NBS CIRCULAR 585

The Measurement of Thickness

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards

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The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

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Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.25) and its Supplement ($0.75), available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

To Accompany
National Bureau of Standards Circular 585
THE MEASUREMENT OF THICKNESS

NOTE

The survey on which this Circular is based was completed in 1955. More recent developments are not included. Since no other comparable compilation has appeared in the meantime, it is considered that the contents will be of value even though incomplete.

ERRATA

Page	Section	
13	1.152	The illustrations of figures 33 and 34 are transposed
17	1.203 (3d par. last line)	should read $d<D/4$
22	1.234	penultimate line should be deleted
41	4.41	transpose last five lines of left-hand column to top of page
43	4.53	caption omitted on last figure: Fig. 105, Circuit of sheet metal thickness comparator
52	5.4	McNicholas and Curtis reference should be numbered (143a)
52	5.4	Ref. (126) does not apply to this section
54	6.3	Ref. (66) does not apply to this section
	Reference	
72	(120)	should read Instruments in Industry, London (now called Automation in Industry)
72	(126)	second citation should read: Engrs. Digest (Amer. Ed.) 6, 156-7, (1945)
73	(161)	title should read: Elektrische Messung mechanischer Groessen
73	(165)	Citation should read: Revue Générale de l'Electricite (Paris), 44, 265-268(1938)

March 25, 1958

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UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

The Measurement of Thickness

George Keinath

National Bureau of Standards Circular 585

Issued January 20, 1958

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D. C.
Price .... 50 cents

Foreword

Preparation of this monograph on thickness measurement was undertaken to bring together available information on the various methods and problems of measuring thickness that are frequently encountered in scientific and industrial fields. The usefulness of this survey to scientists and engineers is expected to be enhanced by the inclusion of discussion of ranges, accuracy, advantages, and limitations. No attempt has been made to describe methods and instruments in detail. Such detailed information should be sought in the literature references that are appended to the text. A discussion of the bounds that have been set on the scope of the work will be found in the introduction.

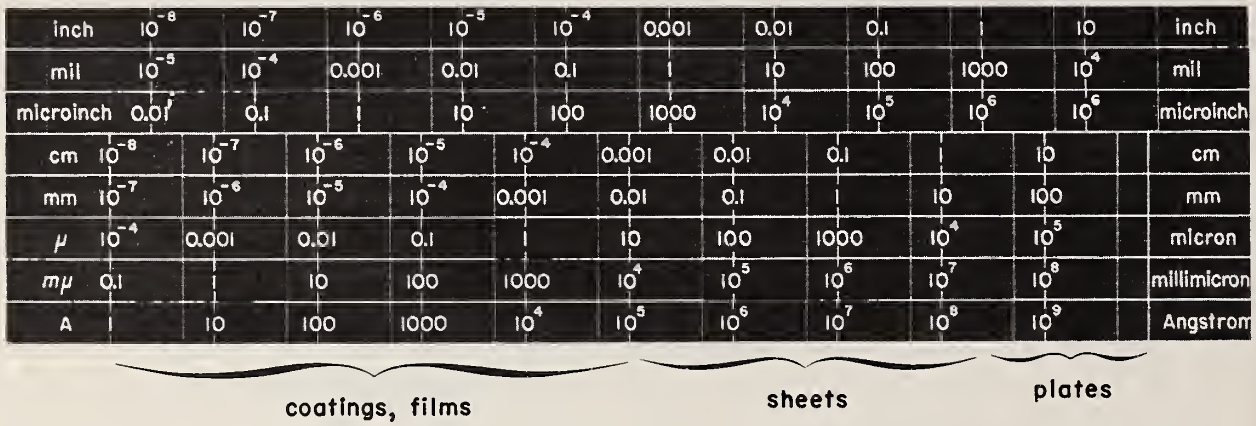
Names and descriptions of specific proprietary instruments are included for the convenience of the user, but completeness in this respect is recognized to be impossible. The omission of any method or device does not imply that it is considered unsuitable or unsatisfactory. Conversely, inclusion of descriptive material on any proprietary instrument, product, or process, does not constitute endorsement.

Some of the information included in this report was obtained from the open literature. The assistance obtained from American instrument manufacturers who furnished catalogs and other information descriptive of their products was vitally necessary to the work and is gratefully acknowledged.

The survey of the field of thickness measurement 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



inch	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	0.001	0.01	0.1	1	10	inch
mil	10^{-5}	10^{-4}	0.001	0.01	0.1	1	10	100	1000	10^{4}	mil
microinch	0.01	0.1	1	10	100	1000	10^{4}	10^{5}	10^{6}	10^{6}	microinch
cm	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	0.001	0.01	0.1	1	10	cm
mm	10^{-7}	10^{-6}	10^{-5}	10^{-4}	0.001	0.01	0.1	1	10	100	mm
μ	10^{-4}	0.001	0.01	0.1	1	10	100	1000	10^{4}	10^{5}	micron
mμ	0.1	1	10	100	1000	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	millimicron
A	1	10	100	1000	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	10^{9}	Angstrom

Conversion table.

Conversions among a number of units in which thickness is expressed.

The Measurement of Thickness

George Keinath[1]

The numerous methods for the measurement of thickness in laboratory or shop are treated in seven groups according to physical operating principles: Mechanical—weight/dimension relationships, acoustics, vibration, displacement with various conversions; chemical—stripping, spectrochemical analysis; electrical—dielectric breakdown, resistance, electrochemical, capacitance, thermoelectricity; magnetic—attractive force, reluctance, saturation, inductance, eddy currents; optical—microscopy (also electron microscopy), interferometry, diffraction, shadow; X-ray—absorption, diffraction, backscatter, spectrometry; radioactive radiation—absorption, backscatter, tracers. Ranges, accuracies, advantages, and limitations are discussed. A bibliography of references, a limited list of suppliers, and a detailed index of the gages, methods, applications, and trade names covered are appended.

Introduction

The measurement of thickness is the measurement of the distance from a point on one bounding surface of a material body, through the body, to the opposite bounding surface. If the surfaces of a body are parallel, as the two sides of a sheet of metal or the inner and outer surfaces of a pipe, the thickness is obviously the distance between the bounding surfaces measured along a normal. However, if the surfaces are not parallel the direction in which the thickness is to be measured must be defined. Sometimes the measuring instrument itself determines the direction along which the thickness is measured.

Further complications in measuring thickness are introduced by the lack of definition of the bounding surfaces of a body. For example, the thickness of a textile material is rather indefinite. Here, also, the measuring instrument importantly influences the "measured" thickness.

Thickness measurements as above described deal with the measurement of a distance between two points. However, for some purposes the measurement of the average thickness of a body is of more significance.

This survey is intended to assemble for convenient reference as many of the methods of dealing with the problems of thickness measurement as possible. It is not limited to direct measurement of thickness, but gives sufficient background information on the types and principles of operation of the devices to reduce the need to seek the basic information elsewhere. The survey includes information on the measurement of physical parameters involved in the practical measurement of thickness, such as displacement, for example. It also deals with some more general aspects of the measurement, such as dynamic response. The extent to which these are treated is determined in general, by the principles and makeup of existing instruments.

Considering only industrial problems, the maximum thickness is about 10 million times the minimum. The low limit is 0.01 microinch, as found in very thin coatings on glass. The high limit may be one or more inches, as in rolled or cast metals. This discussion will be primarily concerned with the measurement of the thickness of walls, sheets, and coatings of all kinds. Thickness of wires and threads is also included, although "diameter" is the term more generally used if the sample has a circular or an elliptical cross section. Distance measurement (as in spark gaps) is omitted, though the "feeler gages" for such measurements are called thickness gages.

The methods of thickness measurements may be destructive or nondestructive, contacting or noncontacting, with relation to the sample. It is very difficult to establish clear definitions of these terms for methods of measurement. For instance, the use of a needle to penetrate an insulating coat on a metallic base is a destructive method at the point of measurement. However, the manufacturer of the gage may consider his method nondestructive, because the tiny hole in a paint coating is practically invisible and unimportant in the use of the product. In the simplest problems the object of measurement is a small specimen accessible from both sides. Difficulties arise when the object is accessible from only one side. Such an object might be a moving sheet coming from a steel mill red hot, vibrating violently, covered with water or grease, and made almost invisible by a cloud of steam. In such a case the use of noncontacting thickness meters would be necessary.

Units of thickness: In this compilation, thickness has usually been expressed in "mils," i.e., thousandths of an inch, so that values of thickness will be easy to compare. It should be noted, however, that although this practice of stating thicknesses of flat metal sheets and plates and diameters of wires in mils is increasing, the specification of such sizes by numbers in one of several gage systems is still widely prevalent. In these systems, a given number is used to designate different thicknesses depending on the material under consideration, e.g., steel,

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[1] Larchmont, N. Y.

brass, or aluminum. Since 1941 the American Standards Association has issued Standards for Preferred Thicknesses for uncoated thin flat metals under one-half inch, covering in the latest issue the range from 4 to 236 mils in 40 steps by values progressing in accordance with the 40- series of preferred numbers, each step being 3 percent higher than the preceding one. The 1941 issue has only 20 steps, with a difference of 6 percent from step to step.

Conversions among a number of units in which thickness is expressed are presented in the accompanying table on preceding page IV.

References to the literature and to patents are indicated by numbers, in brackets and parentheses, respectively, referring to the bibliographic listings on pages 69 and 75.

In writing this monograph the author has received a variety of assistance from the staff of the Office of Basic Instrumentation. This assistance is gratefully acknowledged. Deserving particular mention are the extensive editorial review and the contributions to the sections on application of interferometry, radiographic, and nuclear radiation methods.

Methods of Measurement

1.00. Mechanical Methods

In this section are assembled methods in which the first measurement action is mechanical. The mechanical displacement, which is a function of the thickness, may in turn be measured by optical, pneumatic, electric, or other means, generally with the purpose of increasing the accuracy.

1.01. Weight [147; 190, p. 7].[2] If a material is homogeneous and of known density, a sample of controlled size can be weighed, and its thickness calculated from its weight. It is possible with sheet materials to cut samples of a specified size at each measurement and thus facilitate the determination of thickness. Wires are measured in standard lengths. Balances that indicate thickness directly are available or can be calibrated according to need.

1.02. Volume [168]. The thickness of nonporous insulation of wires may be determined in the following way: A length of wire of about 8 inches is cut off and put in a narrow cylindrical measuring vessel, filled with alcohol. The rise of the level gives the total volume. After stripping and dissolving the insulation, the measurement is repeated. From the volume difference the average thickness may be calculated. This method has been used successfully for several years by the Physikalisch-Technische Reichsanstalt in Berlin, for wires from 0.75- to 10-mm^2 section (AWG No. 18 to No. 7) with an accuracy of about 2 percent.

1.03. Oblique Cut.

1.031. *Vitreous Enamel* [111] **(fig. 1).** A method has been developed to measure the thickness of acid-resistant enamel coatings on iron plumbing fixtures (fig. 1). From a section of suitable size, along a new-cut edge, the enamel is ground off in a plane at an angle of approximately 5 degrees to the surface, exposing an oblique section of the enamel coating and part of the underlying metal. The lines (aa_3, a_1d_1, a_2d_2, and a_2d_3) shown in figure 1 are marked with a ceramic underglaze pencil. The specimen is refired just enough to obtain a fire polish on the oblique section of the enamel. After cooling, the specimen is immersed in 10-percent citric acid and dried. Colored wax pencil is applied to the whole surface, which is then rubbed with a cloth. The colored wax is readily removed from the acid-resistant section, which will have retained its fire polish. This section is now clearly bounded by the line aa_3, and the colored wax deposit. From measurements made along the parallel lines a_nd_n of the thickness of the total coating and lengths along the cut, the thickness of the acid-resistant coating is computed. The method is accurate to about 0.5 mil in a total acid-resistant thickness of 2.5 to 8 mils.

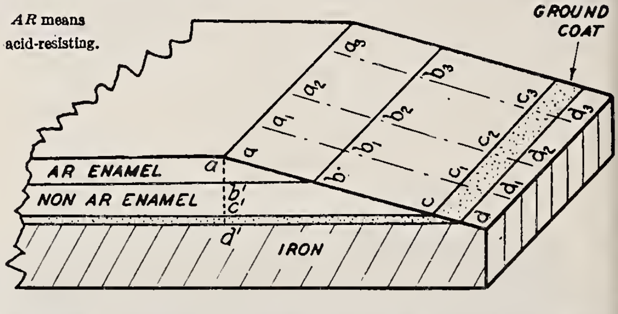
AR means acid-resisting.

FIGURE 1. *Sketch of specimen showing cross section and oblique section of enamel applied in three coats over iron.*

1.032. *Case Depth (Hardness Traverse)* [10, 157, 172, 175]. Effective case depth in steel is defined as a distance measured perpendicularly from the surface of a hardened case to a point of hardness equivalent to Rockwell "C" 50. Total case depth is defined as a distance measured perpendicularly from the surface down to the point where carbon enrichment ceases. The specimen is cut, ground, and polished in either steps, taper, or perpendicular section. The exposed surface is tested for hardness until the effective case depth is reached.

1.04. Chord Cut [35] (fig. 2). Mesle's chord method for measuring the thickness of coatings depends on barely cutting through the coating—on a plane surface, with a grinding wheel of

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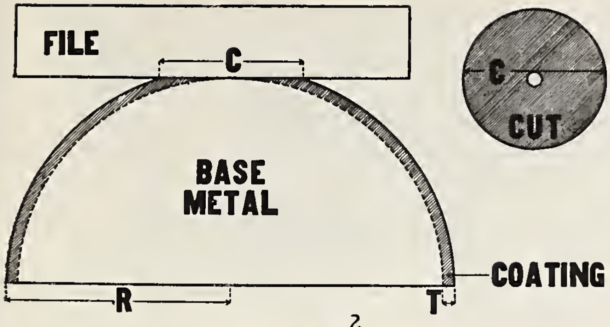
[2] Figures in brackets indicate the literature references on page 69.



$$T = \frac{C^2}{8R}$$

FIGURE 2. *Chord method to determine thickness of coating on a spherical surface.*

known radius fed perpendicularly; on a curved surface, by a chordal cut. In either case the thickness can be computed from the chord and the radius of the segment removed. The reference cited [35] gives the formula for calculating thickness for a number of different intersecting shapes: Plane surface and grinding wheel; convex spherical surface and flat file; convex spherical surface and grinding wheel; and concave spherical surface and small-radius grinding wheel. The curvature of spherical surfaces is determined with a spherometer. The measurement is difficult when coating and base have about the same color, in which case the cut surface is treated with chemicals that cause a color change.

With a grinding wheel radius of 3 to 4 inches the least thickness measurable is 0.05 mil, the chord length being about 40 mils. The accuracy is about 5 percent for nickel or composite coatings on steel plates, and about 10 percent for nickel coatings on copper or brass plates. For very thin coatings of chromium (about 0.02 mil) used for decorating purposes, a very small grinding wheel is recommended to produce a narrow but well-defined cut which can be measured with a microscope.

1.05. Manual Roller Gages.

1.051. *Euverard Gage for Wet Films* **(figs. 3, 4).** This gage, developed for the measurement of wet film thicknesses, is essentially a graduated eccentric wheel supported by two concentric wheels (fig. 4), all machined to an accuracy of 0.008 mil. When rolled over a plane surface, there is a clearance ranging from 0 to 4 mils (fig. 3) between the inner eccentric wheel and the surface upon which the outer two concentric wheels rest. When the gage is placed on a wet surface in the position of the greatest clearance, and rolled until the clearance is eliminated, the eccentric wheel will at some intermediate point contact and "pick up" the wet film. The measurement is usually performed in two perpendicular directions and the average of the readings taken as the true wet-film thickness.

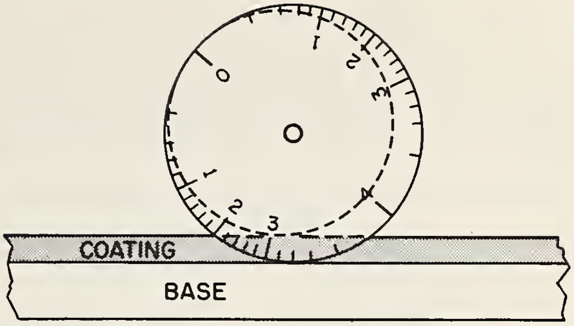


FIGURE 3. *Roller thickness gage.*

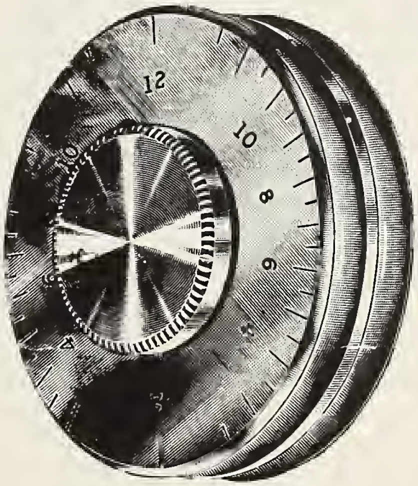


FIGURE 4. *Roller thickness gage.*

The standard instrument with a wheel 2 in. in diameter has a measuring range of 0 to 4 mils. Each scale division on the eccentric wheel represents 0.2 mil and readings to the nearest 0.1 mil are possible. The following instrument ranges are also available: 0 to 0.4 mil, 0 to 1 mil, 0 to 2 mils, 0 to 12 mils, 10 to 30 mils, and 20 to 60 mils; and the scale graduations, 0.02, 0.05, 0.1, 0.5, 1.0, and 2.0 mils.

Manufacturer: Henry A. Gardner Laboratory, Bethesda, Md.

1.052. *Euverard Gage for Dry Films* **(figs. 5, 6).** An adaptation of the wet-film gage described above makes it suitable for measuring the thickness of coatings, especially paint coatings, on a nonconducting base like wood or glass. The same wheel is used, but the film is removed from the base along two suitably spaced strips, to permit the outside concentric wheels of the gage to rest on the uncoated base. By the use of a suitably adjusted mirror or lens, the degree of clearance between the measuring surface of the gage and the film coating can be seen with the aid of a diffused-light source directed toward the gage. As long as there is a gap between the measuring surface of the eccentric wheel and the coating, it is possible to observe a brightly illuminated area which has the

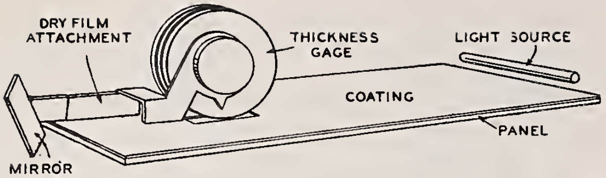


FIGURE 5. *Roller gage to measure thickness of dry coatings.*

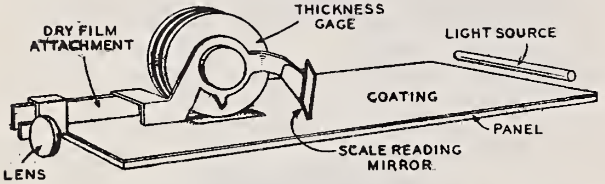


FIGURE 6. *Roller gage to measure thickness of dry coatings.*

width of the measuring surface and the height of the space between this surface and the coating. The gage is slowly turned until the illuminated area disappears, at which point the reading is taken, in two directions if desired. A magnifying lens is provided for better observation of the luminous area. The scale can be read from the mirror without moving the operator's eye from the viewing position (figs. 5, 6). It is claimed that this method, which applies no pressure to the film, gives the true thickness more accurately than other methods which require decoating.

Manufacturer: Henry A. Gardner Laboratory, Bethesda, Md.

1.06. Sphere Penetration Gage (figs. 7, 8, 9). The Pfund paint-film thickness gage is used for the determination of the thickness of wet paint or varnish films (fig. 7). A convex lens, L, whose lower surface has a radius of curvature of 250 mm, is mounted in a short tube, T_1, which slides freely in the outer tube, T_2. The compression springs, S, keep the convex surface out of contact with the paint film until pressure is applied to the top of T_1. The instrument is rested on the painted surface and the lens is forced down as far as it will go. Upon releasing the pressure and removing the gage, a circular spot is left on the lens as well as on the painted surface. The diameter of the spot on the lens is measured to 0.1 mm with a steel scale and then converted to thickness by using tables. The accuracy has been found to be within 0.04 mil for films 1.6 to 2.6 mils thick.

Manufacturer: Koehler Instrument Co., Jamaica 33, N. Y.

1.10. Mechanical Gages, Direct Reading [**78; 190, p. 6-8**]. Direct-reading mechanical gages, examples of which are discussed below, are the most universally used thickness meters, especially for making measurements on small pieces. Their use is prescribed in many of the ASTM specifications and standards. They give the thickness at the spot where the measurement is

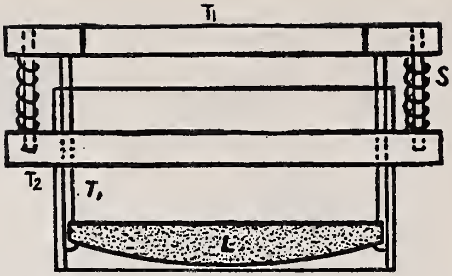


FIGURE 7. *Pfund film-thickness gage.*

FIGURE 8. *Pfund film-thickness gage.*

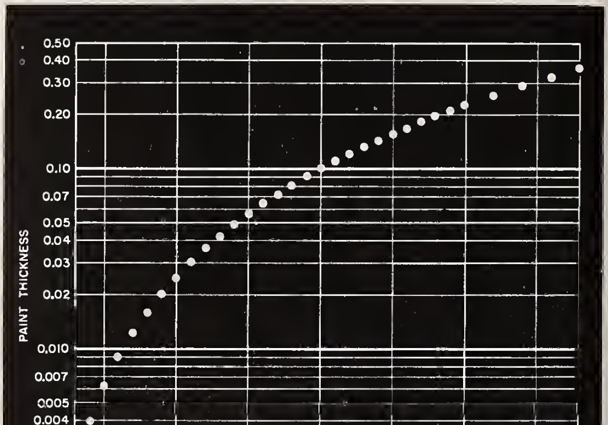


FIGURE 9. *Paint thickness as a function of the paint-spot diameters for the Pfund gage.*

FIGURE 10. *Slide caliper with vernier attachment.*

made. For large objects one must determine the average thickness by making a number of measurements at a number of evenly distributed spots and calculating the arithmetic mean. The thickness of very fine paper, such as that used for capacitors, is often measured by stacking an assembly of 10 sheets and using a parallel-plate gage. With paper about 0.25 mil thick, using dial gages or screw micrometers, the thickness of one sheet might be measured as 0.34 mil, whereas the average thickness based on 10 stacked sheets might be only 0.24 mil. The difference in values between measurements on a single sheet and measurements on stacked sheets depends on the "packing fraction" (the extent to which the thicker areas of one sheet coincide with the thinner areas of another sheet). The stacked thickness values are preferred as a practical matter because they tend to be more nearly uniform.

1.11. Slide Calipers [27] (fig. 10). Slide calipers are among the simplest devices for thickness measurement. The reading accuracy is about 0.1 mm (4 mils) for direct reading, because the smallest discernible distance is about 0.07 mm for the average human eye [27]. With a vernier attachment the accuracy can be much increased, with 0.018 mm as the possible limit. In view of the thickness of the graduation lines a practically feasible value is 0.050 mm (2 mils). By using a magnifying lens, a vernier with 50 divisions, and a line thickness of not more than 0.07 to 0.1 mm, a least reading of 0.02 mm may be obtained.

1.12. Joint Calipers (fig. 11). There are three types of joint calipers (fig. 11) which are customarily used as comparators to transfer a dimension to a steel scale for measurement:

(a) Firm-joint calipers with legs that hold their position by friction, giving the advantage of very quick adjustment.

(b) Screw-adjusted firm-joint calipers, similar to (a), but with fine adjustment.

(c) Spring calipers, the most widely used type.

1.13. Screw Micrometers [15, 20, 27, 118, 206] (fig. 12).

1.131. *Micrometer Caliper* [27]. The micrometer is essentially a calibrated screw. By turning the thimble the screw revolves in a fixed nut in the frame, and the spindle, which is the unthreaded portion of the screw, moves up or down relative to the anvil. The spindle moves through a definite distance depending on the pitch of the screw. As a rule, there are 40 threads to the inch; hence one turn of the thimble moves the spindle $\frac{1}{40}$ in. = 0.025 in. = 25 mils. The major divisions of 25 mils are marked on the hub and 25 subdivisions are marked on the beveled portion of the thimble attached to the screw.

