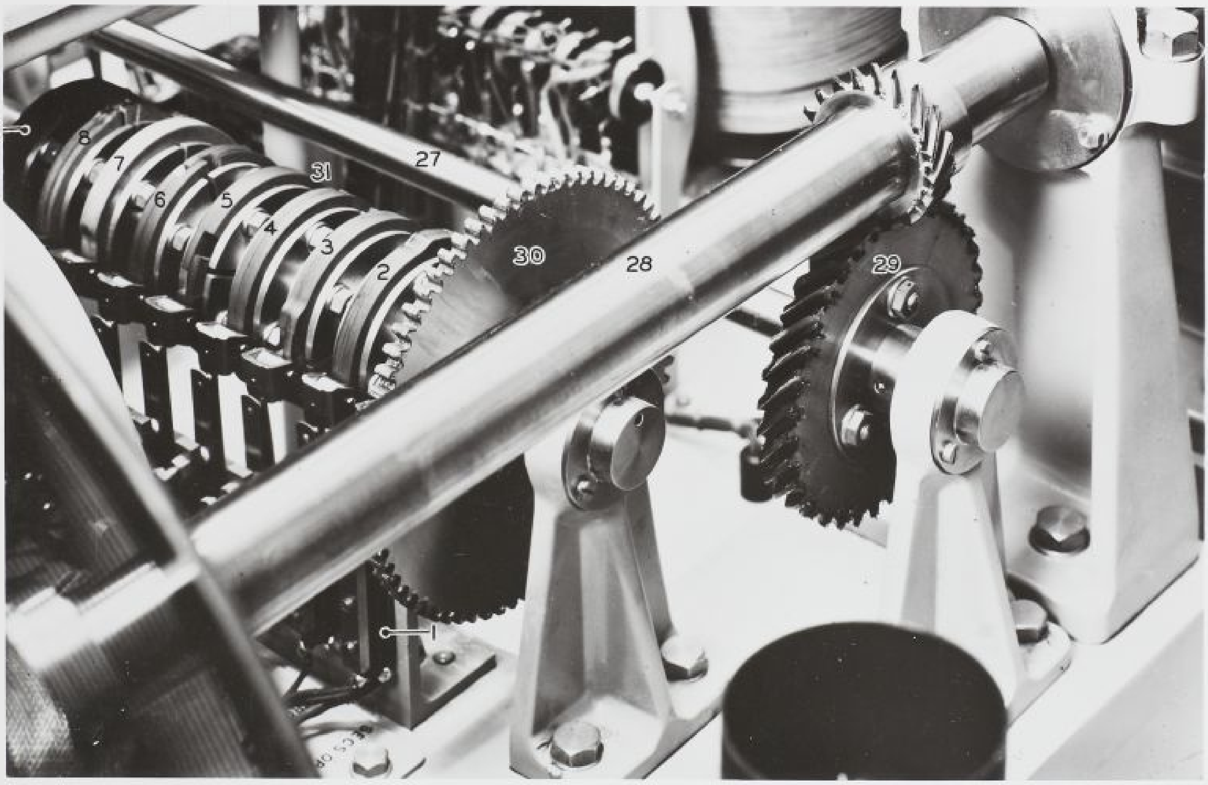
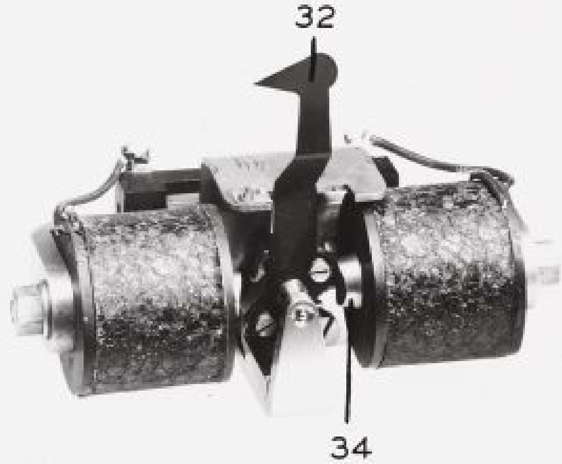


FIG. 3

CLOCK, SPEAKING. SHUTTER MECHANISM AND OSCILLOGRAM OF OPERATION.



