NBS CIRCULAR 601

Recorder Survey:
Recording Surfaces and Marking Methods

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Recorder Survey: Recording Surfaces and Marking Methods

George Keinath

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Foreword

Preparation of this survey on recording methods and devices was undertaken to bring together available information on the various methods and problems of recording scientific and technical data. The survey covers some of the physical principles either currently or potentially available for recording variable measurands in laboratory experimentation or industrial production. Not included are techniques using coded perforation of tape or cards, or those for conventional magnetic or optical recording of speech, music, or other phenomena with continual millisecond or microsecond variation. This first volume deals with marking methods and recording surfaces. It is expected that work under way in the reviewing of recorder actuating mechanisms, special recording problems, and data presentation may result in the issuance of a later report on these aspects.

Many recording principles have found practical application in commercially available recorders, and both illustrations and performance information have therefore been drawn largely from manufacturers' literature. Information obtained from commercial sources has been carefully reviewed, but no test program was carried out to verify performance claims. The omission of any method or device does not imply that it is considered unsuitable or unsatisfactory. Conversely, inclusion of descriptive material on any proprietary instrument product or process does not constitute endorsement.

As far as is known there is no comprehensive treatise on this subject available in English, although a brief survey appeared in the May and August 1958 issues of *Instruments and Automation*. In German there is a 220-page book by A. Palm, *Registrier Instrumente* (1950). For the present monograph, acknowledgment is due to those manufacturers who supplied illustrations, descriptive material, and technical data; to Dr. H. L. Mason for his general supervision of the project and detailed editing of the text; and to M. S. Thompson for preparation of the section on chromatographic recording.

This survey and the preparation of this circular were carried on as a project of the NBS Office of Basic Instrumentation, which administers a Bureau-wide program of research, development, and dissemination of information relating to measurements and instruments. This program is cooperatively supported in part by the Office of Naval Research, the Office of Scientific Research of the Air Research and Development Command, and the Atomic Energy Commission.

A. V. Astin, *Director.*

Contents

Recorder Survey: Recording Surfaces and Marketing Methods

George Keinath

This Circular surveys the characteristics and comparative advantages of continuous traces, dotted traces, and printed characters, as produced by inking, incision, impression, indentation, deposition, heat, light, electric discharge, electron beam, magnetism, chemical action, or fluid streamlines. Descriptive and reference material is included on three physical components of the recording system—the reservoir of material or energy, the marking point or matrix positioned by the measuring element, and the chart surface which preserves the record.

1. Introduction

Because the words "recorder" and "recording" have many meanings, it is necessary to define the scope of this survey. According to Merriam-Webster a recorder is "one who remembers," but this definition is too broad for our purpose. A narrower definition would be "a device which remembers," but this would include recording of speech and music, which is not our intention. A definition of a recorder which serves to define the scope of this survey is:

> "Any device or method which automatically preserves, as long as needed, a graph, number, or picture of a physical condition or change."

There is no clear distinction between "indicators" and "recorders." The cathode ray oscilloscope might be considered a "two-dimensional indicator," but if we preserve the screen picture on photographic film the combination is a true recorder. We do not restrict ourselves to recording versus time or even to a sequence of recordings, and we shall include, for example, recorders which disclose the peak current of a lightning stroke or the thermographic picture of the surface temperature of a complicated valve casting carrying high-temperature steam. Nor do we exclude invisible records, such as those made by residual magnetism caused by a lightning current, or records which are not permanent and last only as long as needed, which may be a matter of microseconds, just long enough to be remembered by the human eye. This covers the cathode ray oscilloscope, the trace of which may fade in less than one second.

Referring to "automatically": this restriction is meant to exclude hand-operated recording devices in which the position of an indicating pointer, or the reading of an automatically balanced potentiometer presented to the operator as a pointer deflection, is plotted on a chart by pressing a button. There is, however, no clear boundary line between "automatic" and "hand-operated" plotting devices, and this survey covers also some hand-operated recording devices. For example, there are X–Y recorders in which both axes can be fed with electric signals of millivolt character. Others of this type use either hand-positioning of the chart or a hand-operated marking device and are thus only partly automatic.

Recorders are used in many fields, but the most frequent application is to supervise industrial processes and to carry out the mechanical, electrical, and chemical testing of materials and products. In some fields the recording instruments which we use today are basically the same as those of 50 years ago. This applies to the recording of electrical variables in power stations, also to simple mechanical pressure and temperature recorders. On the other hand, the last decade has given us practical instruments whose principles were hardly known 15 or 20 years ago to the average engineer. The recording mass-spectrometer is an example.

In the chemical field, many reactions formerly measured by purely chemical methods, e.g., acidity or sludge formation in transformer oil, are now more easily followed with continuous recording electric instruments measuring changes in electric properties, e.g., dielectric loss or resistance. Fifty years ago the Saladin X–Y recorder was developed in France to determine the transformation point of steel: today X–Y recorders are in common use. Twenty-five years ago a Swiss food manufacturing company used recording instruments to detect rancidity in food oils by an increase of power factor with time.

This survey will present a broad picture of recording methods, both available and potential. Details may be found in the literature references provided. This volume deals with marking methods and recording surfaces; it is hoped that a later circular may be issued to cover special problems of recording, data presentation, and actuating mechanisms. Some new terms have been deliberately used in place of those generally accepted in the trade literature. For example, the adjective "electronic" is not herein applied to an optical or electrical method which merely uses electronic means to amplify a current or voltage.

Many references are made to European developments arising from the author's experience as Chief Engineer of the instrument division of a large German electrical firm, founder and editor of the technical magazine "Archiv fur Technisches Messen," and author of the 3-volume work, "Technische Messgeraete," before coming to the United States in 1935.

The field of conventional industrial recorders is here treated rather briefly and no attempt has been made to mention all the various commercial forms, or to cover the details which differentiate them. However, in some sections "historical" instruments have been given brief mention because with modern electronic devices some old ideas might be used to advantage to meet the new problems of our day. Behar states [1] that the first recording instrument appears to have been built almost 300 years ago in Oxford, England, as a recording thermometer. The first X–Y recorder was an engine indicator built as early as 1795 by John Southern, one of the collaborators of James Watt. A rapid development of recording instruments began after World War I, and was accelerated after World War II with the help of electronic and nucleonic discoveries.

There are more than 100 manufacturers of recording instruments in the United States, but it appears that many fields of application have hardly been touched, especially in inspection and testing. These may involve either the record of deviations from a standard value in mass production, or a chart with all essential data from the testing of a single elaborate device. One recently developed analyzer for 6-cylinder automotive engines [2] uses a CRO picture to reveal engine performance by the shape of six traces simultaneously displayed.

There is a great variety of marking methods which are usable for recording. Generally, a choice of several is available for any specific problem. An important limitation is the torque output of the measuring system. With high torque the marking stylus may write directly on the recording surface without errors resulting from friction. However, special methods have been developed to get accurate records directly from moving elements with very low torque.

The necessary speed of recording also influences the choice among marking systems. The action time of a rocket motor may be only a few seconds, yet during this short period it is necessary to make hundreds of measurements, preferably in such a way that the result is visible immediately after the test, without time-consuming data reduction. Enormous improvements have been made in the last ten years. It is now possible to make up to 1,000 records per second from a number of transmitters with an accuracy which 10 years ago allowed only 1 or 2 measurements per second. By magnetic tape techniques, tens of thousands of "readings" per second can be recorded, although the subsequent conversion to visibility is much slower.

The presentation of the results of the measurements may be very different. It is frequently very desirable to have a readily understandable display *during* the test, not hours or weeks *after* the test. For some applications the conventional line diagram is not necessary, and a numerical presentation is preferable, either to avoid the transcription of a curve to a tabulation of figures, or to use the result in computing machines. The need to make copies of the diagram will influence the choice of the method. For problems which do not require a permanent record, the result may be erased automatically a few seconds or hours after the test, so that the recording surface can be re-used. This procedure is used for magnetic recording as well as for line recordings on paper.

2. Papers and Inks

Most recording instruments trace an inked line, or print marks, on paper. Because the paper in most cases shows a printed scale not impressed simultaneously with the record, the influence of temperature and humidity is very important. Without humidity control, changes of 0.3 to 0.5 percent in the dimensions of the chart can be expected and in extreme cases even 1 percent. In the strip chart the change of *length* is unimportant, because the holes for the driving sprocket are punched at the same time the scale is printed. More important is the change of chart *width* with humidity. This has been compensated in some recorders by matching the change with a change in the sensitivity of the mechanism, i.e., the pointer deflection corresponding to a given measure and value. However, it requires special attention to keep a calibration tolerance of 0.1 percent which is promised as the static accuracy of some recording instruments.

2.1. Inks

The quality of the ink is of the greatest importance for a recording instrument. There is no universal ink to be used for all recorders and all applications. In some cases the ink must remain liquid at temperatures far below freezing and flow properly at more than 50° C. Often it must remain usable for weeks or months after the pen has been filled; hence, the ink should dry very slowly. On the other hand, the same ink is expected to dry almost as soon as it touches the paper; this refers especially to test recorders with high chart speeds and with a chart rewinding device. In some recorders a roll of blotting paper

[1] M. F. Behar, Handbook of Measurement and Control, Instruments Publ. Co., Pittsburgh, Pa. (1951).
[2] Dumont Company, Passaic, N.J.

dries the diagram soon after it has left the pen. A common vehicle of recording inks is a mixture of 25 percent glycerol and 75 percent water; for very low temperatures it is necessary to add alcohol. Inks for recording instruments are made in various colors. The composition and properties have been the object of intensive studies.[3]

2.2. Opaque Paper

This is the most common recording material, and is used almost exclusively for recorders in industrial applications—for strip-chart recorders as well as for round-chart recorders. The chart paper has to be selected for the ink or vice-versa. It should be porous enough to let the ink dry within a reasonable time, but not so porous that the lines "feather" or have uneven contours. Its thickness is generally between 3 and 4 mils.

The Bureau of Ships Specification 53P40, for paper used in a ceilometer recorder, contains the following:

E–2. The paper stock shall be manufactured from not less than 25 percent of new first grade rag cuttings, the balance to be first grade bleached sulfite stock.

E–3. All paper shall have fine texture and smooth surface to give minimum pen friction, and the formation of the paper shall be such that it will blueprint readily.

E–4. Paper shall give a sharply defined record with blue recording ink and/or with imprints made with typewriter ribbon, using a marking stylus without traces of feathering when the record paper is travelling at any chart speed up to 12 in./hr.

E–5. The paper shall be free from lint or loosely bound surface fibers that could be picked up by the recording pen, and shall be so sized that no sizing or other matter can accumulate on the pen point.

E–6. Tearing strength of the paper shall be not less than 26 g in the lengthwise direction, nor less than 30 g in the crosswise direction, when tested at 50 percent relative humidity and an ambient temperature of 25° C.

E–7. The chart paper shall be not less than 0.0017 in. nor more than 0.002 in. thick.

E–8. Paper shall be cut to width only after conditioning at a relative humidity of 50 percent, and the width of the paper shall not vary from nominal dimensions specified by more than 0.25 percent of a 15 percent change in relative humidity when exposed to an ambient temperature of 25° C.

E–9. The length of the paper shall not vary more than 0.1 percent for a 15 percent change in relative humidity when exposed to ambient temperature of 25° C.

2.3. Transparent Paper

Transparent paper is not much used in this country; it is more common in Europe where it is used in temperature recorders with a chopper bar and an ink-providing device *under* the chart. This paper has a thickness of about 1 mil, at most 2 mils. Its advantage is that blueprints can readily be made from it.

2.4. Washable Charts

To save the expense of frequent replacement of charts, especially of the circular type, washable charts[4] were introduced several years ago. The chart is formed of three sheets of plastic laminated under pressure, with its ruling printed on an inner opaque sheet held between two transparent sheets. The record can be removed with a damp cloth so that the same chart can be used over and over again. It is claimed that such charts have less shrinkage and expansion than charts of ordinary paper. On the other hand, the cost of labor may make the use of this type of chart more expensive than charts of conventional material.

[3] G. E. Waters, J. Research NBS 17, 651, 1936; and NBS Circ. 426, 1940.
[4] Made by Allegheny Plastics, Inc., Coraopolis, Pa.

2.5. Chemical Erasure

There are other methods of reducing the cost of chart replacement, when the chart cycle is 24 hr or more. One way is to use a rapidly fading ink, either with daylight or artificial light in the recorder housing, so that only the last hours of the diagram stay visible. Another way is to destroy the coloring matter in the diagram line by using a chart impregnated with certain salts which react slowly with the ink. Some "wet" (i.e. humid) electrosensitive chart papers act in this way and can be re-used.[5] A more complicated method[6] is to expunge the diagram, which is traced with a solution of phenolphthalein or of "Victoria Blue," with gases which are generated in the recorder for this purpose.

Apparently none of these three methods has been used generally. They may be of interest in recorders which have to work unattended over long periods of time, perhaps using endless strip charts on which the diagrams are only of interest shortly after a disturbance.

2.6. Mechanical Recoating

This method is used in a vehicular recorder.[7] In the case of an accident the driver can give proof of his speed and of the proper use of his brakes. The recorder dial (fig. 1) has a diameter

[5] E. J. Kohn and D. L. Venezky, Development of the NRL Electrochemical Recorder Paper, Naval Research Laboratory Rept. 4685, p. 19, 1956.
[6] German patent application Z18946/IX, 42 d, Jan. 30, 1931, Zeiss Co., Jena, Germany.
[7] Hasler Company, Berne, Switzerland.

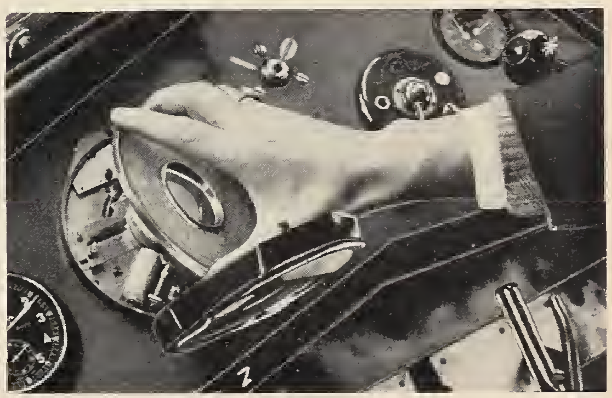

FIGURE 1. *Wet-paint disk recorder with self-erasing device (Hasler Co.)*

of 5 in. and makes 1 revolution with a car travel of 260, 520, or 1,040 m. The recording surface is a glass disk, painted on the underside, and the curves (indicating speed and travel while the brakes are applied) are scratched in this wet paint layer. After a full revolution of the disk the diagram is wiped off automatically and a new layer of paint is automatically applied. The scale divisions are permanently printed on the upper side of the glass disk.

A similar method is used in a disturbance recorder[8] for power stations. Here moving coils with very short response times trace continuous curves on a cylinder *D* (fig. 2), covered with wet paint and motor-driven at constant speed. The smaller cylinder *F* continuously transfers paint from the trough *T* to the large drum *D*. At the end of the pointer is a sapphire pin *S* which scratches a furrow in the dark paint. This record is stored for about ¼ revolution, and is then obliterated. If a disturbance occurs, relay *R* presses the chart *P* against the printing drum *D*, giving a white trace on a dark background, and including up to 1¼ sec of the baseline reading.

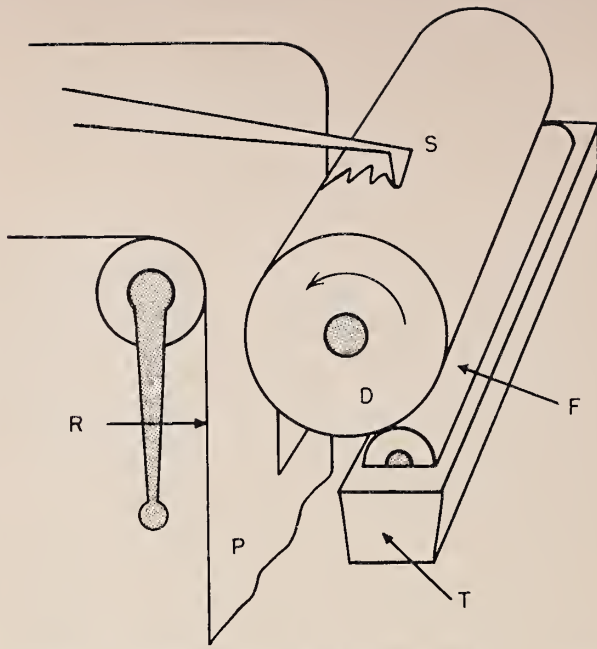

Figure 2. *Transfer from paint-coated cylinder (Hartmann & Braun).*

3. Chart Shapes And Chart Drives

3.1. Drums

Paper-covered drums have been used for many years in Europe, but not extensively in this country in industrial applications. In all the older designs the chart was prepared, cut to size, printed, and held on the drum surface by clamps. This primitive arrangement was acceptable because most of these charts were changed only once a day or once a week. Modern drum recorders, especially those used for facsimile recording, have a large paper supply inside the drum, so that one merely cuts off the used surface and pulls out a new chart. Of course, the storage of a roll of paper inside the drum greatly increases the rotational inertia, so that this design cannot be used for X–Y recorders where the drum angle has to be positioned by the measuring system. However, if we make the drum stationary and make the stylus rotatable, we have only to limit the inertia of the stylus system.

For diagram tracing the drum recorder has the disadvantage that it shows only about half the chart. However, if the stylus is rotated about a stationary drum it is possible to arrange to record at the front that part of the diagram which is of maximum interest.

Drum recorders are used in this country for laboratory recorders, and for meteorological data such as atmospheric pressure and temperature, water level, and snow depth. One instrument for water-level recording[9] has a drum diameter of about 10 in. The chart is 14 in. wide and recording is accurate to 0.01 in. or 0.07 percent of the chart width. A laboratory design[10] has interchangeable gears to give chart speeds from 8 in./sec to 8 in. in about 6 months, each of the 36 steps having ⅝ the speed of the previous one. Another design, with two vertical drums carrying an endless belt, is in fact an endless-strip-chart recorder. (See section 3.4.)

A modern design[11] used for recording the spot movements of one or several cathode-ray oscilloscopes or lightbeam galvanometers has either a 6 in. or 12 in. drum with surface speeds up to 200 ft/sec. Photographic paper or film of up to 10-in. width is wrapped around the drum. Using 6 dual-beam cathode-ray oscilloscopes, 12 channels can be recorded at the same time. An important feature is the shutter, which is opened electromechanically in less than 0.01 sec and closes again after 1 revolution of the drum.

[8] The Masson, Perturbograph, manufactured by the companies Carpentier in Paris, Hartmann & Braun in Frankfurt am Main, and Trueb Taeuber in Zurich.

[9] Leupold & Stevens, Portland 13, Oregon.

[10] Gorrell & Gorrell, Haworth, N.J.

[11] Alinco Dynadrum, Allegheny Instrument Co., Cumberland, Md.

3.2. Cylindrical Segments

In an early recorder[12] built about 1910, a rectangular chart moved by a clock was slid between guides on the *inner* side of a cylinder segment. The axis of the measuring system coincided with the axis of the cylinder, the pen writing on the inside of the segment.

In a modern version[13] (fig. 3) the chart is stationary. The pen is connected with two measuring systems, the X-system driving it through a pinion engaging a rack concentric with the cylinder axis and the Y-system swinging it about that axis through a parallelogram linkage. The chart has a maximum size of 11 by 16.5 in. The marking may be made either as a continuous trace or so that only dots are plotted.

In the continuous strip chart recorders pictured in figure 4, the writing is performed on the *outer* surface of a cylinder.

[12] Ateliers Carpentier, Paris, France.
[13] X–Y recorder of the Librascope Company, Glendale, Calif.

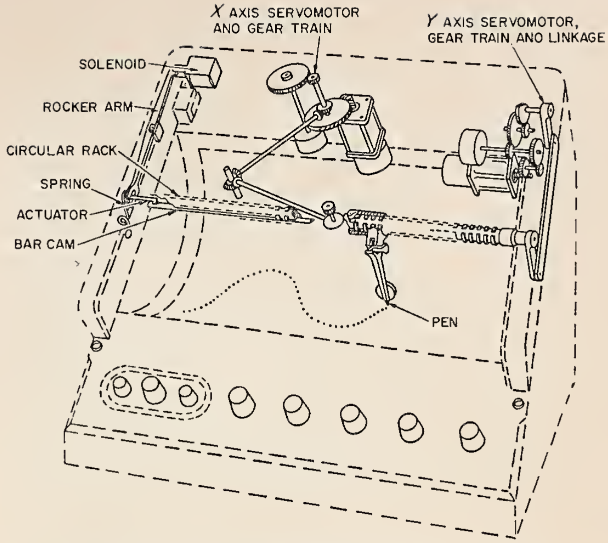

FIGURE 3. *Internal cylindrical segment recorder (Librascope Co.).*

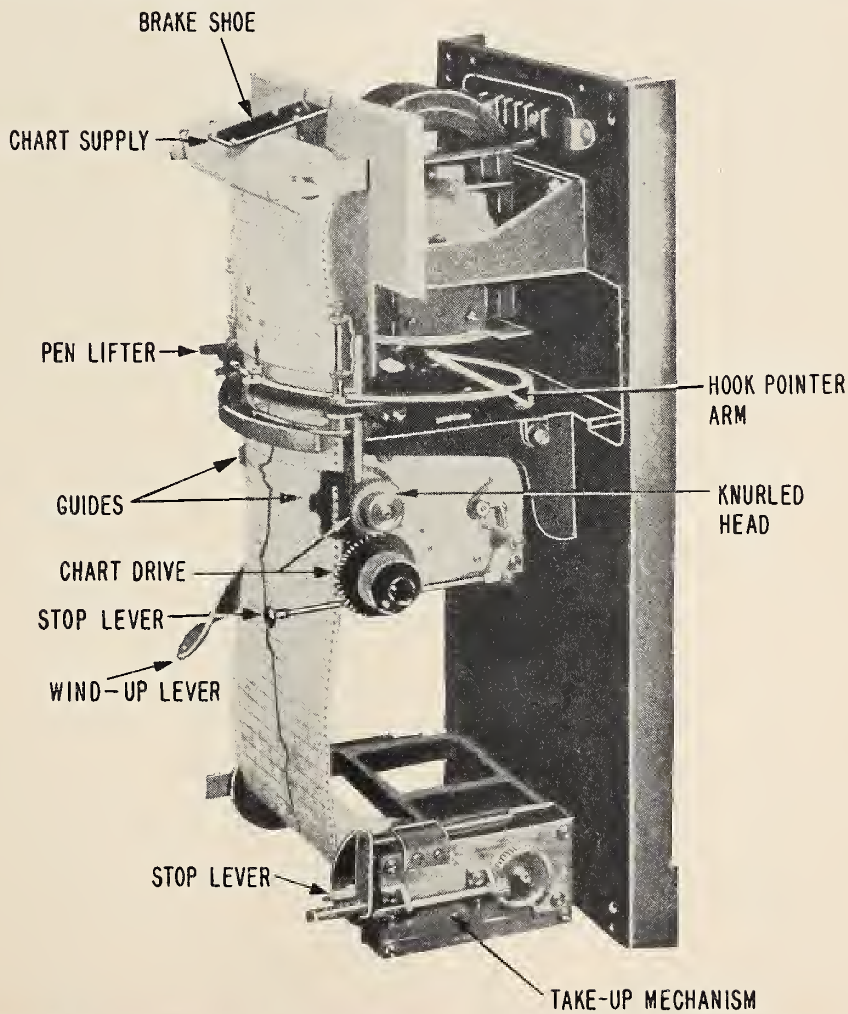

FIGURE 4. *External cylindrical segment with hook-pointer (Hartmann & Braun).*

3.3. Continuous Strips

The continuous strip chart is one of the two most common recording surfaces; the other is the disk chart. By using lengths of 120 ft or more, frequent chart changing is avoided, 6 to 10 in. of the record are kept visible, and the time base is extended to months or even longer. It appears doubtful whether a chart of this length has any real advantage in industrial use; it is difficult to handle, and in most plants a day's run is regularly cut off for inspection in the office. Since one type of paper may be used for many recorders, this requires identification of the diagrams with the transmitters which originated the information. There are many plants where 100 and more strip chart recorders are continually in operation. Operated at only 1 in./hr, the daily chart consumption for 100 recorders is 200 ft, the monthly, 6,000 ft.