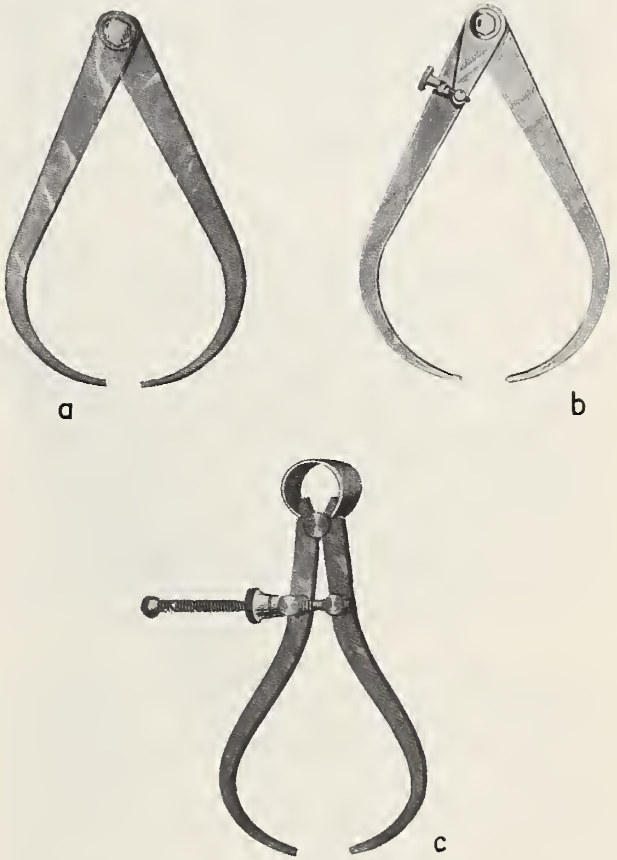


FIGURE 11.
a, Firm-joint caliper; b, firm-joint caliper with screw adjustment; c, spring caliper.

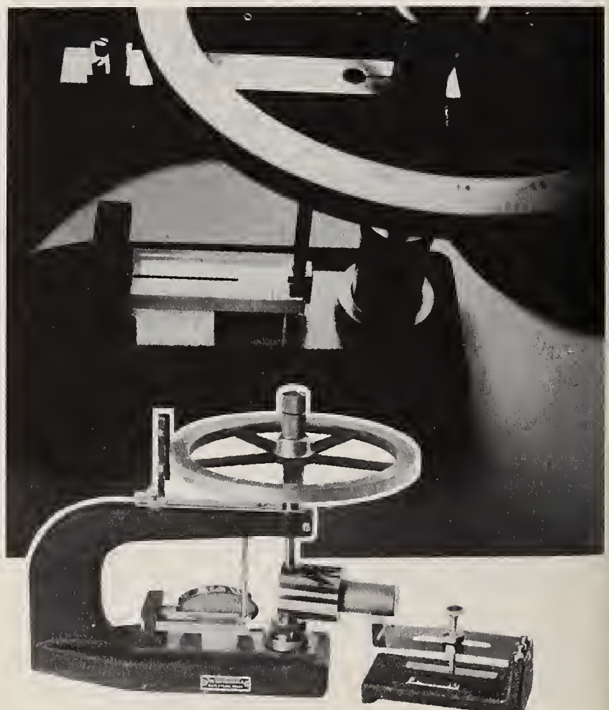
Other micrometers of greater precision are also made. It should be noted, though, with the more finely divided screw and the more precise instrument, greater care must be taken in its use. Accuracy of measurement depends largely on the pressure exerted on the work and on the compressibility of the material. The more compressible the material, the greater the error. Many types of screw micrometers use a friction clutch or ratchet for rotating the screw in order to obtain constant and correct pressure. Generally the accuracy obtained is ±0.1 to ±0.5 mils.

One design of micrometer caliper with a nonrotating sleeve reads by vernier down to 0.025 mil. Optical magnification with a simple 5 or 10× hand lens is often used with such instruments. In the most elaborate designs [27] the reading error is reduced to 1 μ (0.04 mil) and even 0.1 μ. The total accuracy of measurement is, of course, less than the reading accuracy.

Procedure and permissible errors of micrometer calipers with and without ratchets are discussed in ASTM standard D374.

FIGURE 12. *Micrometer caliper.*

1.132. ***Screw Micrometer With Optical Indication of Pressure*** [206] **(figs. 13, 14).** This micrometer (figs. 13, 14), which utilizes optical pressure indication, has been developed to provide the highest accuracy of screw micrometers [206]. The micrometer screw, machined with great precision, carries a 6-in.-diameter aluminum wheel with 0.1-mil graduations about 100 mils apart, a magnification of 1,000. This permits readings of 0.01 mil. Combined with this mechanical-screw micrometer is an optical indicator of pressure, which enables the operator to apply exactly the same pressure on the object for each measurement. This pressure indicator is a combination of an optical flat, a chromium-plated steel flat, and a red selenium-glass screen, so arranged that the slightest upward pressure on the micrometer spindle causes interference bands to move past a reference line. Each interference band is a measuring unit of 0.01 mil. The bands are spaced about ⅛ in. apart. Any measuring load from 0 to 2.5 lb can be applied. When in proper adjustment, two or three bands will show, from the left-hand edge of the steel flat up to the cross-reference line, when the spindle is not touching the anvil. Each additional band that is moved up to this reference line corresponds to an increase of measuring load of 6 oz. The load is selected to suit the material under test. The ranges of this light-wave screw micrometer are 0 to 1, 0 to 2, or 0 to 3 in. The threshold sensitivity of measurement



FIGURES 13 and 14. *Pressure indication on light-wave screw micrometer.*

is 0.005 mil, and of load, ½ oz. Readings can be duplicated to 0.01 mil.

A special design has a range of 0 to 3 in. and a number of features that insure still higher accuracy and convenience in use.

Manufacturer: The Van Keuren Co., Watertown 72, Mass.

1.133. *Screw Micrometer With Electrical Indication of Contact* [15, 118] **(figs. 15, 16).** Most mechanical gages for thickness measurement impose a load on the object. For compressible materials any load interferes with making precise measurements, unless controlled in some way, such as that described in 1.132. For metallic specimens, another solution of the problem is the use of a low-voltage signal lamp to indicate contact of the metal tip. This is not fully satisfactory, because the current over the contact points may cause pitting.

Carson Electronic Micrometer: The circuit of the Carson Electronic Micrometer [15, 118] is shown in figures 15 and 16. The circuit adopted uses a negligible current to light an indicator lamp by means of a relay at the moment of contact. A displacement of 0.005 mil is sufficient to trigger the relay. Electrical contact is established through the work piece itself, when measuring metallic materials. For nonconductors, electrical contact is made within the gage head when mechanical contact with the work closes the small gap between two elements in the gage head. It was found that the presence of appreciable current at the contact surfaces tended to build up carbonized layers which soon reduced accuracy.

The dial diameter is 3 in., with 250 divisions about 40 mils wide, each representing 0.1 mil, corresponding to a screw pitch of 25 mils. The magnification is about 400. The accuracy of the instrument is given as 0.02 mil. For the measurement of compressible materials the standard anvil pressure (supplied by a spring in the upper anvil) is ⅛ oz (3.4 g), but with interchangeable springs it can be increased to 2, 4, or 8 oz.

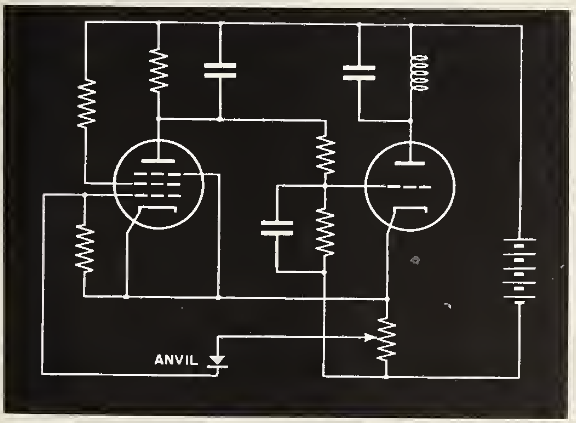
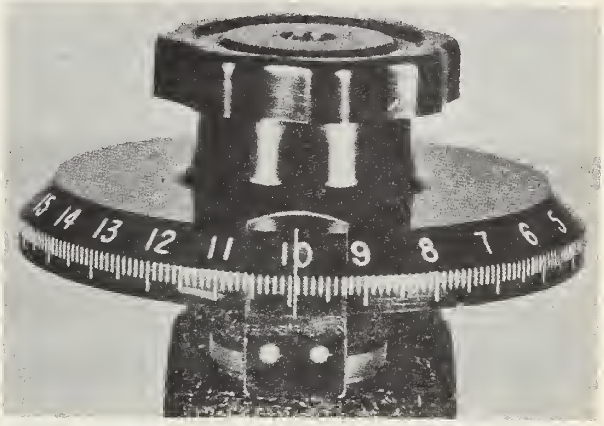


FIGURE 15. *Simplified circuit of the Carson gage.*

Manufacturer: J. W. Dice Co., Englewood, N. J.

ASTM standard D374 covers the measurement of the thickness of solid electrical insulation with machinist's micrometers and deadweight dial micrometers; it allows tolerances considerably wider than those obtainable with the Carson micrometers.

Wall Thickness Meter for Tubes: A mechanical micrometer with electrical contact is used to test the wall thickness of hollow propellers and of tubes up to 6 ft long. The gage consists of two long arms mounted on a base. Contact points at the ends of the arms are connected to an electronic control box, giving both optical and acoustical signals when contact is established between the micrometer screw and the object under test. After a preliminary adjustment of the equipment, two readings on the vernier dial of the micrometer screw are taken, one with the tubing under test in place, the



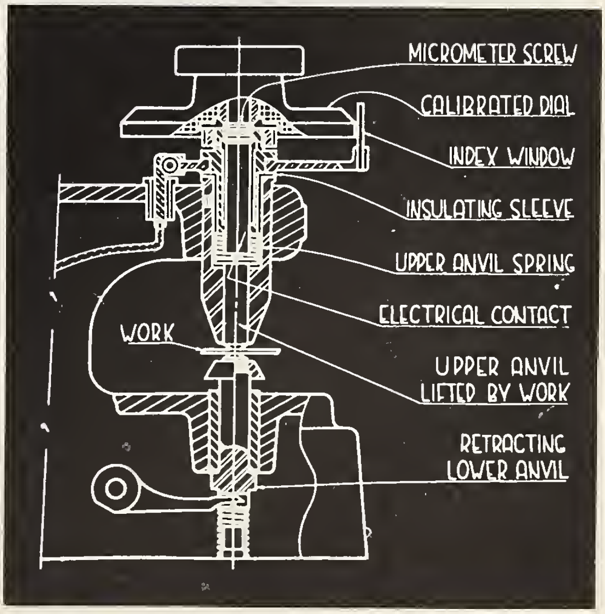


FIGURE 16. *Carson gage to measure thickness.*

other with it removed and the upper contact point touching the lower contact point. Differences in wall thickness of 1 mil can be determined in this way.

Manufacturer: Fairchild Aircraft Co., Hagerstown, Md.

1.134. *Penetrating Needle* **(figs. 17, 18).** A penetrating-needle-type gage is used for the measurement of the coating on either flat or curved metallic surfaces. The body of the gage rests with three points on the surface to be tested. The dial screw, 4, moves the needle, 8, downward until it has penetrated the film of insulation, and makes contact with the metallic base. This lights signal lamp C. The dial makes one full revolution for 2 mils movement of the needle and the scale can be read with an accuracy of 0.01 mil. The instrument is generally used in a gage stand, which holds the gage vertical. A pressure of 0 to 10 lb is applied on the large foot that carries the needle; this pressure is adjusted according to the hardness of the surface film. For zeroing, the gage is placed on an uncoated plane metal surface.

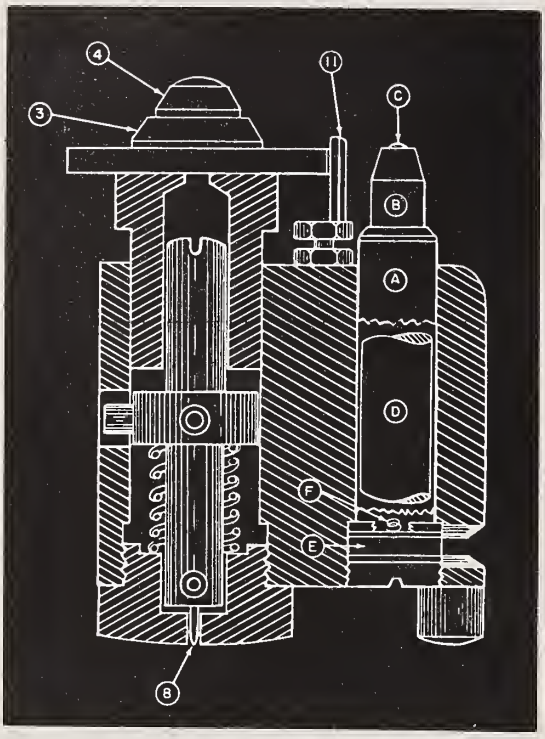


Figure 17. *Cross section through measuring head of Gardner gage.*

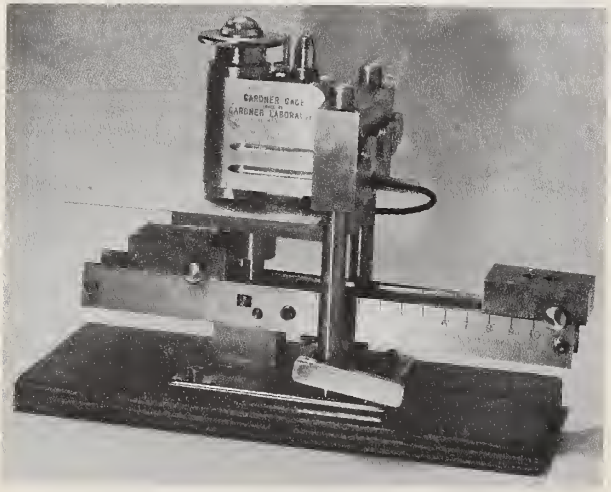


Figure 18. *Gardner thickness gage with stand.*

Manufacturer: Gardner Laboratories, Bethesda, Md.

A gage, operating on the same principle, with an electronic relay circuit to light the lamp, is manufactured under the trade name "Bathytrol."

Manufacturer: Electronic Control Corp., Detroit 7, Mich.

1.14. Dial Micrometers [20].

1.141. *Simple Dial Micrometers (Medium Sensitivity)* **(figs. 19, 20).** Even a simple dial micrometer provides much higher magnification than is possible with the standard screw micrometer, thus facilitating the reading of small changes of thickness. The movement of the anvil is magnified by mechanical means, the simplest using the lever principle. Mechanical gears are often used (fig. 19). Very sensitive gages of this type make one full revolution of the pointer for 4 mils displacement of the anvil, with graduations of 0.05 mil. For greater thickness, the pointer makes up to 10 revolutions, which are read on a smaller dial (fig. 20). In this device, the magnification of the anvil movement is about 2,500. Generally the magnification of dial micrometers is 500 to 1,000.

An instrument with a fan-shaped housing and ±45° deflection, "Micronar," has a range of

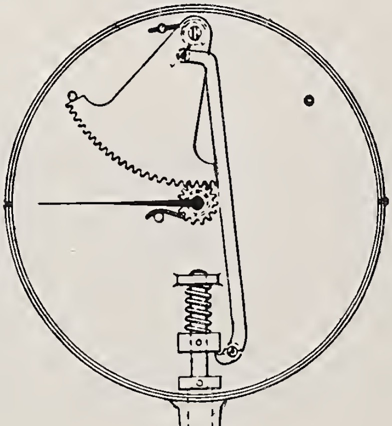


Figure 19. *Principle of a dial micrometer.*

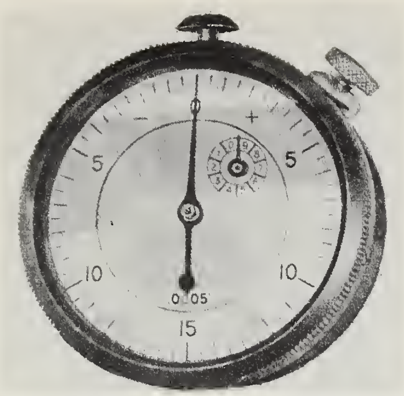


FIGURE 20. *Dial micrometer with revolution counter and a range of ±15 mils in divisions of 0.5 mils.*

±1.8 mils. Other divisions of 0.1 mil are spaced 150 mils apart, whereas divisions near the scale center are subdivided to 0.02 mil. The magnification is 1,500.

Manufacturer: Standard Gage Co., Poughkeepsie, N. Y.

1.142. *Dial Gage Micrometer With Screw Micrometer* **(fig. 21).** This instrument can be used either by reading the dimension on the barrel or by setting the barrel to the desired value and reading the deviation on the dial. The range of the dial indicator is ±1 mil, with each division 0.1 mil.

Manufacturer: Federal Products Corp., Providence, R. I.

1.143. *Dial Gage Micrometer With Joint Caliper* **(figs. 22, 23).** This meter is used to determine the thickness of walls, sheets, and sections of castings and forgings. It is trigger-operated and the dial micrometer has a revolution counter. One mil is represented by 2 in. on the dial, corresponding to a magnification of 2,000. The maximum jaw opening is 4 in.

1.144. *Dead-Weight and Spring-Loaded Gages* **[20, 116a] (figs. 24, 25, 26, 27).** For exact measurements of objects that are not perfectly flat or that have a fibrous structure, the measured thickness depends very much on the applied pressure. For the measurement of paper a gage foot between 14.3 and 16.5 mm in diameter is used, so that local variations of thickness are eliminated, and the maximum thickness of the sheet is read. For special applications, e.g., to measure the thickness of capacitor paper 0.2 to 0.4 mil thick, mechanical gages with ball and anvil have been used by the Bell Telephone Laboratories. The balls used were 10 or 20 mils in diameter and the load 30 to 200 grams, giving, despite the light load, a relatively high pressure.

For highly compressible materials, special mechanical dead-weight gages have to be used. Examples are knitted, woven, and pile fabrics; blankets, felts, rug underlays; sheet rubber (foam or solid); paper, etc. The following defi-

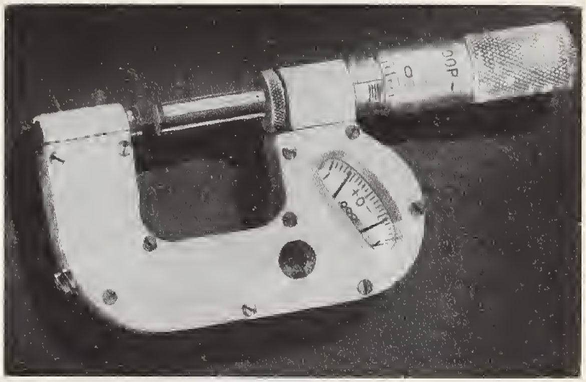


FIGURE 21. *Combined screw micrometer and dial indicator.*

FIGURE 22. *Combined joint caliper and dial gage.*

FIGURE 23. *Combined joint caliper and dial gage to measure the wall thickness of elbow tubes.*

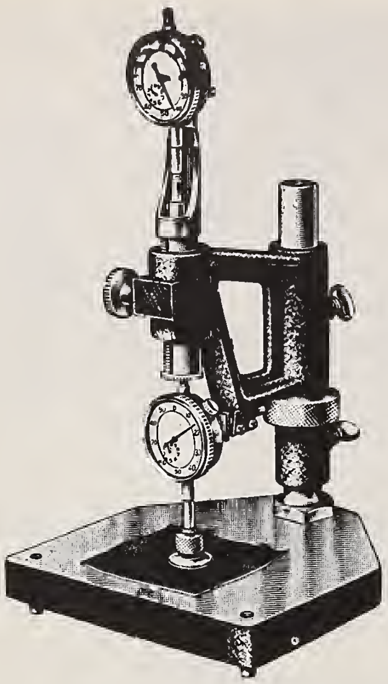


FIGURE 24. *Compressometer, thickness gage for compressible material.*

nitions for the thickness of compressible materials have been given: (1) The thickness of a specimen is the distance between the foot and the anvil when the pressure has reached a specified level. (2) The standard thickness is the thickness when the pressure has been increased to 1 lb/in.^{2}, all other conditions being standard.

ASTM Standard D1056 provides that in measuring the thickness of cellular rubber a dead weight of 25 grams on a circular area 1¼ in. in diameter be used.

Typical instruments are following:

(a) *"Compressometer"* [179] (fig. 24). In this instrument the specimen is placed on the anvil and the knob turned until the circular foot is resting on the fabric. The upper dial, by measuring the extension of the calibrated spring, indicates the amount of pressure being exerted on the material under test. The distance between the anvil and the foot, i.e., the thickness, is indicated on the lower dial. The compressibility of a material can also be determined with this instrument by taking a series of readings with alternately increasing and decreasing pressures.

Manufacturer: American Instrument Co., Silver Spring, Md.

(b) *Amthor Dead-Weight Thickness Gage* (fig. 25). The handle on the top is used to lift the weight before the material is put in place. The 6-in. scale of the instrument has 0.1-mil divisions, with a maximum range of 40 mils for one full revolution.

FIGURE 25. *Dead-weight thickness gage.*

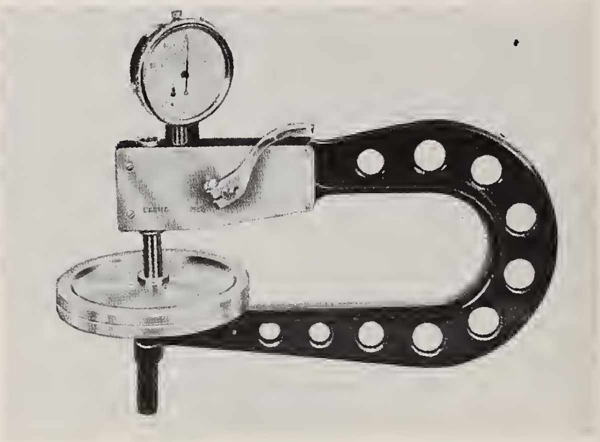


FIGURE 26. *"Pileometer" to measure thickness of plush.*

Manufacturer: Amthor Testing Instrument Co., Brooklyn, N. Y.

(c) *"Pileometer"* (fig. 26). This instrument is used to measure the thickness of plush, carpets, etc. Capacities of the standard types are 500, 750, and 1,000 mils. The disk has a diameter of 4 in. One revolution of the dial gage pointer represents 100 mils, with graduations of 1 mil.

Manufacturer: F. F. Metzger & Son, Philadelphia, Pa.

(d) *"Measure-Matic Gage"* (fig. 27). This gage is used to measure mats and blankets of loosely associated fibrous materials such as jute, wool, or glass fibers. The platen covers an area 1 ft^2 under a load of approximately 2 g/in.^{2}, which requires a total weight of 0.635 lb, with

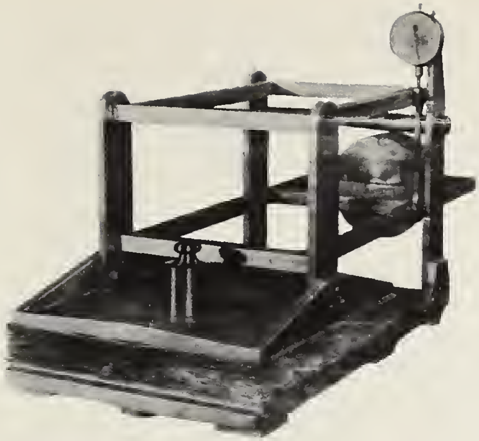


FIGURE 27. *"Measure-Matic" gage to measure thickness of fibrous materials.*

the material extending to or beyond the platen on all sides. Before the measurement is made, the platen is balanced by adjusting the counterweight on a threaded rod behind the uprights. The movement of the platen relative to the table is transmitted to a dial indicator giving the distance between table and platen with an accuracy of 10 mils up to 5 in. total distance.

Manufacturer: Gustin-Bacon Manufacturing Co., Kansas City, Mo.

1.145. ***Special Designs*** **(figs. 28, 29).** Many special designs of dial thickness gages have been developed. A few examples follow: The Federal Products Corp. portable dial gage (fig. 28) has wide-face spring-loaded upper and lower anvils to hold the gage perpendicular to the sheet surface. The ring thickness gage (fig. 29), of Federal Products Corp., has a movable gage system which alines itself radially. The Guyer gage, used for rapidly checking the thickness of large sheets, clamps on the sheet just long enough to read the dial, and then is automatically released for removal to the next point to be measured. Up to 38 measurements per minute are possible.

(e) *Holt Gage for Rubber Specimens* [116a]. Screw micrometers combined with a very sensitive electrical-contact indicating device have been adapted to measuring the dimensions of soft rubber parts. Two vertical gages have been built for thickness measurements, and a horizontal gage for the diameter of cylindrical or spherical parts. The measurements agree closely with those computed from the volume because the specimens are compressed only very slightly in making the electrical contact.