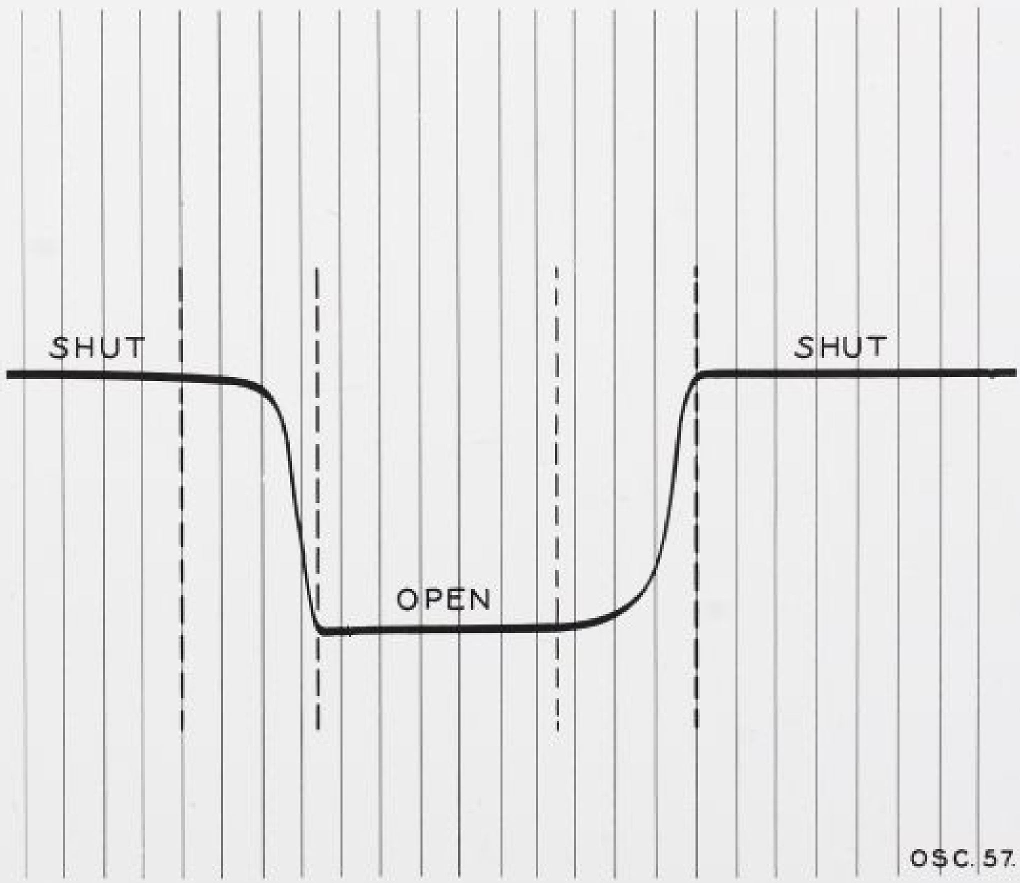


FIG. 4

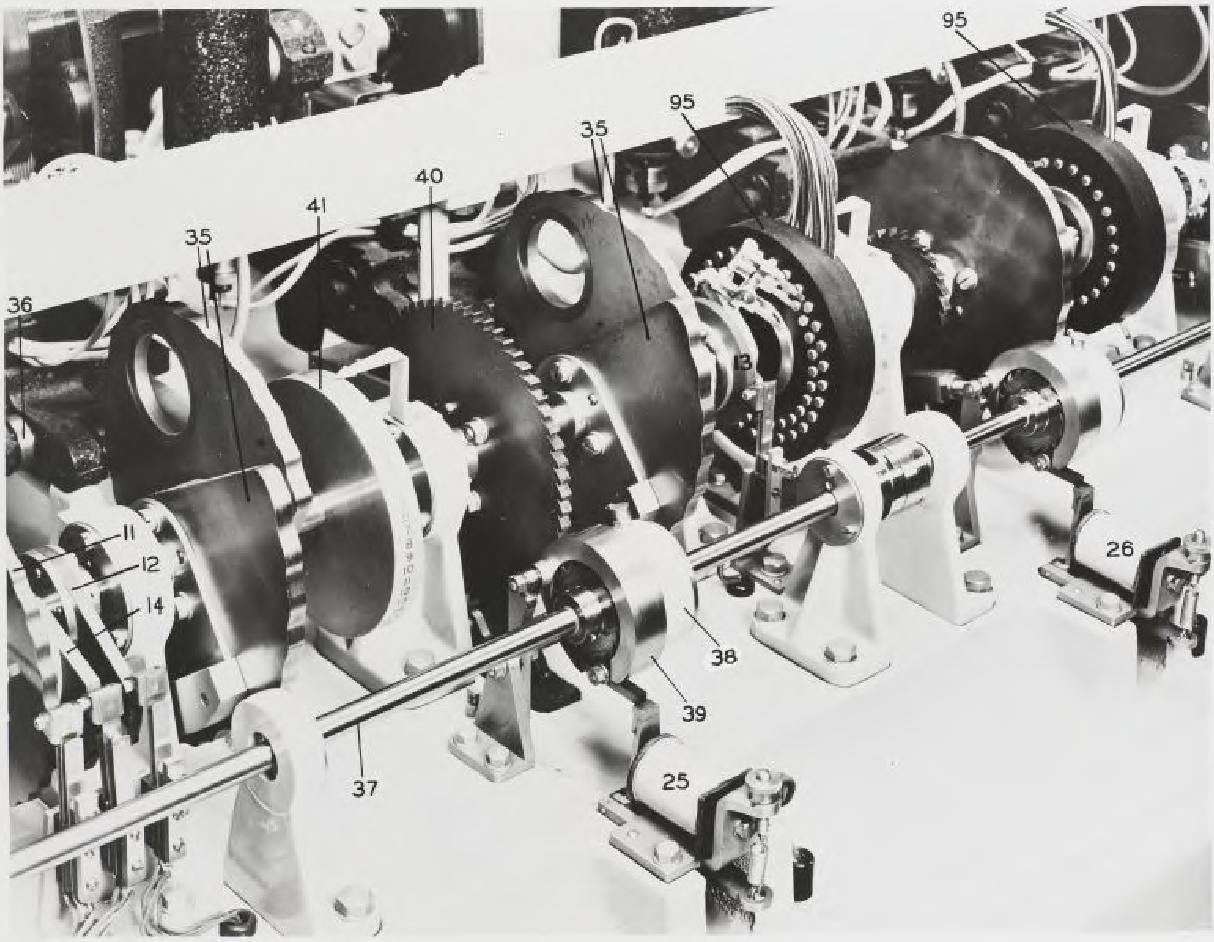


FIG. 5

CLOCK, SPEAKING. "MINUTES" AND "HOURS" CAM SHAFTS.