An interesting design of a multiple strip chart has been developed for a 36-point sweep-balance recorder.[14] There are six chart systems, one above the other, and on each of them six styluses move side by side in a width of 12½ in. However, with this chart arrangement the last recorded points disappear to the back of the instrument after a few seconds.

The chart width of most industrial recorders is between 3 and 12 in. Wider charts increase reading accuracy, but errors due to humidity expansion also increase if not corrected or excluded with special compensating devices.

Most strip charts move vertically, driven through circular holes in one margin and oblong holes in the other, the drive sprockets being powered by clockwork or a synchronous motor. The oblong holes allow lateral variation of 1 or 1½ percent. Very wide charts may have three rows of holes, the circular holes being in the middle. This scheme cannot be used for all types of recorders because the sprockets may hinder free movement of the pen. For very high speeds or for test recorders, charts without perforation are used, the paper being moved by sharp needles or by friction rollers.

Almost all strip-chart recorders use rectilinear pen motion to trace the diagram in rectilinear coordinates, or use arcuate ordinates. Only a few designs are known which bend the chart into a cylindrical surface to get rectangular ordinates from a pen movement in a 60° or 90° arc (fig. 4). For facsimile work [15] the arc is increased to 360° allowing a full circle movement to the recording element. Such a facsimile recorder provides in effect an infinitely long drum.

[14] "Multitron Recorder" of the Reed Research Co., Washington, D.C.

[15] R. J. Wise & I. S. Coggeshall, Proc. I. R. E. 29, 237–242 (1941).

Tape between 0.5 in. and 3 in. wide is generally used for time signals or for recording in code or in numerals. A tape of Teledeltos paper only 0.75 in. wide, moved at a speed of about 0.6 ips through a concave guide of 0.5 in. radius, is used by Western Union for their "Teletape" facsimile receiver.[16] The tape used in most of the magnetic recording devices consists of paper or plastic coated with a thin layer of dispersed magnetic particles.

3.4. Endless Strips

To avoid poor visibility of a considerable part of the diagram, as is the case with a large drum, an endless strip chart may be used. The chart is looped around two rollers 1 or 2 in. in diameter, thus making more than 40 percent of the total chart length visible from the front. This scheme has been little used in the past, but recently has received impetus from applications of the segmental strip-chart technique.

One typical segmental recorder [17] uses a conventional null-motor mechanism to record the variables across the chart in the usual manner. The chart length, however, is divided into a number of 6-in. segments, each covering a 24-hr record for 1 to 10 variables. (fig. 5) The chart is not moved continuously, but intermittently, the shift from one segment to the next taking about 0.5 sec. The

[16] Leon G. Pollard, Trans. A.I.E.E. 67, 511–15 (1948).

[17] C. G. Dell and L. P. Haner, I.S.A. Journal 1, 27–30 (1954).

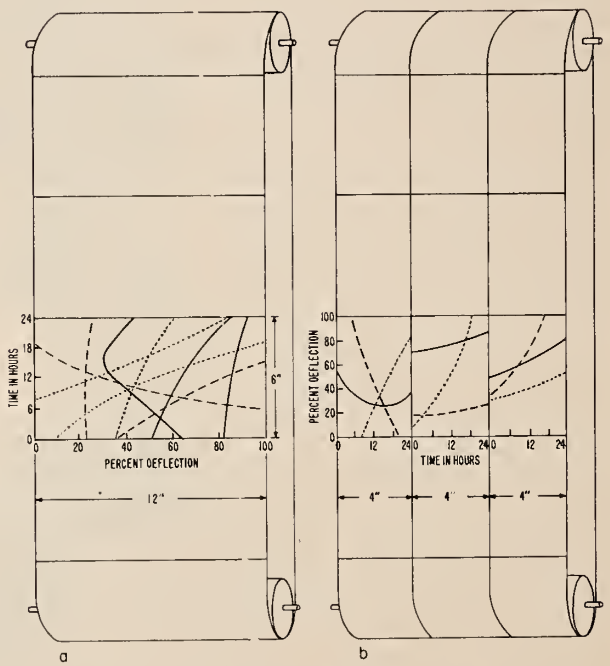

FIGURE 5. *Comparative arrangements of endless strip chart:*

a, Dell-Haner; b, sweep balance.

time interval between chart movements depends on the time needed to plot all points in a given segment. In some equipment[18] the chart movement may be initiated as soon as the last point is plotted in the segment under the pen.

In a recorder of this type,[19] built for 576 temperature records, the chart is 10 in. wide and its length of 144 in. is divided into 24 segments of 6 in. each. Each of these segments is divided laterally into 6 strips 1.67 in. wide. In each one of these narrow strips 4 different temperatures, which are expected to differ but little, are recorded within 2 sec. The chart stands still while the recorder is switched to the 4 thermocouples assigned to the next 1.67-in. strip, and so on until 24 temperatures have been recorded in the 6 by 10 in. panel. The time for this is only about 12 sec because between any 2 recordings the pen need not travel more than ⅙ the chart width. Now the chart is moved to the next frame, and again 24 temperatures are recorded, until, after about 5 min, the full cycle of 576 temperatures is completed. Superimposed on this discontinuous movement of the chart from one frame to the next is a slow movement to advance the chart so that a 6-in. time base is covered in 24 hr, or about 10 mils between 2 recordings. It is obvious that if the temperatures were considerably different from one another a scale width of only 1.67 in. would not be satisfactory, so that this recording system is best suited to supervise irregularities in magnitudes which are controlled to a constant value. A reading accuracy of 20 mils would correspond to 1.2 percent of the scale width, while for a similar conventional recorder the guaranteed accuracy is generally 0.2 percent.

Exactly the same arrangement of the diagram frames with almost the same design elements (endless chart, servomotor recording system) is obtained with the "Identichart" recorder.[20] The difference in design is that the chart runs continuously and the printing of the mark is done "on the fly." This avoids the frequent (every 2 to 12 sec) start of the chart motor, though the starts and stops of the balancing motor are still equal to the number of measurements made during the operation of the recorder. In this recorder an identification of the record is printed automatically in each frame.

In the sweep balance system[21] time is plotted horizontally as is usual for the time coordinate in engineering practice. In this way it is easy to compare the readings in one strip (fig. 5) at a certain time, because their time bases are alined. The chart is in continuous motion. With sweep balance many variations of frame size and shape are possible with not much more than a change of mechanical gear. To record 108 variables for 24 hr on a chart 72 by 12 in., the deflection range might be increased to 6 in. and the time base reduced to 4 in. with use of 3 styluses, which could operate either at the same time or in sequence. It seems better practice to allow a large deflection, with higher reading accuracy and better separation of the curves, as in figure 5, than to extend the time base at the expense of the deflection.

A recent development[22] intended mainly for magnetic memories of high capacity, appears also usable for analog recording on long loop charts. Information is recorded on an endless magnetic tape 14 in. wide and from 8 to 600 ft long. The drum has a diameter of 12 in. and rotates at 20 rps. Inside the drum are 128 magnetic heads mounted in a straight line, the pole pieces extending slightly above the drum surface. The tape, wrapped around half the drum circumference, is stationary while recording or reading. The magnetic layer on the tape is turned away from the drum and the tape is slightly lifted from the drum while recording, reading or erasing, so that not even the base material of the tape is exposed to wear. The information to and from the 128 heads is coupled to the rest of the unit through slip rings on the drum shaft. Ten "pages" of the tape, each half a drum circumference long, can be advanced in 2.25 sec.

3.5. Moebius Chart

The Moebius strip[23] discovered in 1858 by the German mathematician Moebius, is not only a mathematical curiosity but also a practical device—a one-sided surface. It is formed by joining the ends of a potentially rectangular strip of sufficient length, after twisting one end so that at the joint different sides of the paper meet. In the rectangle *abcd* of figure 6 the right ends *cd*

[18] "Electronik" recorders, Brown Instrument Co., Philadelphia, Pa.
[19] Panellit Company, Skokie, Ill.
[20] Royson Engineering Company, Hatboro, Pa.
[21] G. Keinath, Instr. and Automation 22, 200–210 (1946).

[22] "Tapedrum," Brush Electronics Co., Div. of Clevite Corp., Cleveland, Ohio.
[23] A. W. Tucker and H. S. Bailey, Jr., Sci. American 182, 18–24 (1950).

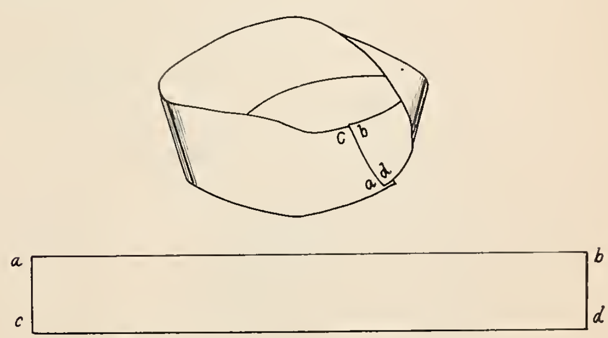

FIGURE 6. *Moebius' one-surface strip.*

are so connected to the left ends, that d comes to a and c to b. As a variety of the endless strip chart, the Moebius strip could give twice the chart length without interrupting recording to reverse the chart. As far as we know, no practical application of this system has been made, but it seems to deserve application, especially for tape recorders used to record time intervals.

3.6. Round Charts

This type of chart, also called a disk chart, like the continuous strip has long been used. It is the preferred type in this country, while in Europe strip or drum recorders are preferred. The size used in many industrial plants has a nominal outside diameter of 12 in., the outside diameter of the diagram being about 10 in., the inner circle about 1.75 in. in diam. For a 24-hr chart, this gives time scales of about 0.13 in./hr at the inner circle and 1.38 in./hr at the outer circle. For most disk charts, the pen travels in an arc of about 5 in. radius, over a range of about 60°. The round chart offers the advantage that the whole diagram is visible at all times, but at the cost of nonuniform time scale and of inversion of a part of the diagram. The comparison of diagrams is more difficult than with rectilinear recording.

In an early British design,[24] the round chart was driven by a vertical spindle, terminating in a hemispherical head several inches in diameter, upon which the chart was fastened centrally with its plane horizontal. The back and front portions of the chart were bent down and passed between guides so that the arch was formed. In this way the crown of the chart presented a relatively rigid writing surface for the pen, the depth of the case was kept within reasonable limits, and the time lines were radially straight.

Generally the round chart rotates through 360° in a period of 24 hr, tracing from 1 to 6 curves. It is, however, possible to supervise a much larger number of variables if the chart is divided into a number of segments, shortening the travel of 24 hr to a small fraction of the full circle. In each one of these segments up to 6 diagrams may be traced. A chart for a segmental recorder for 24 variables[25] (12 temperatures, 12 dew points) is shown in figure 7. Here there are only two ranges, alternating with each other, but it would be possible to have a different range for each segment. A more recent development[26] uses 16 segments with 6 variables, shown in 6 colors in each segment, to get a total of 96 variables on 1 chart of nominal 12-in. size. The time base for this recorder is about 0.13 in./hr at the inner edge, and 0.89 in./hr at the outer edge of the chart.

Segmental round-chart recorders are also used for short-time testing of up to 48 specimens with strain gages. In this case no time recording is necessary. The test load is increased in 10 steps from 0 to 100 percent on all samples, and the strains are recorded by rotating the chart successively to the proper specimen number. In this design[27] the small chart area available for each

[24] Evershed & Vignoles, Ltd., Chiswick, London W4.

[25] Foxboro Company, Foxboro, Mass.

[26] Fielden Instrument Div., Robertshaw Fulton Controls Co., Philadelphia, Pa.

[27] Foxboro Company, Foxboro, Mass.

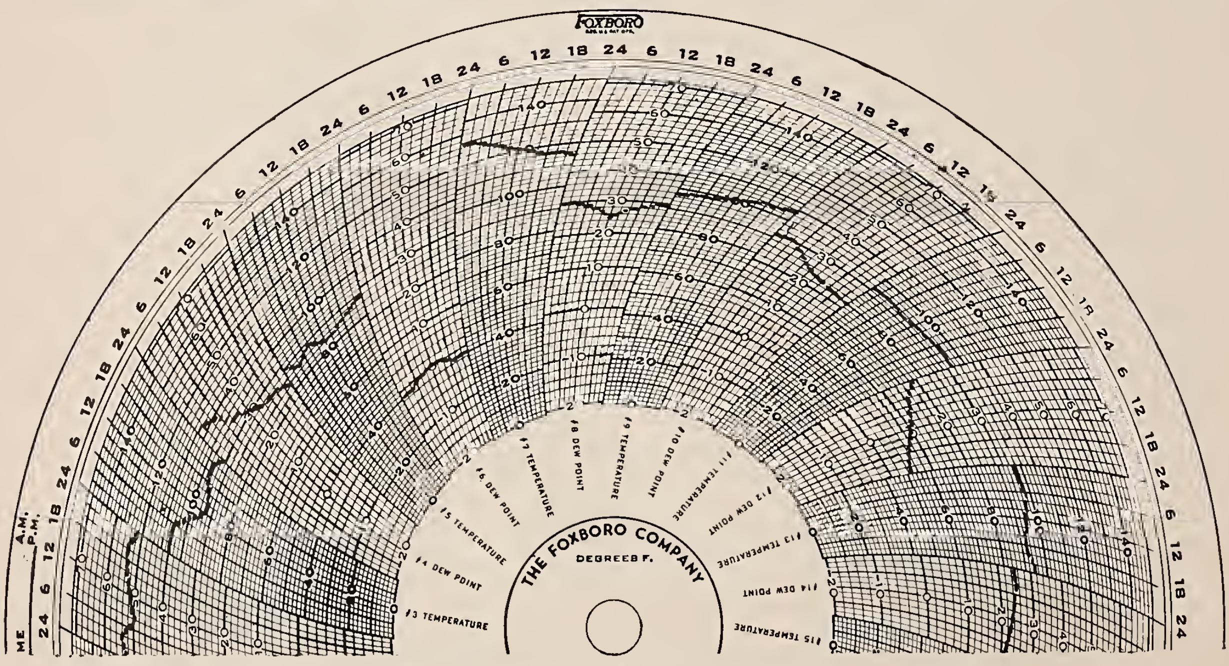

Figure 7. *Segmental disk chart* (*Foxboro Co.*).

specimen is not disturbing because only the radial position requires precision.

3.7. Plotting Boards

Flat rectangular plotting boards from 10 by 15 in. to 50 by 50 in. are now built for stress-strain recorders, data plotters, and other recorders of the X–Y type. One or two pens are moved in two directions by independent servo-systems; the table is generally stationary and may be either vertical (fig. 8) or horizontal.

A vertical panel 10 by 10 in. is used in a creep-rupture testing machine [28] tracing elongation versus time. The elongation is amplified by electrical means. In this recorder the panel is stationary, the stylus being moved by load and elongation.

In other recorders of modern design used in testing materials, the chart-holding panel is moved, as in the oldest engine indicators. Figure 9 shows a stress-strain recorder [29] which is built with chart panels up to 10 by 12 in. The panel is positioned in proportion to the load. Elongation is recorded either directly or with mechanical amplification up to 20:1.

[28] Developed by Westinghouse Research Labs., Pittsburgh, Pa. (Testing Topics, Baldwin Locomotive Works, 3, Aug.–Oct. 1948).

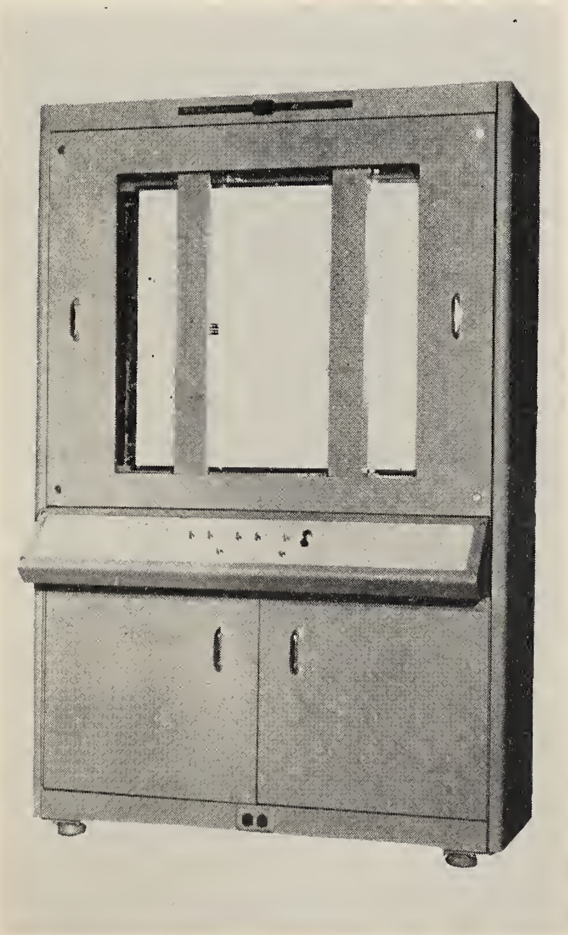

Figure 8. *Vertical plotting table, chart 30 in. by 30 in.* (*Electronic Assoc., Inc.*).

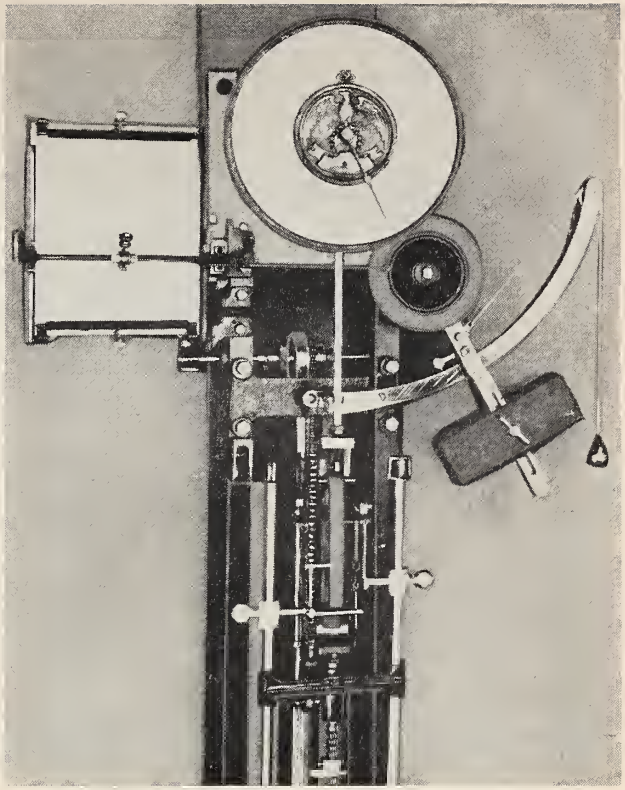

Figure 9. *Stress-strain recorder with moving panel* (*Scott Testers, Inc.*).

A very large plotting board [30] was built for the British Royal Air Force (fig. 10). The chart has a net width of 25 in. and a length of 120 in., providing 200 frames 3 by 5 in., for recording the deformation of aircraft parts. A sheet of Teledeltos paper is clamped to the table, which is used in a vertical position. The recording sweep balance system is mounted in a carriage which is positioned by hand horizontally along the board in accordance with the load, while the sweep is vertical.

3.8. Chart Drives

In almost all recording devices the recording surface is moved continuously in proportion to time within very wide limits of speed, ranging from small fractions of an inch per hour to hundreds of inches per second. Using a mechanical clock has the disadvantage that only a few foot-pounds of energy can be stored to supply power for a week or more. The speed of all these clocks is somewhat dependent on the load, represented

[29] "Serigraph" of Scott Testers, Inc., Providence, R.I.
[30] Aircraft Prod. (London) 12, 131–32 (Apr. 1950).

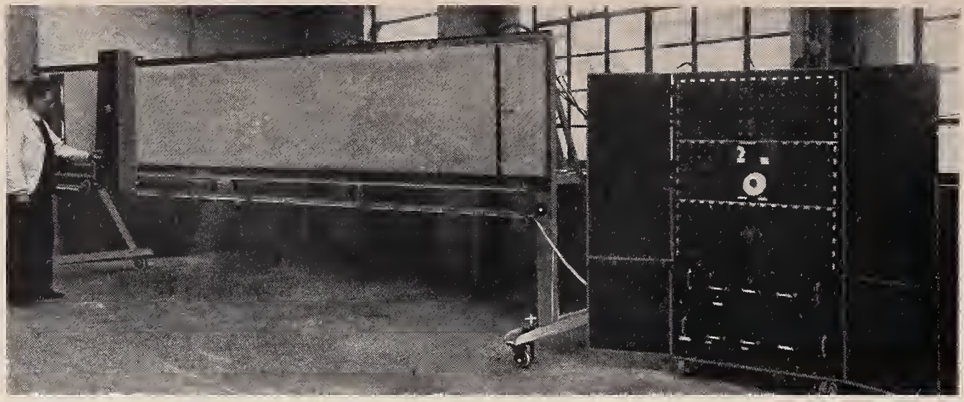

FIGURE 10. *Large plotting-board recorder, chart 25 in. by 120 in. (Mullard Co.).*

by the friction of the chart in the guide, and by the variable load of unrolling and rerolling long charts. The time scale is much better maintained by using small synchronous motors. Many recorders have a combination of both systems; the synchronous motor, besides driving the chart, winds the spring of an auxiliary clock to move the chart in case of power failure for periods ranging from minutes to hours, so that no part of the record is lost.

For high chart speeds constant speed can be maintained only by rather powerful motors. If the high speed is needed only for a short time, we have the problem of high accelerations. If the inertia of the driving motor is high, the motor is usually kept running all the time, and the start signal couples the chart drive to the motor through a high-speed clutch. Accelerating the chart within small fractions of a second may cause the driving sprokets or needles to tear the paper if it comes from a heavy supply roll. This is avoided by using friction rollers to move the chart.

a. Quick Trip Attachments

In one design of disturbance recorders [31] an auxiliary motor runs continuously. When a disturbance occurs, a relay is actuated and the motor is shifted into high gear by a powerful spring. The chart then runs at 3,600 times its slow speed, inches per second instead of inches per hour. Generally the disturbance is eliminated after 24 sec, and the previous low chart speed is then reestablished with the normal time scale. If the disturbance should persist, a second or third high-speed cycle of 24 sec is started.

In one oscillograph design [32] a stationary supply drum with about 120 ft of photographic paper is put in place and the length desired for the next run is pulled out and folded loosely in a lightproof container (fig. 11). To start the paper a motor-driven roller is pressed against the chart, accelerating it within a few milliseconds to speeds up to 30 fps. For tests of long duration the chart is taken directly from the storage drum and the speed is limited to 15 fps.

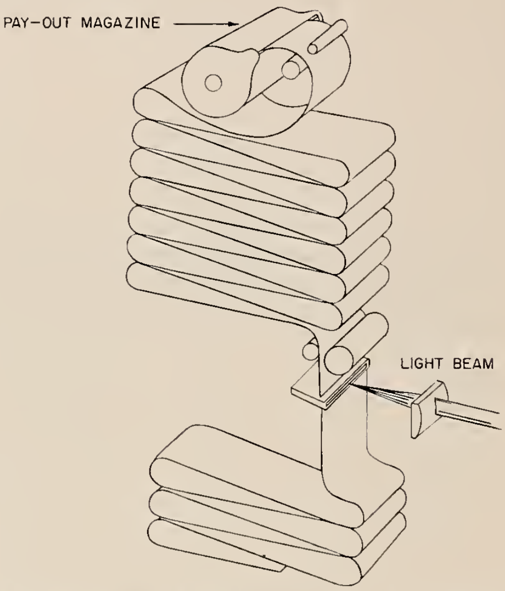

FIGURE 11. *Chart storage for quick trip (Siemens & Halske).*

b. Discontinuous Movement

When an ink recorder operates under a continuously fluctuating signal, the diagram will not be a line but a more or less broad zone of ink. Heavy damping is not a satisfactory solution, because deflections of very short duration would then not be recorded. It has been suggested that if the drive advanced the chart in jumps, say about 0.03 in. every 2 min, a shaded diagram would result which would dry much sooner and require less ink.