1.146. ***Roller Gages*** **[177] (figs. 30, 31).** Roller gages are used for the continuous measurement of moving strips, as in drawing wires or in coating wires with insulating material. The anvils are replaced by balls or rollers. This can be done in various ways. In a "single roller gage" (fig. 30) (Federal Products Corp.) the

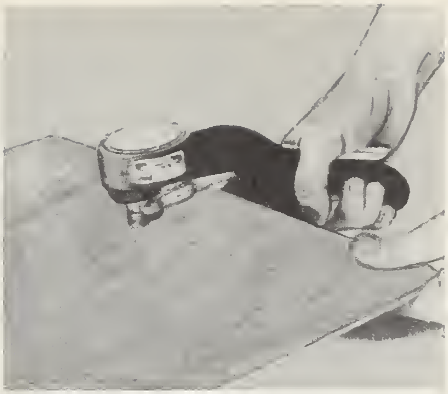


FIGURE 28. *Sheet-metal dial micrometer.*

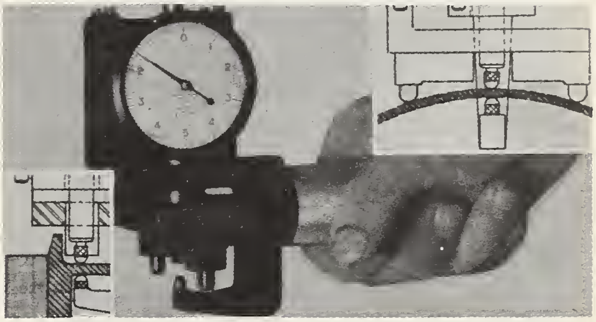


FIGURE 29. *Ring-thickness dial micrometer.*

FIGURE 30. *Single-roller gage.*

FIGURE 31. *Differential-roller gage.*

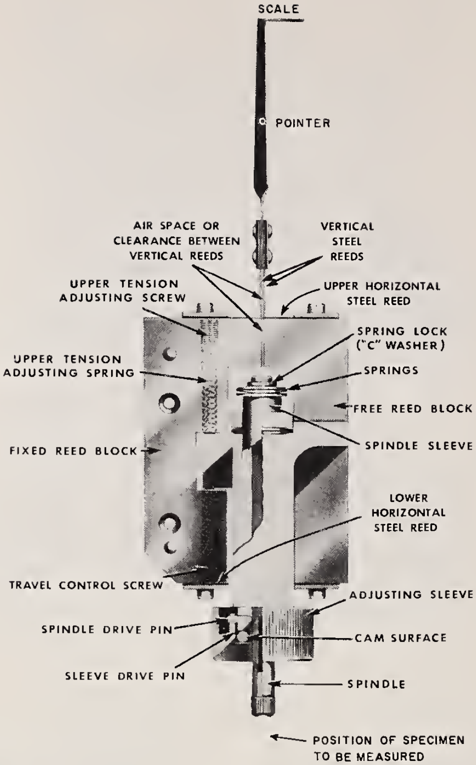


FIGURE 32. *Reed gage for mechanical magnification of displacement.*

roller on the gage bears against one side of the stock while the other side is in contact with a reference surface, a ground roller, or a platen over which the strip can be passed.

When the material is passing over a calender roll, a "differential roller gage" (fig. 31) is used, in which a cylindrical roller rides on the stock and a barrel-shaped roller rides on the calender roll. Such double roller gages carry their own reference roll as well as a measuring roll, and are particularly suited to measure the thickness of wet paper stock before it enters the calender rolls.

"Floating gages" permit the gaging head to follow variations in the pass line of the work while keeping the reference roll in contact with the underside. They are used to measure rods that are not perfectly straight.

Manufacturer: Federal Products Corp., Providence, R. I.

1.147. *Averaging Gages.* In many cases it is sufficient to maintain an average thickness. To measure the average, it is necessary to introduce a lag or damping into the indications (up to 100 seconds for slow moving material). This can be done most simply by using mechanical-electrical gages and damping the moving-coil indicator.

1.15. Dial Gages, High Mechanical Magnifications.

1.151. *Parallel Reeds* [7] **(fig. 32).** Two vertical reeds of thin steel are used to measure and magnify displacement by mechanical means (fig. 32). They move parallel to one another, one being held by a fixed block, the other by a free-moving block. The relative movements of the reeds are magnified so that the pointer swings through a much wider arc. The amount of its swing is proportional to the distance the floating block is moved. These reed gages are ordinarily used with additional optical magnification (see 1.164).

1.152. *Twisted Ribbon* [1] **(fig. 33).** The basic design of the twisted ribbon gage for the mechanical magnification of displacement is shown in figure 33. It is generally known as the "Swedish Gage" and by the trade name "Mikrokator." The pointer is mounted on the middle of a twisted strip of phosphor bronze. The twist of the strip is left-handed on one side of the pointer and right-handed on the other side. When such a strip is stretched, the center portion carrying the indicator pointer will rotate about an axis through the center line of the strip, i.e., unwind. The sensitivity is increased by perforating the central portion of the strip. The diaphragm that supports the spindle at the lower end is cut out as shown in "A" to permit free vertical movement of the spindle. The upper end of the spindle is fastened to a plate spring. A coil spring, which is adjusted by a collar on a spindle, furnishes the required force between feeler and specimen.

The standard instrument uses a strip of phosphor bronze 0.06 by 0.0025 mm, 40 mm long, twisted 4,000 degrees, and has a tapered glass pointer 30 mm long. The magnification is about 5,200. Magnification about 10 times higher is obtained with the leverage of a "spring knee." The force required to produce a 90° rotation is as low as 0.3 gram.

Using only mechanical means, the manufacturer claims as much stable magnification as 200,000. Using a mirror and a light beam 900 mm long, the magnification can be brought up to 12 million. The least sensitive standard instrument has a measuring range of ±3 mils, the most sensitive, a range of ±0.1 mil (2.5 μ). The latter is graduated to 0.1 μ. Special designs have a range of ±1 μ and graduations of 0.01 μ, with an operating force of 0.3 gram. The instruments are automatically protected against overload and possible damage by shoulders on the spindle which engage corresponding shoulders on the body.

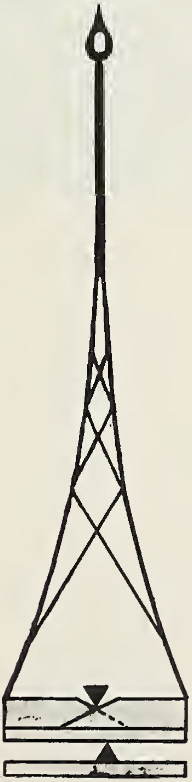


FIGURE 33. *Twisted ribbon gage for mechanical magnification of displacement.*

Manufacturer: C. E. Johansson Gage Co., Eskilstuna, Sweden, and Swedish Gage Co. of America, Detroit, Mich.

1.153. ***Tilting Block*** **(fig. 34).** A lever construction for mechanical magnification is shown in figure 34. The "Comparitrol" (trade name for this design) uses a V-notch block, which is tilted by the feeler point, a steel ball, or a diamond or tungsten-carbide point (the lower pivot in the figure). The magnification obtained in this way is 500 for a standard model, 1,000 for special instruments. The scale length is ±1.5 in. It was manufactured by George Scherr Co., New York, N. Y., but production has been discontinued.

FIGURE 34. *Lever magnification of movement.*

1.16. Dial Gages, Optical Lever.

1.161. *Mirror Principle* **(fig. 35).** Optical magnification of angular movement caused by the displacement of an anvil brings a number of advantages:

(a) The reflecting mirror adds very little weight and moment of inertia to the moving system, and such systems generally withstand shocks and overload better than instruments with long pointers.

(b) Reflection on the mirror provides magnification of 2, which means that an optical system with 4-in. radius is effectively an 8-in. mechanical pointer.

(c) Very long scales can be obtained with several designs. Figure 35 shows the principle

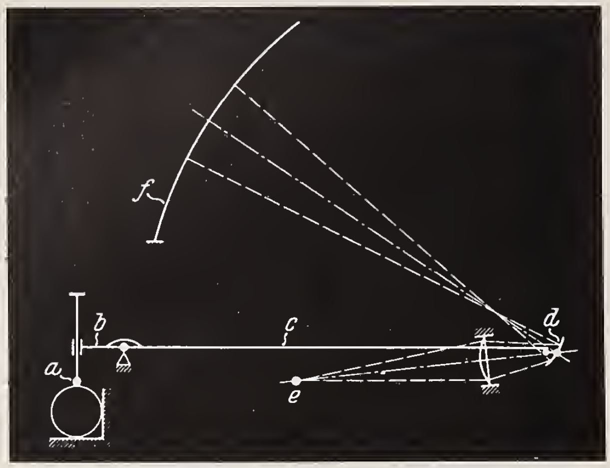


FIGURE 35. *Optical magnification of displacements.*

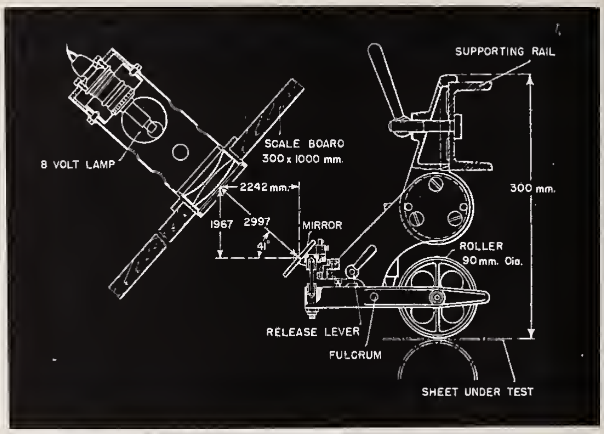


FIGURE 36. *Optical magnification of roller movement.*

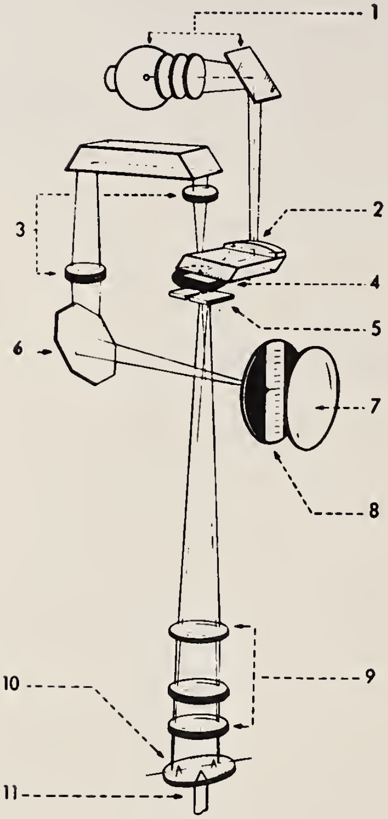
of optical magnification. The feeler (a) rests on the piece under test and is connected with the short end (b) of the two-arm lever (b–c). At the end of the long lever is the mirror (d) reflecting a light beam coming from the small lamp (e). Indication is given on the scale by a bright circle with a dark diameter line.

1.162. ***Roller Gage with Optical Magnification* (fig. 36).** Detail of the optical arrangement, used in a steel mill to indicate the movements of a roller gage, is shown in figure 36. The lower roll (it may be a drum) is fixed, and the upper roll swings in a fixed support, positioned according to the thickness of the material. The concave mirror is illuminated by a low-voltage, 50-watt lamp. The scale is at a distance of 10 ft and has a length of 40 in., which corresponds to a thickness of 90 mils. The magnification in this example is 450.

1.163. ***"Projectometer"* (figs. 37, 38).** A portable instrument for the measurement of thickness of individual test pieces uses a tilting mirror and an optical magnification system (figs. 37 and 38). An important measuring element of this instrument is a master glass scale of high accuracy. When the tested piece is put under the contact tip, a greatly magnified image of both scale and index is thrown against a screen so that a distance of 0.1 mil is enlarged to 125 mils, a magnification of 1,250. This image is further enlarged by a 1.5x magnifying lens. A 6v-5a lamp is used for illumination. The measuring accuracy is given as 0.005 mils.

A more recent development, known as the "Ultra-Projectometer," has a magnification of 10,000. The scale divisions are directly in 0.005 mil, which, with the 400 divisions of the standard projectometer scale, give a total range of ±1 mil.

A direct-reading thickness meter, the "Leitz Vertical Measuring Machine," has a master scale 4 in. long and gives measurements in 0.05



1 Lamp Attachment
2 Illuminating Prism
3 Relay System
4 Plane of Scale
5 Tolerance Marks
6 First Surface Mirror
7 Viewing Lens
8 Screen
9 Objective
10 Tilting Mirror
11 Contact Tip

FIGURE 37. *"Projectometer," optical magnification.*

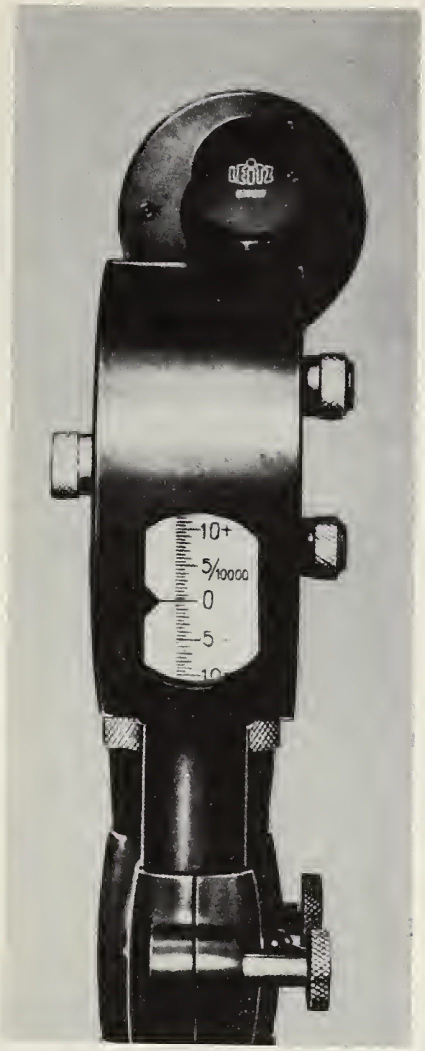


Figure 38. *"Projectometer," reading scale and measuring head.*

mil. The magnification of this instrument is 2,700, and the tolerance is given as ±0.008 mil.

Manufacturer: Leitz, Wetzlar (Germany).

1.164. ***"Visual Gage"*** **(figs. 32, 39, 40).** This instrument (fig. 39) uses the reed magnifier (fig. 32) (see 1.151) to get a pointer displacement proportional to the anvil movement. In one of the two designs, the end of the pointer bearing a flag is projected optically onto a curved scale, which has a length of 4 in. at the bottom of the opening in the gage housing. This meter is built for magnifications of 500, 1,000, and 2,000, the highest magnification showing 1 mil as 2 in. With a different design of the optical magnification (fig. 40) using a longer beam of light, magnifications of 5,000 and 10,000 are obtained on a scale 5 in. long. Here, 0.1 mil is represented by a deflection of 1 in.

Manufacturer: Sheffield Corp., Dayton, Ohio.

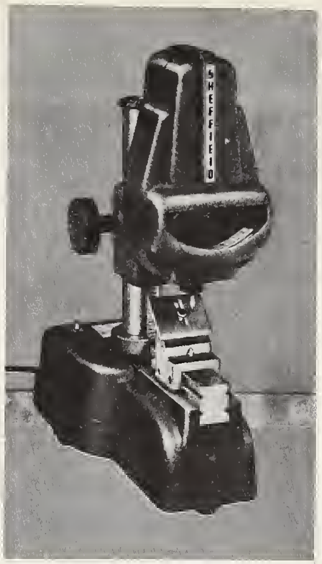


Figure 39. *"Visual gage," using both mechanical and optical magnification.*

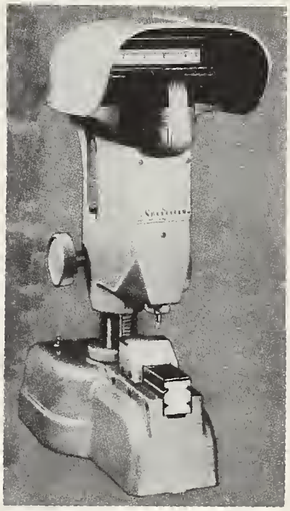


Figure 40. *"Visual gage" for magnifications of 5,000 and 10,000.*

1.20. Pneumatic Gages [3, 4, 6, 7, 67, 85, 104, 123, 176, 187, 213] (pats. 3, 4).[3] In pneumatic gages the flow of compressed air is influenced by the mechanical dimensions of the work under test. With increasing distance of the jets from the piece under test, the air flow to the gaging head increases and an indicator may be directly calibrated in units of thickness.

There are two basic types of pneumatic gages: Back-pressure and rate-of-flow gages.

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[3] A list of patents is given on page 75.

1.201. ***Back-Pressure Gage* [4, 67, 104, 116] (figs. 41, 42, 43, 44).** The fundamental form of the back-pressure gage for measuring thicknesses of individual pieces (fig. 41) consists of an air supply of constant pressure entering an orifice of predetermined size, with a pressure-regulator valve and an indicator on the constant pressure supply. A filter removes excess moisture and other foreign materials, which might spoil the parts tested or foul the small orifice through which all the air must pass. The pressure at the entrance of the restrictor orifice is identical with that in the large-bore tube whose open lower end is submerged in a tank of water. The constant pressure in the tube can be changed only by changing the water level in the tank. A small vertical sight-glass has one end connected to the conduit of the gaging head, the other end to the lower portion of the water tank. When conduit and gaging head are open this indicator will show, under atmospheric pressure, the height of the water level in the tank. Increasing back pressure, with increasing resistance to the flow of air out of the gaging head, depresses the water level in the indicator tube. Because of the necessary height of the water tank, this type of gage seldom operates at more than 1 psi (1 lb/in.^{2}) air pressure. Higher pressures can be used with mechanical pressure gages which measure the constant supply pressure and the working pressure below the restricting orifice.

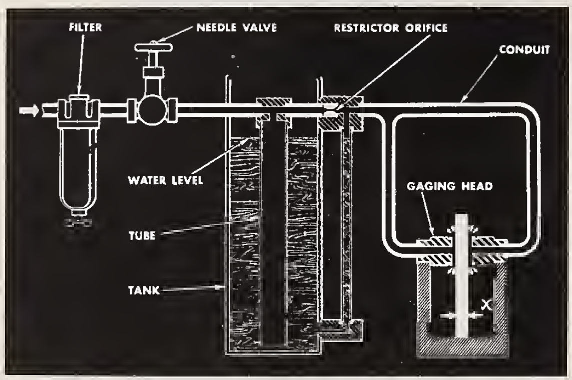


FIGURE 41. *Water-column back-pressure air gage.*

Figure 42 shows the principle of the "C" type of gage using an adjustable compensator. By means of its automatic orifice the compensator maintains a constant flow of air regardless of the gaging pressure. This allows approximately twice the nozzle clearance and twice the wear allowance of gages with a simple orifice. The maximum magnification of these gages is 8,200, which means that a deviation of 0.1 mil from the standard value is indicated by a pointer deflection of 0.82 in.

Manufacturer: Moore Products Co., Philadelphia, Pa.

Another type of back-pressure pneumatic thickness meter is the "Dimensionair" (figs. 43, 44). Pressure indication is given either by a dial manometer for high pressure (40 to 100 psi), or by a glass tube manometer for low

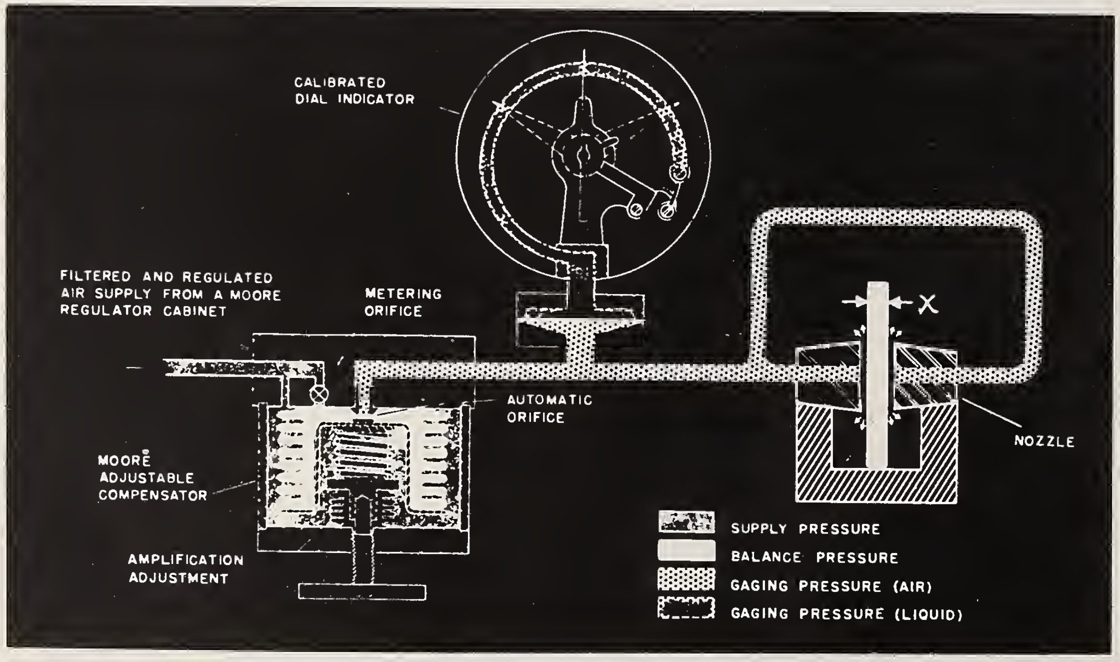


FIGURE 42. *Pneumatic back-pressure gage with adjustable compensator.*

FIGURE 43. *"Dimensionair" pneumatic gage.*

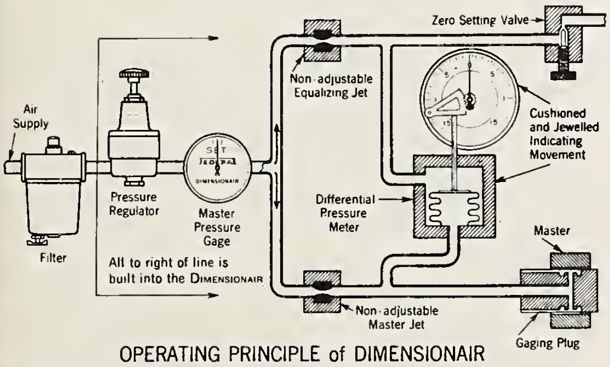


FIGURE 44. *"Dimensionair" pneumatic gage.*

pressure (1 to 2 psi). The magnification is 2,500 with the high-pressure type, 4,000 with the low-pressure instruments. The range is ±1.5 mils, the scale length 7.5 in.

Manufacturer: Federal Products Corp., Providence, R. I.

A pneumatic micrometer [176] gives a magnification of 32,000 with a measuring range of 10 μ (0.4 mils). The 300° indicator scale has only 10 divisions, each 32 mm (1.25 in.), and is equipped with contacts for make-and-break control.

1.202. *Continuous Gage for Threads and Wires* [25, 85]. The National Physical Laboratory in London developed a pneumatic gage for the wool industry in England [25, 85] for measuring the diameter of threads or wires in the range 7 to 10 mils, with continuous indicating and recording. The measuring head consists of a small box with entrance and exit orifices through which the filament is run at speeds up to 1,000 ft/min. Air blown into the head through a tube at the top escapes through the two orifices. The material fills the orifices almost completely, and the closer the fit, the higher the sensitivity. The pressure measurement is made by a spring-loaded piston which displaces $\frac{1}{16}$ in. for 1 in. of water pressure. The displacement is measured with a pneumatic amplifier so that pressures from 2 to 14 psi are obtained over the range of the instrument.

The indicating instrument has a 3-in. dial and the pointer makes one revolution for a piston movement of 100 mils. The scale has a length of 6 in., and because the piston has already magnified the change of the measuring jet 1,000 times, the total magnification is 60,000. One scale division of 10 mils represents jet displacement of 0.001 mil.

1.203. *Continuous Gage for Moving Strips* **[67, 104] (pat. 3) (fig. 41).** *Solex.* Instruments have been developed for use in rolling mills by the Societe d' Application de Metrologie Industrielle in Courbevoie (Seine), France, under the name "Solex." In the simplest design (fig. 41) compressed air flows under constant pressure from a tank into a chamber, from there through the measuring orifices. The back pressure behind the two orifices, one on each side of the strip, indicates the thickness. The differential pressure is read on a manometer. The magnification of this instrument is 4,800, so that a thickness change of 1μ is indicated by a scale deflection of 4.8 mm. For a total measuring gap of 35 μ the range of the instrument is ±5 μ and the resolution 0.5 μ.

The French company is represented in the United States by Arnolt Corp., Warsaw, Ill.