RESEARCH REPORT No. 8627

CLOCK, SPEAKING. WAVE TRACE (X2)

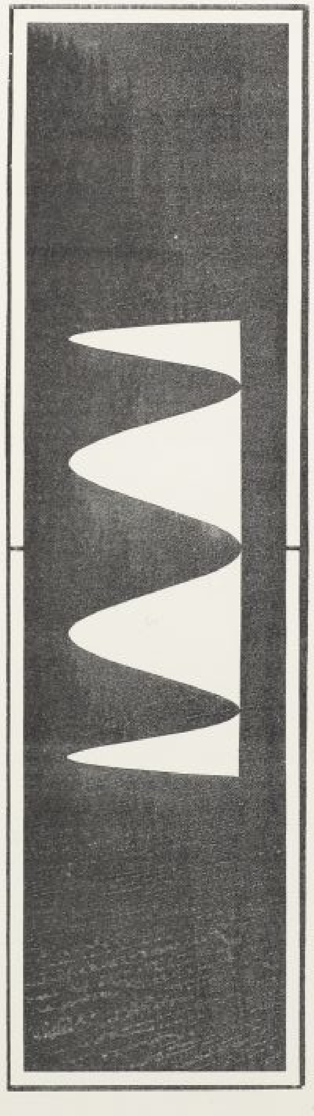


FIG. 6

CLOCK, SPEAKING.

HOURLY RECORD OF RATE OF FREE PENDULUM.

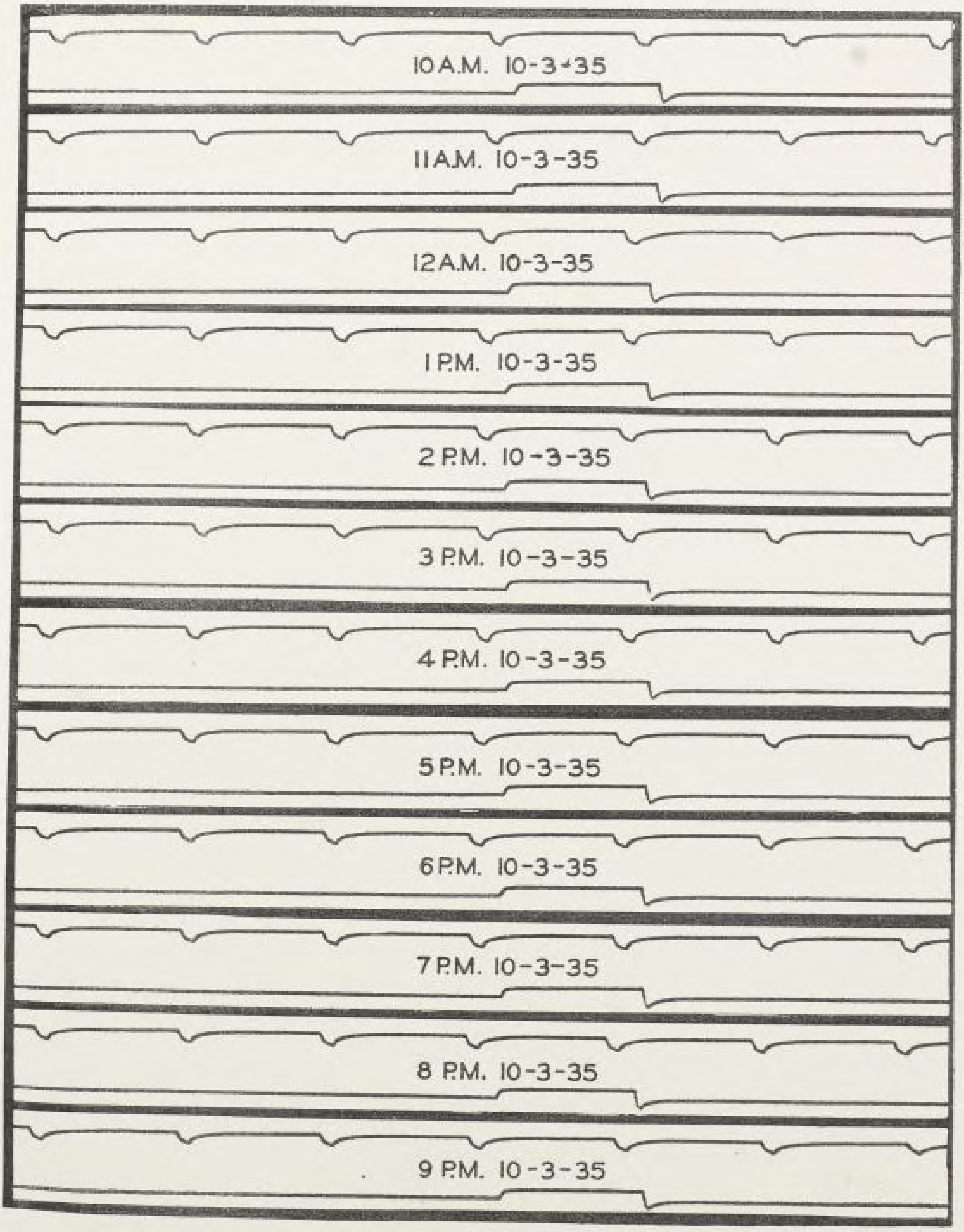


FIG. 7A

CLOCK, SPEAKING.