Another type of discontinuous movement of the recording surface has been used in the strain-gage scratch recorders described in section 5.3. Here the stylus is operated in such a way that with each deflection the metal "chart" shifts a fraction

[31] Esterline-Angus Co., Inc., Indianapolis, Ind.
[32] Siemens & Halske, Karlsruhe, Germany.

of a millimeter. Of course, there is no time scale for such a recorder; it can show only the total strain during the time the recorder was used.

A jumping movement of the chart or tape is used by most digit-printing devices, moving the chart either at regular intervals or whenever a recording has been made.

While most recorders of variable phenomena move the recording surface as a function of time, in X–Y recorders it is moved in proportion to a second variable.

c. Logarithmic Movement

Chart travel proportional to the logarithm of time is desirable for test recorders, especially for fatigue testing under vibration, constant load, or high temperature. Such experiments are generally conducted for 1,000 or even 10,000 hr, and the changes over the first 10 hr are very important. To record the whole test for 1,000 hr at constant speed on one chart of reasonable length, such as 40 in., the first hour would correspond to only 40 mils. If, however, the chart scale starts with 0.01 hr (36 sec) and has a logarithmic time scale with 5 decades, the first 10 hr are spread out to 24 in.

In a logarithmic chart drive for a fatigue test recorder [33] the drum is rigidly mounted on the shaft 2 with the arm 1 (fig. 12). Driving members are the several wheels 3, geared together so that each wheel is driven at a fraction of the speed of the preceding wheel in the direction of the arrows. Each wheel has a wedge-shaped rim. The outer edge 4 of the arm 1 engages the wheels 3 in turn and thus rotates shaft 2. The edge 4 is so shaped that when the trailing end 6 leaves one wheel at a point adjacent to its axis the leading edge of 1 is just beginning to engage the next wheel. The logarithmic movement is provided by the shape of the edge 4.

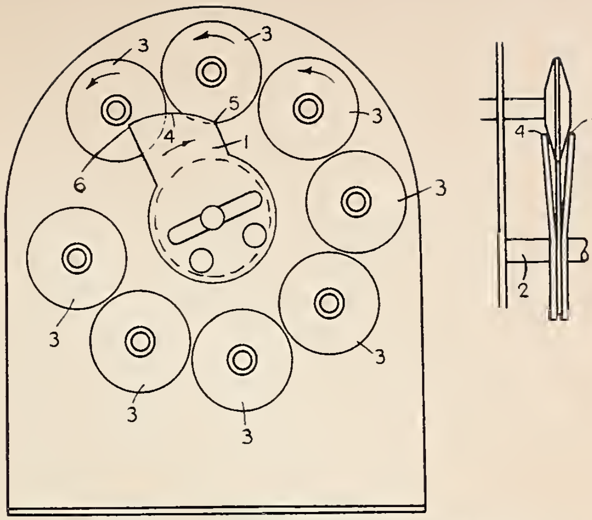

FIGURE 12. *Logarithmic chart drive (Salford Electrical Instruments, Ltd.).*

Recorders with this relatively simple friction drive for the drum are manufactured [34] with a total ratio of 1 : 10,000, say 40 to 400,000 sec (4.6 days). Such recorders, although first used for fatigue tests, are desirable for life tests of many electrical devices, e.g., lamps, heaters, resistors under load, switches (contact resistance change). The solution mentioned is not the only one; there are electrical as well as different mechanical methods to get a logarithmic time movement.

4. Inked Traces

4.1. Continuous Traces

A continuous line drawn by pen or pencil is the most common method for recording only one magnitude, but it is also used for recording two or three magnitudes.

a. Pencils

In steam-engine indicators, the first recording instruments, used commercially in England about 1796, a "lead" pencil recorded a line on white paper. For this type of recorder the dry stylus is still used for very-high-speed engines, probably because ink cannot be supplied fast enough to follow the rapid movement. In modern indicators the stylus is of silver or a soft silver alloy, recording on very glossy paper to reduce the friction errors to a minimum. With all these recorders the stylus has to be replaced frequently.

b. Ink Holders on Pointer

Ink recording provides clearer marking and at the same time less friction than pencil, and for this reason it is used in most industrial recorders, although it too has its shortcomings. J. Sharp and F. G. Schreyer discuss the application and maintenance of pens.[35] Pens are of several forms; very common is a V-shaped reservoir (fig. 13) at the end of the pointer, containing from ¼ to 1 cm^3 of ink. The bore of the V-pen point is rather fine, only about 3 mils. Recorders having high driving torque can use the fountain pen (fig. 14) or the bucket pen (fig. 15) which hold a month's supply of ink. Several years ago pens were made entirely of metal. More recently pens of glass or plastic with a metal tube inserted at the tip are used. With proper care and protec-

[33] Brit. Patent 438 720 (H. C. Turner and T. C. Nuttall, 1934).

[34] "Logtime" recorder, Salford Electrical Instruments, Ltd., Salford 3, Lancs., England.

[35] Instrumentation 1, 26–27 (Sept.-Oct. 1944).

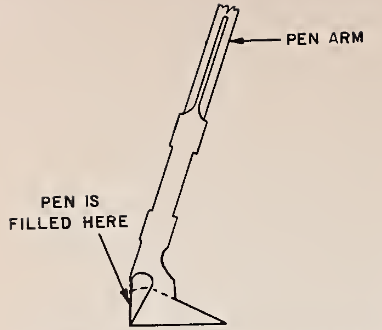

FIGURE 13. *V pen for self-operated recorders (Brown Instrument Co.).*

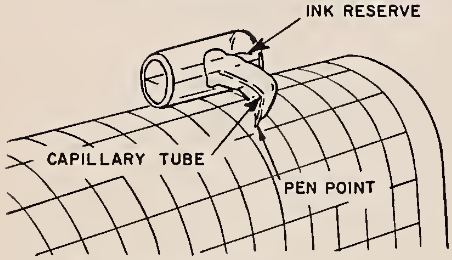

FIGURE 14. *Fountain pen for motor-operated recorders (Brown Instrument Co.).*

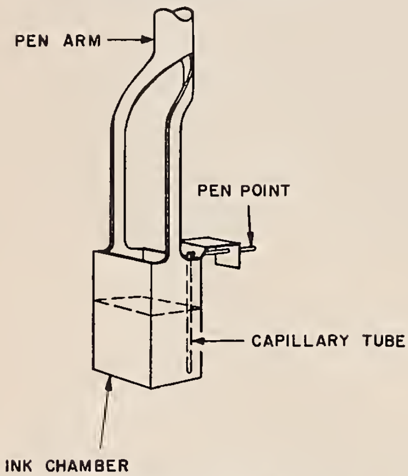

FIGURE 15. *Bucket pen with short capillary (Brown Instrument Co.).*

tion from exposure to dust, a pen with ¼ cm^3 capacity and a 3-mil bore is able to draw a line 12,000 in. long, the equivalent of 2 to 4 weeks average use. With a larger opening, say 5 mils, the pen can record more rapid pointer fluctuations, writing a continuous trace with a line speed (not chart speed) up to 20 in./sec and a total line length of about 2,000 in.

Recorders for industrial plants are generally built with the recording surface vertical. If the pointer moves in a vertical arc, the varying amount of ink in the holder at the end of the pointer causes a position error which depends on the ratio of the ink weight to the torque of the instrument.

Ballpoint pens of special design with a smaller, shorter reservoir are used in some recording instruments. Much more pressure has to be applied than for ordinary pens and it is necessary that there be a movement of at least 3 mils between the chart and the ballpoint to get a visible trace.

c. Capillary Pens

To avoid frequent refilling and the error caused by a variable ink reserve, most modern ink recorders of the angular deflection type use a fine capillary tube which moves with the pointer about a vertical axis and carries the ink to the paper from a fixed well (fig. 16). The designer has to locate the pen point slightly above the level in the well to avoid siphoning the ink when the chart is stationary. With a capillary pen the friction of the ink in the long capillary tube retards the flow of ink needed for fast writing. Therefore, capillaries for high-speed test recorders (e.g., inking oscillographs) have to have much larger bores than capillaries for low writing speeds. The maximum linespeed with capillary pens is of the order of 100 ips. With the Dreyfus ink oscillograph,[36] using a capillary pen in which a variable constriction establishes higher ink flow for higher amplitudes, the line speed is as high as 400 ips.

[36] J. A. Dreyfus-Graf, Geneva, Switzerland.

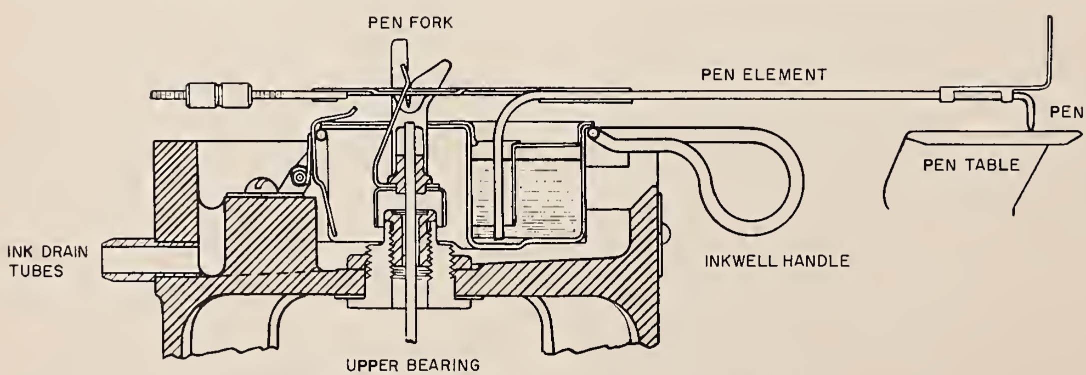

FIGURE 16. *Capillary pen and reservoir (Esterline-Angus).*

A number of solutions of the problem of ink spillage in transport have been devised. One design [37] has for each capillary pen an ink sac of plastic transparent material, sufficient for 1 yr of continuous operation. Another [38] uses a heavy plastic throw-away inkwell holding 3 oz of ink and a metal capillary pen which dips into the inkwell at the axis of the moving element, so that an opening of $\frac{5}{32}$ in. in the well is sufficient to allow movement of the pointer. In one design of capillary pen [39] the ink duct is enclosed in a tube of larger diameter to form a closed annular chamber. A small orifice connects this to the ink duct, so that the liquid inertia and the pneumatic compliance constitute a dynamic filter which is intended to eliminate the spattering of ink. The ink supply is a sealed transparent cartridge, punctured by vent and outflow needles upon insertion.

d. Ink Jets

An ink-recording oscillograph which uses a high-pressure stream of ink was recently invented by Dr. Rune Elmquist of Sweden [40] and described by him in a private communication to the author. The moving system (fig. 17) consists of a conducting loop between the poles of a permanent magnet, as in mirror oscillographs. A capillary glass tube ending in a very fine nozzle of only 0.01 mm (0.4 mils) diameter is fastened to the loop and fed with liquid ink at the very high pressure of 200 to 750 psi. When an electric current flows in the loop, its two sides are oppositely deflected, rotating the nozzle and so deflecting the line on the chart in proportion to the current. In this way a pointer with a very small moment of inertia is obtained, resulting in a very high natural frequency for the moving element.

[37] Bailey Meter Company, Cleveland, Ohio.
[38] General Electric Company, Schenectady, N.Y.
[39] Massa Laboratories, Hingham, Mass.
[40] "Mingograph", Elema Company, Stockholm-Hagalund, Sweden.

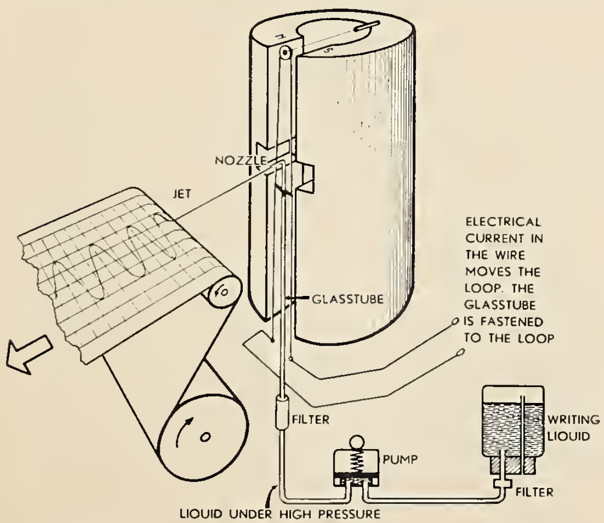

FIGURE 17. *Ink jet with high pressure* (*Elema Co.*)

The jet hits the moving chart at a distance of 20 or 40 or 60 mm, depending on the choice of the customer. The long beam, of course, is for wide charts (50 to 90 mm). A line with a width of only 0.03 to 0.05 mm is traced with a total amplitude of 15 mm at 1,000 cps and chart speeds up to 1 m (40 in.) per second, giving line speeds up to 30 m (1,200 in.) per second. The maximum deflection angle is ±35°. When several measuring systems are used side by side spaced at 25 mm, the jets can cross each other without interference. The record is correct within ±1 percent up to 500 cps, even without frequency compensation common in other ink oscillographs. An important advantage of the system is that it gives diagrams in rectilinear ordinates without the use of linkages, while most other direct-inking oscillographs have curved ordinates. The error that would occur because the recorded deflection is proportional to the tangent of the angular displacement is greatly reduced by the fact that the galvanometer response is a partially opposing function of the angle. Further reduction is achieved by an amplitude correction network in the amplifier.

This recording system is not quite as simple in operation as it may appear at first sight. The trajectory of the jet in air has to be considered and this may cause a slight distortion of the curves from their true shape. This effect of air resistance has been called by Dr. Elmquist the "pacemaker effect." It occurs when the recorded frequency is so high that a great part of the ink for the cycle is on its way from nozzle to paper at the same time. Fluid particles forming the extremes of the curve are bunched closely behind one another so that the air resistance to those at the rear is less than for forming the zero passages, which travel side by side. Therefore the extremes of the curve are slightly advanced in phase in comparison with the zero passages. This error is hardly recognizable for frequencies up to 500 cps, but becomes visible at frequencies of 1,000 cps.

Another possibility of error is in the lag of the recorded point behind the nozzle direction. This error decreases with the ink pressure, and for this reason the ink pressure can be regulated between 150 and 900 psi in the latest designs. The standard pressure is 300 psi. Most of this pressure is used for overcoming the resistance of the capillary and only about 90 psi remain for accelerating the jet at the nozzle to about 35 m/sec. This speed provides a very satisfactory trace with the above-mentioned line speed of 30 m/sec.

As mentioned, the line is much finer than with other ink recorders using ink vessels or capillaries. Sometimes the user considers heavier lines to be desirable, e.g., in electrocardiograms. This is accomplished by superimposing a small 2,000 cps voltage on the variable emf of the electrocardiograph system. The line is heavy (0.5 to 1 mm) at zero but increasingly fine for deflections from zero.

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A similar ink-jet recording system has recently been developed.[41] For this recorder, which has the same 0.01 mm nozzle, the natural frequency of the system is around 700 to 800 cps, the length of the jet is 50 mm, and the maximum deflection on the chart is 30 mm, corresponding to an angular deflection of ±18°. The deviation from linearity of deflection between the middle and the maximum is only 4 percent. Up to 7 recording systems are supplied from a 100-cm³ container of nonfading ink. Each jet system uses 1 mm³ of ink per second, so that the supply is capable of 4 hr of uninterrupted recording of 7 curves. The pump is started and stopped with the chart, and the line thickness can be regulated by changing the pressure. It is claimed that the nozzles do not clog even when the recorder is not used for many months.

e. Gas Jets

Instead of using ink flow from a capillary tube attached to the deflection system, a fine stream of gas, e.g., hydrogen sulfide, may be moved over a chemically prepared surface. This method has been used for recording seismometers.[42] The chart must be kept moist, as with electrolytic recording papers. The disadvantages are that the gas may attack other parts of the recorder and that it is foul-smelling. Nevertheless, the method must be mentioned as one of the frictionless means of recording.

f. Electrostatic Inking

If a capillary pen is used which does not touch the chart (in this way eliminating friction) and if a high voltage is applied between pen and paper, charged particles of ink are drawn out onto the chart. With the voltage continuously applied, a line tracing is obtained, the ink flowing out in a steady stream. With the voltage applied in pulses, a dotted line which resembles a chopper-bar recording is obtained (section 4.2a). Surface friction is eliminated, but electrostatic forces may cause errors. On this account the method is used only for movements with rather high torque, and for facsimile recording[43] where minor deviations are not important. See section 13.8 for other electrostatic methods.

g. Carbon Paper

This method is used in an inexpensive electrocardiograph[44] (fig. 18). Two moving paper strips are used. The transparent record strip *e* running over fixed prism *f* is marked by the pressure of the recording arm *b* against a strip of slowly-moving carbon paper *d* between *b* and *e*. The trace has a thickness of about 0.1 mm with rapid fluctuations, and 0.3 mm with constant deflections. A high-torque measuring system is necessary for this type of recording, but no data are available as to the actual torque used. To reduce friction, 50 cps dither is superposed on the direct current of the measuring system.

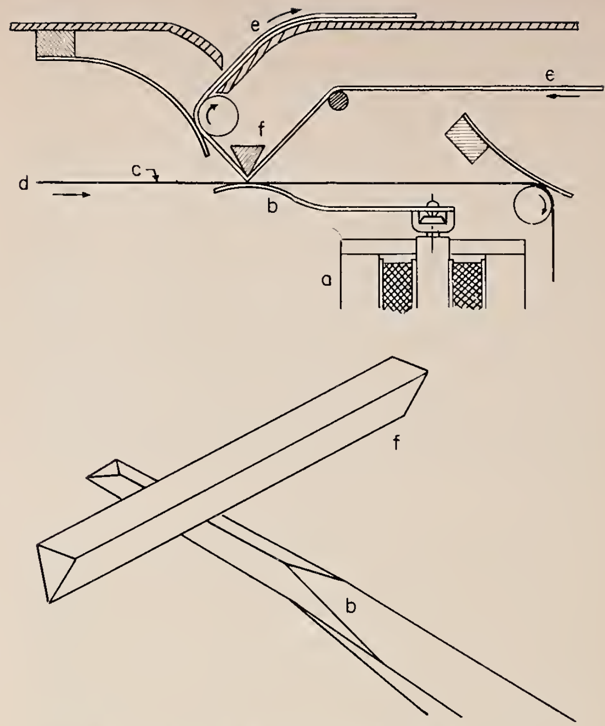

FIGURE 18. *Carbon paper for continuous line diagrams (Schwarzer, Munchen Posing).*

a, Measuring system; b, recording arm; c, carbon-coated side; d, carbon paper strip; e, record paper strip; f, fixed prism.

4.2. Dotted Traces

a. Chopper Bar

The immediate impetus for the development of this type of recorder was the low torque of electrical instruments for measuring temperature. In chopper-bar instruments the pointer swings free a few millimeters above an inked ribbon or thread suspended close to the chart. At regular intervals (generally every 5 or 10 sec for low-torque instruments) a bar is depressed against pointer, ribbon, and chart, marking a clear spot with a diameter of about ½ mm. From 1900 to about 1920 this was the standard instrument for recording temperatures; in Europe it is still widely used. Until recently the chart width of these chopper-bar recorders was limited to 5 or 6 in. A recent development[45] for temperature measure-

[41] "Cardirex," Siemens & Halske, Karlsruhe, Germany.
[42] C. Mainka, Z. Instrumentenk. 1, 195 (1920).
[43] U.S. Patents 2 143 376, Hansell to RCA, and 2 173 741, R. J. Wise et al. to Western Union.
[44] Schwarzer, Muenchen Pasing, Germany. See K. H. Gaeth, Radio Mentor, 1949, p. 095, 096.
[45] Joens Company, Duesseldorf, Germany.

ment, using a high-torque indicator with a straight-line linkage, has a 10-in. chart with a chopper bar operating up to 60 times per minute.

A special application of the chopper bar in this country is an "inkless recorder," [46] (fig. 19) designed for power-station measurements (amperes, volts, kilowatts). These instruments use standard typewriter ribbon, have high-torque measuring systems, can be exposed to extremely low and high temperatures in outdoor use, and need service only at long intervals. In this application the recording interval may be much shorter than for temperature work, and instruments of this type have been built with chopper-bar oscillation up to 10 strikes per second. The standard design strikes once per second.

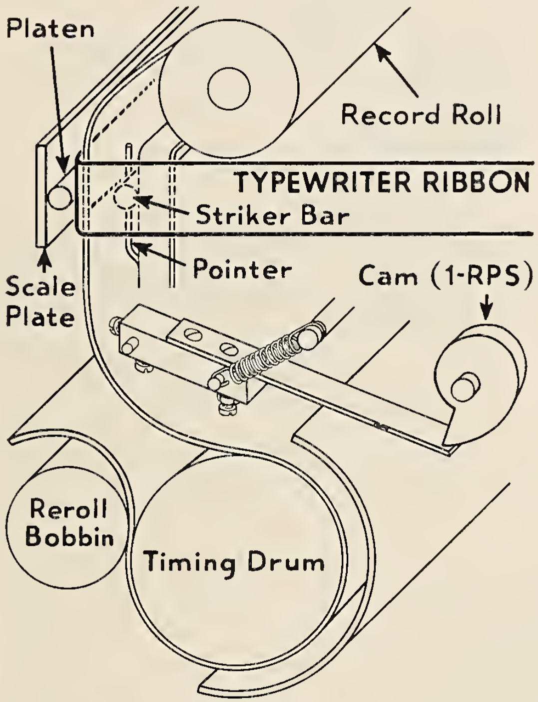

Figure 19. *Chopper bar and typewriter ribbon (General Electric Co.).*

b. Hammer

Hammer recorders differ from the type described in section 4.2a in that they do not have a chopper bar which reaches across the full width of the chart. Instead there is a single small hammer held in a carriage which is moved by a null-motor system in synchronism with the balancing element, and arranged to strike when the balance point has been reached. Figure 20 shows a design used for multicolor recorders.[47] Under the

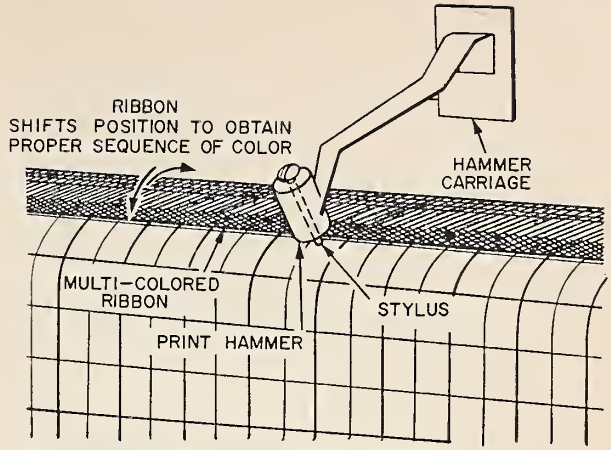

Figure 20. *Print hammer (Brown Instrument Co.).*

hammer is a 6- or 8-color ribbon which is shifted to obtain the proper sequence of colors, and at the same time moved across the chart so that with each blow of the hammer a freshly inked surface is used.