Etamic. Another continuous gage for moving strips, Etamic (pat. 5), uses air flowing at critical (sonic) speed in nozzles under high pressure (about 50 lb/in.^{2}). The strip to be measured passes between two orifices located on either side of the strip. Both of these orifices are located at the downstream end of a measuring tube which has a calibrated nozzle at the upstream end. The change in absolute pressure in the region between the upstream nozzle and the gaging nozzle, formed by the orifice and the strip, is a linear function of the distance, d, if each orifice is circular, has a diameter D, and is a distance $d<D$-4 from the strip.

The gage can be set to operate at any standard capacity from 0 to 10 mm thickness. The accuracy is given as ±1 μ for a measuring range up to 80 μ. The sensitivity is given as 0.1μ. Maximum and minimum tolerance limits can be set to any value between 1 and 100 μ. The clearance between orifice and strip must not be less than 170 μ.

Manufacturer: Ateliers de Normandie, Paris, France.

1.204. *Rate-of-Flow Gage* [6, 7] (figs. 45, 46, 47). In this type of gage, the restrictor orifice is completely eliminated. Air is supplied at constant pressure (through filter and regulator) and the rate of air flow escaping through the gage head is measured. The rate-of-flow meter used consists of an internally tapered transparent tube, vertically positioned, with the wide

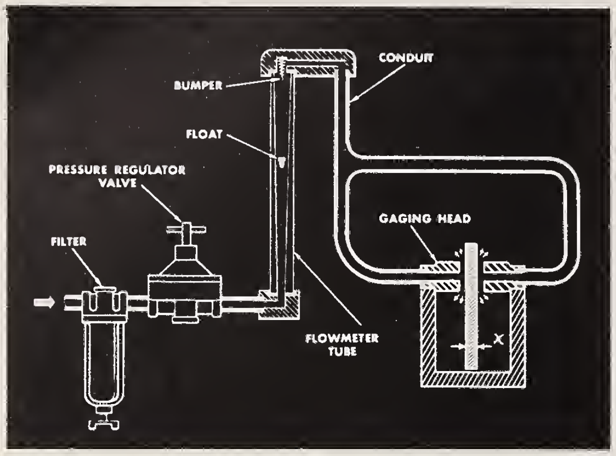


FIGURE 45. *Pneumatic gage operating with constant pressure and indicating dimensions with a rate-of-flow air gage.*

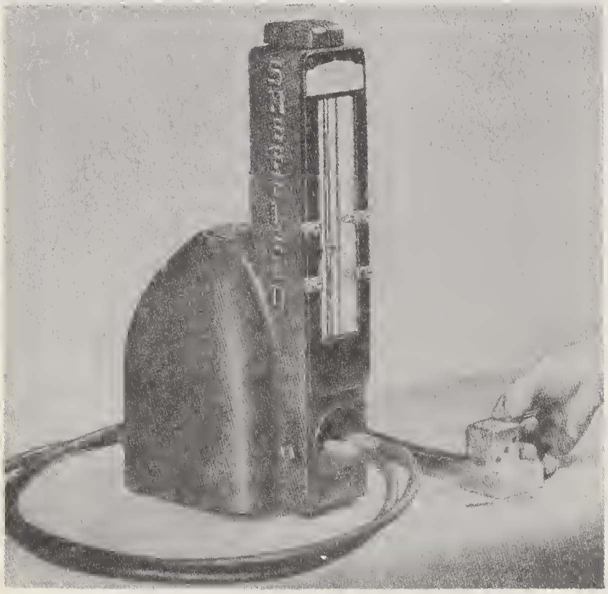


FIGURE 46. *"Precisionaire" thickness meter and measuring head.*

end upward, generally called a rotameter. A light-weight metal float positions itself in the taper according to the velocity of the air passing through the tube, so that the position of the float is a direct indicator of rate-of-flow and hence of thickness. Figure 46 shows a complete instrument, the "Precisionaire" of the Sheffield Corp. To measure thickness, special gages have been developed with two sets of directly opposed jets (fig. 47), so that perfect contact between the piece under test and the reference surface is not necessary.

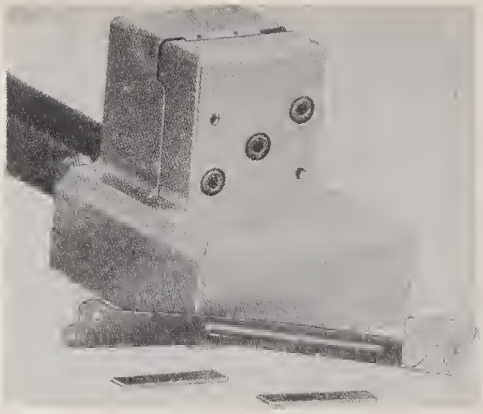


FIGURE 47. *"Precisionaire" thickness meter and measuring head.*

The sensitivity of these pneumatic gages is very high. Standard magnifications range from 1,000 to 40,000, representing a dimensional difference of 1 mil as a float movement in the indicator tube of 1 to 40 in. For the maximum magnification, with a scale length of 8 in., a deviation of ±0.1 mil is ±4 in. As far as accuracy is concerned, it must be noted that all pneumatic gages, like most other mechanical gages, depend on calibration with a sample of known standard thickness, for which the float is set to zero by adjustment of a bleeder valve. In general the deviation from this standard thickness is not magnified more than 10,000 times. The indication of this deviation is affected by changes of the supply pressure, which, however, can be kept within very small limits.

Manufacturer: Sheffield Corp., Dayton, Ohio.

There are other ways of measuring the rate of flow to the gaging head. An electrically heated wire may be placed in a tube and the cooling effect of the escaping air measured in the conventional way, for instance with a Wheatstone bridge arrangement. The device described in [154] may be used for measuring the thickness of wires and threads. This introduces the advantages of electric indicating, controlling, and recording to pneumatic thickness meters.

To measure the fineness of textile fibers a fiber grader ("Micronaire") has been developed by the Sheffield Corp. Air is forced through a plug of fibers and the air flow is greater for coarse than for fine fibers. The repeatability for cotton fibers is given as 0.1 μg/in., or 0.36 mg per 100 yards.

1.21. Deflection. An instrument known as "Bondimeter" has been used to measure the thickness of metal sheets in airplane structures with only one side accessible. The gage consists of an inverted cup or shell with a top wall of transparent material and the bottom edge faced with a rubber gasket. Mounted inside the shell is a dial indicator, graduated in mils, equipped with a stem reaching to a spherical foot which, when the instrument is in use, rests against the test surface. A valve in the top of the case is connected to an external pump so that the device can be partially or completely evacuated.

When in use, the gage is placed on the area to be inspected, the valve opened, and the air inside the instrument allowed to reach normal atmospheric pressure. A reading is then taken which serves as a reference standard for the test. With the valve again closed, the air is evacuated and the sheet metal deflected upward into the cup. A new reading of the dial is taken, and the difference of the two is compared with precalibrations on samples of the same metal, with the same mechanical properties and a known thickness.

Manufacturer: American Instrument Co., Silver Spring, Md.

1.22. Vibration [38, 50, 71, 79, 81, 82, 89, 94]. If the material under test is in the form of sheet or strip and if it has good elastic properties, the thickness may be determined by the vibration frequency of a reed of known width and length cut from the material. A thickness change of 1 percent causes a frequency change of 3 percent.

1.221. *Sonic.* The time of reflection of a sound signal from the bottom of the sea gives the thickness of the layer of water under the sound emitter mounted in the bottom of a ship. The speed of sound in water is 1,450 m/sec, hence a depth of 725 m is indicated by a time delay of 1 sec. In metals the speed of sound is several times higher. In a piece of steel, 0.32 in. thick, the echo will return in about 1 μsec. Sound-reflection methods are also used in geophysical exploration to determine the thickness of different subsurface layers.

1.222. *Ultrasonic* [38, 39, 50, 71, 81, 82, 89] **(figs. 48, 49, 50, 51, 52, 53).** *Sonigage* **(fig. 48).** This is one of a number of industrial thickness meters using the reflection of ultrasonic waves. The measurement is made by bringing the work piece into resonant vibration in the test direction and measuring the resonance frequency. Driving energy is provided by an electronic oscillator and a small quartz crystal which is pressed against the work piece. The frequency of the oscillator is changed until the indicator gives a maximum deflection and, for any given material, the frequency dial may be calibrated in units of thickness. The frequencies employed for thickness measurement of steel are in the range of 1.4 to 2.8 megacycles per second for a thickness range from 0.125 to 12 in. By switching several inductance coils into the oscillating circuit and by interchanging crystals, a wider variety of measurements can be handled by a single instrument. One quartz crystal may be used over a frequency range of about 2:1. The natural frequency of the crystal is always much higher than the frequency used for the measurement.

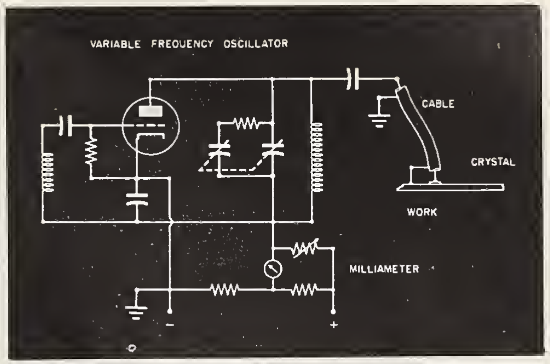


FIGURE 48. *Circuit of the "Sonigage."*

FIGURE 49. *"Audigage" thickness meter.*

Audigage. Another instrument of this type [38, 39], the "Audigage" (fig. 49), uses a headphone in place of the indicating meter, taking advantage of the fact that the ear is faster in response than sensitive moving-coil instruments. The operator is free to use his eyes for other duties, e.g., best placement of the transducer probe.

Manufacturer: Branson Instrument Co., Stamford, Conn.

In another design [81, 82], the tuning capacitor is rotated continuously by a small motor. The indicator is a cathode-ray oscilloscope. The horizontal deflection plates are connected with the sweep voltage, and the plates for the vertical deflection represent the output of the oscillator. When the oscillator frequency is equal to the resonance frequency of the object, a vertical deflection is obtained, as shown in figure 50. Thickness scales are printed on transparent slides and changed with the range of the instrument.

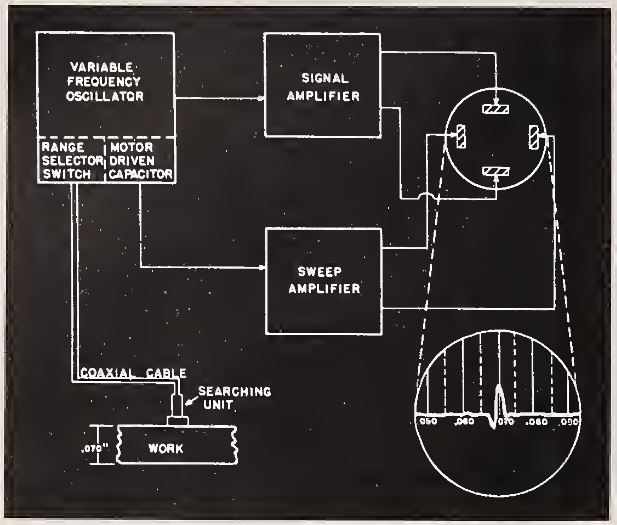


FIGURE 50. *Block diagram showing the major components of the "Reflectogage."*

FIGURE 51. *Crystal transducer searching unit.*

Reflectogage. The design of the "Reflectogage" [50, 71, 89] (figs. 50, 51, 52) has the four ranges, 25 to 50 mils, 45 to 90 mils, 80 to 160 mils, and 150 to 300 mils.

Manufacturer: Sperry Products Corp., Danbury, Connecticut.

Sonizon. The "Sonizon" ultrasonic thickness gage, under license of General Motors Corp., has the ranges 12.5 to 25 mils, 25 to 50 mils, 45 to 90 mils, 80 to 160 mils, 150 to 300 mils, and 250 to 500 mils. It is possible to measure thickness above the nominal maximum by reading the indications from higher harmonics. If the range up to 90 mils is selected and a piece of 240 mils tested, there will be two readings of 80 and 60 mils on the scale. The general relation is

$$T = Rr/(R-r)$$
$$(\text{eg., } 80\times 60/80-60=240)$$

where T is the actual thickness, R the higher reading, and r the lower reading on the scale of the oscilloscope.

Manufacturer: Magnaflux Corp., Chicago, Ill.

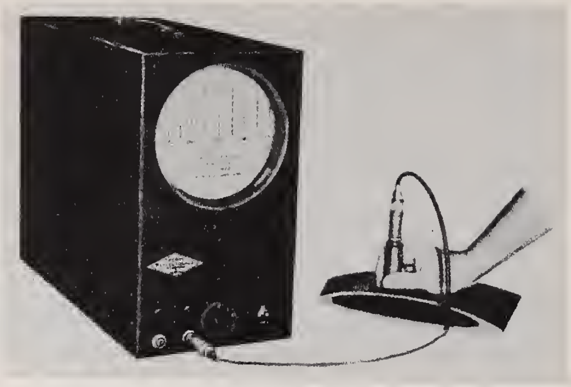


FIGURE 52. *Typical application of the "Reflectogage."* Testing a hollow propeller blade for thickness.

FIGURE 53. *"Metroscope" thickness meter.*

Metroscope. A similar instrument (fig. 53), based on the same patents, is manufactured under the trade name "Metroscope" by Photocon Research Products, Pasadena, Calif.

Mechanical-Electric Methods. The operating principle of all mechanical-electrical gages is a mechanical feeler element which is in contact with the work and follows all changes of thickness with a variable displacement of the feeler. This displacement is transformed by resistive, inductive, or capacitive devices into proportional electrical signals, which are used for indicating, recording, or controlling at a distance.

1.23. Displacement With Resistive Pickup.

1.231. *Slide Contact* [62]. Basically a dial-gage mechanism moves a slide contact on a resistive voltage divider, which is fed by a constant voltage supply, and operates a voltmeter calibrated in displacement of the dial-gage spindle or thickness of the specimen under test. In a British design [62] a conventional dial micrometer was equipped with a bare resistance wire of 3 ohms resistance around the scale, and a small contact was mounted at the end of the pointer. The pointer contacts the resistance wire every 2 seconds (for recording), and is free to rotate normally for the rest of the time.

1.232. *Resistive Strain Gages* [99] **(figs. 54, 55, 56).** Small movements, representing thickness or change or difference of thickness, can be transformed into resistance change by resistive strain gages. Wire strain gages, which are almost exclusively the type used in this country, may be of either the bonded or the unbonded type. The bonded SR4 strain gage (Baldwin Locomotive Works) consists of a fine resistance wire, with a diameter of 1 mil or less and generally a resistance of 120 ohms, wound in meander shape, pasted on paper and cemented to the test object. When the gage is stretched 0.1 percent of its length, the resistance of the wire increases 0.2 percent or more, depending on the gage factor of the material, defined as the proportional change of resistance to length. For a gage length of 10 mm we get an elongation of 0.01 mm (0.4 mils), and about 0.24 ohms resistance change, which, with a gage current of 10 ma, gives a signal of 2.4 mv. Usually four of these gages are connected in a d-c Wheatstone bridge in such a way that two gages are stretched, two others compressed, and the sensitivity (millivolts/elongation) is increased fourfold.

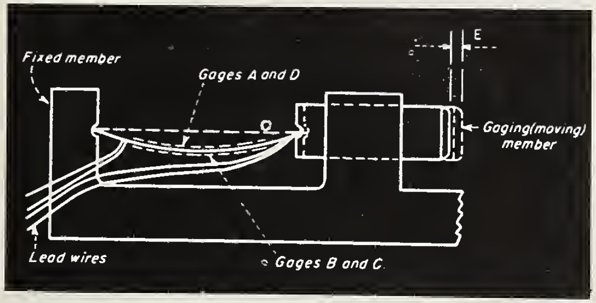


FIGURE 54. *Bonded wire strain gage, as used for measuring thickness.*

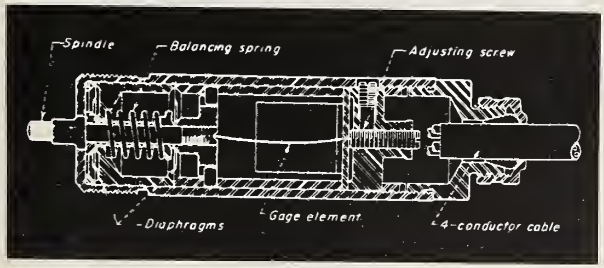


FIGURE 55. *Cartridge-type displacement transducer with bonded wire strain gage.*

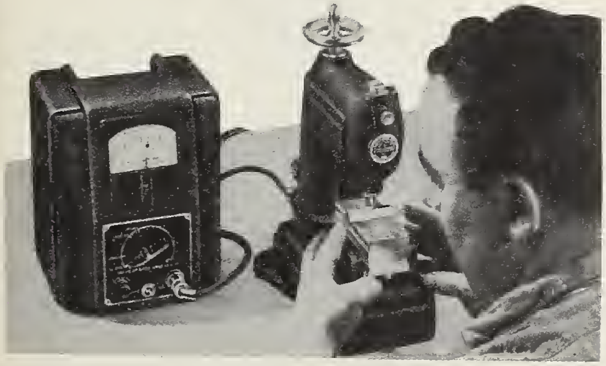


FIGURE 56. *Brown & Sharpe "electronic thickness gage."* The SR4 strain gages are in the head of the "external comparator" at right; the 1,000-cps oscillator, amplifier, and indicator are in the measuring unit at left.

A commercial application of strain gages for measuring thickness is the Brown & Sharpe electronic thickness gage [99], built with SR4 gages which are mounted in a flat spring held at both ends (figs. 54, 55, 56). The power supply is 2.8 v, 1,000 cps ac. Motion of the feeler produced by the varying thickness of the specimen deflects the spring gage element and thereby changes the resistance of the attached resistance wire gages. The scale of the indicating instrument has a length of 3.6 in. and 20 divisions. At the highest sensitivity one division of 180 mils represents a displacement of 0.01 mil, giving a magnification of 18,000. The instrument indicator has five sensitivities, 0.01, 0.02, 0.025, 0.05, and 0.1 mil corresponding to the ranges 0.1, 0.2, 0.25, 0.5, and 1.0 mil.

Manufacturer: Brown & Sharpe Mfg. Co., Providence, R. I.

1.233. *Variable-Resistance Spring* [216]. The variable-resistance spring transducer can be used to measure small displacements. The active element of the device is a helical or conical spring with a corrosion-free surface, wound in such a way that the initial tension varies slightly along its length. Thus, when the ends of the spring are pulled apart, the turns separate one by one, not all at the same time as with an ordinary helix. The entirely closed spring has the resistance of a cylindrical tube, and the completely opened spring has the resistance of the total length of the coiled wire. Displacements (or thickness changes) of 0.01 mil can be measured without the use of amplifiers. The accuracy of this gage is given as ±10 percent of the indicated deviation from the standard thickness. The "gage factor" may be 100 and even higher, which means that a displacement of 0.1 percent of the spring length may cause a resistance change of 10 percent or more.

1.234. *Linear-Motion Potentiometer.* Precision wire-wound linear-motion potentiometers are available with displacement ranges of 0.5 to 20 in. Maximum departure from linearity may be as low as ±0.5 percent. Operating force may be as low as ±0.5 percent. Operating force may be as low as 0.5 oz.

1.24. Displacement With Inductive Pickup. In this type of instrument the thickness of the sample, frequently a moving sheet, causes a mechanical displacement which in turn causes the unbalance of an electric-inductive circuit and generates a voltage in proportion to the relative movement of a coil.

1.241. *Mutual Inductance* [113, 114, 144]. One design of mutual-inductance gage, applied to measure the thickness of nonmagnetic moving sheets, consists of a standard head, a measuring head, and a 1,000-cps oscillator to energize both heads, which are continuously balanced against each other in a bridge circuit. Standard and measuring heads comprise the primary and secondary windings of special audiofrequency transformers. Changes in the spacing between primary and secondary vary the degree of coupling and hence the secondary voltage. The relationship between displacement and output of the bridge is linear for displacements between 125 and 1,000 mils. The sensitivity of the system is high enough to give full scale readings on the d-c meter with as little as 0.5-mil deviation from the standard thickness. The usable range of the instrument is approximately 1 to 1,000 mils. Production of this thickness meter has been discontinued as a more universal system (see 1.243) is now used.

The Foote-Pierson electronic gage [113] also operates by change of mutual inductance. The gage head contains two coils, one fixed and connected to a 100-kc oscillator, the other mounted on a spindle which is actuated by the work piece. The second coil is coaxial with the fixed coil and, as it moves in accordance with the thickness of the material, a varying voltage is induced which increases linearly with the spindle displacement. The output is rectified and indicated by a d-c instrument. Four magnifications are possible, the highest approximately 14,000, with a 0.2-mil movement of the spindle head producing full-scale deflection on the meter. Other ranges are 0.6 mil, 2 mils, and 6 mils, the corresponding magnifications 4,650, 1,400, and 465.

Manufacturer: Federal Products Corp., Providence, R. I.

1.242. *Double-Airgap Reactance Ratio* [45, 113, 130, 170] (figs. 57, 58, 59). This principle is used for many designs of electromagnetic thickness gages (fig. 58). Gages operating on the double-airgap reactance ratio consist of two electromagnets with a movable armature between them. The armature is made of a magnetic material. As its position shifts from center, the airgap increases on one side and decreases on the other, introducing corresponding inductance changes in the two circuits. The inductance is increased as the armature is brought close to an electromagnet, decreased as it moves in the opposite direction. Compensation for the change is made with a voltage divider. The amount of compensation necessary to balance the circuit is directly measurable and can be calibrated in units of thickness. The circuit can also be adjusted with a standard so that deviation rather than actual thickness is shown on the indicator.

1.2421. "ELECTROLIMIT" GAGE. The "Electrolimit" gage (fig. 57) is representative of the double-airgap reactance ratio. The circuit is shown in figure 58. As the central core moves from the point of perfect balance, the output voltage is, within wide limits, proportional to the movement of the core. Resistor R adjusts the amplitude to compensate for change in supply voltage; voltage divider S is used to adjust the point of zero deflection to any desired value. With sensitive moving-coil instruments for indication, the sensitivity can be adjusted to almost any value. Gages of this type can be built to multiply the actual thickness or thickness change as much as 20,000:1, to read down to 0.005 mil on the dial. In one special design, the "Electrolimit Millionth Comparator," the full scale of 10-in. recorder is 0.1 mil, each of the 100 divisions is one millionth of an inch, and the magnification is 100,000.

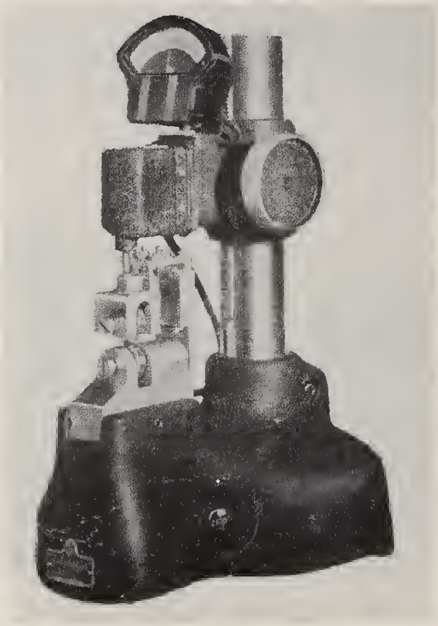


FIGURE 57. *"Electrolimit" gage, equipped with a roller gage to measure thickness of 35-mm film.*

There are several designs for production supervision (some with the trade name "Magnetic Gage") that use the same measuring principle. One of the designs has an indicator with a 3-in. scale on the top of the measuring head, giving magnifications of 1,000 to 5,000. Another instrument with a separate light beam gives a magnification up to 10,000 on a 5-in. scale.

Manufacturer: Pratt & Whitney, Inc., West Hartford, Conn.

It must be kept in mind that for all thickness meters that transform a displacement into an electrical signal, these figures mean sensitivity rather than accuracy. Accuracy must always be established by inserting dimensional standards into the measuring system and adjusting the electric circuit accordingly.