HOURLY RECORD OF RATE OF FREE PENDULUM.

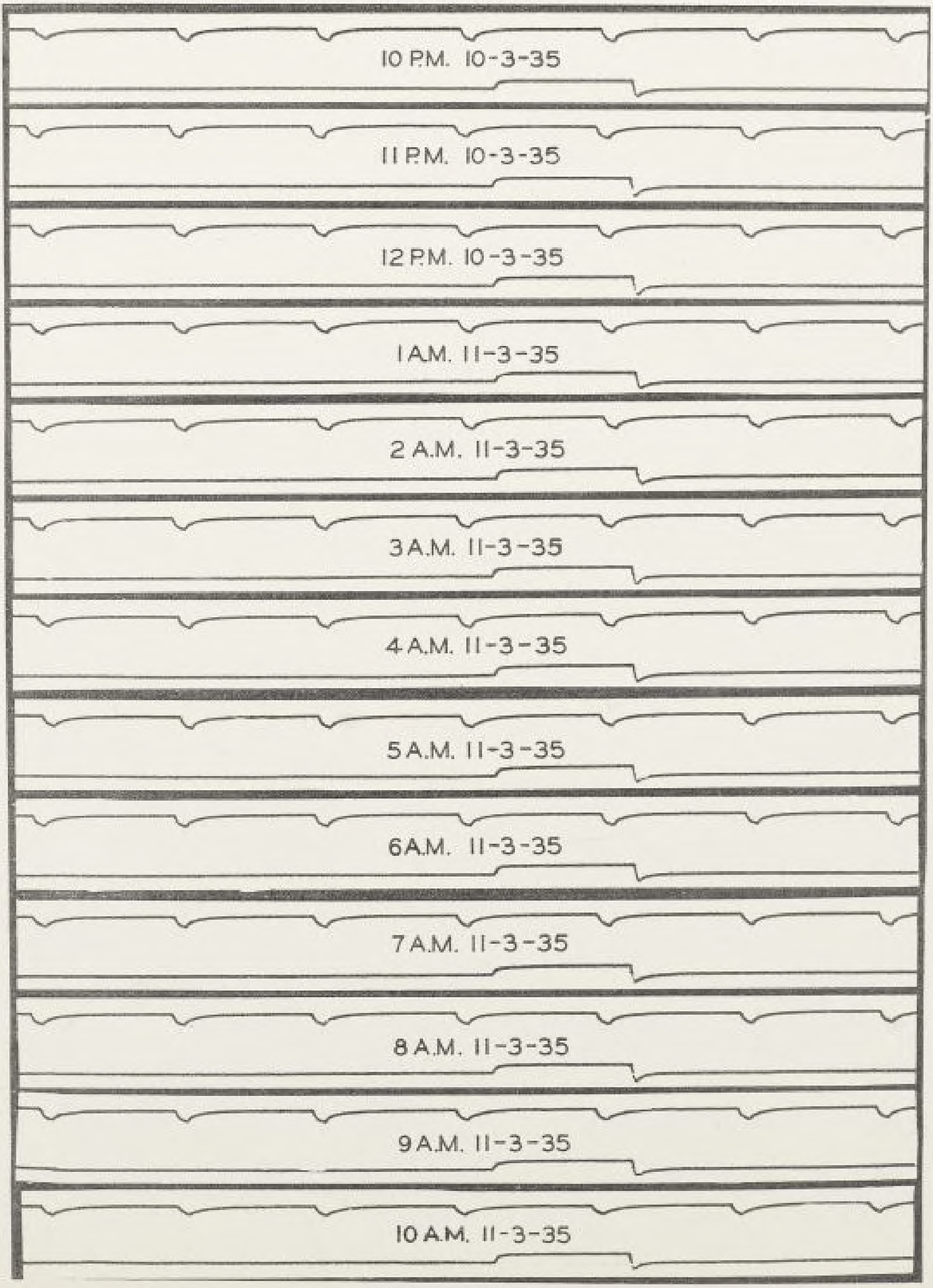


FIG. 8

CLOCK, SPEAKING, SCHEMATIC DIAGRAM OF DRIVE.