Such a printing hammer can be built with a smaller moment of inertia than can a long chopper bar, and therefore much shorter recording intervals can be obtained. It is easy to operate such a hammer with a timing accuracy of one millisecond, and with an energy of only a few milliwattseconds, as obtainable from a capacitor discharge. Hammer mechanisms as used for other recorders of the digit-printing type (section 4.3) have been built to get an actual timing accuracy of better than 0.3 msec. Such fast operation is required for high-speed recorders. One manufacturer estimates that the actual duration of impact is probably of the order of 0.01 msec. Used in a sweep-balance recorder, this would allow a sweep period of only 10 msec with a tolerance of 0.5 percent of the sweep period.

c. Multicolor Inking

In an early European design of a multicolor recorder [48] a horizontal wire pointer was used. Between indications, the end of the pointer was dipped into one of six small ink vessels. Then the pointer swung to the position which indicated the temperature, a chopper bar pressed it against the paper and all ink was transferred to the chart. This provided dotted traces in six clear colors.[49]

In another design [50] an assembly of six pens was arranged horizontally and moved across the chart by a small motor, revolving 60° after each recording to print in a new color. The cycle was completed in 3 min.

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[46] General Electric Company, West Lynn, Mass.
[47] Brown Instrument Company, Philadelphia, Pa.

[48] Paul Braun Company, Berlin, about 1910.
[49] G. Keinath, Elektrische Temperatur-Messgeraete, p. 199–200, R. Oldenbourg, Munich, 1923.
[50] R. Hase, Elektrotech. Z. 50, 1301–02 (1929).

In a modern recorder design[51] (fig. 21) there are six conical pens, *a*, arranged around a pen wheel, *b*, and six felt pads, *c*, each impregnated with a colored ink; both sets rotate in synchronism with the switching of the measurement points. To print, the single pen arm swings over to the pen wheel and picks up one of the six pens. A tiny but powerful Alnico magnet is used to set the pen precisely in the pen arm and to hold it firmly in place. After this color is printed the arm swings back and replaces the pen. Contrary to earlier instruments of the direct deflection type, this one has a very high torque, because it is operated by a null-motor mechanism. The time for recording all 6 colors is 36 sec.

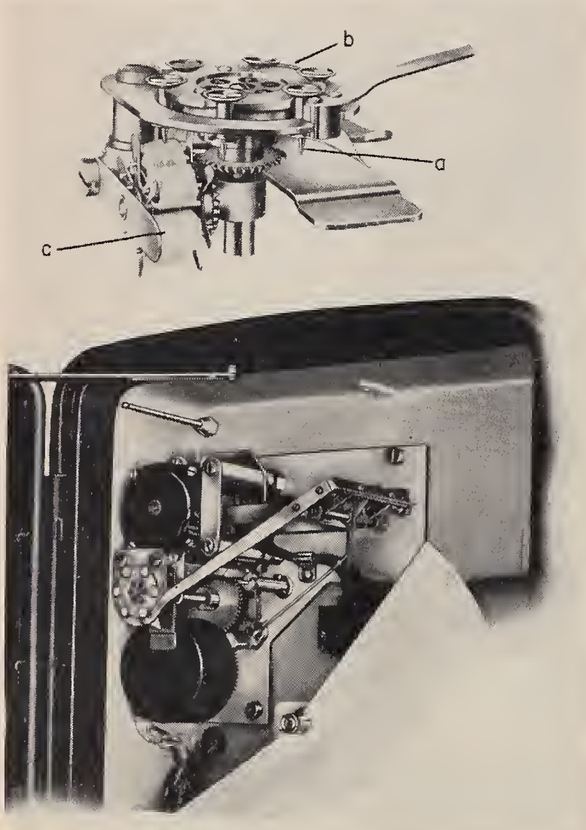

FIGURE 21. *Six-pen six-color unit (Foxboro Co.).*

Another recent design[52] also used in a high-torque null-motor instrument has a "turret-pen" assembly. There are six capillary pens and six reservoirs of different colored inks. The whole assembly hangs at the end of the instrument pointer and is moved away from the chart after each printing. It is returned to the chart after the pointer has taken up its new position, and the next pen, having been positioned by rotation of the turret, is pressed gently but firmly against the chart. Six points are recorded in a 30-sec cycle.

d. Print Wheels

Print wheels are used generally for multipoint recording, in 1 to 8 colors. They receive ink from a set of rotating pads (fig. 22) rather than from typewriter ribbons. There are two main parts, the print wheel proper, carrying 12 or even 20 characters, and the ink-pad wheel. The two are connected mechanically so that the proper synchronism between type and color will be maintained. The whole assembly rides across the scale on a drive shaft, as used in most servo-motor recorders.

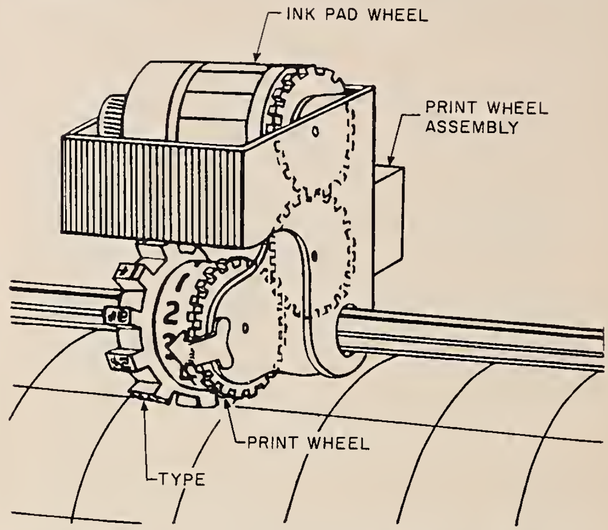

FIGURE 22. *Print wheel with synchronized inking pads (Brown Instrument Co.).*

The recording mark usually consists of a dot with a number beside it. While a dot needs only about 0.3 mm of chart movement to be clearly distinguishable from the next one, a separation of nearly 2 mm is necessary when numbers are printed beside the dot. If 2 mm is allowed for each point, and one plotting every 2 sec, the 24-hr chart would be 284 ft long. To avoid this, most such recorders include a device which prints a number only with every sixth or tenth point.

A schematic view of a print-wheel arrangement developed recently[53] for potentiometric null-motor recorders is shown in figure 23. The whole print mechanism is moved by the coupling wire 3 over the guide rod 4 to meet the balance point of the potentiometer. By using an impulse current to swing the rail 6 about rod 4, one of the six pins on the print wheel 1 is pressed to the chart surface 5. Between recordings the wheel 1 is indexed by gears 7 and the pins are successively pressed against the six varicolored ink pads of the drum 2.

[51] "Rotacolor Dynalog" of the Foxboro Company, Foxboro, Mass.
[52] Fielden Instrument Div., Robertshaw-Fulton Controls Co., Philadelphia, Pa.
[53] Siemens & Halske, Karlsruhe, Germany, and Hartmann & Braun, Frankfurt am Main.

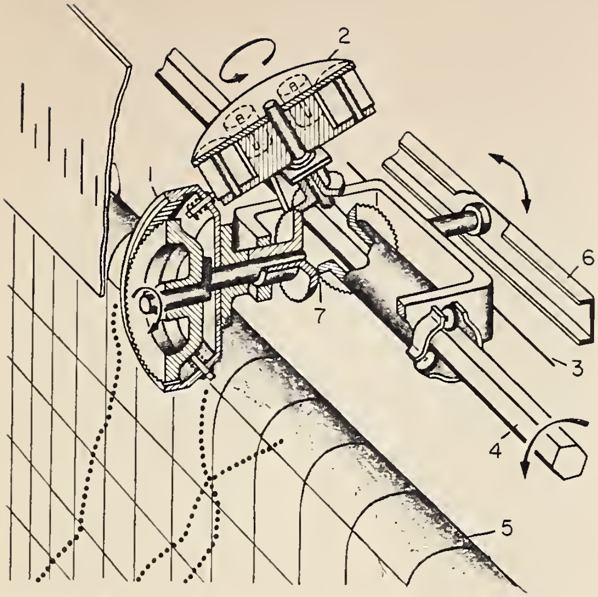

FIGURE 23. *Print wheel with synchronized inking pads (Siemens & Halske).*

e. Fixed Styluses

The successful use of microsecond pulse techniques for digital computation has led to their application in analog recording also (fig. 24). A row of styluses is fixed across a strip chart, and an electric discharge provides a mark at the desired point, as described in section 13.5. One recent design [54] uses 256 or 630 styluses, permits marking at a rate of 24,000 times a second and gives an accuracy of 0.2 percent when calibrated lines are continuously drawn by each tenth stylus.

[54] "ADAR" system of Radiation, Inc., Melbourne, Fla.

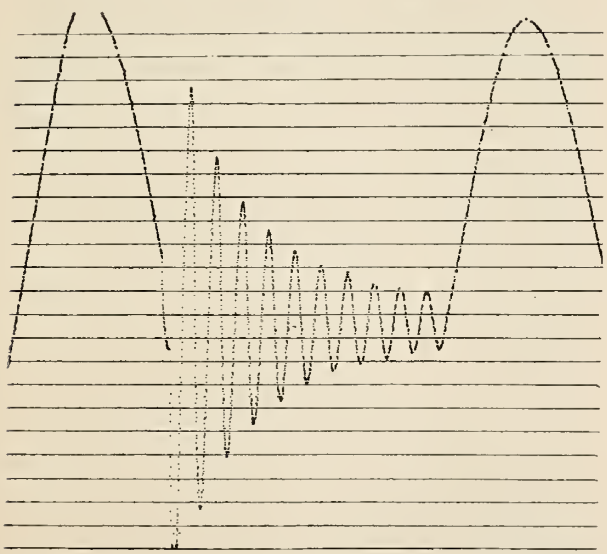

FIGURE 24. *Analog record from fixed styluses (Radiation, Inc.).*

4.3. Digit Printing

Most recorders trace a line or dot a curve, following the fluctuations of the variables under test, and give in this way a picture of the operation. When, however, the recording is needed for computing or accounting, e.g., determining the number of kilowatt-hours used or the number of objects manufactured in certain time-intervals, it is desirable to have the reading of one variable printed in a single column. With mechanical counters, digit printing is the simplest and least expensive way of recording. It also provides more precise readability than a line-tracing recorder, which is in many cases not better than 0.5 or 1 percent of the maximum. With three digits, giving a maximum of 999, we have a resolution or potential accuracy of 0.1 percent.

A fundamental theorem of information theory, due to C. E. Shannon, states that a time function is completely determined when the sampling rate is twice as high as the highest frequency contained in the function.[55] Hence, the digital value of a fluctuating variable must be printed out at least twice as frequently as the highest frequency to be observed. With intermittent scanning that is relatively slow, the potential accuracy is realized only for a cumulative discrete count or a longtime integration.

The speed of mechanical devices is limited by the amount of inertia of the moving parts. However, 15 characters per second are easily possible with a type wheel and print hammer. Higher speed is possible with optical recording of the position of the count wheels by light flashes.

For recording more than one variable, there are two possibilities. One is to make the recordings all in one column on tape, one after the other. In this case it is necessary to print not only the reading, but also the time and identification of the transmitter. This makes it rather difficult and time-consuming to follow the variations of one specific condition, although this can now be done with new mechanical readers. In considering digit printing from coded recording, the primary recording, say on magnetic tape, can be done at speeds of perhaps 100 measurements per second from each of 200 transmitters. However, the withdrawal of the data from one of the variables takes much more time, because it may be necessary to scan millions of readings to find those wanted.

The other way of recording a great number of variables in digits is multi-columnar. Here, a strip chart or loop, 10 to 30 in. wide, is used, with preprinted designation of each column as to indicating point, units of measurement, and scale factor. One recorder of this type [56] has a chart width

[55] M. L. Klein, F. K. Williams and H. C. Morgan, Instr. and Automation 29, 1519–24 (1956).

[56] "Panalog" of Panellitt Co., Skokie, Ill. R. J. Marmorstone, ASME paper #55–IIRD–13, abridged in Instr. and Automation 29, 890 (1956).

of about 26 in., and types up to 72 readings of 3 digits in a line across the chart in about 1 min. With 3 segments on a chart 26 in. wide and 40 in. long, 216 variables can be recorded. Under normal conditions, each variable is printed once an hour with up to 12 intermediate values available on demand. Thus each variable appears in one vertical column; abnormal conditions are printed automatically in red at the bottom, identified by time and transmitter number.

The digital log recorder is a radical change from the conventional methods of supervision by a large number of indicating or recording instruments tracing line or multipoint diagrams. It is an important step towards centralization of supervision, giving the data from many transmitters all on one chart in much less space. Multipoint recorders can show momentary variations, but one must usually examine long strips of chart with criss-crossed traces to get an over-all picture for any single variable. Even the digital logger with its long-interval printing presents thousands of readings from a day's operations, and such a chart will always require study to make intelligible the interrelations of all the variables concerned. The combination of a small-diagram multi-recorder for all variables to give a comprehensive picture of the operation, with a digital logger recording either the most important variables or those required for computation and billing, may be the final solution. Neither instrument alone can fully meet all requirements of plant supervision.

Scratch recording has been used in many applications where ink recording is not acceptable either on account of the difficulty of refilling the ink reservoirs, or because an inked line is too wide in comparison with the maximum deflection expected.

5. Incised Traces

5.1. Smoked Surfaces

This is probably the oldest technique for scratch recording. In the earliest designs, soot from a smoky oil flame was deposited on a glass or metal surface or on glossy white paper, generally just before the chart was put in the recorder. Today special smoking torches are available.[57] Strip charts with a coating of soot particles are also obtainable in rolls—the layers separated by thick border strips.

To prepare charts in the laboratory the paper is first coated with lacquer, giving it a very smooth surface to reduce friction of the stylus, which is usually a fine steel wire with a round polished point. The pressure of the stylus on the chart may be as low as 1 mg, which is about one-tenth of the pressure needed for ink recorders. To produce the smoke, kerosene with addition of turpentine or other ingredients, or wax candles are used. When no special precaution is used, the soot is rather coarse and the recorded line will not be finer than 0.1 mm. With special care it is possible to get very fine lines by burning liquid fuel from a wick. According to Eldrege[58] it is possible to trace 50 lines per millimeter, with a line thickness of about 10 μ (0.01 mm). With a first-class surface, these smoked chart diagrams need be magnified only about 10 times for reading, to a line thickness of 100 μ. To preserve the diagrams for storage, they are fixed with a spray of lacquer or dipped in a fixing solution. In some special recorders foils of aluminum or copper have been used as the base for the soot.

In a modern design of a direct recording oscillograph[59] a cellulose acetate film of 35 to 60 mm width is used. Here the surface is coated with a very fine layer of black varnish which after treatment with a plastic spray can be handled without damaging it. The stylus for this recorder is of very hard material and leaves a trace only 0.01 to 0.02 mm wide. The normal amplitude of the oscillogram is only about 1 mm. For reading, the diagram is magnified 20 or 50 times.

5.2. Waxed Surfaces

The base is generally a dark paper (red, blue, or black) coated with a thin layer of fairly opaque wax. This layer is penetrated by a fine needle at the end of the pointer, so that lines of the color of the base material become visible. This method is used in an inexpensive electrocardiograph.[60] If it is necessary to make blueprints of the curves, a thin transparent base paper is used, and the wax coating is either red, orange, or black. Some papers have the graduations and time divisions printed by impression on the wax coating. For recording with rather low chart speed the marking may be made by vibrating a fine needle point at high frequency against the surface.

One line of wax-coated papers is manufactured in 11 types and 6 colors.[61] The melting point of the coating is 140° F, and a pressure of 0.25 oz is necessary to produce a legible record line.

5.3. Metal and Metal-Coated Surfaces

A very simple all-mechanical strain recorder was designed by A. V. deForest[62] for the record-

[57] Gorrell & Gorrell Company, Haworth, N.J.
[58] K. R. Eldrege, Rev. Sci. Instr. **21**, 199 (1950).
[59] Compagnie des Compteurs, Paris; Acton Laboratories, Inc., Acton, Mass.
[60] The "Cardiostat" of Siemens & Halske, Karlsruhe, Germany.
[61] Waxon-Carboff Co., Rochester, N.Y.
[62] Formerly manufactured by Baldwin Locomotive Works, Philadelphia, Pa. Production now discontinued.

ing of deformations between 0.1 and 50 mils over a 2-in. gage length. The record is in the form of a scratch which indicates the exact value of the deformation. The whole gage weighs only two grams. It consists of two parts: one, the target, which is polished and chrome-plated; the other, the scratch arm tipped with abrasive held in a rubber matrix. The special feature is the method of advancing the "chart," which depends not on time, but on the difference between the coefficients of static and moving friction.

Referring to figure 25, the scratch arm is pressed upon by the friction bar, which is part of the target, so that considerable friction is obtained. The extremes of the two parts are screwed or soldered in place across the gage length to be tested, with the arm in the center of its travel. The arm is then moved to one side or the other by hand, which simultaneously establishes the zero and sets up a restoring force in the fulcrum spring. The friction is sufficient to retain the arm while there is no deformation, but when strain occurs, the force of spring S causes arm A to return slightly towards the center with each elongation or contraction of the test length. Some force is required to overcome the friction between A and B, but this is negligible in comparison with the total force available.

In this device the record may consist of a number of scratches parallel to each other. One of these is selected for measurement and the rest disregarded. The diagrams are viewed at 250 magnification with a metallographic microscope, and photographs can be made up to 1,500 magnification. A later development is the half-target which may be renewed as desired.

Gold-coated glass was used [63] about 20 years ago for a direct-writing electrocardiograph. The amplified current was recorded with a fine needle driven by an electromagnet similar to that in a loudspeaker. The diagram had about 8 mils amplitude, with a line width apparently about 3 μ. After the recording, the glass slide could be swung under a microscope attached to the recorder, to give an image 70 times larger.

A recent development of the British Ministry of Supply is a crash recorder for airplanes.[64] The recording surface is a glass disk of about 1 in. diam, coated with a thin layer of gold. The disk is rotated by clockwork, which is released by a shock of 5 g and rotates the disk at the rate of one revolution in 3 sec, after a delay of 17 msec. The pointer of a mechanical accelerometer with a natural frequency of 100 cps scratches a trace from the edge of the disk to the center. The recorder has a total weight of about 500 g, and both it and the record can withstand temperatures up to 400° C.

5.4. Uncoated Glass

Diamond marking on uncoated glass has been developed to high perfection by Pabst and Freise [65] at the Deutsche Versuchsanstalt fuer Luftfahrt for measurements on aircraft. Miniature diagrams can be traced with recorders of extremely small dimensions. The record can generally be recovered even when crash or fire destroys the airplane. Figure 26 shows the cross section of such a recorder. For normal length of recording, its overall dimensions are 40 by 40 by 35 mm, and the total weight is only 135 g. The recording surface, *b*, is a glass cylinder of 25 mm diam and 5 mm length. A diamond point, *c*, is at the end of a small tube, which is connected with the object whose movements are to be recorded. Another diamond point is used to make time markings.

The styluses are ground to a 60° cone. This point traces a line which can be read to an accuracy of 0.001 to 0.002 mm, even under extreme shocks such as occur during landing. With a pressure of 5 g on the stylus, the resistance is 1 to 2 g. The diagram length is 80 mm for a full

[63] Kipps & Zonen, Delft, Netherlands.

[64] Instrument Practice (London) **10**, 53 (1956).

[65] W. Pabst, V.D.I. Zeitschrift **73**, 1629–34 (1929) with more literature references on the subject. H. Friese, Arch. tech. Messen, **Lf. 89**, T151–152 (Nov. 1938) and **Lf. 90**, T160–162 (Dec. 1938); also V.D.I. Zeitschrift **82**, 457–61 (1938).

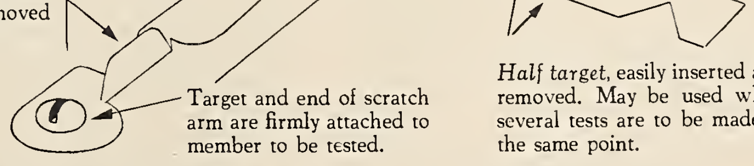

FIGURE 25. *deForest recording scratch gage (Baldwin Locomotive Works).*

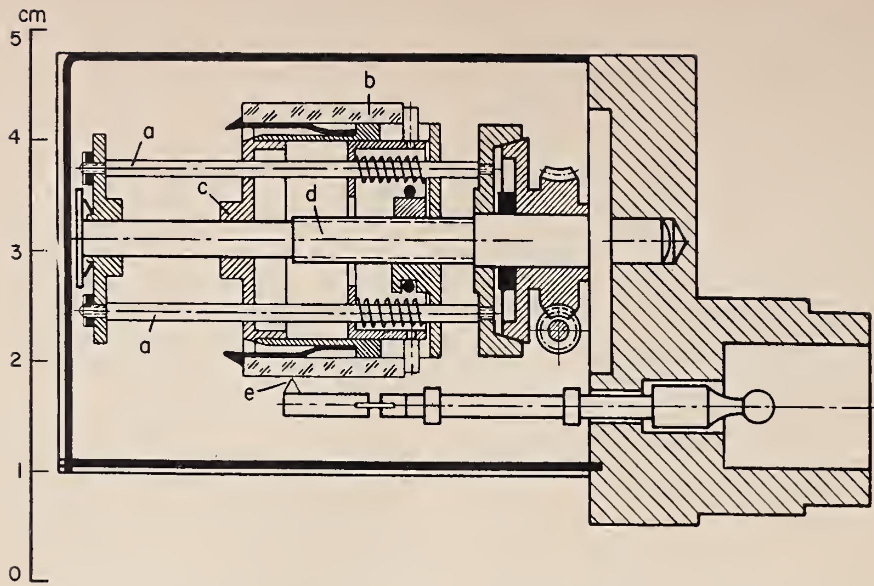

FIGURE 26. *Scratch recorder, diamond on glass cylinder* (*Arch. tech Messen*)
a. guide rod; b, recording cylinder; c, mounting drum; d, threaded spindle; e, diamond point.

revolution of the drum, the amplitude 0.2 to 0.3 mm. Enlarged 100 times, this gives a chart of 8 m length and 30 mm amplitude, and a line thickness of 0.2 mm.

For recording over long periods of time, a longer glass cylinder, which is moved axially 0.5 mm for each of 25 turns, is used. With the standard amplification of 100, this gives an equivalent chart length of 200 m at 60 mm/hr. The weight of the long-time recorder is about 200 g. Auxiliary equipment permits continuous transfer of the diagrams to a photographic enlargement.

6. Impressed Traces

6.1. Plastic Film

An impressed trace, unlike an incised trace which removes material from the surface, merely causes plastic flow of the material under the stylus. It was used first [66] about 40 years ago for recording vibrations on a tape of transparent celluloid, about 1 in. wide and 5 mils thick, with a stylus of fine steel wire having a spherical end of 0.4 to 1 mil radius. Pressing lightly on the celluloid, the stylus causes the film to flow plastically under the point, producing a narrow shallow groove, which can be viewed with a microscope of 6 to 10 magnification. This instrument contains a flashlight battery, a bulb, and a reflecting mirror arranged so that the light is directed up through the film to give the necessary contrast between the record and the background. The width of the impression is about 0.12 mils; this is also approximately the minimum amplitude which can be read.

The line produced possesses optical characteristics entirely different from those of a scratch. When viewed as described the indentation appears as a narrow, sharply-defined dark band on a bright ground, with a still finer bright line in the center of the dark band. When the method is applied to vibration measurement, a total magnification from 100 up to 1,000 times is used.

Celluloid film recording has also been used more recently in this country.[67] With this recorder it is possible to read amplitudes to 0.1 mil; amplitudes over 1 mil can be read with an accuracy of 5 percent.

6.2. Metal Foil

In the flight recorder developed by G. O. Haglund and J. J. Ryan (General Mills, Inc.) to CAA–CAB specifications [68] the recording surface is a roll of aluminum-foil ribbon 2¼ in. wide, 1 mil thick, and 100 ft long. There are 5 styluses,

[66] Cambridge Instrument Company of London.

[67] H. C. Werner, Instr. and Automation 15, 83–87 (1942).
[68] ASME 1955 preprint 55–S–27.

displaced longitudinally, which indent traces 2 mils wide as the foil passes over a platen. Chart speed ranges from 3.2 to 5.5 in. hr, depending on roll diameter, and the record will cover 300 hr. The double-walled case measures 13½ by 16 by 15 in., but the complete instrument weighs only 25½ lb. The record remains intelligible after 100-g shock, exposure to 1,100° C flames for 30 min, or immersion in sea water for 36 hr.