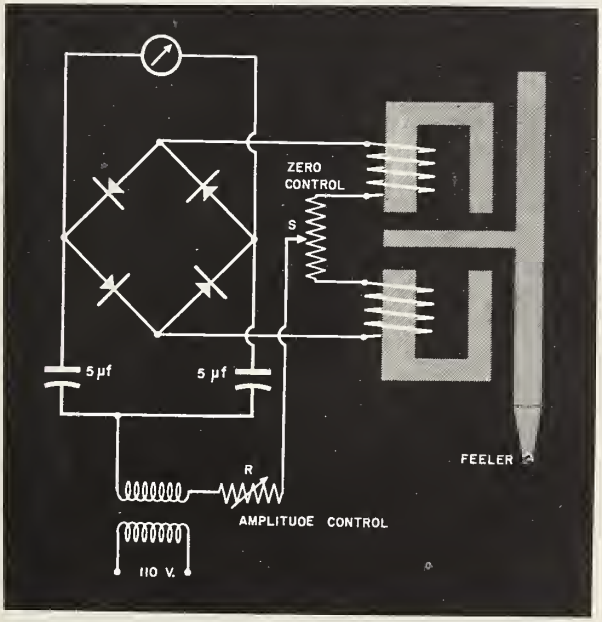


FIGURE 58. *"Electrolimit" gage, equipped with a roller gage to measure thickness of 35-mm film.*

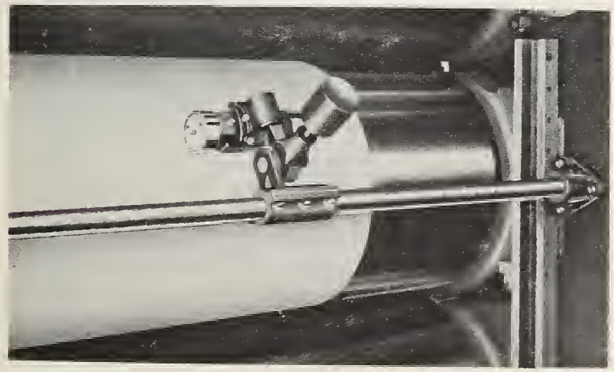


FIGURE 59. *Transmitter assembly of a "Schuster gage" to measure the thickness of paper on a calender roll.*

Schuster Gage (fig. 59). This is a special design of the "Electrolimit" gage to measure the thickness of sheet materials such as paper, rubber, film, or asbestos, during production. The gaging head consists of a roll carriage, accurately ground rolls, and the Electrolimit coil assembly.

Manufacturer: Pratt & Whitney, Inc., Hartford, Conn.

1.2422. "ELECTRIGAGE." This instrument also operates on the principle of the double-airgap reactance ratio. The range of the standard indicating instrument is 1.2 mils and the scale has 24 divisions of 0.05 mil each. The magnification is 2,500. Interpolated readings of about 0.01 mil are possible.

Manufacturer: The Sheffield Corp., Dayton, Ohio.

1.2423. "METRON" GAGE (fig. 60). Two sets of circular coils, which are connected to the indicating unit by a cable, are embedded and sealed into the core, L, of the measuring head (fig. 60). The coils with the core are inductances which produce a magnetic flux. The flux links the coils, and passes across two airgaps and through the iron armature on the spindle. The airgaps are only a few mils in length, so that with the displacement of the spindle by the thickness of the test object, the flux that links the coils changes by a relatively large percentage, as does the inductance of the coils. The four coils are part of a 60-cycle a-c bridge, fed with constant voltage, the output of which is measured with a sensitive moving-coil instrument across a dry-disk rectifier. The spindle assembly is held in the housing by two circular diaphragms so that there is no friction of the gage pin in its bearings.

In its most sensitive design, this instrument will give full-scale deflection for 0.02 mil. Each division is 0.001 mil, equivalent to a magnification of 100,000. The least sensitive instrument

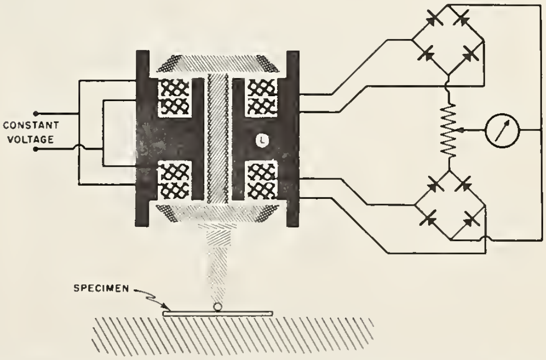


FIGURE 60. *Measuring head and circuit of the "Metron" comparator gage (double airgap reactance ratio system.)*

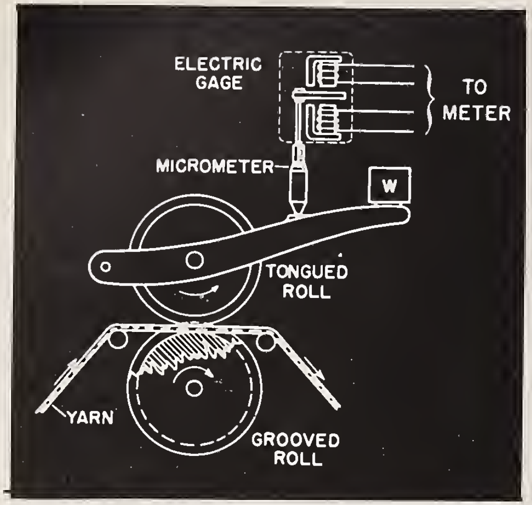


FIGURE 61. *Measuring system of the "Pacific" evenness tester for yarn.*

of this type has full scale with 20-mil displacement, 1 division equal to 1 mil, and a magnification of 100.

Manufacturer: Metron Instrument Co., Denver, Colo.

1.2424. "PACIFIC" EVENNESS TESTER [125, 136] (fig. 61). This instrument has been developed by Pacific Mills, Lawrence, Mass., and the General Electric Co., to measure the thickness of yarn and sliver in the textile industry. The twisted material, with uneven surface, is led through a guide with tension controls into the nip of a pair of tongued and grooved rolls, at a speed of 12 yards per minute. The groove is square, so that the material is compressed into a rectangular shape. The bottom roll establishes three fixed sides. Variations of the thickness cause the top roll, whose force is constant, to move up and down. This, in turn, changes the position of the middle core of a GE double-airgap-ratio meter (fig. 61). The output of this electric micrometer may drive the pen of a recording instrument, or may be used for analysis devices. For testing yarn the rolls have three sets of grooves, 6, 9, and 12 mils wide. The rolls for testing sliver have groove widths of 3, 125, and 312 mils. One head for extra heavy sliver has a groove 625 mils wide.

In the strict sense, this instrument is not a thickness meter, but a volume meter; for given density of the compressed sliver, it measures the weight of the material per unit length.

Manufacturer: Anderson Machine Shop, Inc., Needham Heights, Mass.

1.243. *Differential Transformers* [76, 138, 170, 178, 191, 195] (fig. 62). The arrangement of an assembly of one fixed-primary coil and two fixed-secondary coils with a moving iron core is being used more and more to measure displacements. Figure 62 shows one of the many possible arrangements of the coils. With proper dimensions and proper spacing of the coils the voltage unbalance is, with high accuracy, proportional to the displacement of the moving core. The source of power may be a 60-cps supply line or it may be an oscillator operating at frequencies up to 100,000 cps. Operation at 60 cps makes it possible to avoid the necessity for amplification of the output signal. It is only necessary to rectify the output to operate a sensitive moving-coil indicator. Highest sensitivity is possible with the higher frequencies and amplified output. For portable thickness meters to be used where no line supply is available, battery-operated systems have been developed.

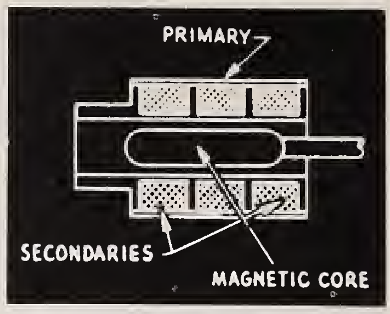


FIGURE 62. *Differential transformer system to measure small displacements.*

1.2431. "ATCOTRAN" AND SCHAEVITZ DESIGNS [138, 178] (figs. 63, 64, 65). These devices are used in many designs of displacement meters. A Schaevitz design gives, with an input of 2,500 mv and 21,000 cps, an output of 25 mv for a core displacement of 1.6 mils, with a linear characteristic. Standard designs of differential transformers of the "Atcotran" type have a full range of ±10 mils. Without step-up transformer, the output is given as 0.25 mv per input volt per mil armature displacement. With a 22:1 step-up transformer the output is 5.2 mv per input volt per mil displacement. Deflection systems with indicating instruments are dependent on fluctuations of line voltage and frequency, at all points other than the balance point. With bridge circuits, it is possible to be independent of voltage fluctuations over the full range, but the output varies widely with the frequency. However, it is possible to select an operating frequency that allows wide frequency variations. The accuracy of the "Atcotran" thickness meters is given as ±0.25 percent for the total system, including reasonable variations of temperature, voltage, and humidity.

Manufacturer: Automatic Temperature Control Co., Philadelphia, Pa.

A system that automatically balances and records is shown in figure 63. In this circuit, the primaries of two transformers, one in the

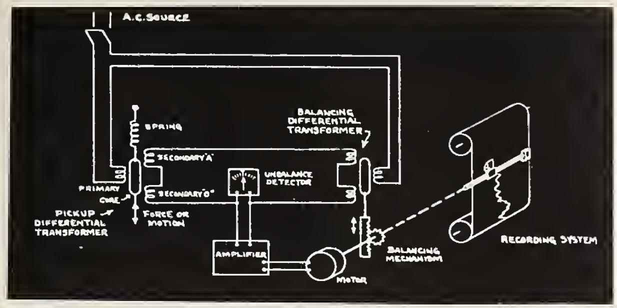


FIGURE 63. *Automatic balancing and recording thickness meter with differential transformer.*

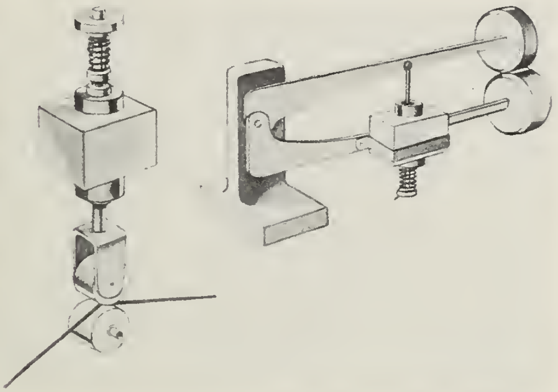


FIGURE 64. *Application of differential transformer systems to measure thickness.*

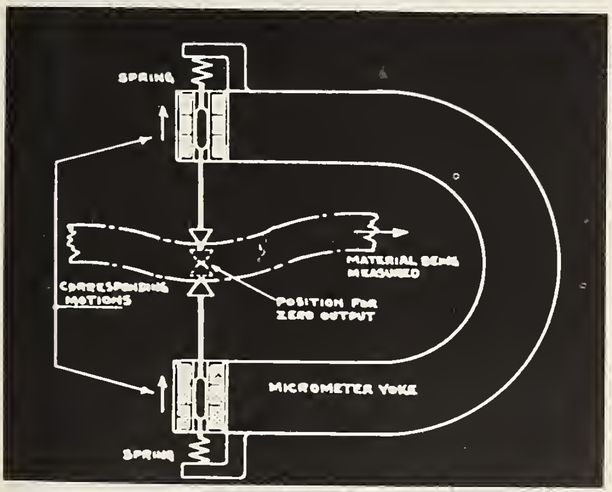


FIGURE 65. *Micrometer with floating anvils and differential transformer.*

pickup device, the other in the indicator or recorder, are connected in series to the source of voltage. The secondaries are also connected in series, but opposing. When the position of the core in the indicator is the same as the core in the pickup, the voltage fed to the detector is zero. If the pickup core is moved, voltage is fed to the detector and the indicator shows a need for movement of the balance core to achieve correspondence between the two cores. This rebalancing motion is accomplished automatically, and a recording pen is positioned to indicate the thickness on a chart.

Manufacturer: Schaevitz Engineering Co., Camden, N. J.

There are many arrangements of the coils and the circuits used in differential transformers. Figure 64 shows the use of differential transformers to measure the thickness of wire or ribbon. A micrometer with floating anvils is shown in figure 65. The two transformers are connected so that no voltage output is present when the two anvils are together, even though they are in motion. However, should their position differ due to material between the anvils, the output will be a measure of the material thickness. Slight movements of the material in the vertical direction will not affect the accuracy.

"Dyna-Myke" Micrometers. These instruments, developed to measure the thickness of moving sheets, use a pickup with a differential transformer of the Schaevitz type 0100LC and replace an older device described in [96]. The Dyna-Myke is operated at 8,000 cps and the indicator has a plus-minus scale 4.5 in. long. If the material to be measured is flexible enough to be held in contact with a base which acts as a reference point, thickness can be measured with a single gage head. For more rigid materials, such as glass, sheet metals, or solid plastics, two gage heads are required. These are mounted on either side of the material and electrically connected in such a manner that any lateral motion of the material is without influence, the gages indicating only the relative distance between the two points of contact. The Dyna-Myke, used for indicating and recording, may have the following five ranges: ±100 mils, 22.5 amplification; ±10 mils, 225 amplification; ±1 mil, 2,250 amplification; ±0.1 mil, 22,500 amplification; ±0.01 mil, 225,000 amplification. With the maximum sensitivity, one scale division of 112 mils corresponds to a thickness difference of 0.02 μin. The over-all accuracy is given as ±2 percent of the scale range.

A similar device with the same pickup, the "Myke-A-Trol," is used for control in ranges from 0.1 to 100 mils.

Manufacturer: Industrial Electronics, Inc., Detroit, Mich.

1.2432. STEVENS-ARNOLD PORTABLE INSTRUMENT. (fig. 66). For portable instruments, to be used in places where ac is not available, a battery and a dc-ac converter may be used to feed the coils. A device of this type is shown in figure 66. The plunger moving the iron core has a travel of ±10 mils or 0 to 20 mils. The d-c indicator has a scale length of 4 in., giving a

FIGURE 66. *Transmitter for electric micrometer.*

magnification of 200. The accuracy is given as 0.25 mil. The pressure on the plunger can be adjusted between 3.5 and 10 oz.

Manufacturer: Stevens-Arnold, Inc., South Boston, Mass.

1.2433. "LYN-A-SYN" TRANSDUCER. A recently announced transducer for sensing small motions is available in 32 models, with linear displacement ranges from 3 mils to 2,000 mils, under the trade name "Lyn-A-Syn." Operation is based on the linear change in coupling between the primary coil and secondary coils as a result of the displacement of the high permeability metal core. The smallest unit for the 3-mil range has an outer diameter of ¼ in. Total length of this unit is also about ¼ in.

Manufacturer: Minatron Corporation, Belle Mead, N. J.

1.244. *"Metrisite" Transducer.* The "Metrisite" is a position-sensitive transducer capable of measuring very small displacements. The basic structure of this device consists of three coils on the three legs of a laminated magnet. In the center leg of the three there is an airgap containing a loop of conducting material around the yoke. The loop is free to move along the base and mechanically connected with the feeler to indicate displacements.

The coil on the center core is connected with a constant 60-cps a-c voltage. With the short circuit loop exactly in the middle of the center leg the magnetic flux spreads in equal parts over the outer legs, which carry two coils so connected that the signal output is zero. If the loop is displaced, the balance of the two flux halves is disturbed. The side to which the loop moves has a higher magnetic resistance and the resulting output from the secondary coils is, within certain limits, in proportion to the displacements of the loop. The output signal is in phase with the input on one side of zero and 180° out of phase on the other.

The total travel of the loop is 860 mils. For ±200 mils the output is linear within 0.1 percent of the maximum, which is obtained with 300 mils movement.

The amplifier of standard instruments provides four ranges giving full scale on the indicator for 0.1, 1, 10, and 100 mils movement. Without amplifier the full range is obtained with 5 mils. With a special amplifier, full-scale response has been obtained with armature movements of only 0.001 mil (1 μin.) and the sensitivity of such an instrument (not accuracy) corresponds to 0.1 μin.

Manufacturer: Graydon Smith Products Corp., Boston 14, Mass.

1.25. Displacement With Capacitive Pickup.

1.251. *Change of Capacitance* **[5, 17, 61, 66, 70, 91, 96, 103, 110, 124, 133, 134, 135, 141, 149, 151, 154, 155, 169, 183, 191, 215].** The capacitance of an air capacitor consisting of two parallel plates changes inversely as the distance of separation of the plates following a hyperbolic law. Reducing the distance to one-half gives twice the capacitance. The dimensions for such capacitors are rather limited. The useful diameter is no more than 3 to 4 in., the initial distance not less than 10 to 20 mils, which gives an initial capacitance of about 100 to 200 $\mu\mu$f. To keep the change of capacitance fairly linear with the change of distance, the change of distance can only be from 3 to 10 percent of the initial value, which gives deflection ranges from 0.3 to 2 mils and capacitance changes in the order of 2 to 20 $\mu\mu$f, which have to be measured with a precision of better than 1 percent. None of these devices can be operated at line frequency, because the required insulation cannot be attained. They are all operated with frequencies from 1,000 to 100,000 cps.

Ultramicrometer. The "Ultramicrometer" is described in [215].

Dowling Micrometer. The Dowling micrometer [70, 154] obtained a maximum stable sensitivity of 1-mm galvanometer deflection per 20-μin. displacement, or a magnification of 2,000.

Gerdien Micrometer. The Gerdien capacitive micrometer [103, 124, 149], used in connection with electromagnetic oscillographs to measure very high pressures by the deflection of a capacitor plate, gave magnifications of 10^5 and even 10^6. A displacement of 1 μin. was represented by a deflection of 1 in. on the chart of the oscillograph. The accuracy of the best mechanical designs of capacitive micrometers is limited to a distance of about 0.2 μ, or 8 μin.

Manubel. A capacitive micrometer, the "Manubel" comparator [91], is manufactured in France and Switzerland. The fixed capacitor plate consists of a ground and metallized steatite disk. The movable anvil is in the shape of a piston, whose upper face forms the second plate of the capacitor. The change of capacitance is measured by change of frequency, as with most capacitive micrometers. The indicating instrument, with a scale length of about 50 mm, has two ranges, ±5 and ±10 μ (±0.2 and ±0.4 mil). This corresponds to a magnification of 10,000 for the lower range. The accuracy is given as 0.2 μ (0.008 mil).

Manufacturer: Establissements Edouard Berlin, Paris; also Manufacture de Machines du Haut-Rhin, Mulhouse.

Cornelius Co. Meter. Another mechanical-electrical capacitive meter [17] uses a quartz crystal as a frequency standard. The full-scale deflection of 100 mm on the indicator can be reached with a displacement of only 1 μ, corresponding to an amplification of 100,000. The instrument is described as highly stable with constant temperature and full-scale deflection. The indicator deviation is less than 0.02 μ or 2 percent of full scale.

Manufacturer: Cornelius Electronic Instrument Co., Ltd., England.

1.252. ***Change of Capacitance Ratio*** **[135, 149, 185] (fig. 67).** This method (fig. 67) resembles the double-airgap inductance ratio meter used, for instance, in the Electrolimit gage. The use of a single capacitor has, as already mentioned, the disadvantage that the capacitance change follows a hyperbolic law and is proportional to the thickness for only a small percentage of the initial value. Measuring the ratio of two capacitances, formed by two electrodes and one moving member, gives linearity over a wide range of displacement of the movable electrode. Here, too, the low capacitances make it necessary to use higher frequencies. Magnifications up to 1 million are possible. The limit of sensitivity is given as 0.0025 μ (0.1 μin).

There are other ways of obtaining a linear change of capacitance with the displacement of an electrode [149], such as the axial displacement of one cylinder into another. A thickness gage of this kind is described in British Patent 629,648 (G. Jacot and J. Monti), the scale reading in fractions of a micron.

Recently a much simpler thermal device has been developed, moving a vane in vertical position between two heated nickel helixes which are part of a Wheatstone bridge. No air current is used. Displacement of the vane causes heat-radiation losses of the helixes to change and a differential voltage is generated in the diagonal of the bridge. The sensitivity, measured in vane displacement and millivolt output, is about the same as with the previously described bolometer. With 0.1-mm displacement, 20 mv are generated in the diagonal.

Manufacturer: Ferngteuergeraete OHG, Berlin-Zehlendorf.

1.26. Displacement With Thermal Converter [160, 191] (fig. 68). A schematic diagram for an electric-thermal device for measuring thickness ("Bolometer gage") is shown in figure 68. The feeler, a, is positioned without friction by the reed springs, b. The movements of the feeler are transmitted by the spring, c, to the moving coil, d, swinging in the field of the magnet, h, part of a bolometric amplifier system. This consists of four heated nickel helixes. The a-c magnet, l, vibrates a reed, m, to produce a flow of air, going through the slots n past the two edges

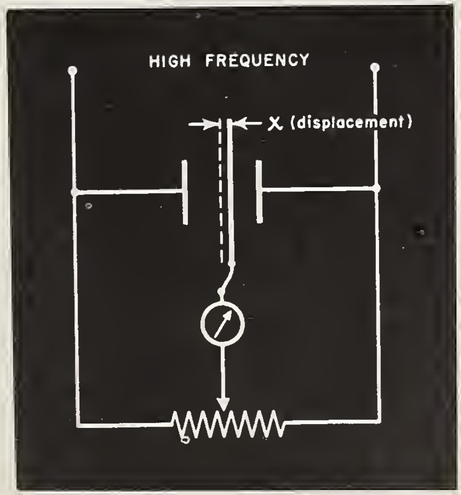


FIGURE 67. *Displacement measuring system, using the principle of change of ratio of the capacitance of a double airgap capacitor.*

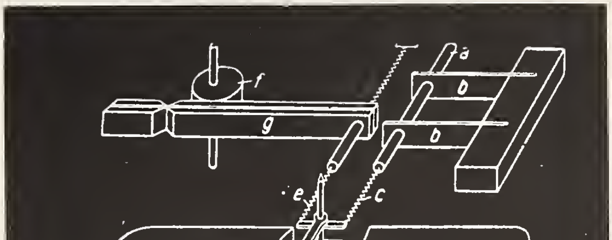


FIGURE 68. *Electric bolometer system to measure small displacements.*

of the vane, i, moved by the galvanometer coil. In the center position, the air flow on both sides of the vane is the same and the bridge with the four heated arms is balanced. When the feeler is moved, the flow of air strikes one pair of helixes more than the other and a current is generated in the diagonal of the bridge in proportion to the displacement. This unbalance controls current to coil d to maintain the position of vane i in the neutral or zero position, while the current necessary to do so is a measure of the thickness. The spring e balances the spring c, while f and g are used for the zero adjustment of the gage. With the range of 50 to 150 μ (2 or 6 mils) the output of the bridge is about 100 mw, sufficient to operate control elements or ink recorders. The accuracy is given as ± 1 μ ($1/_{25}$ mil). With a 120-mm scale width on a recorder chart, the magnification is 120,000/50=2,400.

Manufacturer: Siemens & Halske, Berlin.

1.27. Displacement With Electronic Converter [108] (fig. 69). This micrometer employs a species of vacuum tube whose electrical constants are changed by a mechanical displacement applied to the end of a short rod. Figure 69 shows the tube in its simplest form. A hot filament provides a stream of electrons which flows to insulated plates 3 and 5. These plates are carried on a short rod, 13, with motion permitted through the deformation of the vacuum-tight diaphragm 25. In this manner the resistance of one plate-filament circuit is increased while the other is correspondingly decreased. Because of the instability of emission in vacuum tubes the two plate-filament circuits are incorporated in a bridge arrangement. Resistances 17 and 19 are nearly equal when the filament is centered between the plates. Thus, the reading of microammeter 31 normally measures the mechanical departure of the plate system from its midpoint and is only slightly dependent upon irregular emission or plate potential.

The sensitivity is given as approximately 6 ma/μ (0.04 mil) deflection. Using a conventional portable microammeter, with a deflection of 4,000 mils per 5 ma, a magnification factor of 120,000 is obtained. The torque necessary to deflect the rod 1 μ is about 1 gram-centimeter.

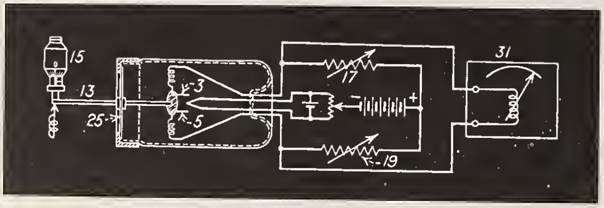


FIGURE 69. *Principle of a mechanical-electronic micrometer.*

1.28. Displacement With Photoelectric Pick-up [73, 126, 181, 204, 207] (figs. 70, 71). *Principle:* A beam of light (fig. 70) passes through a condenser lens, a slot, c, and a second lens system, to a photoelectric cell. Between the cell and the light source a knife edge, b, cuts off a part of the light beam going to the cell. This knife edge is moved by a mechanical feeler, a, in proportion to the thickness of a sheet or the diameter of a wire, thus changing the light quantity falling on the photocell. The current of the photocell varies in proportion to the movement of the knife edge, in other words with the thickness of the specimen. In this arrangement the indications are dependent on variation of lamp voltage as well as of photocell sensitivity, and frequent recalibration is necessary.

Figure 71 shows a more satisfactory device. Light source LS emits either two beams or one that is split. One is directed through the condenser lens system, CL, to the photocell, P_1, just as in figure 70. The other beam is sent over the mirror, M, and the grey wedge, W, to a second photocell, P_2, identical with P_1. The difference of illumination of the photocells is in proportion to the movement of the knife edge of the micrometer head, which measures the sample of unknown thickness. The zero of the scale is adjusted by placing a standard thickness under the knife edge and adjusting the comparison beam by moving the grey wedge W. The output of the two photocells is amplified in a conventional way and the moving-coil indicator may give either thickness or deviation of thickness from a standard value (see also section 4.53 and fig. 123).