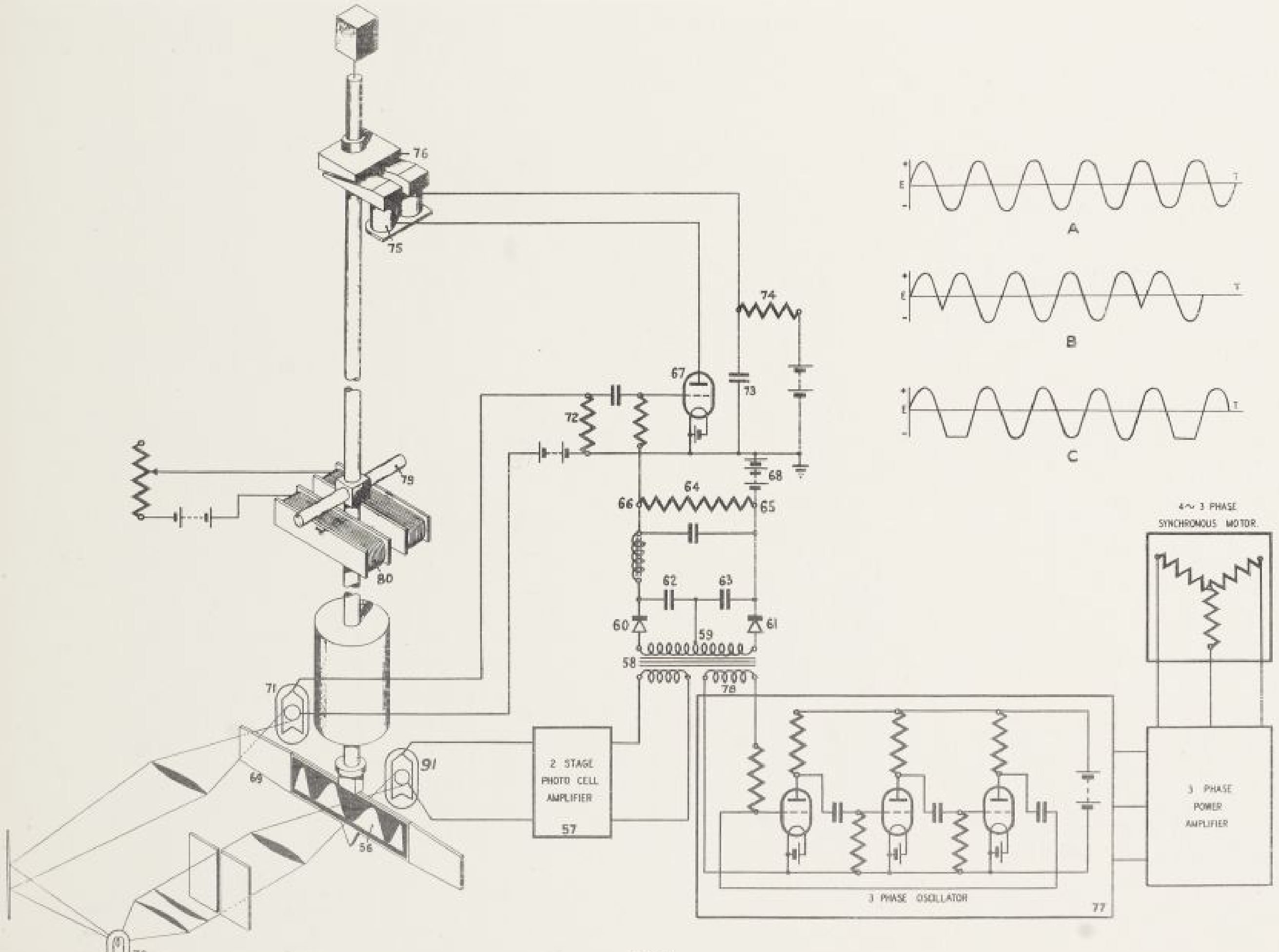


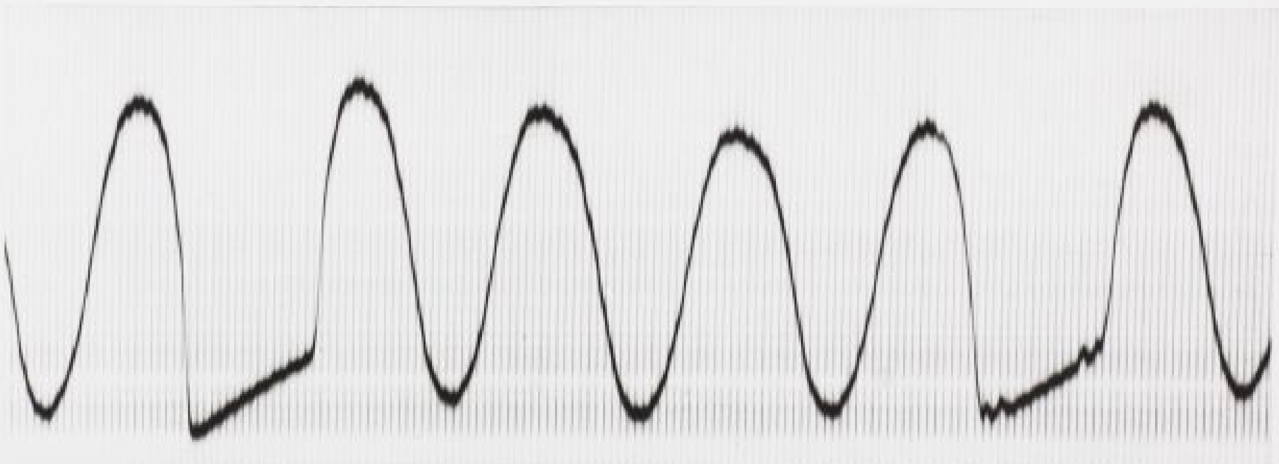
FIG. 8

CLOCK, SPEAKING. WAVE-FORM OF OUTPUT OF PHOTOCELL AMPLIFIER.

Ⓐ AMPLITUDE OF SWING TOO SMALL.

Ⓑ AMPLITUDE TOO GREAT.

Ⓐ



Ⓑ

FIG. 9

CLOCK, SPEAKING. PENDULUM UNIT.