7. Indentation

Recording by indentation provides only *one* reading of one, or in some cases several, variables or conditions. A hard steel or diamond indenter is pressed either steadily or by impact into the surface of a softer material. The volume deformed, and hence either the value of the impressed force or the softness of the material, is indicated by the dimensions of the depression.

7.1. Hardness Testers

For testing hardness with indentation methods, a known load is applied to the indenter to force it into the test surface. There are five common geometries; procedures for three of these have been standardized by the ASTM:

(a) Rockwell, ASTM E 18: based on the penetration depth of a hardened steel ball;

(b) Brinell, ASTM E 10: based on the diameter of such a circular depression;

(c) Vickers, ASTM E 92–57: using the point of a square-base pyramidal diamond of 136° angle, and averaging the diagonals of the depression;

(d) Knoop: described in NBS RP1220 (1939) as a pyramidal diamond with 130 and 172.5° angles, to give a 7:1 ratio of diagonals, particularly useful for thin materials and for distinguishing the directional properties of crystals;

(e) Grodzinski: using the sharp edge of a double-coned diamond of 2 mm radium and 154° included angle.[69]

While the basic principle of the indentation hardness test has been known and used for many years to determine the "macrohardness" of materials under rather heavy loads, the method has been perfected in the last 10 years to determine the "microhardness" of thin layers, needle points, and tiny pinions used in watches, under loads as low as 1 g. To determine microhardness, the pyramidal test can be combined with an optical interference method. A detailed research on this subject has been made.[70]

7.2. Electromagnetic Actuation

British Patent 299 749 (1927) describes an electromagnetic instrument having a coil which attracts an iron core, to drive a cone of hard steel into a material such as annealed copper whose hardness is reasonably constant. An instrument using this principle has been used [71] for recording the short-circuit currents which trip the oil circuit breakers. The indentation is made on a strip of copper, automatically moved forward to a new position after each actuation of the breaker. The diameter of the depression in the copper is an indication of the peak value of the current which has passed through the coil. For such a simple device, high accuracy is not possible and for the application described is not required.

8. Deposition

Deposition of airborne solids on a glass plate for subsequent counting or measurement is well known. The method has been mechanized for measuring the amount of soot in industrial flue gases.[72] A known quantity of the gas is filtered through porous paper tape, so that a deposit is an indication of the ash content of the entire flue. The tape, 35 mm wide, with time markings, is moved with a constant speed of 6 to 12 mm/min.

The same principle has been used in a design for measuring air pollution.[73] In this instrument, air is aspirated at a rate of approximately ¼ cfm through a 1-in.-diam circular area of filter paper which is supplied as tape from a spool. Every 6 hours the tape is advanced 1 in.

An extremely sensitive dust detector and recorder was recently developed [74] for monitoring of film manufacture. Air is sucked through a narrow tube blown at supersonic speed against a thin plastic sheet, and the dust deposited there in a narrow strip. An electric eye reads the density of the deposit and a recorder traces a graph within seconds. According to the manufacturer, the sensitivity is such that if a few mils of fine dust on the head of a pencil are dispersed through an average room the recorder will detect its presence.

[72] E. K. von Brand, Mech. Eng. 72, 479–81 (1950).
[73] W. C. L. Hemion, J. Deane Sensenbaugh, G. F. Haynes, Jr., Instr. and Automation 26, 566–67 (1953).

[69] P. Grodzinski, Sheet Metal Ind. 31, 303–389, 408 (1954).
[70] R. Schulze, Microtechnic 8, 13–26 (1954).
[71] Siemens-Schuckert Company, Berlin.
[74] Eastman Kodak Company, Rochester, N.Y.

A lightbeam, concentrated to a very small diameter and deflected by the variable under test so as to strike a light-sensitive surface, has long been used to record the movement of sensitive instrument systems in order to avoid pen friction. There are many advantages:

(a) Much higher sensitivity is obtainable, because the length of such an optical pointer, generally not less than 8 in., can be almost unlimited.

(b) A much smaller actuating torque is permissible, since the measuring system is not loaded by pen friction.

(c) The amount of inertia of the moving system can be made much lower, resulting in a much higher natural frequency.

(d) The writing speed is much higher than with any ink recorder—as high as 0.6 mps (0.04 in./μsec) for electromagnetic oscillographs, and as high as 6,000 mps (400 in./μsec) for cathode ray oscillographs.

Years ago the crater of an open carbon-arc lamp was necessary to provide the needed intensity of light. In our day smaller and much more convenient sources are supplied by tungsten-filament incandescent lamps or minature arc lamps. The beam of one source can be used for several moving elements, using lenses or mirrors.

In almost all oscillographs the measuring system deflects the lightbeam in proportion to the variations of the measured quantity. There are, however, a few exceptions. In the glow-lamp oscillograph, developed by E. Gehrcke [75] we have a simple instrument with a frequency response up to 100,000 cps. The *length* of the luminous discharge, projected to a moving photographic recording surface, is an indication of the voltage. The application of this instrument to the study of high voltages has been described.[76]

Another exception is the recording lamp of photofacsimile and photographic sweep-balance recorders. This optical system [77] consists of a glow modulator tube with a lens system and an aperture plate assembled into a housing, and so arranged that a spot of light 0.1 to 0.2 mm in diam is provided at the end of the lens barrel. The intensity of the illumination is in proportion to the plate current between the limits of 5 and 35 ma. This light source is operated intermittently in flashes of short duration. Each signal makes a black spot on the chart, representing a black spot on the original of a facsimile recorder, or the balance point of a sweep-balance recorder. The line speed is 20 ips and with the maximum current of 35 ma marks of 0.2 mm diam may be made in 0.4 μsec.

[75] Z. Instrumentenk. 25, 33–37 (1905).
[76] L'Elettrotechnica 23, 40–43 (1936).
[77] Times Telephoto Equipment Inc., New York 19, N.Y. recorders by Times Facsimile Corporation, New York.

9.1. Light-Sensitive Surfaces

The photographic effect on the recording surface is dependent on two factors, either of which must be matched to the other:

(a) the intensity of the light, or electron-beam, which is moved in accordance with the changes of the variable under test.

(b) the sensitivity of the surface to the spectral emission of the light source. Many recording devices require a special paper for the light used (or vice versa).

a. Ordinary Photographic Paper and Film

One company [78] offers 11 different emulsions. The highest sensitivity among these films is obtained with the "Linagraph Pan Film" for blue light, as emitted by cathode-ray tubes. It has an exposure index of 640 for blue light and, according to the manufacturer, it has a line speed of thousands of miles per second. For green light the highest speed is obtainable with Linagraph Ortho Film, with an exposure index of 160. The most sensitive *paper* offered by this manufacturer is Linagraph 1127 with an exposure index of about 250 for blue light, about 20 for green light.

High film sensitivity (speed) is essential in lightbeam oscillographs to allow the use of very small mirrors, low-powered light sources, and large deflections on the chart. For micro-recording the grain size of the emulsion is expressed by the "resolving power" in lines per millimeter. For standard films it is between 50 and 180 lines/mm. This means that for a deflection of 5 mm on the curve the reading accuracy with a film of 100 lines/mm resolution is about 1/500 of the beam deflection, or 0.2 percent of the maximum. Special high-resolution plates and films, as used for spectroscopic analysis, have a resolving power in excess of 1,500 lines/mm.

b. Camera-Processed Film

The Land photographic process,[79] provides a finished positive print 1 min after exposure. Applied to photography of CRO screens, the standard emulsion permits a trace speed of about 1 in./μsec (with a 5-in. P–11 screen, 12,000 v acceleration, and an f/2.8 lens). Recently special emulsions have been developed to compete with the most sensitive conventional photographic emulsions. The highest sensitivity is available with "type 44" with an ASA speed of 400 for daylight and 300 for tungsten lamps. High speed can be used also with types 32 and 42, with 200 daylight and 150 tungsten, while the least expensive of the films, types 31 and 41 still have a sensitivity of

[78] Eastman Kodak Company, Rochester, N.Y.
[79] Polaroid Corporation, Cambridge 39, Mass.

100 daylight and 70 tungsten. All these have a fine grain, especially the new type 43, with a grain so fine that it is not seen at 400 magnification. The time needed for development in the camera is still 45 to 60 sec.

The process involves the simultaneous development of both positive and negative images in adjacent layers of emulsion, the positive image being formed from the unexposed silver halide grains of the negative image. Attached to the strip of printing paper at the head of each frame is a small airtight pouch ("pod") which contains a jellied chemical reagent. After exposure the negative emulsion surface and the positive printing surface are unrolled together from their respective spools and drawn between steel rollers, breaking the reagent container and spreading it between the layers of paper to develop the picture.

The standard print size is 3¼ by 4¼ in., but two or more oscillograph pictures can be taken on one frame. Reproductions are generally made by photocopying the resulting positive. However, it is possible to make a paper negative which may be contact-printed on photographic paper.

c. Color Film

When a great number of curves must be traced on a film and only a minimum of space is allowed, the use of color film has been recommended [80] although it is not possible to get the same high line-speed as with ordinary films. Generally each variable has its own colored lightbeam—four, six, or eight. For intermittent recording of a number of variables with only one lightbeam, the color filters might be inserted in synchronism with the selector switch. Although no description of the second type has apparently been published, the system seems promising, allowing a very high speed of multiple recording with only one measuring system. With 8 variables and 100 recordings per second, the cycle time would be 0.08 sec and for each variable there would be 12.5 points per second. A chart speed of 0.4 ips would be appropriate.

Color films are manufactured by a number of companies, and the latest products have nearly the sensitivity of standard black and white films. However, for storage over years, colors are not fade-proof. Tirk [81] has used seven colors: green, white, magenta, cyan, red, yellow, blue, with six cellophane filters used singly or in combination. The writing speed was 240 ips.

d. Immediately Visible Diagrams

For very low recording speed, when hours are available to trace the diagram, it is possible to use celloidin paper or blueprint paper, with a light source of sufficient intensity. A new paper and the necessary light source, as developed by Heinrich Stabe,[82] allows recording speeds which come near those generally used. In a commercial 4-channel recorder,[83] the light source is a high-pressure mercury lamp with a high output of ultraviolet rays and very high brightness. The photographic paper has high sensitivity for ultraviolet and blue light, but low sensitivity for red light and daylight. For a chart speed of 4 ips the diagram is immediately visible. Recordings made at chart speeds up to 60 ips are possible if the diagram is subsequently exposed to diffused daylight or lamplight for a few minutes. Once visible, the diagrams are not destroyed when handled in indirect daylight or artificial light low in ultraviolet. Over long periods of time, even for years, they can be kept under covers of yellow paper without fading.

Dr. C. A. Heiland [84] developed special emulsions which give an immediately visible diagram when irradiated by either infrared or ultra-violet light. A recorder [85] using such paper is now available. It operates at paper speeds up to 25 ips and is stated to give readable traces at writing speeds up to 10,000 ips.

e. High-Speed Developing

During the First World War the German army used high-speed automatic developing and fixing of the film from moving-coil oscillographs of their sound-ranging equipment. The time between exposure and finished chart was about 10 sec, and of course the record did not have to be durable. A recently available magazine attachment [86] for an oscillograph provides continuous developing of the traces on standard photographic paper in less than 1 sec, and the record is said to be permanent.

There is available [87] a "rapid oscillogram developer" for paper (not film) that develops and dries at speeds up to 12 fpm, handling charts up to 12 in. wide and 250 ft long in 25 min. Four tanks are used: developer, stop-bath, and two stabilizers. The device is portable and can be used on the test site.

Very high speed of photographic film development has been reported for a heat-resistant film [88] used in a facsimile recorder. Eight feet of film are developed in 15 sec at a temperature of 125° F, with a drying time of 25 sec.

f. Photo thermal Paper

There is a reproduction paper, "Kalfax," [89] which uses a new principle. When exposed to

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[80] W. J. Leiss, F. R. Nitchie, B. B. Undershil. Instr. and Automation **20**, 709–11 (1947).
[81] C. J. Tirk, Elec. World, **128**, 76 (1947).

[82] Feinwerktechnik **57**, 198–203 (1953). Arch. tech. Messen **Lf. 215**, 281–84 (Dec. 1953). Z. wiss. Phot. **48**, 19–44 (1953).
[83] "Lumiscript" Rlt 4. Hartmann & Braun, A.G., Frankfurt, Germany; M. E. Gerry & Co., Upper Darby, Pa.
[84] U.S. Patent 2,580,427, August 1944.
[85] Visicorder, Heiland Division of Minneapolis-Honeywell, Denver.
[86] "Datarite," Consolidated Electrodynamics Corp., Pasadena, Calif.
[87] General Electric Co., West Lynn, Mass.
[88] "Ultrafax," developed by Eastman Kodak and RCA. Electronics **22**, 77–79 (1949).
[89] "Kalfax," 714 Gerard St., New Orleans, La.

light, there is a decomposition of the chemicals in the coating. For development of a positive picture, the sheet is heated between rollers. Areas which have not been exposed to light are not changed by the thermal treatment and additional information can be added later in these areas. The sensitivity is said to be comparable to ordinary blueprint paper. The material is now used for contact copies of drawings, which require 3- to 5-sec exposure and 5-sec heat treatment, while enlargements from microfilms on 35 mm to sheets of 14 by 20 in. take about a 30-sec exposure time. Kalfax has also been made in the form of 35 mm film. The resolution of the process is at least equivalent to very fine-grain silver-type photographic emulsions, and is more than sufficient for microfilm applications. At the present time the use of Kalfax paper for the reproduction of cathode ray oscillograms is under consideration using emulsions with higher speed.

g. Emulsions for Other Radiation

Generally, "photographic" recording means picturing the position of a moving beam of visible light. In this case film or paper (sometimes glass) is used with an emulsion having a sensitivity spectrum which covers both visible and ultraviolet light, the latter being the main component in most of our industrial light sources. Sometimes it is necessary to record other wavelengths of radiation. One example, photographing infrared radiation of heated bodies, will be described in some detail in section 9.44. Several emulsions are available for infrared photography, sensitive through the visible spectrum and the infrared to approximately 900 μ, with maximum sensitivity in the region from 770 to 840 μ.

A different type of emulsion is used for "autoradiography," i.e., exposure by contact with radioactive materials. Herz [90] describes its use in tracing the flow of radioactive drugs and chemicals in living beings and plants. Numerous other literature references on the subject, covering especially the medical field, are available from the Eastman Kodak Company in Rochester, N.Y. For alpha particles or beta particles, "nuclear-track" plates are used; for gamma rays, X-ray film.

9.2. Traces From Lightbeam Oscillographs

a. Long Beam

This method of recording has been used as long as photosensitive materials have been available; for many years it was the only means for high-speed recording.[91] A lightbeam is deflected by a mirror mounted on a galvanometer element, the angle of deflection being twice the angle of rotation of the mirror. By use of additional mirrors the lightbeam can be folded into a smaller compass, and each additional reflection from the galvanometer mirror will double the effective angular motion. Many oscillograph systems have an equivalent "pointer" length of 40 in., and special designs may be even longer. With frictionless bearings we get an instrument of high precision, and if desired (at the cost of loss of sensitivity) with natural frequencies up to 12,000 cps. The maximum possible line speed depends on the intensity of the light source, the length of the "pointer," the diameter of the mirror and the photosensitivity of the recording surface. Line speeds of 40 in./msec are by no means the maximum.[92]

With a light source of constant brightness, the exposure of the recording surface is inversely proportional to the writing speed. This does not necessarily mean that the line thickness varies in proportion; it depends on the characteristic of the photographic film how much variation there will be in the line. In any case, an improvement could be achieved by changing the intensity of the lightbeam in proportion to the writing speed, which for most oscillographs is proportional to the rate of change of current in the moving element. This is not simple with lightbeam recording, but it can be done with electron-beam recording [93] (see sec. 9.2b).

b. Flashing Styluses

In most lightbeam recorders a continuous line is traced. For multiple recording, as many measuring systems (with one light source) as there are variables are generally used. Only for scanning recorders or in photographic facsimile recorders are light flashes used. A special glow lamp replaces the stylus and makes a light mark of less than 0.1 mm diam, without further optical means in the immediate vicinity of the chart, allowing the tracing of miniature diagrams of only a few millimeters amplitude which can be enlarged 5 or 10 times. As with all scanning recorders, the speed is much lower than with one measuring system for each variable.

Flashing styluses are also used to make time markings on oscillograph films.

c. Shadows

This method was apparently first used to record the movements of string galvanometers. The deflected ribbon producing the shadow moved in the path of a lightbeam which illuminated the whole width of the moving photographic film. In this way the diagram was obtained as a white line on a black background. This instrument, first used by Einthoven in Holland some 50 years ago, be-

[90] R. H. Herz, Radiography and Phot. 26, 46–51 and 84 (1950).
[91] H. Kaiser, Z. tech. Physik. 16, 303–314 (1935); Arch. tech. Messen Lf.63, T121–T122 (Sept. 1936).
[92] W. Haertel, Frequenz 9, 319–324 (1955).
[93] E. Alberti, Elektrotech. Z. 58, 121–123 (1937).

came the typical electrocardiograph, although the diagrams were far from perfect, in that they showed a very heavy curve with a line thickness of 2 or 3 mm, thinning out to a fraction of a millimeter only for rapid fluctuations. Physicians were apparently so accustomed to this type of diagram that for the moving coil galvanometer, which gives a clear and thin black line on a white background, it was considered necessary to produce diagrams like those delivered by the string galvanometers, with the same heavy lines.[94] To get this effect, a fixed wire was interposed in the beam of light to cast a shadow on the recording paper.

A modern multiple-shadow recorder [95] (fig. 27) using orthochromatic chart paper uses up to eight moving-coil instruments. The measuring elements are 2-in. moving coils whose pointers travel from both sides over a slot of 0.5 mm width which is illuminated by small lamps, with no lenses at all. Identification of the curves is made by the thickness of the pointer shadows. Minimum space is the most important requirement. The 8-element recorder, using a chart 3½ in. wide and 25 ft long, is in a housing with the dimensions 6¼ by 6¼ by 3¾ in.

In another design of a shadow recorder,[96] built for testing relays, the shadow of the relay spring was superimposed on the conventional diagram of the current in the relay, to give a picture of the mechanical movements, including vibration.

[94] Instromatic Cardiette, manufactured 1942.
[95] D. L. Supernaw, Instruments 20, 532–535 (1947).
[96] P. Husta, Bell Labs. Record 30, 223–226 (1952).

d. Ultraviolet on Moving Screen

Such a device has been used in Europe to display electrocardiograms to a large audience on a wide screen. A light source with high ultraviolet radiation is used and the beam is directed to a large screen in the form of an endless moving belt covered with luminous material having a long afterglow. The speed is about 20 ips and the length of the belt such that two electrocardiogram periods were visible, the curves fading slightly as they moved towards the left, and completely during the return half of the belt travel.

9.3. Traces From Electron Beam of CRO

a. Direct, Internal Film

In the earlier cathode-ray oscillographs (CRO) as well as in the most modern and elaborate European designs, the recording surface is directly exposed to the cathode rays. Such oscillographs are all-metal units which are permanently connected to a vacuum pump, and the photographic plates or films are inserted into the evacuated envelope. This was proposed as early as 1894 by Hess but the first recorders of this type were built between 1915 and 1920 in France. The method was much improved by Dufour, tracing frequencies up to 1,000 Mc with line speeds up to 40,000 mi/sec (2,500 in./μsec) although the quality of the diagrams would not meet today's requirements. A number of European companies have continued this technique. G. Induni has de-

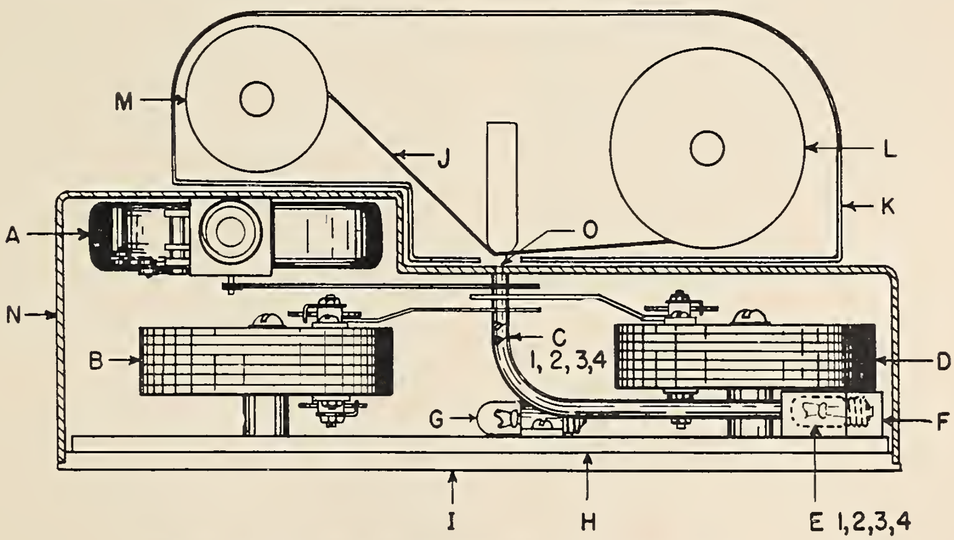

FIGURE. 27. *Multiple-shadow recorder (Instruments Publ. Co.).*

A—Bourdon-type pressure gage
B—Voltmeter
C 1,2,3,4—Impulse light guides
D—Voltmeter
E 1,2,3,4—Impulse exposure lamps
F—Impulse light housing
G—Slot exposure lamp
H—Bakelight instrument base
I—Recorder base
J—Sensitive paper
K—Magazine housing
L—Take-up spool
M—Supply spool
N—Recorder housing
O—Slot

veloped a 4-beam oscillograph [97] tracing curves on films 140 by 140 mm with a guaranteed line speed of 6,000 mi/sec (400 ips) and a line thickness from 0.05 to 0.3 mm. Using a plate instead of film inside the instrument [98] has the advantage of a higher accuracy, guaranteed at ±1 percent, and affords a ±1 percent distortion limit for the coordinate net. It is claimed by Induni that these metal-cased oscillographs are capable of recording frequencies of 100 Mc, higher than is possible for oscillographs with a glass envelope, without being more expensive for high voltages.

With all these instruments two pairs of deflecting plates provide true X–Y recording; to obtain a recording versus time the beam must be swept across the recording surface in proportion to time. To make recordings of voltages whose timing is uncertain, trigger circuits can release the beam to the plate in only 0.2 μsec.

b. Indirect, From Screen

(1) *Luminous Spot and Moving Film.* The natural frequency of the moving element in a light-beam oscillograph is seldom higher than 10,000 cps, and 20,000 cps is probably the limit. However, the cathode-ray tube, even a very inexpensive one, has practically no frequency limit. We get a cathode-ray oscillogram similar to the conventional lightbeam oscillograms if we photograph the movements of the luminous spot on the screen. The time ordinate is given in this case not by horizontal deflection of the spot but by the traverse of the photographic film. The maximum film velocity for a readable trace is then dependent on the brightness of the spot and the photosensitivity of the emulsion. The brightness can readily be varied, by changing the beam voltage, to give a crude indication of a third variable.

A phosphor-coated screen is used to transform the energy of the electron beam into useful light output. Many different phosphors have been developed, but not all of them are useful for photographic applications. For instance, in continuous recording, long-persistent phosphorescence would cause blurring of the picture. A detailed discussion of different types of screens and their properties may be found in the 150-page "Catalog of Equipment for Oscillography".[99]

In the Cossor-Robertson electrocardiograph,[100] the CRO serves two purposes. Using the sweep circuit on the time axis, the cardiogram may be seen on the long-persistent screen. With the sweep circuit switched off, the Y-deflections are photographed on a continuously moving 35-mm paper or film.