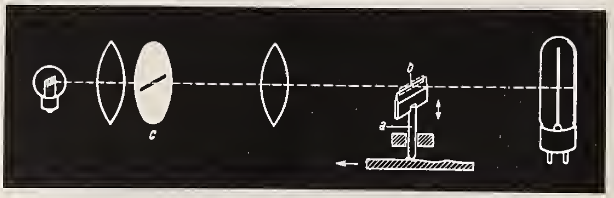


FIGURE 70. *Mechanical-optical method of thickness measurement.*

a, Feeler; b, knife edge; c, slot.

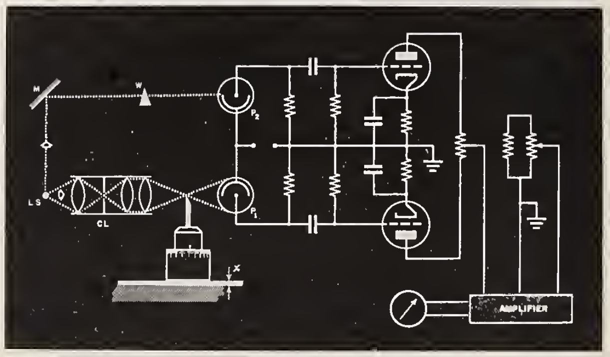


FIGURE 71. *Thickness measurement with two photocells in differential arrangement.*

2.00. Chemical Methods

2.1. Stripping and Weighing [16, 30, 36, 145] Destructive stripping is often used to determine the thickness of the metallic coating of sheets or wires. A measured and weighed area of coated metal sheet (or length of wire) is put in a solution that dissolves the coating. The average thickness is calculated from the loss of weight. By dissolution of the base metal, the weight of the coating may be obtained directly. For measuring the thickness of the tin coating on sheet iron, specimens 4 by 8 in. are used and the iron is dissolved in hydrochloric acid.

The stripping method is also applied for the determination of the thickness of gold coatings on fine wires of silver, tungsten (wolfram), or molybdenum 3 to 10 mils in diameter. The base metal is dissolved, and the remaining metallic gold is weighed.

See ASTM Standard A90, Weight of coating on zinc-coated (galvanized) iron and steel articles.

2.2. Optical Projection With Stripping [80] (figs. 72, 73a, b). *Coating thickness of corrosion-protected iron screw threads:* The highly magnified contour of the finished screw is projected by means of an optical contour projector on photographic paper through a graphscreen which provides reference lines along with the contour of the thread. Next, the coating is chemically removed by the stripping solution, which is applied to the thread with a dropper, without disturbing its position. After this, the screw is carefully washed with distilled water and dried by a stream of hot air. A second exposure is made on the same photographic paper. The resulting picture shows the dissolved coating as a halftone, clearly demarcated from the base metal.

2.3. Spectrophotometry [54]. Applicable to metallic gold-plated sheet with a total thickness of 30 mils or less, this scheme uses a disk of 1 mm^2, cut out with a punch and treated with diluted nitric acid, which dissolves the base metal and leaves a small piece of gold. This is washed in water and then dissolved in a few drops of aqua regia, after which it is evaporated to dryness by impinging a jet of purified air on the surface of the solution. The quantity of gold is determined with a spectrophotometer from the intensity of yellow color produced when a measured volume of a solution of *o*-toluidine (3-3′-dimethylbenzidine), dissolved in normal sulfuric acid, is added to the air-dried residue. Quantities of gold up to 10 μg, corresponding to 0.5 μ (0.02 mil), of gold on 1 mm^2 of surface can be determined accurately.

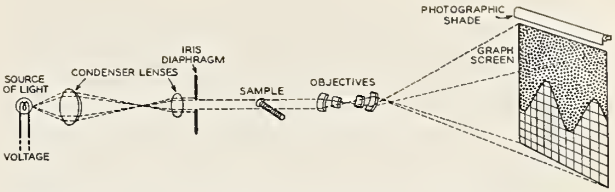


FIGURE 72. *Optical contour projector, used to determine thickness of coating on screw threads.*

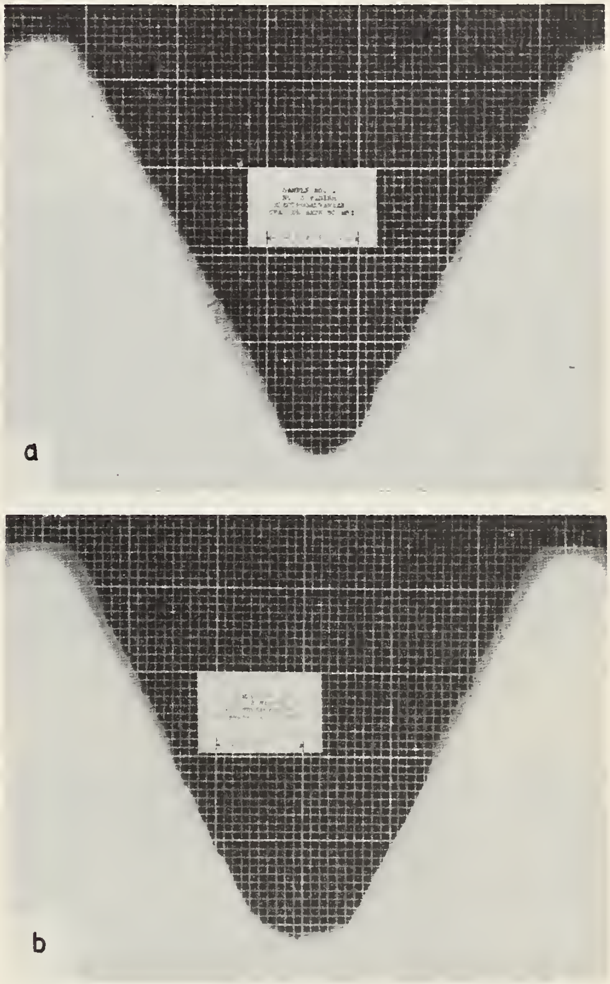


FIGURE 73. *Shadowgraphs of plated screws.*
a, A satisfactorily plated screw; b, an unsatisfactory plate—the deposit is almost entirely on the outside of the thread.

2.4. Spectrochemical Analysis [145, 156]. To measure thickness of a metal coating by spectrochemical analysis, the coating is sparked. The actual thickness is determined in one of two ways. The intensities of specific lines in the spark spectrum are compared with those obtained with standard specimens, or the time required for the spark to reach a given intensity is measured. This principle is not useful for metals with low melting points, such as tin. It is applicable, however, not only to sheet metals, but also to pipes, rods, and other such shapes.

2.5. Color Change [16]. The coating, generally of a different color than the base material, is destroyed by the application of a chemical solvent, usually an acid, in a standardized intensity of application. The time needed to see a change of color is an indication of the thickness of the coating.

2.51. *Spot Test (ASTM A219)* [18] **(fig. 74).** This is used for chromium coatings 0.03 to 0.05 mil thick. One drop of hydrochloric acid of 1.180 specific gravity at 60°F is placed with a dropper within a wax ring 250 mils in diameter on the cleaned chromium surface. The time required from the beginning of gas evolution until the first appearance of nickel is measured to ±0.5 second with a stop watch.

The temperature must be carefully observed. A change of ±1°C at 20°C changes the time (and apparent thickness) ±3.7 percent (fig. 74).

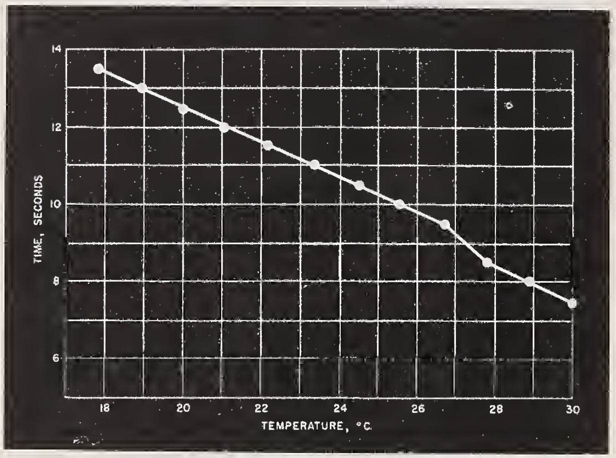


FIGURE 74. *Time to dissolve a chromium coating 0.01 mil thick as a function of temperature.*
From ASTM Standard A219.

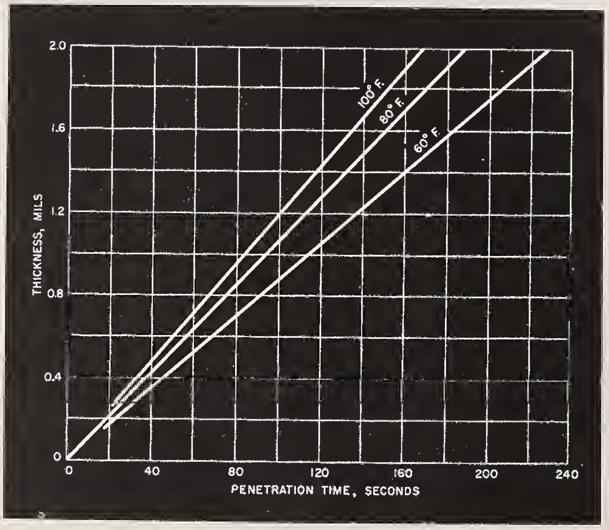


FIGURE 75. *Thickness of zinc platings as a function of penetration time for three temperatures (dropping test).*

2.52. *Dropping Test* [41, 46] **(fig. 75).** To determine thickness of coatings of lead, zinc, or cadmium on steel, plane or curved, the corrosive test solution is dropped from a funnel at a rate of 100 ±5 drops per minute onto the specimen, which is held at a 45° angle about 0.5 in. below the tip. The time for the solution to penetrate through the coating is measured.

The test solutions for lead on steel are 3.5 percent by volume of glacial acetic acid, or 3.5 percent of 30-percent hydrogen peroxide; for zinc and cadmium on steel, chromic acid, 200 g/liter, or sulfuric acid, 50 g/liter. Figure 75 shows the thickness of zinc plating as determined with the standard corrosive solution at temperatures of 60, 80, and 100°F. The accuracy of the method is 5 to 10 percent, the temperature influence 1.5 to 2 percent per degree C.

2.53. *BNF Jet Test* [60]. The BNF (British Non-Ferrous Metals Research Association) Jet Test is similar in principle to the spot or dropping test, the difference being that here the corrosive liquid is delivered to the test surface in a stream or jet. The increased speed with which the liquid is delivered results in a corresponding decrease in testing time. The method is applicable for either plane or curved surfaces. The apparatus is easily portable and the accuracy is about ±15 percent.

2.6. Electric Potential [117]. The following is a procedure for measuring the thickness of inhibiting films on glass electrode surfaces. The glass electrode of a *p*H meter is an extremely sensitive indicator of the presence of inhibiting films, thinner than 0.06 μ, on the outer surface of the electrode.

The *p*H response (millivolts per *p*H) of glass electrodes is changed considerably by films of either conductive materials like silver, or nonconductive like petrolatum. It is possible to detect films with a thickness of only 0.003 μ (30 A) by the voltage deviation from standard values.

3.00. Electrical Methods

3.1. Insulation Breakdown. The breakdown voltage of thin insulating coatings on metal is approximately proportional to the thickness. This method is generally applied to determine the thickness of electrochemically deposited oxide on pure aluminum.

3.11. *Aluminum Oxide Testers* [11, 19, 122] **(fig. 76).** *Bell Laboratory Testers.* The Bell Telephone Laboratories, Inc. [11], have used a chromium-plated steel sphere electrode of about ⅛-in. diameter under a spring force of 2 to 4 lb. The 60-cps voltage is increased in steps of 25 volts up to breakdown voltage, which is generally less than 1,500 volts. The thickness is proportional to the breakdown voltage within

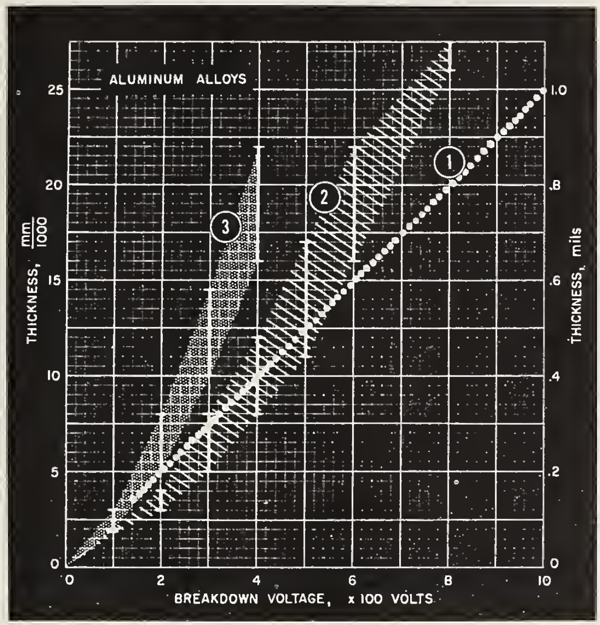


FIGURE 76. *Thickness of aluminum oxide coatings as a function of breakdown voltage.*

1, Tests of the Bell Laboratories, 1942; 2, tests by Herenguel and Segond, without Cu Si; 3, tests by Herenguel and Segond, with Cu and Si.

about ±10 percent (about 1 mil for 1,000 volts) (fig. 76).

French Method. In a French study of this method [122], not only aluminum but aluminum alloys with copper, silicon, magnesium, and other metals were tested. These tests gave a lower breakdown voltage for alloys with copper and silicon than for pure aluminum and alloys with other metals, as shown in figure 76. The breakdown voltages for a given thickness are lower than the values given by the Bell Laboratories.

GE Tester. A commercial tester for anodized aluminum is manufactured by the General Electric Co. It is not called a thickness meter, and is used only to determine the dielectric strength (breakdown voltage) of anodized coatings. The instrument has three voltage ranges for the different types of coatings. The lowest range, with 0 to 20 volts 60 cps ac, is for chromic-acid-type coatings; the other ranges, 0 to 100 and 0 to 600 volts, are for sulphuric-acid-type coatings. The test voltage is gradually increased from zero until a drop in the voltmeter reading indicates breakdown. The maximum voltage is a measure of the quality of the coating as insulation (see GE Bul. 894, Anodized aluminum testers).

ASTM "Standard Method of Test." The "Standard Method of Test for Dielectric Strength of Anodically Coated Aluminum" (ASTM B110) gives only the test procedure. Permissible breakdown values are left to agreement between purchaser and seller. If it is sufficient to test only the continuity of the oxide film, a solution of 2-percent crystalline copper sulfate and 2-percent hydrochloric acid of 22 deg Baume is spread over the coating. It leaves black copper deposits on any areas that are not covered by the oxide film. Size and number of such spots after 5-min reaction give the degree of continuity. Testing of rubber gloves by electrical breakdown is described in ASTM D120 (Book of Standards, part 6, p. 34-41, 1952).

3.12. *Enameled Wire* [109, 150] **(fig. 77).** A method of counting electric breakdowns is used for production testing of film-insulated magnet wire to indicate thickness uniformity (fig. 77). Immediately after the last coat of enamel is applied, the wire passes through a mercury bath. A d-c voltage of approximately 50 volts is maintained between the mercury and the wire. The electrodes are a pair of 1-in.-diameter metal disks, bolted together with a semicircular 10-mil spacer between them. The central portion of each disk is hollowed somewhat to provide a reservoir for the mercury. Six of these elements are joined in a gang electrode, and two such gang electrodes are connected to a machine with 16 heads of wire.

The test voltage can be set to a minimum of 48 volts dc for singlecoated wire, up to 270 volts for multicoated wire. An electronic relay will trip when a fault of 0.2 megohms or less appears for the lowest setting, or 10 megohms for the highest setting. Whenever a fault occurs, a signal lamp flashes and the corresponding pen on a multipen recorder with 20 pens for 20 machines is deflected. A certain number of breaks per minute is allowed, depending on the type of wire.

This method does not provide a direct thickness measurement, but is a means of counting the spots with less than minimum thickness along the wire.

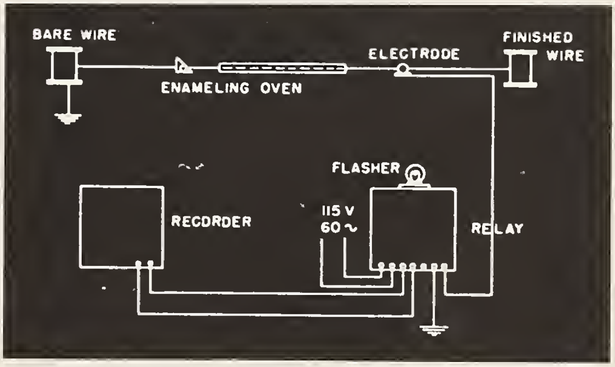


FIGURE 77. *Layout of equipment for fine wire coating thickness-continuity test.*

3.2. Resistance. The principle of all electric resistive methods is to pass an electric current, generally dc, through a known conducting length. Measurement of the resistance then permits calculation of the average cross section.

3.21. *Resistance Method for Wires and Ribbons* [63] (figs. 78, 79). For some applications the mechanical dimensions of a product must be maintained within very narrow limits, e.g., in suspension wires and ribbons for galvanometers. If the resistivity is known, the average cross-sectional area is given by the electrical resistance. In other cases, as in filaments for lamps, the electrical resistance per unit of length must be held within narrow limits, the actual thickness or diameter being of only secondary importance and not necessarily uniform. Generally, the average thickness over the length to be used in the finished product is desired. There, resistance should not be measured over a shorter length. Average thickness is often desirable in nonelectric objects, and again electrical resistance measurements can often be used to advantage.

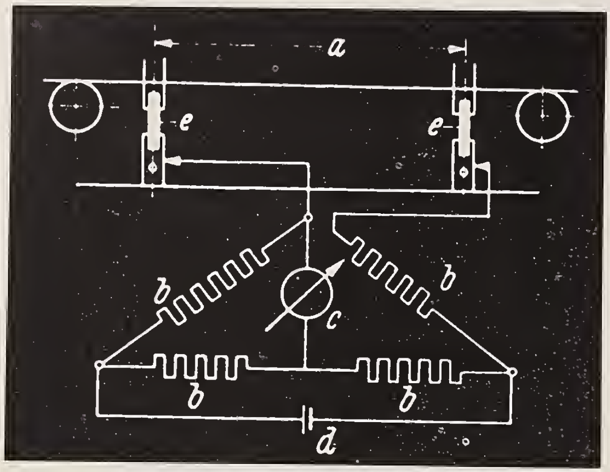


FIGURE 78. *Testing of wire diameter by the electric-resistance method.*

a, Wire length under test; b, bridge resistors; c, galvanometer; d, battery; e, mercury contacts.

FIGURE 79. *Mercury contact for figure 78.*

a, Glass tube; b, mercury; c, iron (or molybdenum) rod; d, brass sleeve; e, positioning screw.

One company has used the method shown in figure 78, with the electrode of figure 79. A glass tube, a, is placed on top of a rod of iron or molybdenum, c, to which the current connections are made. The glass tube has two diametrically opposed holes, b, of 0.5-mm diameter, through which the wire is pulled. The tube is filled with mercury. For lamp-filament wire a current of about 2 ma is sent through the wire, the measurement being made with a Wheatstone bridge. The distance between the electrodes is from 12 to 40 in., the wire diameter between 0.4 and 4 mils. The wire travels between 10 and 17 ft/min. The unbalance current is recorded with an ink recorder by means of a thermal amplifier; length of 1,000 ft. of wire is recorded on 1 ft of chart length. The chart range is ±2.5 percent resistance change from normal, and changes of 0.1 percent in resistance are represented by a deflection of 10 mils. This corresponds to a thickness variation of 0.01 μ for a wire with 1-μ (0.04-mil) diameter.

3.22. *Resistance Method for Metal Sheets From One Side* [200, 211]. If a direct current from two distant points is passed through a sheet, and the voltage drop measured at two points in the path of the current, this voltage drop is an indication of the thickness of the sheet. Four point electrodes are used, two for current, two for voltage, preferably all in a straight line. For steel plates 1 in. thick, with potential points 6 in. apart, the resistance is about 8 microohms, and the potential drop with 10 amp is 80 microvolts. Up to about one-half in., the conductivity is about proportional to the thickness, but for thicker plates the conductivity increases more slowly. One type of low-range ohmmeter gives the resistance independent of current variations, with a linear scale of 0 to 100 microohms. It is recommended that the relation of resistance to thickness be determined by making measurements on sheets with known thickness of the same material. The accuracy of this method is given as ±5 percent.

If the specific resistivity of the material is not known and if it is not possible to calibrate the instrument with objects of known thickness, another method can be used, arranging the four electrodes not in one line but in a square. Two sets of such electrodes have to be used for each measurement, both spaced at distances larger than the expected thickness. From the ratio of the two readings the thickness of the plate can be computed, independent of permeability and conductivity of the material under test. For all measurements, two readings with reversed polarity have to be made to exclude errors from parasitic thermoelectric currents.

An instrument of this type, the Electroflux thickness gage, was manufactured by the Scott Electroflux Co., which is no longer in business. The thickness range for this instrument was given as 0.125 to 2.25 in., the accuracy as 3 percent of the actual thickness. The instrument was battery operated.

3.23. *Resistance Method for Intricate Castings* [201] (fig. 80). This method is used as a high-speed test procedure in production. For intricate castings, current is applied to two fixed points of the casting. The potential drops are measured between contacts which are moved over the surface independently of the fixed current contacts. The movable contact points are about $^{11}/_{16}$ in. apart, and the maximum current for this test is 300 amp. The instrument must be calibrated with a perfect test piece as a reference. It is essential that the electrodes for one type of casting always be placed in the same spot. To do this, templates of plastic material are used with holes for the different test positions (fig. 80). To avoid the use of a battery with high discharge current, the test can also be made with 60-cps ac. Anomalies are detected by the unbalanced emf in two opposed pickup coils connected to a dry-disk rectifier system.

Manufacturer: Record Electrical Co., Ltd., England.

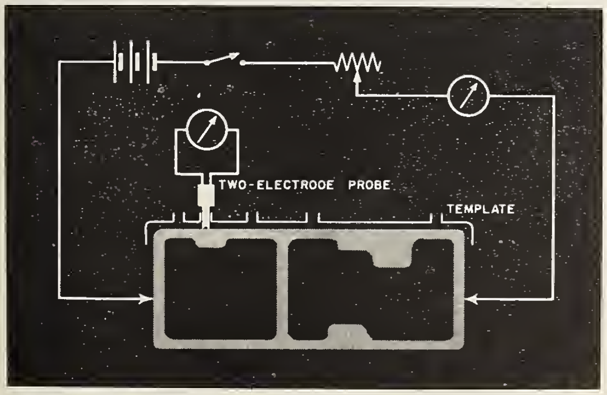


FIGURE 80. *Measuring the thickness of intricate castings by the voltage-drop method.*

3.24. *Resistance Method for Silver Plating* [9, 65]. A waveguide plating quantity indicator based on electrical conductance has been developed to measure the thickness of silver plate on the inside of a stainless-steel wave guide from the outside. A known amount of direct current is passed through a portion of the waveguide wall and the electric potential at two other points is measured. The potential is a function of thickness alone if the current is laminar throughout the material and if the linear dimensions of the material are several times greater than the probe spacing.

3.3. Heating (pat. 8). If an electric current is sent through a conductive sheet or tube, ferrous or nonferrous, in such intensity that the conductor heats up to 100 to 200° C, and the surface is coated with a substance having a melting point just above the temperature reached by a tube with normal thickness, thin spots or flaws that increase the resistance will show up because the substance will melt at such points. Painting the objects under test with a color-changing coating will give even better results.

3.4. Electrochemical Method.

3.41. *Coulomb-Counting.* In electroplating, the weight of the deposited material is proportional to the ampere-seconds (coulombs) used in the process. For a given test area on the plated object, the thickness of the coating is proportional to time, when the current is constant. This process can be reversed, taking the coating off by electrolysis.

3.42. *Potential Change* [8, 210]. A small area of a metallic coating, approximately $1/8$ in. in diameter, inside a small rubber gasket, is anodically deplated. This tester is a miniature reverse-current plating cell in which the article to be tested is the anode and the cell itself is the cathode.

At the start of the test and until the base metal is exposed, a voltage characteristic of the plating exists across the cell. When all of the plating has been removed from the test spot, and the liquid touches the base, this voltage changes sharply and assumes a new value which is now characteristic for the base metal. This sudden voltage change is the "end point" of the test and is amplified to operate a relay which turns off the instrument and the flow of liquid.