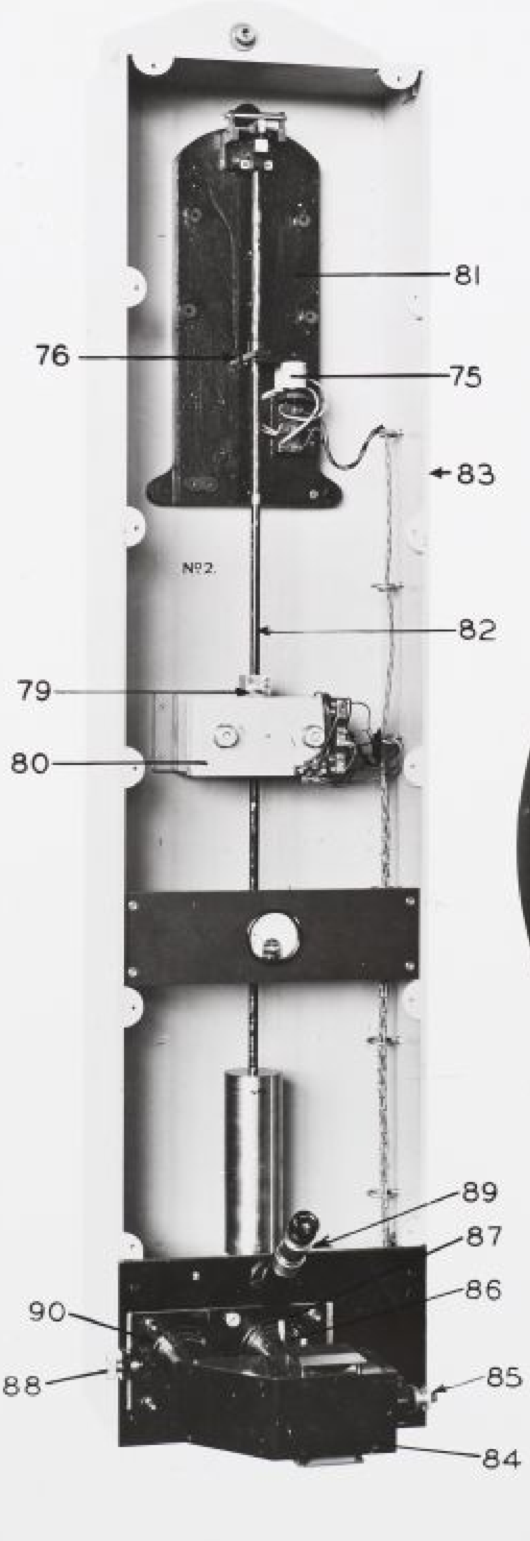


FIG. 10

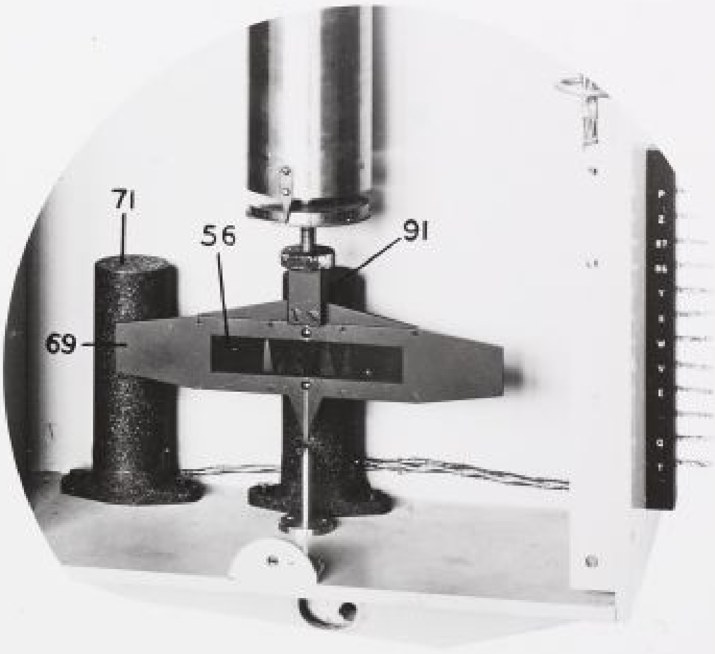


FIG. 11

CLOCK, SPEAKING. MOTOR AND DISTRIBUTOR. (CORRECTING EQUIPMENT).