This system has also been used for multiple CRO recorders.[101] Eight 2-in. cathode-ray tubes were arranged side by side and their indications concentrated on a 35-mm film moving as fast as 12 fps.

(2) *Photographing Screen Picture.* Making a single photograph from the screen of the cathode-ray oscillograph is a relatively simple operation. The apparatus is less expensive than most light-beam oscillographs and it can be purchased as a complete unit or assembled in the laboratory. The technique has been developed to great perfection in recent years, and the results with the best equipment are not far from what can be expected with the much more expensive cathode-ray oscillographs with the photographic film inside the vacuum. Detailed information about the use of cathode-ray oscillographs can be obtained from manufacturers' literature.

In recording single transients, the exposure time is much more critical than with stationary patterns, and it is necessary to select carefully the proper screen material and recording surface. Nevertheless, enormous writing speeds are possible; the upper limit is said to be 4,350 mi/sec (250 in./μsec) using the DuMont P–11 screen, Eastman Linagraph Pan film (5244) and an f/1.5 lens opening. "Maximum writing speed" is defined as the speed which produces a density of 0.1 above film fog. According to Mansberg [102] the fastest recording papers are all slower than the fastest films, the best ratio (E–K paper 697 to E–K Pan X film) being about 73 : 100.

When the phenomenon is repetitive, recording by CRO is quite simple, and if the image recurs unchanged often enough, any screen and any camera can be used.[103] The shutter has to be open long enough to take at least one complete sweep, but not long enough to result in overexposure. Also, if there are changes from wave to wave, as happens even at power-circuit frequencies, there may be blurring of the trace. The exposure time should be so selected that a line of 0.3 to 0.5 mm thickness results (if the system of the CRO is good enough for this). For repetitive phenomena the actual line thickness of the trace does not change with the sweep speed. To determine the writing speed for sinusoidal traces, the DuMont Company has designed a nomogram for amplitudes from 1 to 100 mm and frequencies from 10 kc to 1,000 Mc, covering writing speeds from 0.4 in./msec to 40,000 in./μsec.

9.4. Photography of Indicating Instruments

This refers to the records, usually photographic, of those tests for which it is not possible to apply standard methods of measurement. In some cases there may be considerable doubt whether the methods described are recording and not merely indicating. They are here classed

[97] Arch. tech. Messen Lf.70, 51–53 (Apr. 1937) and Lf.207, 83–86 (Apr. 1953).
[98] Trueb, Taeuber & Company, Zurich.
[99] Allen B. DuMont Lab. Inc., Clifton, N.J.
[100] A. C. Cossor Ltd., London.
[101] P. L. Edward, Elec. Eng. 67, 1064 (1948), abstr. AIEE paper 48–217.

[102] H. P. Mansberg, Techniques of Photo-Recording, The Oscillographer 12, 3–16 (Apr.-June 1950).
[103] R. Feldt, Photographing patterns on cathode ray tubes, Electronics 17, 130–37 (1944).

as recording because only the evaluation of the photographic picture can bring out the desired information.

a. Instrument Scales

(1) *Entire Scales.* In many tests, oscillographs or similar recording instruments cannot be used because special transducers would have to be built and the cost and space requirements for this equipment might be too high. In such cases the moving picture camera becomes a recording instrument. The simplest devices of this kind have been used to make pictures of counters at regular intervals. One application was the recording with a standard movie camera of the message counters in the Amsterdam telephone exchange, when it was built in 1931 for 10,000 subscribers. Each 35-mm frame had the readings of 100 counters, and with 2 m of film all 10,000 counters were recorded in 12 min, thus saving time and avoiding errors.

The same method has been used to replace kilowatt-demand meters in cases where the pattern of the load is wanted only for a few days or weeks, so that the expense of a recording demand meter is not justified. An instrument of this type [104] is an accessory to a standard watt-hour meter, operating without servicing for 4 days, recording at 15 min intervals, and giving the same results as a standard-demand recorder. An American special recording camera [105] uses 35- to 70-mm film controlled by an electric current, radio signals, or sound.

An important application of scale-picture recording is the photo-panel recorder used extensively in flight testing of airplanes.[106] Here the standard instruments are grouped on one or several panels, and photographed at regular time-intervals, with one or several movie cameras. The frequency of recording depends on the nature of the test, but is limited by the frequency response of the instruments used on the panel. In one of the applications described, 85 instruments were photographed with three 35-mm cameras. One frame 24 x 36 mm can be used to picture the scales of 72 instruments. The picture frequency desirable is also influenced by the time subsequently necessary to evaluate the enlarged pictures. With 85 instruments, as shown by Paine,[106] a 1-sec recording interval, and a 15-min run, there are 76,500 instrument readings to be taken and plotted. Assuming 20 sec per reading, this comes to a total data-reduction time of more than 400 hr. The time needed for data reduction will, of course, increase in proportion to the recording frequency. The accuracy obtainable is that of the various indicating instruments used, ranging to 0.1 percent. The method is used in conjunction with other methods of recording, to obtain a simple and economical instrumentation system.

Another example of scale-picture recording is used for the readings of liquid-column manometers. There are two ways. One is to make the picture of a number of liquid columns in the conventional way with a camera. This method has been and is still used in wind tunnel experiments. ISA Paper 55–28–10 reports the tests made by the Convair Company in Fort Worth. The wind tunnel was equipped with 1,000 pressure orifices. It took on the average 30 sec to read one manometer from the film, so that one girl in one 8-hr day could just about complete one set. Besides this, her reliability was not satisfactory, in that as much as 17 percent difference was found between readings of the same film. Some tests required the reading of 6 million pressure points, and it was a full month before the data could be fed into a computing machine.

The other solution is to use an opaque liquid in the manometer, backing each tube with a shield having a narrow slot. Light-sensitive paper is passed in back of the slots, and a light is flashed every 10 sec, giving a record of black lines showing the changes in liquid level. This method was developed for research on moving locomotives [107] but obviously cannot be used for large testing problems.

(2) *Localized Pictures.* Using sweep-balance recording, the following system was developed for high-speed multipoint temperature recording at the Douglas Aircraft Company by T. M. Blackmon (paper read at Los Angeles Meeting of ASME 1946). As described earlier [108] a circular voltage-divider ("potentiometer") with a scale on its periphery is continuously rotated at a speed of 10 or 20 rps (fig. 28). At the instant the balance point is passed during the sweep, a light is flashed and a camera in front of the scale takes a picture of the scale and the marker, together with the time and the number of the transmitter. Higher recording speeds could be achieved, depending on the design of the voltage divider.

(3) *Digital Displays.* The Computation Laboratory of Harvard University has developed the "Numeroscope" [109] for tracing on the screen of a cathode-ray tube the patterns of the arabic numerals from 0 to 9. By photographing these pictures in rapid sequence, a printing frequency of 5,000 lines/sec is considered possible, although the experimental outfit was operated at only about 10 lines/sec. It is possible with this device to display 3 digits at the same time on one tube. For a 6-digit number, 2 tubes would be necessary.

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[104] "Fotomax," Siemens-Schuckert, Nuremberg, Germany.

[105] "Varitron Model C," Photographic Products, Inc., Hollywood 38, Calif.

[106] W. G. Brombacher, Instr. and Automation **20**, 700–08 (1947); and J. P. Paine, Instr. and Automation **20**, 30–34 (1947).

[107] F. H. Gatlin, Gen. Elec. Rev. **46**, 503–504 (1943).

[108] G. Keinath, U.S. Patent 2 427 355, Flash Print Recorder.

[109] H. W. Fuller, Electronics **21**, 98–102 (1948).

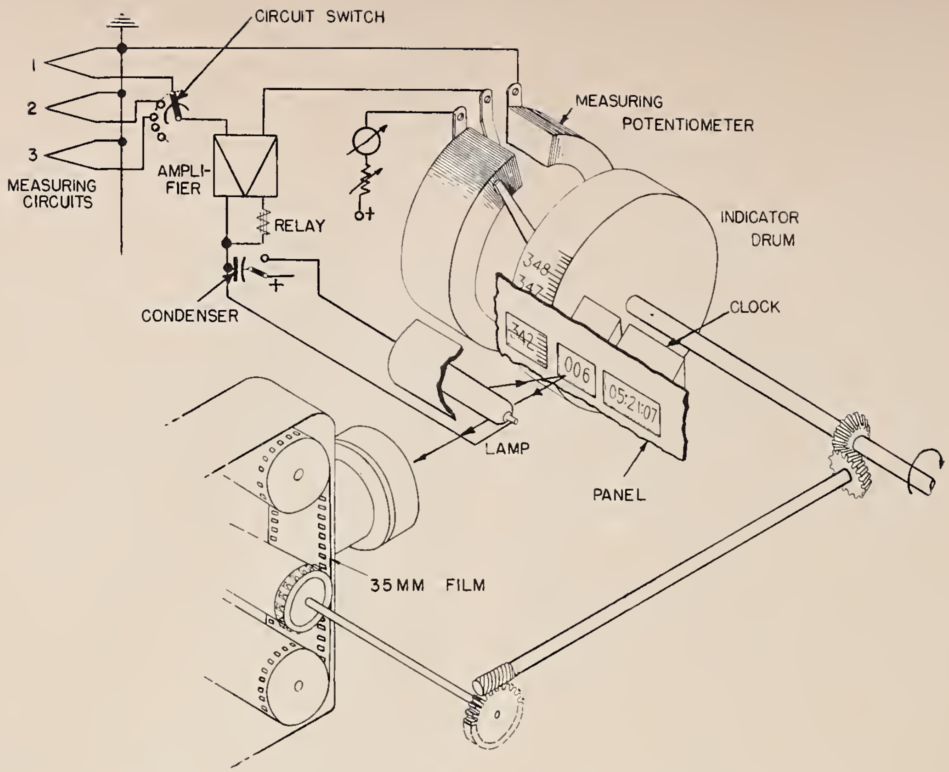

FIGURE 28. *Sweep-balance flash-print recorder* (*G. Keinath*).

Other counting tubes [110] have all ten of the decimal units in one envelope, only one being lighted at a time. Some types have them arranged in a circle, others in a vertical row. In either case, one must photograph 6 tubes to get a 6-digit number. In a given film area, this leaves much of the space unused, and the digit patterns are necessarily much smaller and lacking the alinement that mechanical counters have made familiar.

Recently tubes have become available for displaying any of the ten decimal digits in such a way that an in-line readout is obtained. One arrangement [111] for achieving this is to have the displays alined from front to back, and illuminated in such a way that only one can show at a time. Another arrangement [112] forms the numerals by lighting some combination of short bars; the array forms the figure 8 when all are lighted. A third arrangement [113] uses separate number-shaped electrodes in a neon tube envelope, each electrode being excited as required.

[110] Type ElT, Norelco, North American Philips Co., Inc., Mt. Vernon, N.Y.
[111] Haydu Bros. of N.J., Subsidiary of Burroughs Corp., Plainfield, N.J.
[112] Berkeley Division, Beckman Instruments Inc., Richmond, Calif.
[113] Burroughs Adding Machine Company, Detroit, Mich.

b. Displacements

(1) *Successive Pictures.* There are many measuring problems where it is not possible to transform the movements into electrical signals, but where it is possible to deduce the necessary information from one or more photographs of the object. In other cases direct methods, e.g., electrical measurements, are possible, but the photographic method may give more information because the picture has two dimensions. By taking stereo pictures, we may even have three dimensions, or we can add information by making several exposures on one frame. The photographic method is less expensive than electrical measurement. Further, it needs no transducers attached to the object, which might alter the behavior to be observed, as in the case of a small moving part.

There are four basic mechanical movements amenable to photographic recording: [114]

(a) linear motion from bullets, shells, airplanes, rockets in flight;
(b) rotational movement, as of a revolving gear, to find irregularities and defects;
(c) growth or shrinkage of an object, such as

[114] C. D. Miller and Kenneth Shaftan, Prod. Eng. 23, 167–82 (1952).

the deformation of an aircraft tire under the impact of landing;

(d) homogeneous changes throughout the object.

Single pictures are used for the determination of the speed of missiles in flight, up to 4,000 fps. For such a test the light flash is released when the missile either cuts a wire (older methods) or passes through a "gate," changing the inductivity of a coil. It is generally necessary to use two generators. Alternatively, it may be photographed with a series of light flashes [115] at exactly known rates from 1,000 to 2,000 per second. With X-ray flashes the speed of a shell can be measured before it leaves the barrel; equipment with exposure times down to 0.2 μsec is available.[116] During 0.2 μsec a missile with a speed of 4,000 fps travels only 10 mils.

The main application of photography for measurements is made with moving picture cameras. Very high frame rates have been achieved.[117]

To evaluate such a series of pictures, special devices are built.[118] Films of 16, 35, or 70 mm may be used an enlarged 5, 10, 20, or 45 times on a fine-grain white matte screen 28 by 28 in. Orthogonal cross-wires of only 7 mils diam can be set by hand over the entire screen area with an accuracy of ± 3 mils. The scale values derived from the crosswire position may be noted visually and/or transmitted to automatic plotting instruments, electric typewriters, or storage devices.

Photographic exposures in very rapid succession are sometimes called "time microscopes" (Zeit-Lupe, in German). Occasionally there is the opposite problem of making records of very slow movements, e.g., the growth of plants during period of days or weeks. This is sometimes called "time-lapse" photography.

Just as in moving picture films with sound tracks on the side, it is possible to get a combination of line-recording or other record on the same film as the movement. An example is the picture of relay contacts and their separation, combined with an oscillogram of the current in the relay coil.[119] Special techniques of photography have been developed for motion studies. The subject may carry a tiny electric lamp or a reflector. The picture may be made either with time exposure or, if the speed of the movement is of interest, in rapid succession.

(2) *Interference Fringes.* A very sensitive method for recording small transient displacements is used in the interferometer camera.[120] A diaphragm is mounted on the surface whose deflection is to be measured, e.g., a pressure vessel. Displacements result in changes of interferometric rings of monochromatic light, shaped by a 60° prism into pointed light, then translated by the moving film into continuous streaks. These Newton rings are produced by interaction between the optically flat back-surface of the diaphragm and a concave quartz surface mounted against it. Increasing pressure on the diaphragm causes the rings to move towards their center and disappear, thus increasing the spacing of the rings. The monochromatic light is admitted to this system through a prism so arranged that instead of full rings, only short sections of diametrically opposed arcs appear. The moving film sees one-half of this pattern, thus producing the striated pattern shown in figure 29.

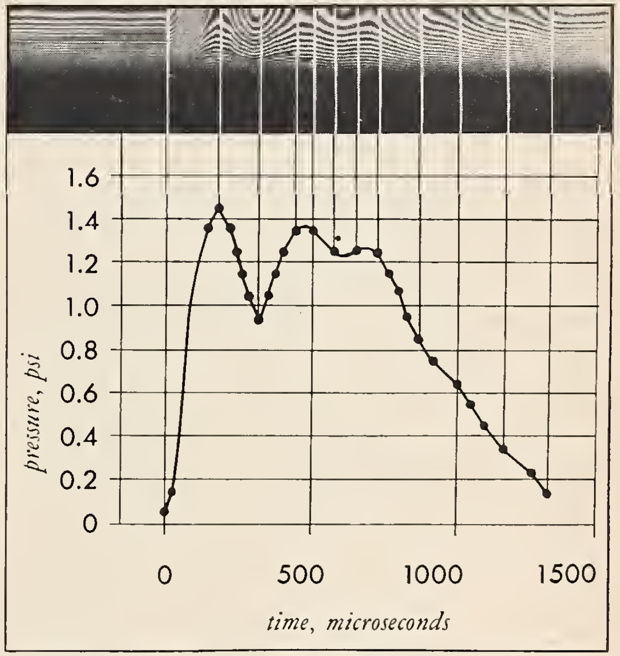

FIGURE 29. *Interferometric recording of a pressure transient (Beckman & Whitley).*

A first approximation of pressure at any place on the film is found merely by counting the total number of fringes across the record. A change in pressure is indicated not only by the change of phase at the center of the pattern, but also by the inward shift of each fringe. The phase change provides a linear calibration of the displacements, but the sensitivity of fringe spacing decreases towards the edge of the pattern.

In figure 29 the film was moving from right to left. At zero time a pressure of 0.05 psi was re-

[115] Ernest C. Barkofsky, Electronics 25, 129–30 (1952).
[116] Microtime Laboratories, Culver City, Calif.
[117] Proceedings of the third International Congress on High Speed Photography, edited by R. B. Collins, Academic Press, 1957.
[118] "Telereadex" Telecomputing Corp., Los Angeles, Calif.
[119] "High-speed motion-picture making in industry," Kodak brochure.
[120] Beckman and Whitley, San Carlos, Calif. See W. E. Buck, J. Soc. Motion Picture Television Engrs. 59, 369–378 (1952).

corded and 175 μsec later a peak of 1.45 psi had been reached. By calibration each fringe was known to represent 0.10 psi.

(3) *Polarized Light.* This method is based upon the property of certain transparent materials to become doubly refractive under stress. Components of polarized light passing through a model made of such materials travel with different velocities in the two perpendicular planes of principal stresses at each point in the model. The relative velocity of the two polarized components is a function of the intensity of the stress differences. The phase difference resulting from the difference in velocity are caused to produce interference bands which can be interpreted as stresses. One assumes that stress conditions in the scaled model are identical to conditions in the full-sized unit of actual structural material (e.g., steel) under proportional loading.

Generally, only a section, not more than an inch thick, is tested. After the model is placed under load, polarized light is passed through it. The interference pattern can be seen on ground glass and it is usually photographed (black-white or in colors) for later study. If a white-light source is used, the isoclinic lines range through the spectrum, each one having a constant color; with a monochromatic light source they are alternately dark and light. These fix the direction of the principal stresses in relation to the axis of the polarizer and analyzer disks.

The method has also been used in X-Y-Z recording by using the 'frozen stress" technique developed by Hetenyi.[121] The model is heated to about 120°C, then loaded and cooled slowly to room temperature under load. In this way the stresses are permanently recorded in the material. The object is then sliced into sections which are examined under polarized light.

See also C. C. Perry, Prod. Eng. **26** 154–161 (1955) for use of bentonite clay in liquids.

A new method of displaying surface strains on structural parts was developed in 1953 in France and is now available in this country.[122] With this process it is not necessary to make a model out of transparent material. The part to be tested is merely covered with a thin layer of transparent photoelastic plastic, either by bonding a thin sheet to it or by coating it with a liquid plastic. When a load is applied, strains are transmitted to the plastic coating, which then becomes doubly refractive. This resulting birefringence is directly proportional to the intensity of stress. If a second coat of plastic is applied to obtain the proper reflection conditions, the birefringence can be observed under polarized light in a specially designed reflection polariscope. A pattern of black and colored fringes reveals the complete geometry of strain.

[121] J. Appl. Mechanics 5, A–149 (1938); see also Max M. Frocht, J. Appl. Phys. 15, 72–88 (1944).

[122] F. Zandman and M. R. Wood, Prod Eng. 27, 167–78 (Sept. 1956).

c. Flow Patterns

(1) *Changes in Refractive Index.* The double-refraction method adds suspended matter to the liquid, leads the flow through a transparent channel, and subjects it to a transverse beam of polarized light. The optical principle is the same as in photoelastic stress analysis. The colors of the bands indicate the shearing strain in the water.

Density changes are utilized in a number of ways: see C. C. Perry, Prod. Eng. **26**, 154–161 (1955). Of the three major methods the simplest is the shadowgraph, using a brilliant point-source of light, so placed that its rays pass transversely through the flowing air around the object. A film on the opposite side will record any density variation in the flow about the model.

The schlieren (streak) method (fig. 30), first used by Cranz[123] comprises a light source S, a lens L_1 for creating a parallel beam of light, a second lens L_2 for converging the beam to a point, a knife-edge S' for obtaining optical sensitivity, and a screen D' for photographing the density variations D. The schlieren method is more sensitive than the shadowgraph method.

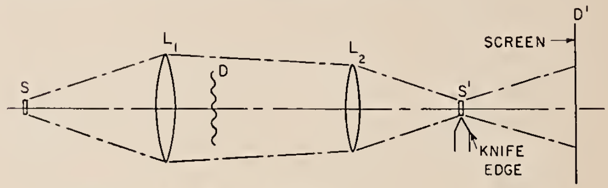

FIGURE 30. *Elements of the schlieren method (Med. Biol. Illus.).*

The third method involves an interferometer. It has a light source, a collimating lens, two light-beam splitters, additional mirrors and lenses, and a screen. The first splitter divides the light, sending half of it through the test area (e.g., wind tunnel) and half by a roundabout path. The lightbeams are reunited by the second splitter and focused on a screen for photography.

Recent research work using these techniques:

F. K. Elder, Jr., N. deHaas, experimental study of formation of vortex ring at open end of cylindrical shock tube. J. Appl. Phys. **23**, 1065–69 (1952).

E. S. Love, C. E. Grigsbey, new shadowgraph techniques for observation on conical flow phenomena in supersonic flow. NACA TN 2950, May 1953, 16 p.

D. S. Schwartz et al., schlieren and shadowgraph techniques and possible applications to medical and biological sciences, Med. and Biol. Illus. **6**, 23 (1956).

George Radinger and L. M. Somers, a simple schlieren system for two simultaneous views of a gas flow. J. Motion Picture and Tel. Eng., **66** (1957).

[123] Experimentelle Ballistik, 3 vols. 1927, pp. 257–278, figs. 19–25.

(2) *Suspended Materials.* To make a flow pattern of a liquid visible is not a measurement in the strict sense, but the methods deserve mentioning. In a two-dimensional system, the flow pattern of a liquid around a model can be seen and photographed after sprinkling the surface with powder of lycopodium, aluminum, or sawdust. Flow velocity is limited to less than 1 fps. For the study of fully enclosed flow in pipes or vessels, the housing can be copied in transparent plastic; and ink, dye, or potassium permanganate can be added to trace the streamlines. Turbulent flow requires granular or flaky additives, like aluminum powder, mica or plastic chips, glass beads, cork particles, or globules of a liquid immiscible with the primary liquid.

To study the flow of gases smoke is used as an additive, introduced into the stream through one or more small nozzles. For very high velocities solid particles of low specific weight are used, like balsa dust, wool, or paper.[124]

(3) *Erosion Effects.* Transitory erosion effects can be recorded by photography. The boundary surfaces of the model (e.g., a boat hull or the walls of a channel) are painted first with a black coat, and when this is dried, with a white oil-paint. The boundary-layer flow will erode lines in the wet paint, indicating by black lines the direction of the local flow. The method can be used for water speeds of 8 to 12 fps. The speed can be estimated from the depth of the grooves. The flow picture develops to maximum usefulness in about 30 sec; if the test is continued too long, all paint will be carried away. Instead of using paint, the snrface can be made of material like soap or ice, and the flow pattern will be made visible by making the test in warm water.[125]

In a somewhat related method, used by the David Taylor Bodel Basin [126] the exterior of the hollow watertight model is painted with white lead. At leading edges, a series of small holes is made. During the test highly acidulated water saturated with hydrogen sulfide is forced from these, and along in the boundary layer, leaving black streaks on the white surface of the model. This technique is suitable for towing speeds from 4 to 20 fps.

d. Surface Temperatures

Whenever a surface temperature is measured by touching the surface with a probe, no matter how small, the temperature distribution around that spot is more or less disturbed, because heat conduction and radiation are changed. The error may be made small, but it always exists with contact methods. Radiation methods, suitable for the temperature range between 300 and 800° C, avoid this. If the surface temperature is high enough, visible light may be used. However, below 500° C only infrared rays are emitted.

(1) *Infrared Photography.* This method was first developed[127] at the I. G. Farbenindustrie in Leverkusen (Germany). The object, e.g., a high pressure steam pipe or valve, is photographed under its own infrared radiation, using emulsions which are available for different temperature ranges. The lowest temperature measurable with a tolerance of perhaps 20° C is round 300° C requiring exposure times of 5 to 10 hr. At 400° C the exposure time is only 15 min; at 500° C it is 15 sec; and at 750° C it is possible to make very short exposures or moving pictures. The method has been used to study the surface temperature of complicated castings.