The time required to dissolve the plating on the test spot is proportional to the thickness of the coating. By correlating the area of the test spot with the current used to strip the plating, the counter can be made to read directly in units of thickness.

The solution, which is in contact with the coating, does not attack the plating chemically, but serves only to carry the current and to receive the dissolved metal. The method can be used for all metallic coating, either pure metals or alloys, but not for insulating oxide and other coatings. The standard instrument has a range from 0.05 to 5 mils, except with chromium coatings, for which the range is 0.005 to 0.1 mil. If an accessory is used, the minimum chromium thickness measurable is 0.5 μin., for other metals 5 μin. The instrument is not designed for heavy chromium deposits, but for light, decorative chromium coatings. The average test requires about one minute at 115 v 60 cps and the accuracy is 5 to 10 percent, depending on the thickness.

3.5. Capacitance. If the material to be tested for thickness (sheets as well as coatings) has very high resistivity, the measurement of the capacitance of a well-defined area under metallic electrodes can be used to determine the thickness. There is wide variety of possible arrangements of the electrodes, and they may be of the contacting or noncontacting type. The instruments have to be calibrated with samples of known thickness and of the same dielectric constant as the material.

Capacitive methods cannot be used for materials with variable water content, because the high dielectric constant of water (10 to 50 times that of most materials) would cause enormous errors. For accurate measurements it is necessary that the water content either be kept constant by using a controlled atmosphere, or that the standard of thickness have the same water content as the test specimen. One percent moisture in the material may cause an error of 40 percent. Capacitance gages can be used with line frequency, but generally higher frequencies are used to get higher currents and to be less dependent on the insulation. There is a wide variety of methods for measuring capacitance, and a variety of electrodes have been used [100, 142, 143] (fig. 81).

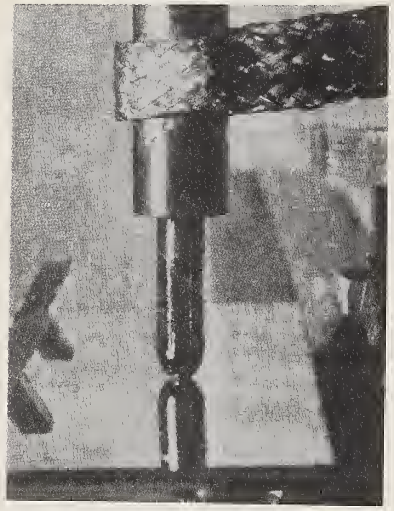


FIGURE 81. *Film-thickness gage using mercury electrodes.*

Mercury electrodes [100] (fig. 81) have been used by the General Electric Co. to measure film thickness of a molecular order of magnitude. A mercury point electrode is used which covers an area of 0.003 in.^{2}, corresponding to a circle 60 mils in diameter. The capacitance is measured between the electrode and the metallic base plate, and from this the film thickness can be calculated within an accuracy of two molecules.

Hand electrodes [142], to be placed on one side of the sheet to be measured, are either two side-by-side half circles, or two concentric electrodes, the diameters between 10 and 30 mm. They are made of metallized sponge rubber to assure good contact.

Liquid electrodes may be used to test objects like rubber gloves for thickness or dielectric strength. The objects are filled with a conductive liquid and immersed in the same liquid in a vessel.

The most straightforward method of measuring capacitance is to use ac of known frequency and voltage and measure the current per unit of area. Some instruments use beat-frequency circuits with either an earphone for tuning or a moving-coil instrument with a rectifier for direct indication of the thickness. Portable, battery-operated instruments are also available.

Very high sensitivities appear possible, especially with beat-frequency methods. Limits of sensitivity with capacitive methods are given as 0.01 μ. The accuracy generally depends more on the uniformity of the object than on the measuring method. For very thin coatings or sheets, an uncertainty of ±5 percent is usually permissible.

3.51. *Fielden-Walker Evenness Tester.* In this instrument the yarn or sliver is passed continuously at a speed of 5 to 50 fpm through an electric capacitor with an effective field length of 1 centimeter. Three different capacitor heads are available, to cover all materials from the heaviest jute sliver to a single strand of 15-denier nylon filament (15 denier means a weight of 15 grams for 9,000 meters of thread). The capacitor head is one leg of an electric bridge, operated with high frequency. The deviation from zero is proportional to the mass inserted into the capacitor. As already mentioned, moisture of the yarn influences the indication to a very considerable extent. If, however, the material has been stored for a reasonable length of time under constant temperature and humidity, the results indicate the irregularities of the material under test in a fully satisfactory way. The instrument generally works with fixed electrodes, but one special design has portable electrodes.

Manufacturer: Fielden Instrument Division, Philadelphia 33, Pa.

3.52. *Noncontacting Capacitors* [53] (figs. 82, 83). *Verigraph.* For sticky sheet materials,

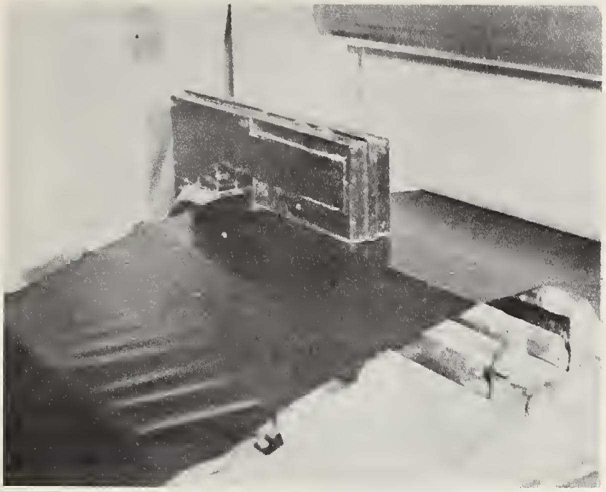


FIGURE 82. *Installation of a "Verigraph" on the conveyor of a calender producing sheet stock for rubber footwear.*

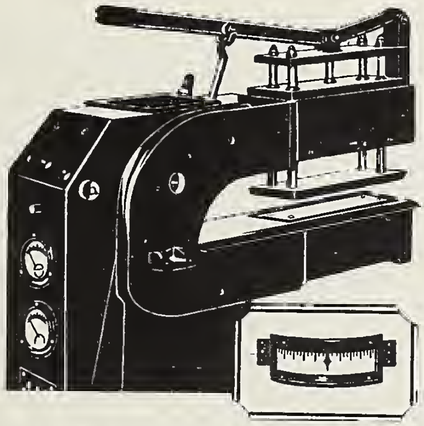


FIGURE 83. *Measuring head of the Foxboro "Verigraph."*

contact methods cannot be used. In this case the sheet is passed between two fixed air-capacitor plates (figs. 82, 83). If the dielectric constant of the sheet material is higher than unity, the capacitance between the plates will be increased. The deflection of the galvanometer in a bridge circuit can be calibrated in terms of thickness for material with a given dielectric constant. This method has been used for "weighing" rubber-coated sheets—cord fabrics for tires, gum stocks for aprons, raincoats, and other articles of rubber—with substantial increase in uniformity and saving of rubber. The capacitor plates are about 2 by 11 in. and spaced 150 mils apart. A frequency of approximately 1,600 to 1,900 kc is used. The diameter of the uncoated threads is about 20 mils. The rubber coating on each side is 10 mils, so that the total thickness is about 40 mils. The travel of the indicator pointer is about 2 in. for a change of 1 mil, a magnification of about 2,000. A thickness change of 1 percent gives a deflection of 800 mils. The accuracy (constancy of calibration) is given as 0.1 mil.

Trade name: "Verigraph," Foxboro Co., Foxboro, Mass.

Idometer. The same basic method has been used in Europe under the trade name "Idometer" (Siemens & Halske, Berlin) [53].

3.53. *Textile Uniformity Analyzer.* A noncontact capacitive method is also used in the "Textile Uniformity Analyzer." The thread is passed between the plates of an air capacitor. The capacitance, measured in a high-frequency bridge, changes in proportion to the weight of the material per unit length. Indications are not affected by the shape of the material, whether it is twisted or not, whether compact or loose.

3.54. *Decker Model 103 Comparator Micrometer* [77]. In the Decker Model 103 Comparator Micrometer, capacitance variation is converted to electrical signal by means of a transducer element called the T–42 Ionization Transducer. This consists of a glass envelope containing two internal probe electrodes and filled with stable gases under reduced pressure. Under these conditions, a d-c output appears across the internal electrodes. Capacitance changes of 10^{-15} farad or motions of 10^{-6} in. can be measured. The d-c signal developed by the transducer is applied to a differential circuit, which provides an output to the indicating meter of 400 μa per volt of input signal. Sensitivities from 0.02 to 0.2 mil for full-scale deflection are given.

Manufacturer: Decker Aviation Corp., Philadelphia 25, Pa.

3.6. Thermoelectric.

3.61. *Thermoelectric Thickness Gage* [115]. The thermoelectric thickness gage is useful for the measurement of the thickness of electrodeposited or other thin metallic coatings. It consists essentially of two probes, one hot and one cold, a power source, a voltage stabilizer to insure uniform heating, a d-c amplifier, and a milliammeter or other indicator of the amplifier output. In the simplest case where the coating and probe tips are of the same metal, heat flows from the hot probe as a result of contact and raises the temperature of the area under it. A thermoelectric potential difference then exists between the base and the coating metals, causing small electric currents to circulate between them. There is a consequent potential difference between any two points on the coating surface, which can be measured by suitable means. This potential difference is dependent on the nature of the two metals, the temperature difference between the hot probe and the work, the pressure with which the hot probe is applied, and the shape of the probe. When these conditions are controlled, the measured potential is related to the coating thickness. Using standard samples, calibration curves are made for each combination of metals that is of interest. The standard deviation of the instrument is about 10 percent for coatings that are 0.5 mil and thicker; it is slightly higher for coatings on the order of 0.2 mil. (General Motors Corp. is thought to be doing some work on an instrument similar to the one described here.)

4.00. Magnetic Methods

4.1. Attractive Force.

4.11. *Magnetic Gages* [18, 31, 37, 40] **(figs. 84, 85, 86).** One type of magnetic gage depends on the attraction between a small permanent magnet and the magnetic base under the nonmagnetic coating (figs. 84, 85). The maximum force is obtained when the coating thickness is zero. Any material between the base and the magnet decreases the attraction, which of course is also dependent on the magnetic properties of the base metal. The choice of the magnet, which has to be constant over long periods of time, depends on the problem. For testing plated coatings, for example, a magnet of 36 percent cobalt steel, 30 mm long and 1 mm in diameter, is used.

The attractive force is measured with a spring balance. To make a measurement, the magnet is brought in contact with the coating and the dial is turned until the magnet is detached. The force necessary to do this indicates the thickness. The principle can be applied to measure the thickness of a magnetic coating like nickel on nonmagnetic base metals such as copper and brass.

The following instruments which operate on this method are manufactured by American Instrument Company under the trade name "Magne-Gage":

Application	Range	Magnet
	Mils	
Type A: Nonmagnetic material backed by iron or steel	0 to 2	M–1
	2 to 7	M–2
	7 to 25	M–3
	25 to 80	M–4
Nickel, which is or can be backed by iron and steel	0 to 0.75	M–1
	0.5 to 2	M–2
Nickel, which is or can be backed by a nonmagnetic material	0 to 1	M–3

There are also special designs of "Magne-Gages," e.g., with extended arm to measure coating thickness on inside surface of objects.

The British Standards Association has developed a pocket-sized thickness gage based on magnetic attraction. It consists of a light magnet attached to a spring contained within a pencil-shaped tube (fig. 86). To make a measurement, the magnet is placed on the test surface and the body of the gage is drawn away, thus stretching the spring. The spring extension is observed on the scale and is proportional to the force required to detach the magnet from the surface, providing a measure of the thickness of the nonmagnetic layer. The range of the instrument is from 0.2 to 10 mils; accuracy is given as ±15 percent.

An instrument working with the same principle is offered in this country by Platers Research Corp., New York City. The range is given as 0.1 to 15 mils.

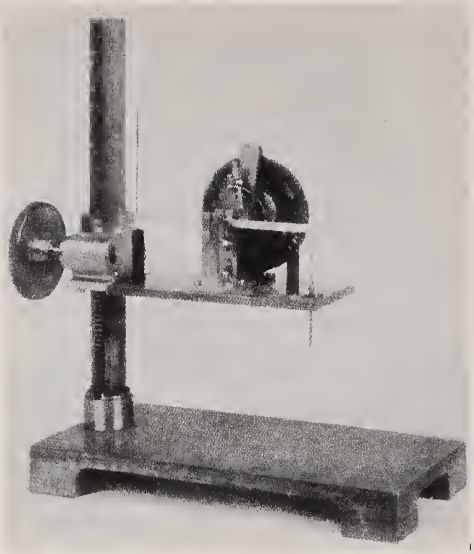


FIGURE 84. *Brenner magnetic-attraction thickness gage.* Spring balance with cover and false bottom removed.

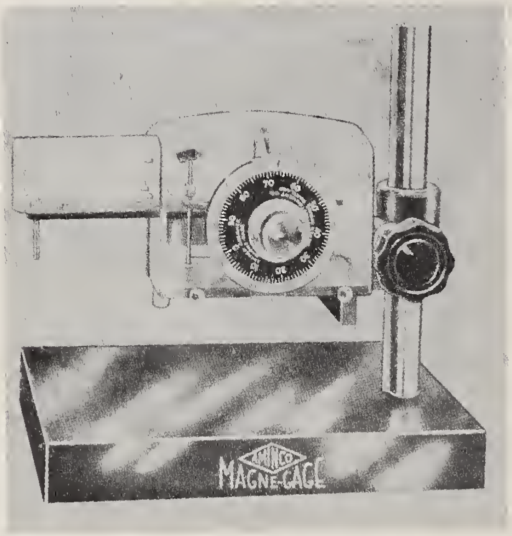


FIGURE 85. *Aminco-Brenner "Magnegage," commercial design, with extended arm.*

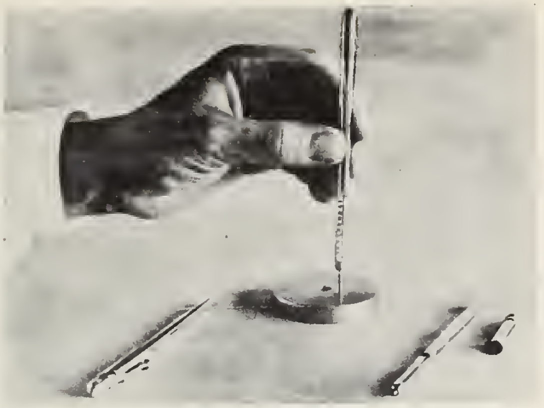
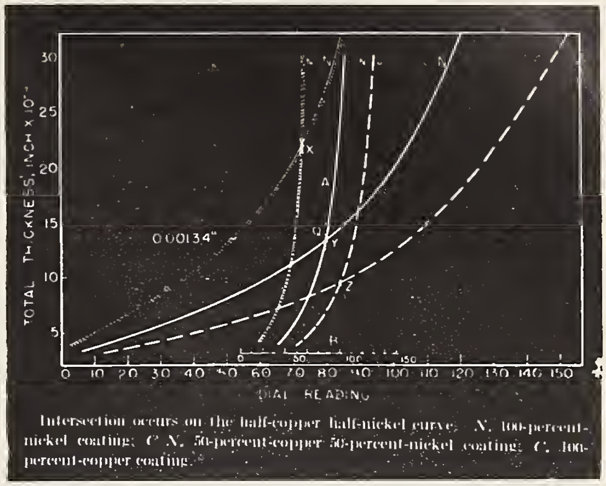


FIGURE 86. *BSA/Tinsley pencil thickness gage.*

4.12. *Magnetic Gages for Glass Bulbs* [68]. To measure the wall thickness of a bulb by the magnetic force method, it is necessary to provide a magnetic base. This is accomplished by filling the bulb with carbonyl iron powder. A mechanical vibrator must be run up and down the bulb to settle the powder. A particle size of 20 μ (0.8 mil) requires about 1.5 minutes. A modified "Magne-Gage" is used and calibrated through aluminum foil cemented over some holes in a test bulb. This is necessary because the readings will depend on the nature and degree of compaction of the iron powder. Sensitivity decreases with the thickness (distance) and also with the size of the particles. With a 3-μ diameter the sensitivity is about twice as high as with a 20-μ diameter, but the necessary time of vibration is about 6 minutes.

The test magnet of the Magne-Gage has to be selected for maximum sensitivity. For a thickness range from 0.4 to 7 mils, magnet M–2 is preferred; for the range 4 to 16 mils, M–3 is better. The accuracy obtained is 2 to 3 percent for thicknesses down to 1.2 mils. For thinner walls the accuracy increases, and measurements accurate to 1 μ (0.04 mil) are easily obtainable.

4.13. *Modified Magnetic Gage for Nickel and Copper on Steel* [40, 43] **(fig. 87).** A modification of the original Brenner gage [40] is used to measure the attractive force between the specimen and two permanent magnets of different strength. In order to compensate for the difference in the attractive force of the two magnets, they are hung at different distances from the pivot on the balance arm. The gage is calibrated for each magnet and for all-nickel, for 50-Ni–50-Cu, and for all-copper. The percentage of copper or nickel is defined by the point where the thickness readings for the two magnets coincide. A graphical method is used, as indicated in figure 87. Here the thickness falls on the calibration curve for half copper and half nickel, and no interpolation is necessary. Using an interpolation method, the gage is found to be accurate within 10 percent of the total thickness and 15 percent of the copper percentage, for a total coating thickness of 0.5 to 3 mils.



Intersection occurs on the half-copper half-nickel curve. N, 100-percent-nickel coating; C N, 50-percent-copper 50-percent-nickel coating; C, 100-percent-copper coating.

FIGURE 87. *Graph to determine ratio of copper and nickel in a composite coating of steel plate.*

Manufacturer: American Instrument Co., Silver Spring, Md.

4.14. *Solenoid Pull Gage* [133] **(figs. 88, a, b).** This instrument for the measurement of thickness of nonmagnetic coatings on steel consists of a solenoid about 4 in. long with a central hole to admit a 3/16-in.-diameter glass tube, on which a scale is engraved. A core of iron wire fits loosely inside the glass tube and carries on one end a cellulose acetate rod to act as a mark for the scale. In the equilibrium position, with the coil energized, the location of the core can be noted by reading the position of the indicator with reference to the scale. To use the instrument, the coil is energized by a-c voltage and held vertically over a coated steel article, and lowered, so that the lower end of the core in the glass tube contacts the coated surface. Then the solenoid is raised slowly. At first the core will stick to the magnetic surface. When chat-

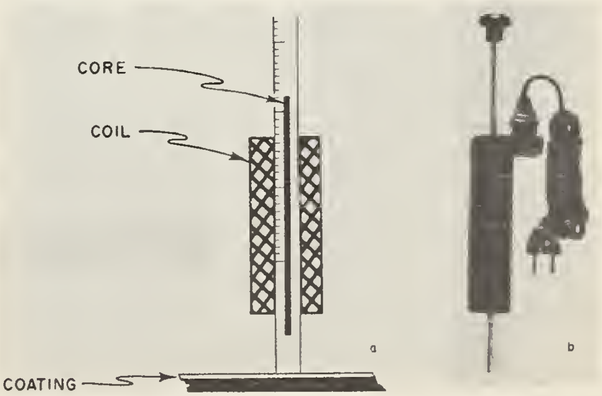


FIGURE 88. *Lea "Lectromag."*

tering can be heard, the core is about to separate from the steel base and finally will go up in the glass tube. When it has come to rest inside the solenoid, the position of the indicator on the scale is read.

The reproducibility of the instrument ranges from ±5 percent for films 0.2 mil thick to ±3 percent for coatings exceeding 2 mils.

Manufacturer: Lea Manufacturing Co., Waterbury, Conn. Trade name: "Lectromag."

4.2. Parallel Magnetic Flux. These devices measure the flux in a path parallel to the object under test.

4.21. ***Moore-Williamson Instrument*** **(pat. 2) (figs. 89a, b).** A strong magnet of U-shape, with large pole ends, P_1 and P_2, is placed on the surface of the iron or steel plate under test (fig. 89a). Two smaller poles, p_1 and p_2, are so arranged that they carry a stray flux parallel to the sheet. In the gap between p_1 and p_2 is placed a magnetic moving element, eccentric to a nonmagnetic spindle. The stray flux between poles p_1 and p_2 will depend on the thickness and permeability of the material between the large poles, P_1 and P_2. Thin materials will draw less flux than thick materials. Thickness is indicated either by the deflection of the moving-magnet indicator, or the torque (adjusted by hand) to move the pointer back to zero. The instrument has to be calibrated with material of known quality, identical with the plates to be measured. The method can be used for materials up to ½ in. thick. Figure 89b gives details of a torque meter which can be used as an inductor to be placed between poles p_1 and p_2 of figure 89a.

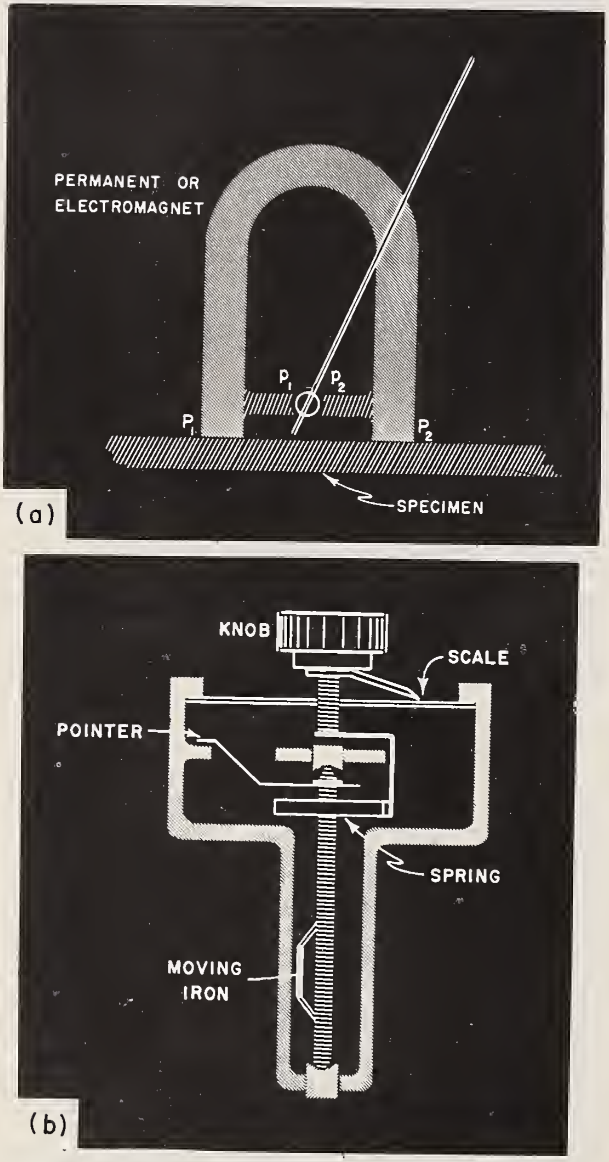


Figure 89. *Magnetic thickness gages measuring the flux in the object under test.*

4.22. ***"Elcometer" Dry-Film Thickness Gage*** **(pat. 7) (figs. 90, 91, 92).** This instrument, described in (pat. 7), consists of a permanent magnet with two soft iron pieces, extending into two soft iron contact spheres. This fixed magnet FM (fig. 91) keeps a moving magnet MM deflected against the force of an opposing spring. When the contact spheres C and C are put on a ferromagnetic base, the flux-path of the fixed magnet is in part closed by the base and the pointer takes a new position, equivalent to zero coating thickness. If, now, a sheet of nonmagnetic material such as paper is placed between the contact spheres and the base, the pointer moves nearer the original position. The pointer can be locked after it takes its position and before it is read.