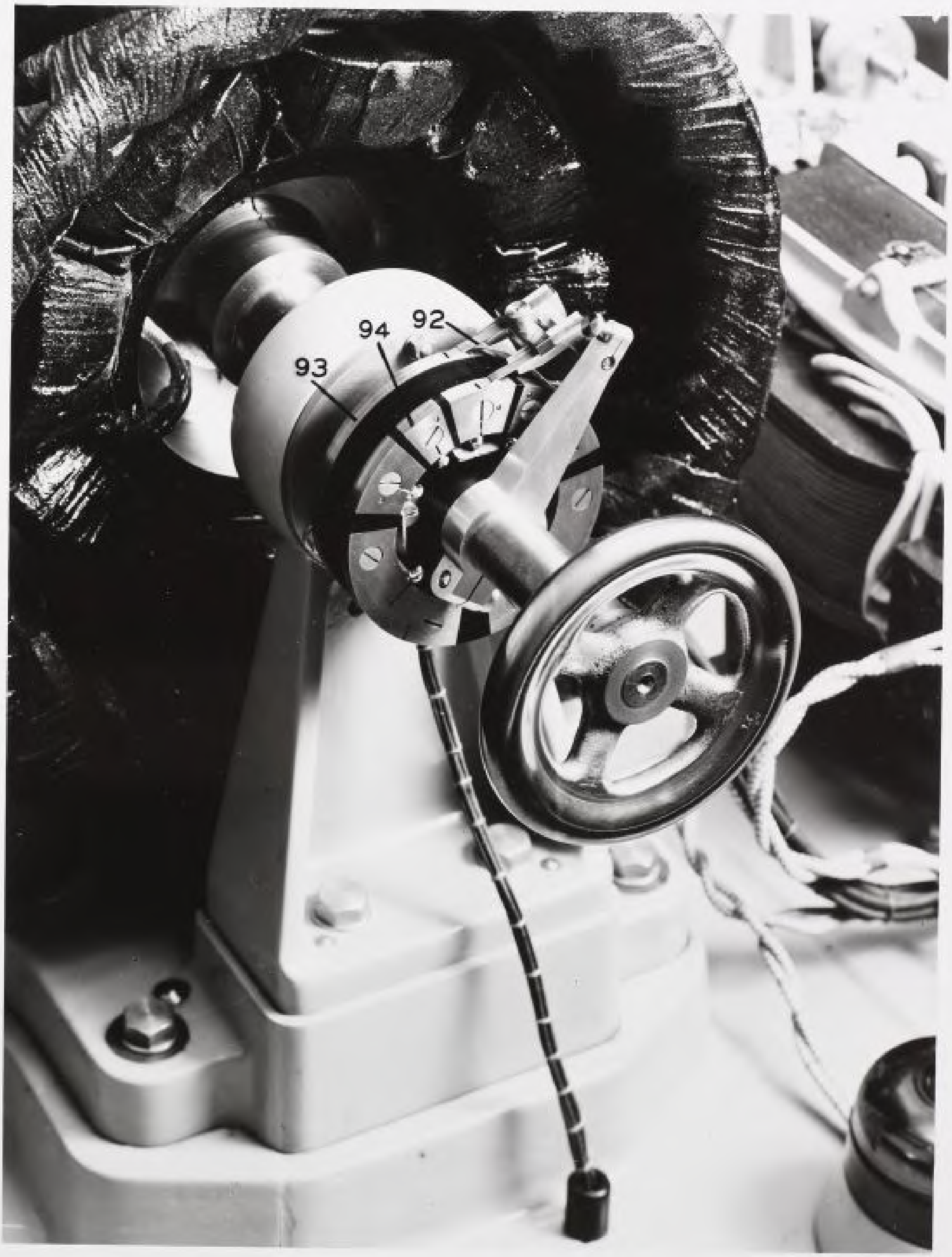


FIG. 12

CLOCK, SPEAKING. AMPLIFIERS AND CONTROL EQUIPMENT.