A recently developed infrared camera [128] senses the radiated energy as a resistance change in a 10-μ flake of thermistor material whose mirror system subtends an angular field of view less than ½° by ½°. Large objects are examined by a cam-driven scanning system for fields of 20° by 10°. The recording medium is photographic film, exposed to the point image of a glow tube whose light is modulated by the amplified electrical signal from the radiometer. A recorder mirror attached to the back of the scanning mirror assures geometric similarity of heat image and light image. For calibration, a series of step voltages modulate the lightbeam during the last few sweeps of the scan, providing 8 steps in a gray scale representing precisely known radiation temperatures. Scanning time varies from 1 to 14 min; temperature range from above 1,000° to below 0°F. Temperature differences as small as 0.2°C can be recorded, with time constants as short as 200 μsec.

[124] S. Eicke, V.D.I. Zeitschrift **80**, 1369–73 (1936; C. C. Perry, Prod. Eng. **26**, 154–61 (1955); M. K. Taylor, Balsa-dust method of air flow visualization, ASME paper 50–SA–29 (1950) also NACA TN 2220, Nov. 1950; J. M. Bourot and J. J. Moreau, Note sur les zones d'inégale luminosité observées dans certaines visualisations d'écoulements, Compt. rend. **228**, 1628–30 (1949); and J. R. Stalder and E. G. Slack, use of luminescent lacquer for visual indication of boundary layer transition, NACA TN 2263, Jan. 1951.

[125] A. Kopp, V.D.I. Zeitschrift **78**, 1332–33 (1934); also C. C. Perry, loc. cit.

[126] G. Stuntz, private communication.

[127] Hencky and Neubert, Arch. tech. Messen **Lf.62**, 100–101 (Aug. 1936) and **Lf.63**, 114–115 (Sept. 1936).

[128] See Techniques, Fall, 1957, p. 3–10, Barnes Engineering Co., Stamford, Conn.

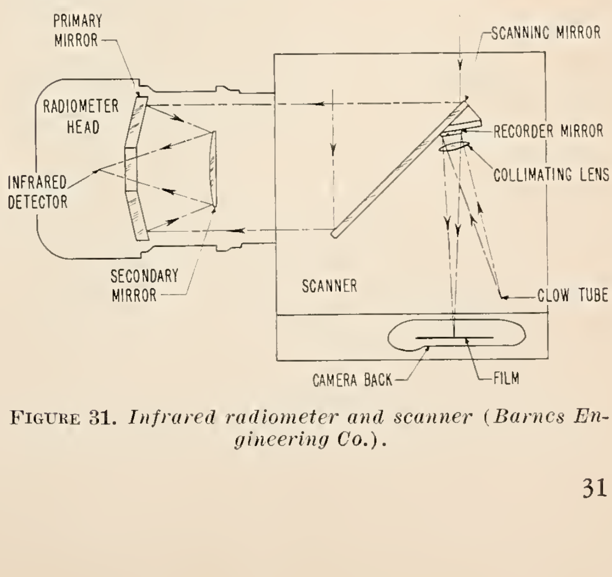

FIGURE 31. *Infrared radiometer and scanner (Barnes Engineering Co.).*

(2) *Thermography.* The most common application of phosphors is their property to convert incident radiation into one with longer wavelength. However, a few phosphors of low sensitivity have the property of emitting light of *shorter* wavelength than they absorb, after they have been previously sensitized with short-wave radiation. In some phosphors of low efficiency the temperature has a very strong effect on luminosity, so that they may be used to indicate temperature. After irradiation with a strong ultraviolet source, the brightness of some of these phosphors changes as much as 20 percent per deg C.

A number of phosphors have the property that their light is extinguished by red or infrared light, and in this way they may be used for temperature measurement. The method appears to have first been used by Neubert (I. G. Farbenindustrie).[129]

Thermography was further developed by Urbach.[130] In contact thermography the surface to be observed is coated with a luminescent material and evenly illuminated with ultraviolet radiation. The temperature distribution on the surface becomes visible as a pattern of brightness of the coating, which may be photographed with ordinary films. It is claimed that after careful photometric calibration, temperatures may be observed with an error of about 1° C. The temperature distribution may be obtained in the form of isotherms, either from calibrated photographic records, or by plotting the data of photometric measurements.

In projection thermography, the temperature-sensitive phosphor (in the form of a thin screen) is placed at the focus of a large concave mirror which forms an image of the object on the screen. The screen is excited to luminescence by an ultraviolet source, and the light is then extinguished by the red and infrared rays of the object as pictured by the spherical mirror. This method records *radiances* of the object, rather than temperatures. With objects which are good radiators, temperature differences of 10° to 15° C may be observed visually; by photographing the screen, differences of about 5° C are detectable.

(3) *Oil Film Camera.* This instrument utilizes infrared radiation; the principle was first studied by Dr. M. Czerny at the University of Frankfurt am Main in the late twenties. The U.S. Air Force suggested application for the armed forces and a new instrument has been developed.[131] Using a lens f/2.25 with an 8-in. focal length and 5° field, it focuses the radiation as an image onto an oil film on a membrane only about 4 μin. thick, located in an evacuated cell between the lens and a viewer, figure 32. The membrane temperature is changed from point to point according to the radiation received from the object and the thickness of the oil film is changed accordingly. White light from the viewer is reflected in different colors, giving a colored picture of the object which can be viewed or photographed. The process is reversible: the oil will condense on pictures of ice and will evaporate on pictures of soldering irons.

The method is very sensitive. For a high emissivity object, it is possible to detect a temperature difference of only 0.3° C at room temperature. The exposure time depends largely on the temperature. It may be of the order of 0.1 sec for Kodak XX film, or 0.5 sec for color film.

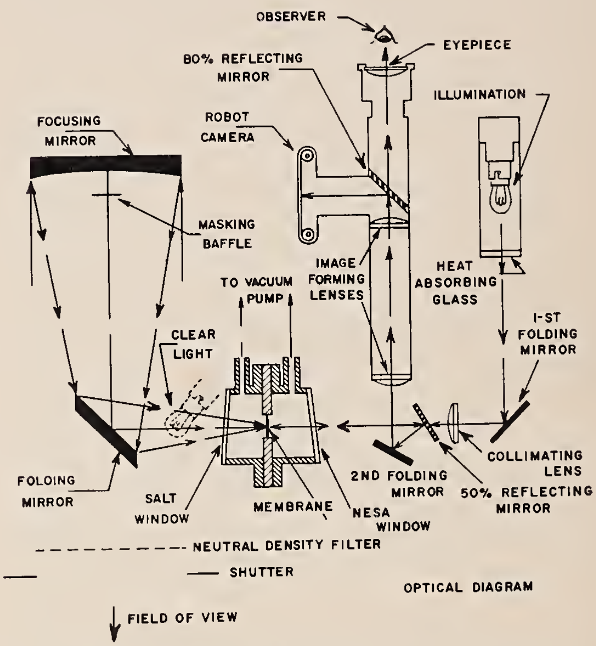

FIGURE 32. *Oil-film camera (Baird-Atomic, Inc.)*

10. Thermal Traces

With this marking method, a line is traced by heat generated electrically either in the stylus or in the recording surface.

10.1. Fusible Coatings

The chart is in principle the same as used for scratch recorders and described in section 5.2. The method is especially used for high-speed direct-recording oscillographs and electrocardi-

[129] Arch. tech. Messen Lf.67, 3 (Jan. 1937). See also German patent 571 076/1933.

[130] F. Urbach, Temperature distribution and radiation, J. Opt. Soc. Am. 39, 1011–19 (1949).

[131] Evaporograph, Baird Associates, Inc., Cambridge, Mass.

ographs. The pointer generally carries at its end a fine electrically heated wire which is kept taut by a bow (fig. 33). In one design [132] the chart with the heat-sensitive surface is drawn over a triangular bar at right angles to chart travel, so that only a narrow strip of paper is in contact with the wire. The record is a dark continuous line (of the color of the paper base) in rectangular coordinates. The permissible line speed is dependent on the temperature and heat capacity of the wire and on the rate of movement of the pointer with respect to the paper. In commercial designs [133] using "Permapaper," chart speed runs from 0.01 up to 4 ips, the latter permitting a line speed of 12 to 20 ips.

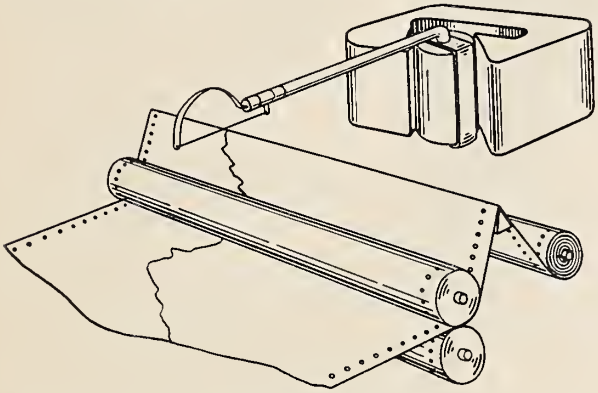

FIGURE 33. *Thermal trace recorder with heated wire (Bell System Tech. J.).*

In place of a heated wire, a stream of hot air as described in British Patent 282 759 (1929) may be directed through a capillary tube to the surface of the wax-coated paper. This avoids the friction of the stylus on the chart.

A disadvantage of wax-coated paper has always been that it must be handled rather carefully to avoid scratches. In recent years, however, quality has been much improved by using plastic materials, thus providing a hard durable surface with a low melting point. The line thickness on good papers is 0.1 to 0.2 mm if the heating current is properly adjusted, and this is quite satisfactory.

There are other coated papers which may be used for line recording. One was developed originally [134] for a thermal facsimile printer, but the material can also be used for thermal trace recording. Timefax NDA paper (see section 13.5) can also be marked with a heated stylus. At temperatures below 95° C no marking is obtained, but at 100° C the chart may be run at about 3 ips. At higher temperatures very high marking speeds may be used, according to the manufacturer. The surface of these papers is rather hard and is not easily damaged by scratches.

10.2. Chemical Impregnation

Many chemical compounds change irreversibly to a darker color when heated. One paper based on this effect [135] began its change from white to dark brown at about 220° C, although the complete reaction required a temperature of 300 to 500° C. Tests showed that 60 cps currents could be written on this paper with 6 mm amplitude (a line speed of about 32 ips). The stylus used for this paper was an aluminum oxide or sapphire rod of about 1 mm diam, with rounded tip, equipped with a heating coil of about 12 mm of nichrome wire, connected to a voltage source of 2.5 to 3.5 v. The heating time was 5 sec, the weight of the stylus between 15 and 25 mg.

One oscillograph manufacturer [136] uses a thermosensitive chemically-impregnated abrasion-proof paper. The stylus is heated, the diagrams are curvilinear, and the chart runs at speeds up to 2 ips.

11. Chemical Recording

11.1. Variable Intensity

This method is used for gas analysis. Metered samples of the gas of unknown composition are directed against an impregnated chart or tape, to cause there a visible effect as an indication of the composition.

A recorder of this type, developed by E. I. duPont de Nemours, is the hydrogen-sulfide analyzer [137] (fig. 34). It is used to determine the content of H_2S in industrial gases, in amounts from 1 part in 10^7 to 1 part in 10^5 or less. A metered quantity of the gas is directed through a restricted area to a permeable, reactive, white paper tape previously impregnated with lead acetate and other reagents. These assure stoichiometric conversion of the H_2S to a spot of brown lead sulfide.

[132] F. H. Best, A recording transmission-measuring system for telephone circuit testing, Bell System Tech. J. 12, 22–34 (1933).
[133] Sanborn Company, Cambridge, Mass.

[134] "Thermofax," Minnesota Mining & Mfg. Co., St. Paul, Minn.
[135] "Pyrochrome," (now discontinued) Polychrome Corp., Yonkers, N.Y.
[136] "Duratape," Rahm Instruments Inc., New York, N.Y.
[137] Manufactured by Rubicon Co., Philadelphia, Pa.

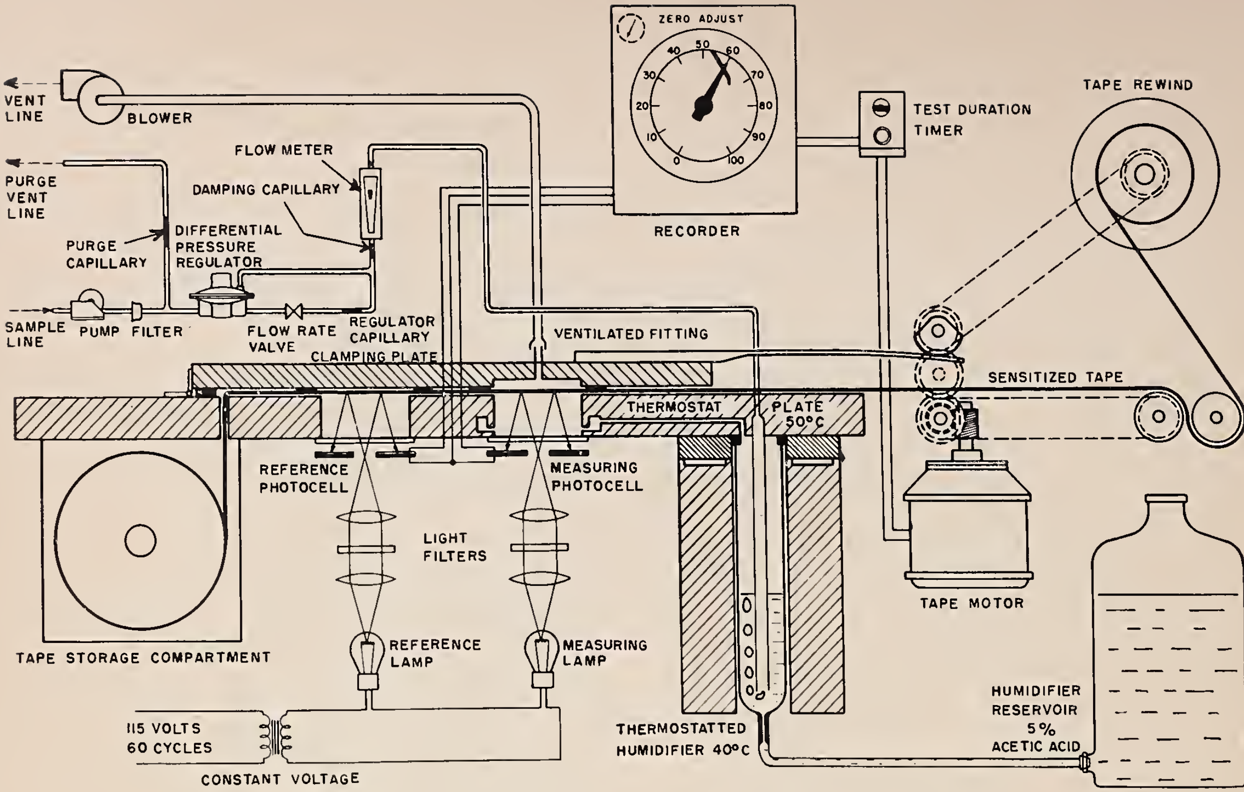

FIGURE 34. *Continuous H_2S analysis by sensitized tape (Rubicon Co.).*

The time allowed for reaction is adjusted to the estimated H_2S content. In the latest designs of the recorder this adjustment is automatic. For the lowest concentration the reaction takes 2 hr to get a spot of sufficient density; for high concentration the reaction time is reduced to 1 min or less. Generally the exposure is set to about 15 min.

After this first "recording" of the effect of the unknown quantity, the reflectance of the exposed spot is compared by a differential photometer with the reflectance of an unexposed part of the tape, and the result charted on a percent scale by a conventional null-motor recorder. The method is somewhat related to recording titrometers in which the color change of a liquid is converted into an electrical voltage.

11.2. Chromatography and Electrochromatography

Chromatography is a technique widely applicable in chemical analysis for determining the identity and concentration of components of a mixture. This technique utilizes a principle whereby flow of a carrier solvent or gas causes the components of a mixture to migrate differentially from an initial zone to adjoining zones of a porous, selectively sorptive medium.

Electrochromatography is a technique akin to chromatography, but differing from it in that the electrophoretic effect replaces the carrier fluid as the driving force. This effect, also known as cataphoresis, is the movement of suspended particles through a fluid under the action of a direct electromotive force. The electric field provides selective driving forces upon ionized or charged particles. Thus charge, bearing components of a mixture migrate differentially from an initial zone of a porous material with an electrolytic medium. If, in addition, the porous material is selectively sorptive then certain nonionized components can also be separated. Other terms used to describe this process are ionography, paper electrophoresis, and zone electrophoresis.

Of interest as recording means are those chromatographic techniques which permit more than instantaneous detection of the separated components by producing more or less permanent color or shade differences on the migration medium. The record may also appear as a pattern of phosphorescence, fluorescence under ultraviolet light, or radioactive tracers. Hence, when a system has been calibrated using pure substances, the position in space or time at which a peak occurs will identify the component, while the amplitude and extent of the effect establish the concentration.

Here the recording media are considered to be the porous materials through which the differential migration occurs. Examples of these are packed powders, gels, resins, and fibrous materials such as chamois and filter paper. For chromatographic purposes these materials must provide selective resistive forces to the migrating substances of interest. For electrochromatography where the driving forces are selective, the media may be chemically pretreated, or processed after the separation run, to provide or accentuate a detection effect. Figure 35 shows a typical pattern produced by paper electrophoresis. Also shown is a curve of dye density versus position and the integral of this density pattern produced by a photoelectric scanner.[138]

For more thorough coverage of the subject see the following reference and its extensive bibliography: H. H. Strain and T. R. Sato, Chromatography and electrochromatography, Analytical Reviews, Part II of Anal. Chem. 28, p. 687–94, (1956).

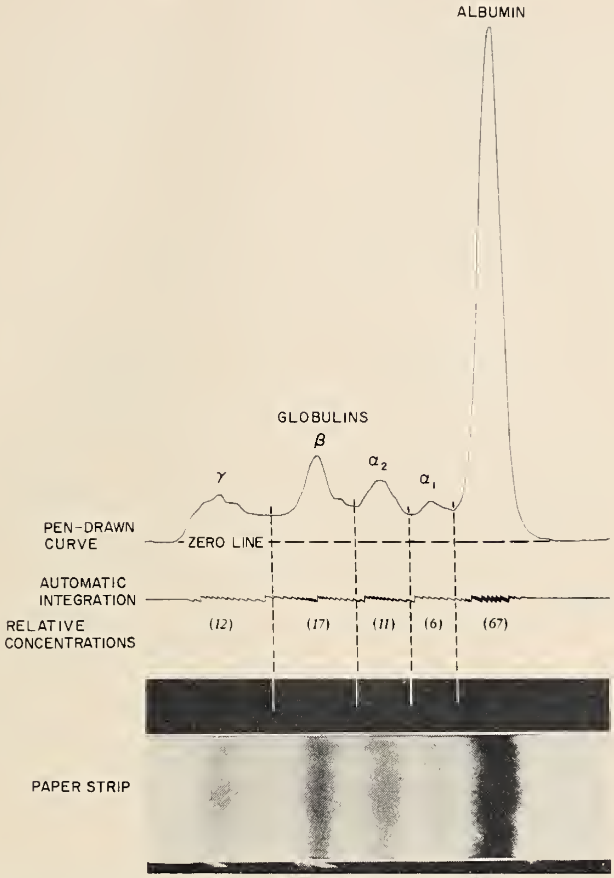

FIGURE 35. *Pattern produced by paper electrophoresis* (*Spinco*).

12. Direct Magnetic Effects

12.1. Residual Magnetism

The magnetic field which surrounds a current-carrying conductor is proportional to that current. If a piece of magnetic material, e.g., a steel rod, is placed in the vicinity of the conductor, it will become permanently magnetized. If it is then removed, the residual magnetism serves to record the maximum current. This method, first proposed by Max Toepler in Dresden (1925) has been used extensively for recording current surges due to lightning and was further developed in Germany.[139] Shortly afterward a surge-crest ammeter [140] was produced here, on a larger scale, and with a special calibrating arrangement. We class the device as a "recorder" because the magnetization of the piece is a permanent record. High accuracy cannot be expected, because the steel rods cannot be identical and because the magnetizing currents may differ in duration. Despite this it

[138] Spinco, Div. of Beckman Instruments, Inc., Belmont, Calif.

[139] H. Gruenewald, Elektrotech. Z. **55**, 505–508 and 536–539 (1934).

[140] C. M. Foust and H. P. Kuehni, Gen. Elec. Rev. **35**, 644–48 (1932); C. M. Foust and G. F. Gardner, Gen. Elec. Rev. **37**, 324–27 (1934).

appears that an accuracy of ±10 percent is possible, although the surge may last only 0.5 μsec.

A much more elaborate design [141] has a current range from 100 to 50,000 amp, and makes it possible to reconstruct a graph of the current surge as a function of time.

12.2. Character-Shaped Fields

A method of printing from particles adhering to a magnetic pattern fixed by the shape of a pole-piece has been called "Ferro-magnetography." [142] An endless strip of thin magnetic material is passed through the airgap between a pulsed electromagnet and one of a set of character-shaped poles, such as the "7" shown in figure 36a. A magnetic image of the pole is formed on the strip. When this is passed into a cloud of iron-oxide dust, particles are attracted to it and can be transferred by pressure to a permanent paper record. Figure 36b shows an arrangement suitable for a tabulating machine. This system is capable of very high scanning speed, because a pulse duration of only 10 μsec will give a good picture.

[141] "Fulchronograph," Westinghouse Co., East Pittsburgh, Pa. C. F. Wagner and C. D. McCann, Trans. A.I.E.E. 59, 1061–68 (1940).

[142] General Electric Co., Schenectady, N.Y. T. M. Berry and J. P. Hanna, High-speed printing with shaped magnetic fields, Gen. Elec. Rev. 55, 21–22 (1952).

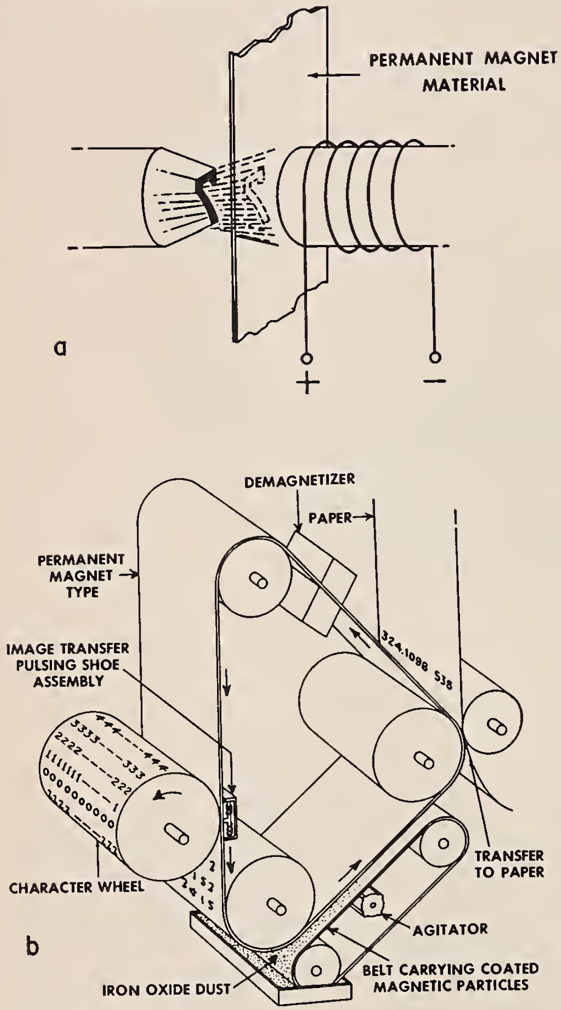

FIGURE 36. *High-speed printing with shaped magnetic field (General Electric Co.)*

a, Shaped field in ferro-magnetography; b, printing process for ferro-magnetography.