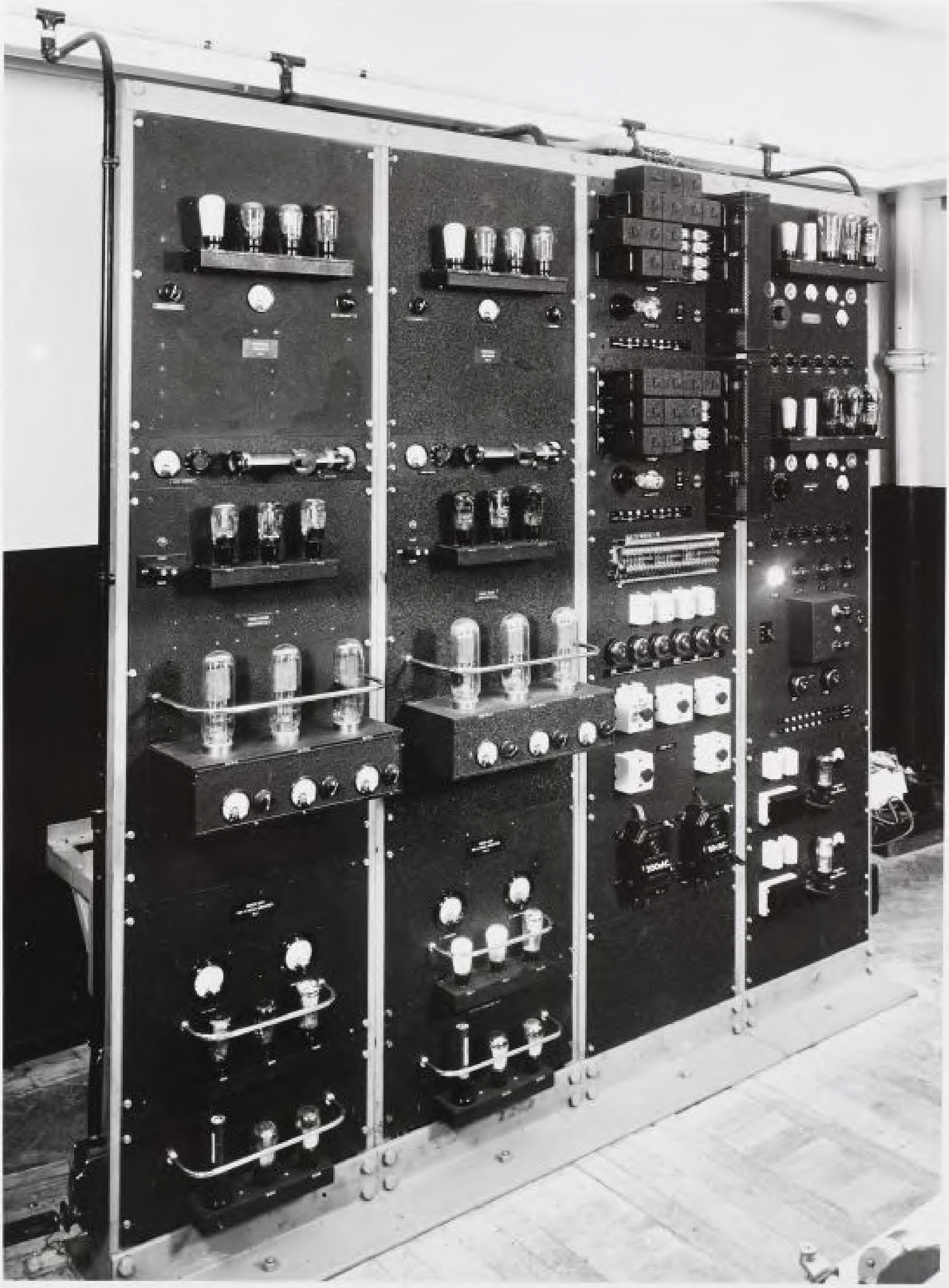


FIG. 13

CLOCK, SPEAKING.

GENERAL LAYOUT OF INSTALLATION.

FIG. 14

CLOCK, SPEAKING. OSCILLOGRAM OF OPERATION OF MAINS-GENERATOR A.C. SUPPLY CHANGEOVER SWITCH.

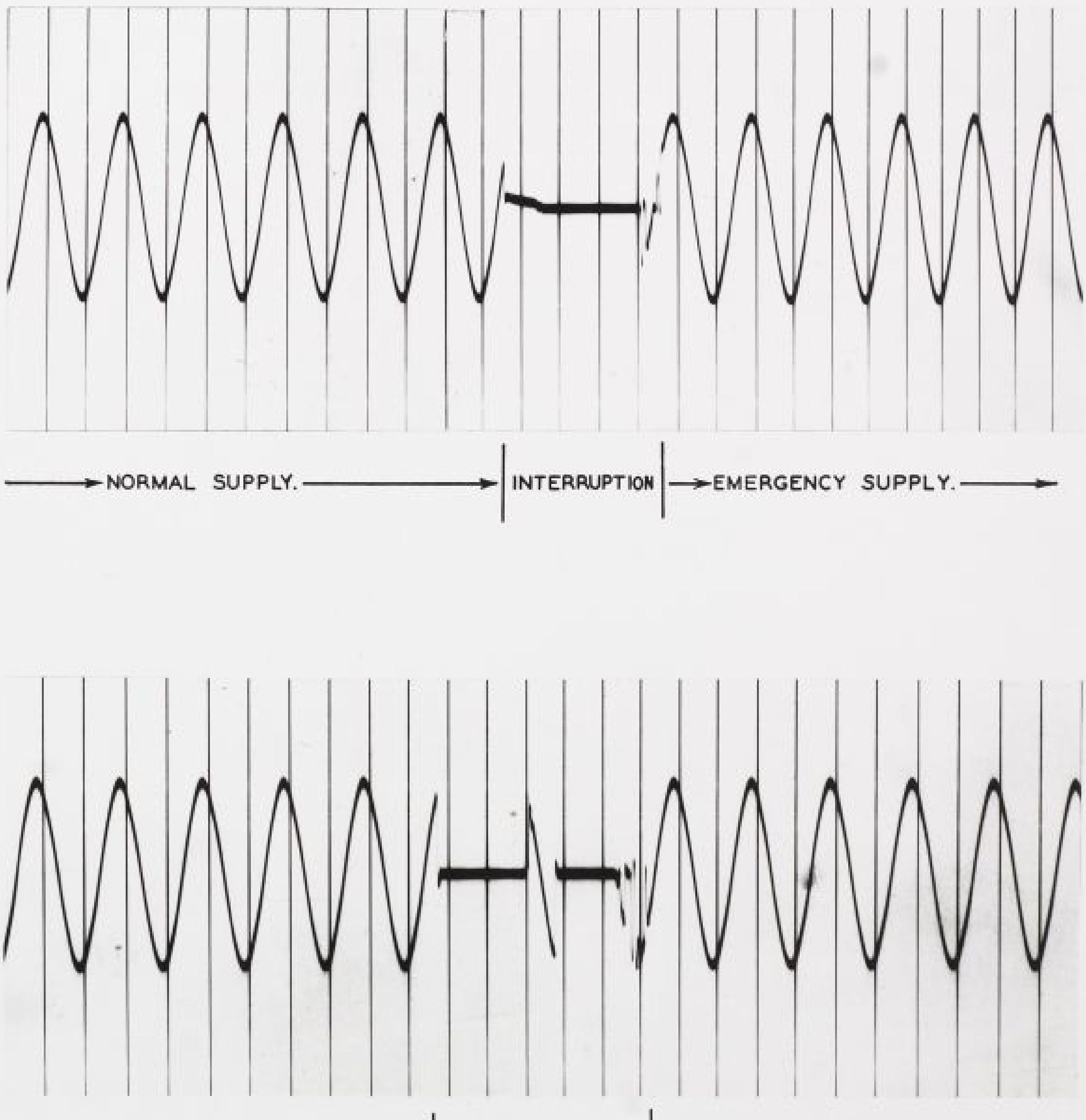


FIG. 15