12.3. Variable Flux

As an outgrowth of studies in the reproduction of pictures, Atkinson [143] developed a method of printing from electromagnetic records which he called "Ferrography." The photographic image was wrapped around a 5-in.-diam drum rotating at 1,500 rpm and scanned helically by a photocell at 200 lines/in., 400 ips. Up to 400 lines/in. was considered suitable resolution for the working model. The voltage from the photocell, modulated and slightly warped to give improved appearance in the reproduction, was impressed on an audio-type recording head. Iron-oxide-coated film, wrapped around a second drum rotating and shifting axially with the transmitter, received a magnetic image whose intensity varied as the density of the original picture. When immersed in an "ink" containing ferromagnetic particles in suspension, the pattern appears in relief. After rinsing, this is pressed against a sheet of paper, and a clear sharp image is reproduced in the tones of the original.

The process has been used commercially [144] for facsimile transmissions and was suggested for oscilloscope records using intensity as a third dimension. Further work by Begun [145] used signals sampled 200 times per lineal inch, and noted that the apparent blackness of the image was increased by increased intensity of magnetization over equal areas.

Compared with photographic recording, ferrography has the advantage that no darkroom is required. Photographic films in themselves have much higher resolution, but for the intended purpose this may not mean an improved picture. Although ferrography has higher resolution than dry or wet electrosensitive paper (sect. 13.5 and 13.7) these papers appear simpler to use.

12.4. Flux Boundary Displacement

A special recording head devised by Daniels and Rubens [146] magnetizes a conventional oxide-coated tape to saturation over its entire length, except for a narrow unmagnetized zone running down the middle. Along one side of this neutral

[143] R. B. Atkinson and S. G. Ellis, J. Franklin Inst., 252, 373–381 (Nov. 1951).

[144] Ferroprint Corp., Los Angeles, Calif.

[145] S. J. Begun, IRE National Convention Record (1958), pt. 5, 190–197.

[146] H. L. Daniels, Electronics, 25, No. 4, 116–120 (April 1952).

boundary zone the tape has one polarity; along the other, the opposite polarity. The head (fig. 37) comprises a strong permanent magnet with a stack of laminations closing its circuit, and a shunt magnetic path influenced by a signal coil. The tape moves continuously across the gap between the shunt and the laminations. As the signal rises and falls in amplitude, the boundary zone is displaced transversely from the centerline of the tape by an amount proportional to the

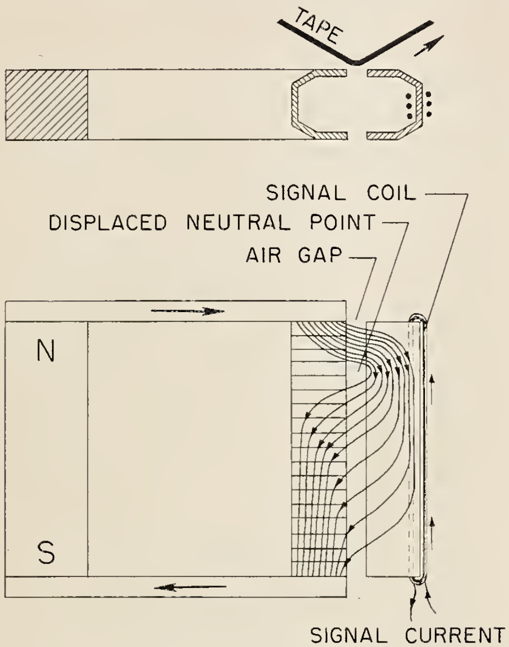

FIGURE 37. *Recording head for flux boundary displacement (Clevite Corp.).*

instantaneous signal intensity. In playback, a conventional pickup head whose gap spans the displacement range receives a net flux closely proportional to the distance difference between the elemental areas of positive and negative saturation, scanned by the gap. The full energy-storing capacity of the medium is available, and linearity is dependent only on the geometry of the heads.

By immersing the tape in a suspension of carbonyl iron powder in alcohol, the boundary region appears as a white line, and such visual records have been produced at frequencies up to several kilocycles. The tape may be relayed magnetically with the powder still present, or it may be wiped clean and reprocessed at will.

Extended investigation of techniques for making the flux boundary displacement visible was recently reported by Gehman.[147] To produce a dark line on a light (brown) background, the tape is fed toward and away from the gap at angles of about 30°, as in figure 37. Since the boundary is most distinct where the flux transient is steepest, pre-magnetization is used so that a d-c signal can be recorded; pulsing from a transverse wire provides this. A basic recording speed of 10 cps was used, with 50 and 200 ips for frequencies of 5,000 and 10.000 cps. Development of the latent image at speeds as high as 4 fps was accomplished by squirting a jet of liquid magnetic "ink" onto its surface, then pressing the tape through a duct for drying by forced air. Timing and calibration lines can be provided, and identification of records can be made by imaging an "8" matrix. On a 1.5-in. tape, the trace is visible within 1.5 sec in a line 0.015 in. wide with linearity of 1 to 2 percent.

13. Electric Recording

This refers to methods in which an electric discharge marks the recording surface directly. There is no clear boundary line between voltage and current effects; in some cases both are active. Electromechanical devices, e.g., hammers, are described in section 4.2.

13.1. Corona Picture

A high-voltage recorder designed especially for lightning discharges has been described by C. F. Wagner and C. D. McCann (Westinghouse).[148] The corona discharge at the tip of a sharp needle touching a photographic film will blacken the light-sensitive coating. As the film is slowly moved, the discharge traces a line, the thickness of which is approximately proportional to the peak voltage. For a single discharge, as received by a lightning rod, radial streamers with a length of an inch or more are traced on the film, leaving characteristic patterns known as "Lichtenberg figures." The length of the streamers indicates peak voltage, and the shape indicates polarity.

13.2. Spark-Perforated Area

A very unusual current recorder has been developed to measure the intensity of lightning strokes on high-voltage transmission lines[149] which may have peaks of 60,000 amp. This instrument is a sheet of thin paper between two flat electrodes which are inserted in the surge circuit.

[147] J. B. Gehman, Application of magnetography to graphic recording, IRE National Convention Record (1958), pt. 5, 198–203.

[148] "Klydonograph," Westinghouse Co., East Pittsburgh, Pa. See Trans. A.I.E.E. 59, 1061–68 (1940).

[149] Westinghouse Co., East Pittsburgh, Pa., Catalog section 38–270, "Surge Current Recorder" (Dec. 21, 1936), gives calibration for 100,000 amp (2-mm hole area) as 14 in. in 10 sec; for 1,000 amp as 3 in. in 200 sec.

The surge burns one or several holes in the paper, the total area being fairly definitely related to the crest value of the surge current.

Since some of the holes are very small and all are irregular in shape, the total area cannot be obtained by geometrical methods. It is measured by the time required to pass a certain volume of air, using a densometer built especially for this purpose. This device consists of two concentric aluminum cylinders, about 30 in. high and 6 in. in diameter, one inside the other. The time required for the upper cylinder to drop a given distance is determined with a stop watch.[149]

13.3. Spark-Perforated Traces

Details of early spark recording are given by Kalman J. de Juhasz.[150] Generally, thin paper (about 1 mil thick) was moved between a metallic surface and a metallic pointer, leaving an airgap of perhaps 40 mils to allow free movement. A voltage with high peak value but low rms value is applied across the gap, resulting in a spark which perforates the chart. This method was used at the beginning of the century to trace curves with low-torque electrical instruments. The voltage, of 3,000 to 5,000 v peak value, was generated by a small d-c induction coil with a vibrator, giving a spark frequency between 300 and 500 cps. The paper was impregnated with nitrate salts to make the markings clearer. A line width of 4 to 40 mils was the result, with the undesirable effect that the chart would fall apart when constant values were recorded. Generally a sheaf of sparks was to be seen, causing not one but several perforations of the chart at the points of minimum breakdown voltage; this, of course, reduces the recording accuracy. The curves were traced in either curved or rectilinear ordinates. Chart speeds were not higher than 0.4 ips, being limited by the generally low natural frequency of the moving element, 5 cps at best at that time.

Much higher accuracy is obtained with spark recorders if the pointer actually touches the chart, which is then made thicker. This is done with high-torque systems of engine indicators, such as the Farnborough type. Further developments on this spark recorder are described by W. J. R. Roach and J. G. G. Hempson in a report of the British Shipbuilding Research Association.[151]

13.4. Fusible Coatings

Thin homogeneous papers have a tendency to fall apart when the recorded variable is constant for a considerable time. With coated papers the spark pierces only the coating, which is generally light-colored, and the trace becomes visible as a dark line. The strong paper base is not damaged.

This is the same kind of chart as used for scratch recording and mentioned in section 5.2. The use of sparks brings the advantage that the pointer need not touch the paper and so avoids friction. However, electrostatic forces are developed between the pointer and the chart, and therefore this way of recording is used only for measuring systems which have a relatively high torque.[152]

13.5. Oxide Coatings

The typical representative of this much-used group of papers is "Teledeltos,"[153] as developed for facsimile recording. There are three layers in this material: (a) the carbon-filled paper base, (b) the conducting back coating of aluminum, (c) the electrically sensitive front coating, light gray in color. The coating is much harder than wax; the charts can be handled without marring it, and the stylus or pointer may touch the chart continuously, as long as the voltage is not applied. The diameter of the tungsten stylus is about 10 mils; the pressure necessary is 10 to 15 g, and wear is very slow. Two paper qualities are used, low resistance and high resistance. At a speed of only 0.1 ipm a potential of 20 v d-c with a current of 10 ma is necessary to make a clear marking. Speeds up to 1,500 ips have been obtained in tests, using up to 600 v and 250 ma. With proper circuit characteristics it is possible, according to the manufacturer, to make marks with a current pulse of only 20 μsec. The energy necessary to make a mark of 10 mils diameter is stated to be 1 mw-sec under best conditions.

In one of the latest designs of facsimile recorder, with an 8-in. chart, the stylus sweeps 30 times per second over the width of the paper, corresponding to a stylus speed of 240 ips. Nevertheless, marks as short as 0.2 mm are clearly visible on the paper, representing lines on transmitted script equivalent to a current pulse of only 30 μsec duration. The analog recorder noted in section 4.25 permits marking a Teledeltos tape, moving at 0.5 to 10 ips, at the rate of 24,000 times a second. Some experimental work has been done using a "Mylar" base for the tape. When voltage and chart speed are low, no spark is visible. But at higher speeds a spark appears, and for this reason many call the method "spark recording." Oxygen is needed for this paper and for that reason it cannot be used at high altitudes. In atmospheres with combustible components a fire hazard exists. For this reason attempts have been made to make paper for special applications with about the same recording properties, but without these disadvantages.

There are other electrosensitive papers which at the first glance appear to be identical with the

[150] The Engine Indicator, p. 133–36. Instruments Publishing Co., Pittsburgh, Pa. 1934).
[151] Engineer 194, 7 and 57 (1952).

[152] NBS Tech. News Bul. 35, 14 (1951), see also Instr. and Automation 24, 288–94 (1951).
[153] Western Union Telegraph Co., Water Mill, N.Y.

above, but which are basically different. One of these[154] has a base of ordinary white stock which, of course, is nonconducting. One side of the base sheet carries a conducting coat containing carbon black; this is masked with a white top coat which is burned away by current from the stylus. When d-c or low-frequency a-c (less than 1,000 cps) signals are used, the conducting layer has to be grounded, usually through the paper clamp. As far as sensitivity is concerned the manufacturer states that the power required for marking increases in proportion to paper speed, but the voltage required increases only slightly. With direct current, about 7 w are required for maximum density, with 100 lines/in., chart speed of 50 ips, and stylus pressure of 7 g. The printing voltage is about 500 v for maximum, 100 v for minimum density. This corresponds to about 0.5 mw-sec to make a mark 0.1 mm long. The paper is made in two qualities, one of which permits making multiple copies by a hectograph process using a gelatin pad. Electrical characteristics are about the same for both.

Recorders for these dry types of electrosensitive papers generally use a stylus made of steel or, better, tungsten, 3 to 4 mils in diam. The scanning helix commonly used for electrolytic papers (section 13.7) is generally not satisfactory, because the slightest misalinement will result in uneven or spurious copy.

13.6. Metallized Paper

This new recording medium was developed in Germany[155] and it is used in many recording instruments in Europe. A layer of cadmium, zinc, or aluminum, only 0.01 to 0.06 μ thick, is deposited on an insulating sheet of paper or plastic. About 20 v is applied between the two electrodes shown in figure 38; one a roller in contact with the full width of the metallic surface chart, the other a tungsten or platinum needle point at the end of the index arm. A current will flow from the former to the latter, and at the point of the greatest current density, under the needle, the metal coating will melt and evaporate, in the same way as with self-sealing capacitors which use basically the same type of paper. The current stops flowing until a new area of the chart comes under the needle point. In this way the movement of the pointer leaves a trace on the chart. The width of this trace does not depend on the chart speed, and does not increase even at very slow speeds.

This method, with properly designed elements, and with current and voltage kept within certain limits, is capable of writing speeds up to 10 m/sec, and the resolving limit is about 0.1 msec.

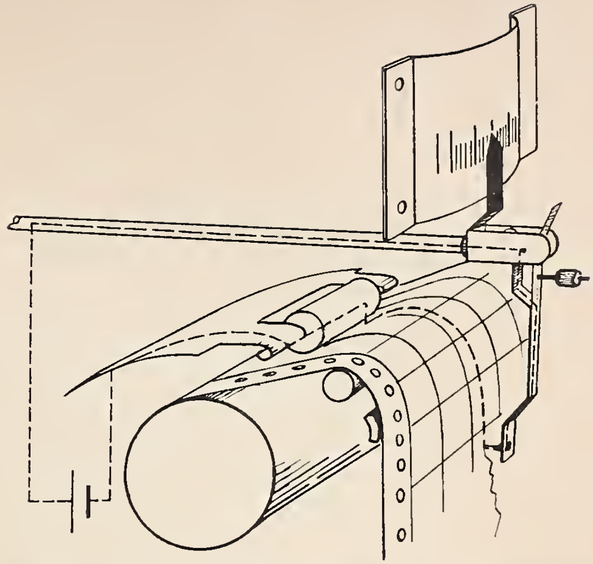

FIGURE 38. *Metallized paper (Allgemeine Elektrietitatesgesellsehaft).*

To melt one spot of 0.5 mm diameter, an energy of about 0.2 mw-sec is necessary, but still smaller energies (from capacitor discharge) down to 0.05 mw-sec leave a recognizable mark. The pressure of the stylus on the chart is of the order of 50 mg and, after tracing a line 20 to 50 km long, the wear is about 1 mm.

13.7. Wet Electrolytic Paper

This type of paper was first used by Edison[156] for recording Morse signals on tape. Even today it is used extensively for facsimile recording. The paper is impregnated with a chemical which reacts with the metal stylus when a current is passed between them. To make this reaction possible, the paper must always be moist, so that the method is better suited to tape or strip charts than to drum and disk charts. In the early days of facsimile recording potassium iodide was the chemical used. With a nickel electrode a brown color resulted, but the diagrams soon faded. Later many other chemicals were used.[157] It is now possible to get a wide variety of colors, ranging from brilliant yellow to red, purple, brown, blue, green, and black. Combinations of a single chemical in the paper with styluses of different metals afford the possibility of multicolor recording, but this has only been mentioned in patent applications. Modern wet electrolytic papers[158] with the proper electrodes give very clear lines, generally from dark brown to black, and these diagrams do not fade over long periods of time.

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[154] Timefax recording paper, manufactured by Times Facsimile Corp., New York, N.Y.
[155] Robert Bosch G.m.b.H., Stuttgart. A. Ortlieb, Elektrotech. Z. 71, 653–656 (1950).

[156] United States patents 160,580 and 168,465 issued 1874 and 1875.
[157] H. G. Greig, Proc. I.R.E. 36, 1224–35 (1948).
[158] Alden Electronic and Impulse Recording Equipment Co., Westboro, Mass.; Hogan Laboratories, Inc., New York 14, N.Y.; and Sangamo Electric Co., Springfield, Ill.

Unlike the coated charts of section 13.5 these papers may carry preprinted graduation lines, but the requirement that the paper be moist presents a serious disadvantage because the expansion may be 4 to 6 percent; 4- to 18-in. widths are commonly used. Therefore the method is better suited to facsimile recording of script or drawings. It is possible to print the calibration lines and the time ordinates at the same time as the signal trace is recorded. The moisture also reduces the mechanical strength of the paper, but charts with high tear-strength are offered for wet operation.

With electrolytic recording the stylus tip enters the chemical reaction and for this reason wears away more rapidly than would a purely mechanical device. How long the electrode metal will last depends on the reaction, and is inversely proportional to the ampere-hours of use. No data of general validity can be given; it can only be said that the necessary replacement of the stylus is not annoyingly frequent. Because the density of the color depends on the intensity of the current, these electrolytic papers can be used for X–Y–Z recording.

With fine electrodes, the line thickness may be only 0.1 mm. The writing speed may be up to 300 and even 600 ips, and pulses of 30 μsec can be recorded as traces 0.25 mm long. One firm states that to obtain a maximum black requires 500 ma-sec/in.^{2}. For a spot 0.25 mm square this is 0.05 ma-sec; with 20 v an energy of 1 mw-sec, the same as given for the dry paper of section 13.5.

Helical traverse is most common for wet electrolytic paper. The rotary speed is generally 6 to 10 rps, but up to 30 rps is possible. Papers manufactured with different impregnants are available for low and high recording speed. All papers have to be stored in vapor-proof wrappings, some under an atmosphere of carbon dioxide. After the recording is made, some papers can be exposed to daylight without fading the diagram.

Detailed studies on wet electrolytic papers have been carried out with stylus speeds up to 4 ips at the Naval Research Laboratory in the years 1948–1952.[159] The marking agent of this NRL paper is benzidine, which was chosen on account of its high sensitivity, wide dynamic range, and fine recording definition. The development was undertaken to improve wet strength, shelf life, and aging stability. The marking of this paper is blue, with high optical contrast to the buff background. Contrary to other papers, the recording process is an oxidizing reaction which permits the use of a chemically inert metal stylus or printing bar. This paper, like others, has to be adjusted to the proper moisture content, wound into rolls, and sealed in polythene bags or stored in sealed metal containers.

13.8. Electrostatic Effects

a. Ink Transfer

About 15 years ago an "electronographic process" was developed [160] for high-speed electrostatic printing of characters and numerals without actual contact between paper and type. The typefaces of the printing wheel are inked as usual and a potential of some 6,000 to 8,000 v is applied, which makes the ink fly from the type to the paper. In the earlier experiments with printing presses the distance was about 125 mils; in more recent designs the distance is reduced to about 1 mil, so that in rotary presses the type actually touches the paper, but without pressure. The method is supposed to give a clearer transfer than conventional methods, and to permit wider dimensional tolerances for the rolls in the presses. For electric digital recording, several different methods of positioning the characters for printing might be used. With sweep-balance, the printing wheels could rotate continuously at constant speed, and a capacitor could be discharged when the balance point is passed on the fly.

b. Charged Dielectric

"Electrography," proposed by Selenyi [161] about 25 years ago, uses an electrical discharge from a point electrode to a grounded metal plate through paper which is coated with a thermoplastic material of high resistivity. The discharge forms a latent electrostatic image on the surface which can be made visible by a powder of colored material, and which can then be fixed by passing the paper over a temperature-controlled hot plate.

The method has since been applied to produce an analog record from 430 in-line electrodes fed by 4-μsec pulses, and also to simulate typewritten text.[162] The individual electrode (a choice from a 5 by 7 pin matrix is used to form a character) has a diameter of 5 mils. The tape speed may be as high as 800 ips (0.8 mils/μsec). Pulse durations as short as 1 μsec leave a latent image. According to the information received, the latent image may be kept "for long durations of time" before fixing, but it can also be erased before fixing so that the tape can be used again. The particles of "ink" have a diameter of about 0.5 mil, and about 60 of them form a dot with a diameter of 10 mils.

[159] E. J. Kohn, D. L. Venezky, R. G. Rice, F. J. Ross, and G. F. Ashbury, NRL Reports 4001 and 4685; the latter contains a number of literature references and patent numbers.

[160] W. C. Huebner, Paper Trade J. 123, 1–4, (1946).
[161] P. Selenyi, Elektrotech. Z. 56, 561 (1935).
[162] H. Epstein, Proc. Western Joint Computer Conf. 1955, p. 116.

c. Photoconductive Dielectric

A method of graphic reproduction which may prove useful for recording conditions or variables is that originated by C. F. Carlson [163] in 1938. First publicized as "electrophotography", the process was a subject of research and development at Battelle Memorial Institute.[164] Because it is a dry process it became known as "xerography." Its rapidity is such that in trial oscillographic applications the writing speed was limited only by the response of the measuring system.

Xerography makes use of a plate consisting of an electrically conducting base coated with a thin layer of photoconductive insulating material such as selenium or anthracene. The plate is sensitized by passing it between wires at a potential of about 7,000 v, thus giving it a charge which it will hold for several hours in the absence of light. Where light strikes the plate, the coating becomes conductive and the charge disappears into the metal base, leaving a latent image. The plate is "developed" by passing over it a mixture of finely divided resinous powder and a granular carrier of larger particle size. In such a mixture, the carrier particles generate an electrostatic charge on the powder (triboelectric effect) so that the powder is deposited only where the charged image overcomes the mutual attraction of the particles. The resulting powder image is transferred to some other material such as paper. When the paper is heated the resin quickly fuses to form a permanent image.

The above process is used in commercially available [165] copying equipment. Another process [166] uses a variation of this dry printing method wherein sensitized paper replaces the plate, and the photoconductive coating is zinc oxide imbedded in an insulating coat of silicone resin. Another variation developed for rapid printing of 120 alphanumeric characters per 11-in. line, 6.4 lines/in., 13 ips, sensitizes a selenium-coated drum from a shaped-beam, cathode-ray tube [167] and transfers the text to untreated paper. When used for trace recording, this printer accepts pulses at 10,000 cps and provides 1,024 discrete points across the 11-in. chart.

The electrostatic method used in a recent design of multichannel oscillograph [168] resembles xerography, the positively charged photoconductive surface of the chart being discharged wherever a lightbeam "pointer" from one of the galvanometers strikes it. Positively charged powder, a mixture of magnetic iron oxide and thermoplastic particles (called toner) cohering by surface attraction, is picked up by a rotating magnetic brush and swept against the paper surface. Along lines traced by the lightbeams the thermoplastic particles adhere to the paper, the induced dipolar attraction along the trace being greater than the molecular cohering force between the toner and the oxide. Magnetic attraction retains the oxide on the brush. Elsewhere on the surface, there is no electrostatic attraction, and the mixture remains on the brush. Observation of the traces is possible 3.5 in. beyond this point, through a glass cover. Finally, the record is run over a heated roller and the toner is fused to the paper, providing traces which are nonfading, opaque, and slightly embossed.

14. Ultrasonic Recording

Special paper for facsimile recording has been developed for the Office of Naval Research,[169] using "sono-chromotropic paper" and a frequency of 10 to 13 kc, with a specially designed stylus which does not touch the paper. The paper is chemically treated to be sensitive to ultrasonic energy impinging upon it. The energy for recording is 2 w. The method has so far not progressed beyond the experimental stage.

[163] U.S. Patents No. 2,297,691 and 2,357,809.
[164] R. M. Schaffert and C. D. Oughton, J. Opt. Soc. Am. 38, 991–8, (1948); M. D. Sinclair, Printing Eqpt. Engr. Nov. 1948.
[165] Xerox, Haloid Co., Rochester, N.Y., cosponsors with Battelle Memorial Institute of xerography development.
[169] Homer J. Dana and James L. VanMeter, Electronics 23, 84–85 (1950).
[166] Electrofax. See C. J. Young and H. G. Greig, R.C.A. Rev. 15, 469–84 (1954); see also R. A. Broding et al., I.R.E. Trans. I–6, 220–24 (1957).
[167] Charactron, Stromberg Carlson Div., San Diego, Calif.
[168] R. A. Broding et al., I.R.E. Trans. I–6, 220–24 (1957).

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