The scale is nonlinear and is calibrated in thickness. Ranges are from zero to 2, 3, 5, 10, 20, 250, and 750 mils, with half the range taking approximately three-fourths of the scale length; suppressed zero scales, 15 to 40 and 40 to 80 mils, are also available. The scale length from zero to infinite thickness is about 32 mm, the

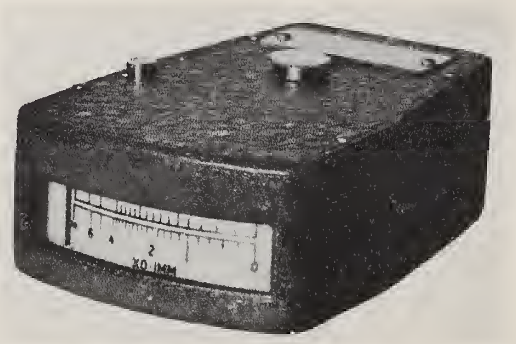


Figure 90. *"Elcometer" magnetic thickness gage.*

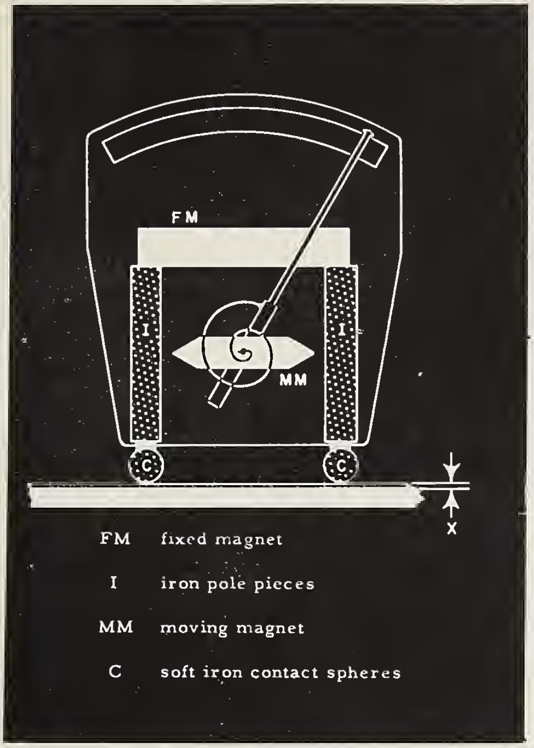


FIGURE 91. *"Elcometer" magnetic thickness gage.*

FIGURE 92. *"Elcometer" magnetic thickness gage.*

useful part of it about 28 mm. The accuracy is given as ±5 percent or ±0.1 mil, whichever is greater.

Manufacturer: Henry A. Gardner, Bethesda, Md.

4.23. *Magnaflux Corporation Meter.* This instrument is a small portable meter consisting of a permanent magnet and a galvanometer. The permanent magnet probe is placed on the sample to be measured and the thickness read directly in thousandths of an inch on the meter. Accuracy is within ±0.0005 in. when used on vitreous enameled steel, and hot-rolled, cold-rolled, and deep-drawing steel sheet. Typical applications include the measurement of thickness prior to deep-drawing so that the dies may be set for the proper thickness of material, and measurement of thickness of tin-can stock to assure the proper bending to form good seams.

This instrument is designed to measure sheet thicknesses from 0 to 0.050 in. Its advantages are its speed, its lack of any power supply such as line voltages or batteries, and its ability to measure sheet from one side only at any location.

Manufacturer: Magnaflux Corp., Chicago 31, Ill.

4.3. Magnetic Saturation. The saturation magnetic flux density (maximum number of flux lines per unit area) of a ferromagnetic material is a property characteristic of the material. When material of fixed composition is included in a magnetic field, strong enough to magnetize the material to saturation flux density, the total flux producing this flux density is a function of the thickness at the area under observation.

Mechanical working, and temperature to a lesser extent, affect the magnetic properties of some materials. For this reason, the reliability of the instrument chosen is somewhat dependent on calibration for the conditions under which measurements are to be made, as well as for the composition of the material.

4.31. *GE Magnetic Saturation Gage* **[52, 188] (figs. 93, 94).** A gage based on magnetic saturation has been developed by the General Electric Co. especially to measure the thickness of common grades of sheet steel from 10 to 45 mils thick, measuring from one side. The principle is the following: The steel sheet with known magnetic properties is magnetized by means of a permanent magnet to saturation. A strong ring-shaped Alnico magnet is used in the measuring head, together with a central pole of soft iron (fig. 94). The flux from the Alnico magnet enters the sheet and flows radially to the central pole, which, together with the yoke (also of soft iron), completes the flux path. The sheet itself must have higher reluctance than any other part of the magnetic circuit; it must be the "bottleneck" for the flux.

The flux in the center pole is determined by measuring incremental permeability. To do this, a laminated transformer core with primary and secondary windings is placed in the central pole (fig. 93). The primary winding carries alternating current, which produces an alternating flux which flows in the laminated core, as shown by the dotted lines. The alternating flux linking the secondary coil is a function of the magnitude of the steady flux supplied by the permanent magnet through the center pole. The average secondary voltage is measured by the voltmeter, V, and is proportional to the peak a-c flux. This flux is a measure of the d-c flux and therefore of the thickness of the sheet.

The bucking transformer, T, suppresses the voltage induced in the secondary winding, S, when the gage is placed on a sheet of infinite effective thickness. The instrument has two ranges, one from 10 to 25 mils for magnetic sheets of medium silicon content; the other from 20 to 45 mils, for low-carbon steel either hot- or cold-rolled. The accuracy is given as 0.5 mil when comparing one part of a sheet with another part of the same sheet, or in comparing sheets of the same grade, provided that the gage is more than one-half in. from the edge of the sheet and that the sheet is not backed up by other magnetic material. The measuring head must make close contact with the sheet.

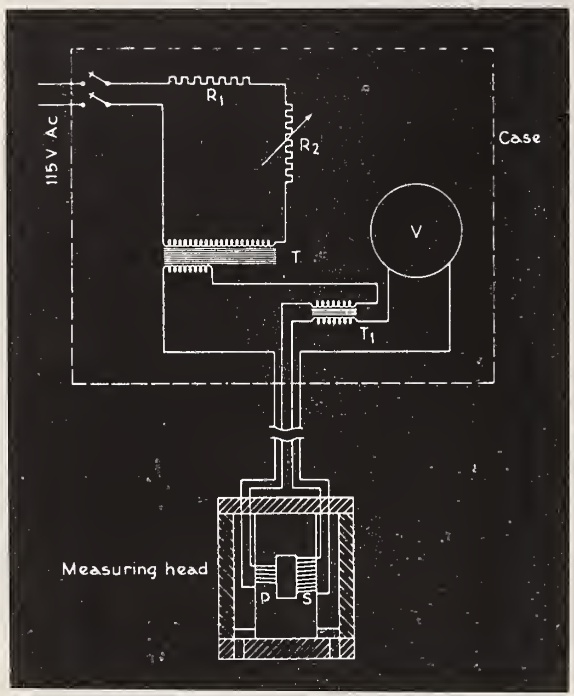


FIGURE 93. *Thickness meter for sheet iron, using the magnetic saturation method.*

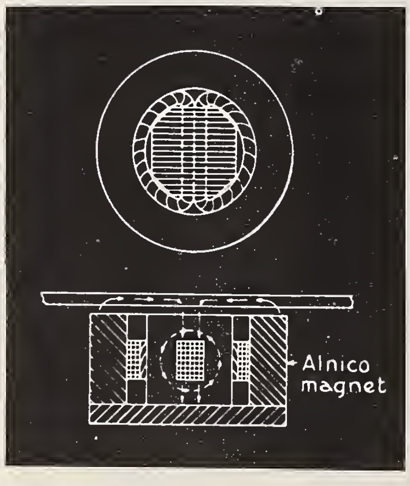


FIGURE 94. *Thickness meter for sheet iron, using the magnetic saturation method.*

Manufacturer: General Electric Co., Schenectady, N. Y.

Another steel plate thickness meter operating with dc has been developed by the British Iron and Steel Research Association [52]. It can be used for steel plates up to 250 mils thick. On normally machined surfaces the error is given as less than 3.5 percent or 3 mils, whichever is greater.

4.4. Coil Reactance [5, 102, 129, 174, 199].

Principle: The ferromagnetic material to be tested, or the ferromagnetic base on which a sheet of the material under test is placed, is part of an otherwise fixed magnetic circuit of soft iron, magnetized by an a-c current of known constant frequency supplied from a known and preferably constant a-c voltage. The total magnetic reluctance, and therefore the reactance of the circuit and the current in the coil, is changed by changes of thickness of the ferromagnetic base, or of the nonmagnetic material acting as an air gap between the ferromagnetic base and the rest of the magnetic system. This principle can be applied in many ways. A large percentage of electromagnetic thickness meters for nonmagnetic sheets or coatings use it.

4.41. ***GE Reactance Gage for Nonmagnetic Coatings on Magnetic Base*** **(figs. 95, 96, 97).** In using this gage, the sheet under test is placed under a measuring head (fig. 95) on a flat iron plate at least 1.4 in. thick, with negligible magnetic reluctance. There is, for zero thickness, a maximum of reactance and a minimum of cur-

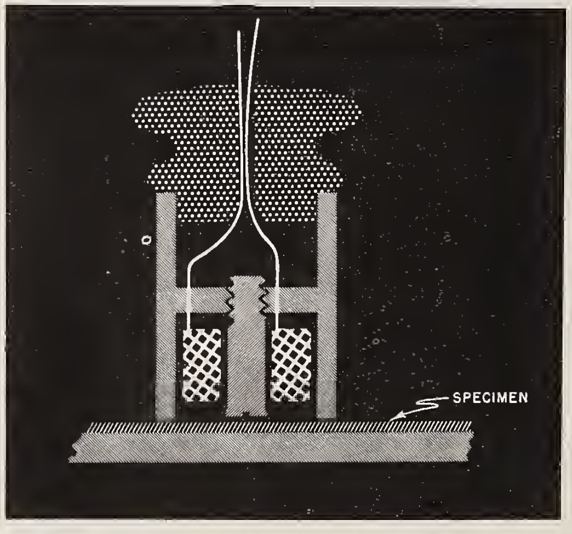


FIGURE 95. *Measuring head of a thickness meter of the reactance type.*

scale length of the ammeter. A better method is to place the a-c magnet system in one arm of an a-c bridge (fig. 96). This compares the variable reactance with a constant reactance with about the same power factor in the opposite arm, which is balanced so that for average thickness there is zero current in the diagonal. The diagonal current is rectified with dry-disk rectifiers.

Use of the bridge method has the following advantages: (a) Independence of voltage variations, (b) independence of frequency variations and waveform of the voltage, (c) an approximately linear scale for thickness, and (d) much higher sensitivity than is obtainable by simply measuring the current with an ammeter. Figure 96 shows the circuit of one of these thickness meters. Such instruments in portable form can be used to measure sheets and coatings down to 0.1 mil thick, and up to 750 mils. To suit typical rent. A nonmagnetic coating or sheet increases the current. In principle, any a-c ammeter can be calibrated in thickness, but it requires constant voltage, and the thickness scale is either very nonuniform or covers only part of the total

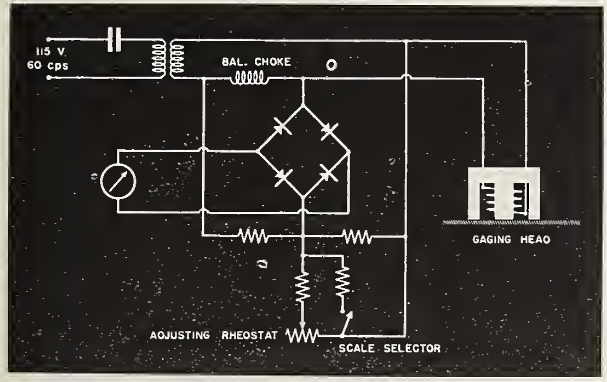


FIGURE 96. *Basic circuit of the GE reactance-type thickness meter.*

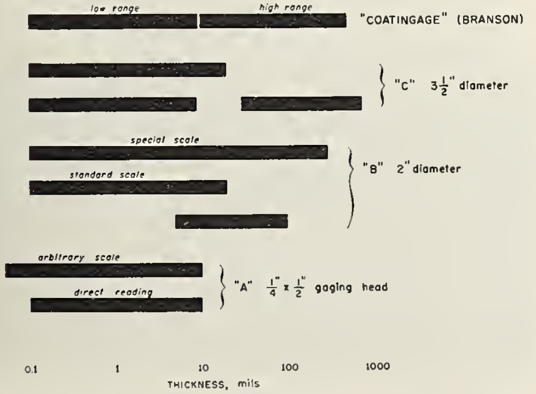


FIGURE 97. *Measuring ranges of different types of GE and Branson thickness gages.*

application problems, GE manufactures three types of such electromagnetic gages to measure the thickness of nonmagnetic sheets and coatings. Type A has the smallest measuring area, about 1.8 in.^{2} Next is type B, with 3 in.^{2}; type C has an area of about 7 in.^{2} Figure 97 gives the ranges for these three types and that of a fourth instrument, described in 4.44, the "Coatingage."

All these gages are generally used to check deviations from a standard thickness. To obtain highest accuracy, it is usual to calibrate the instruments with thickness standards, and if a magnetic base is necessary to make the measurement, to calibrate with the base actually used. The accuracy obtained with this type of gage is generally 5 to 10 percent of the thickness of the standard. The error is a minimum for equal thickness, and increases with the deviation. If a null method is used the accuracy is better, around 1.5 percent of the thickness of the reference standard.

Manufacturer: General Electric Co., Schenectady, N. Y.

Another instrument in this group is the "Magnatest FT–300" of the Magnaflux Corp. It is operated from a 60-cps power supply. A small electromagnet in the detector induces a flux in the part under test. The indicator responds to the reluctance of the path offered to the magnetic flux between the detector pole pieces. This instrument is generally used to measure the thickness of paint or plating. The indicator has a dual range of 0 to 4 and 0 to 20 mils. The accuracy is given as ±2 percent.

Manufacturer: Magnaflux Corp., Chicago 31, Ill.

4.42. *Haskins Turner Co. Gage for Scale Inside Boiler Tubes* [112]. This gage measures the thickness of scale inside boiler tubes. For no scale deposit, the inductance of the search-magnet is highest and the current is a minimum, marked as zero scale thickness on the instrument dial. The current increases rapidly with scale thickness, so that even a scale thickness of 1 mil gives a deflection of about 7 percent of the length of the meter scale. The search unit consists of a cylindrical electromagnet which is held against the inside wall of the tube by means of a spring and guide wheels. The head is simultaneously rotated and pulled through the tube. The scale deposit on the inner side of the tube represents an airgap in the magnetic circuit formed by the electromagnet and the tube. The range of the meter is 0 to 100 mils, with 20 mils in the middle of the scale. The head is connected with a 50-ft graduated steel tape. One operator lowers the probe head down the boiler tube from the upper header or drum; the other operator notes the scale thickness for each foot of travel. Two sizes of probe heads are used, one for tubes with less than 2-in. diameter, the other for tubes over 2-in. diameter. The thickness of the ferrous tube wall has no bearing on the indications. The instrument is operated from a 115-v 60-cps power supply.

Manufacturer: Haskins Turner Co., Jackson, Mich.

4.43. ***"Hurletron" for Paper Production*** [75] **(figs. 98, 99).** Figure 98 shows the gaging head of the "Hurletron" gage, a roller gage of the reactance type which has been developed to measure the thickness of paper board and heavy-weight paper as it comes from the calender. The wet paper is passed over a dryer or idler roll, and the gage measures the distance between the roll and the idler. Measurement is not distorted by the water content of the paper. The current represents the thickness of the paper. The accuracy is given as ±3 percent. Figure 99 shows an installation with three gaging heads.

Manufacturer: Electric Eye & Equipment Co., Danville, Ill.

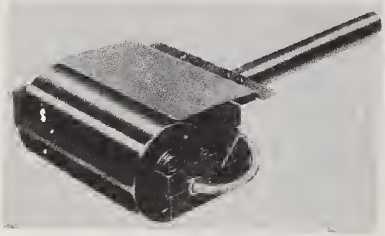


Figure 98. *Closeup of a "Hurletron" gaging head.*

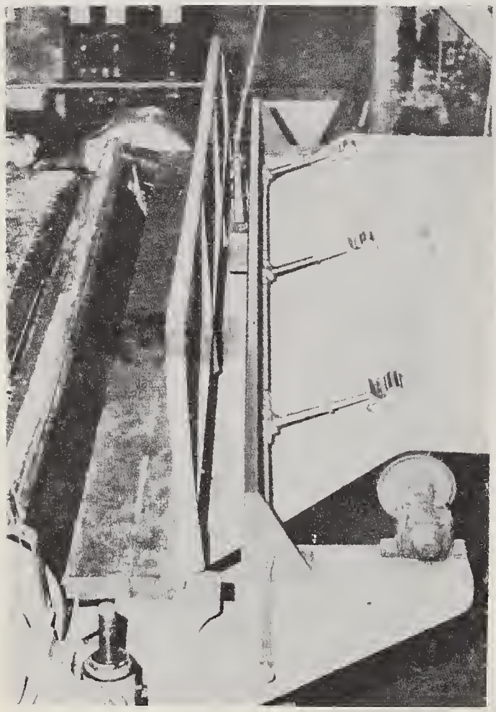


Figure 99. *Typical installation showing three gaging heads in operating position.*

4.44. ***"Coatingage"*** **(figs. 100, 101).** The instruments described so far operate on 60 cps from the power line. To use thickness meters of this type, where no a-c power is available, the "Coatingage" has been developed. It operates from a built-in battery and a low-frequency oscillator. The a-c unbalance current of the bridge is rectified and indicated by a microammeter. The gage coil of the instrument is wound on a chromium-plated steel spool, the flanges of which are placed in contact with the surface being tested. Figures 100 and 101 show circuit and scales of the two-range instrument. The low range is from 0 to 12 mils, usable between 1 and 12 mils, the high range from 10 mils to 500 mils. The tolerance is given as 0.1 mil up to 1 mil thickness of the coating. Above 1 mil the tolerance is 10 percent, provided the magnetic base is at least 125 mils thick and the instrument head is not placed closer than 1 in. from the edge of the sheet.

Manufacturer: Branson Instrument Co., Stamford, Conn.

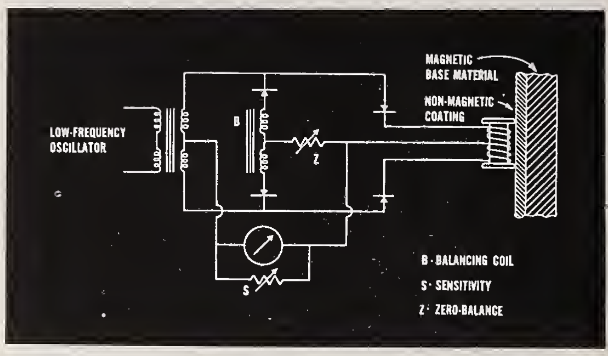


Figure 100. *Circuit of the "Coatingage" thickness meter.*

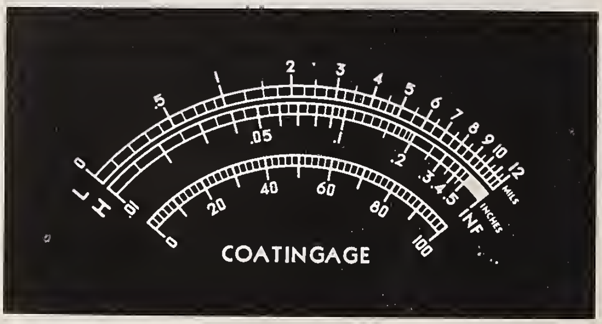


Figure 101. *Scale character of the "Coatingage."*

4.5. Transformers.

4.51. *Transformer Method for Nonmagnetic Coatings on Steel (One Side)* **(fig. 102).** In its simplest form, figure 102, a small U-shaped iron core is used. and the primary winding is connected with the 60-cps power line. Both pole ends touch the coated surface, the magnetic circuit being closed by ferromagnetic base metal of sufficient thickness and high permeability. The voltage of the secondary coil is measured with a rectifier voltmeter. Increasing the thickness of the nonmagnetic coating decreases the secondary voltage. The scale is reversed; maximum deflection corresponds to minimum thickness. The readings are sensitive to voltage and frequency variations.

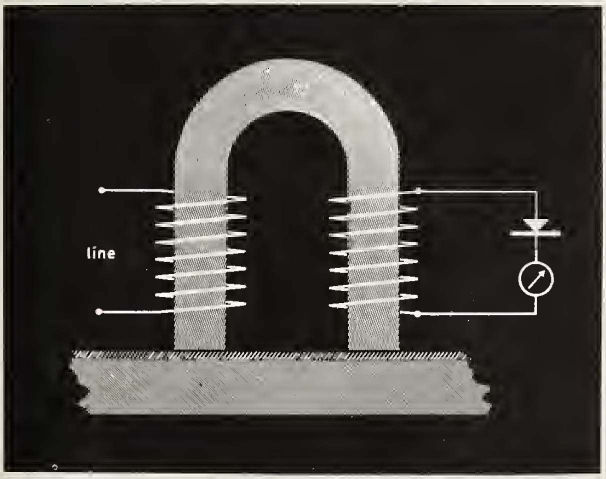


FIGURE 102. *Simplest transformer.*

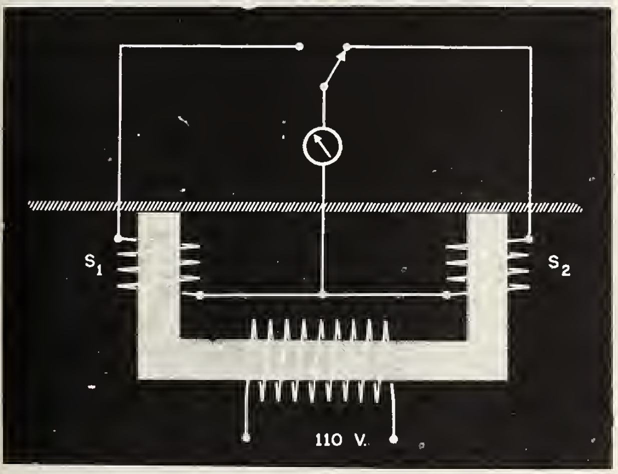


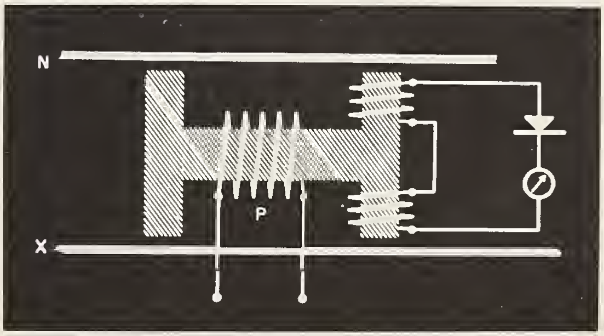
FIGURE 103. *Cylinder-wall thickness meter.*

FIGURE 104. *Cylinder-wall thickness meter.*

4.52. *Transformer Method for Ferromagnetic Materials (One Side)* **(figs. 102, 103, 104).** When this principle is applied to measuring thickness of ferromagnetic materials without coatings, the magnetic reluctance of the material is measured. With the arrangement of figure 102, without a coating, a minimum voltage is produced when the instrument is not in contact with ferromagnetic material. The voltage, measured with a moving-coil rectifier instrument, increases approximately in proportion to thickness until saturation of the yoke is reached. This principle is used in a gage designed to measure the wall thickness of automobile cylinders after rough boring. Two measurements are made, one at the top, the other at the bottom of the cylinder. The magnetic system (fig. 103) is a long, U-shaped magnet with a primary coil connected to the line and with secondary coils on each leg. The whole magnet system is built into a cylinder which fits into the cylinders to be tested. Figure 104 shows the entire assembly. The adjustment of the instrument is made so that with the normal minimum thickness the pointer deflects to 50 percent of the scale length. A thickness change of 10 percent changes the deflection about 5 percent of the scale length. The magnetic properties of the alloy influence the deflection less than about 10 percent.

Manufacturer: Commercial Engineering Laboratories, Detroit, Mich.

4.53. *Sheet-Iron Tester, d-c Operated* **[161] (fig. 105).** This device measures the thickness of sheet iron by comparing it with a standard thickness. The transformer core, figure 105,



has the shape of an H, with one primary winding, P, and two secondary windings in opposition. On one side is the sheet N of standard thickness, on the other the material X under test. One practical design has a core of about 2.4 by 2.4 in., the yokes being 0.8 by 0.8 in. and the poles 0.8 by 0.4 in. Because it is not possible with any sizable pole area to make perfect contact with the magnetic body, this instrument does not attempt full contact, but provides airgaps 1 mil thick under each head. The core rests on three hard points of nonmagnetic material, which penetrate layers of rust or paint.

This device can be operated with ac as well as dc. In using d-c excitation the primary voltage furnished by a battery is reversed and the ballistic deflection of the galvanometer observed. This instrument has been used for measuring ferromagnetic boiler tubes, using curved pole ends.

An instrument based on this principle is manufactured by the Magnaflux Corp., under the trade name "Magnatest Series FT–100." The thickness range is 0 to 80 mils; the accuracy is given as ±2 percent. One design has a portable measuring head with a small indicator for "go" and "not-go" limits.

4.54. *Nonmagnetic Coatings, Differential Voltage* [76] **(fig. 106).** This instrument measures the thickness of nonmagnetic coatings on a ferromagnetic base, using the differential voltage in the two secondary coils of figure 106. The deflection is zero for zero thickness, the difference increasing roughly in proportion to the thickness of the coating. Here the test specimen is clamped between and is a common part of two magnetic circuits, each having a primary and a secondary. The nonmagnetic coating introduces a gap in one of these and produces an unbalance. The output may be indicated directly with a rectifier voltmeter of sufficient sensitivity, or a null galvanometer may be brought to zero reading by restoring balance with adjustment of the resistor R.

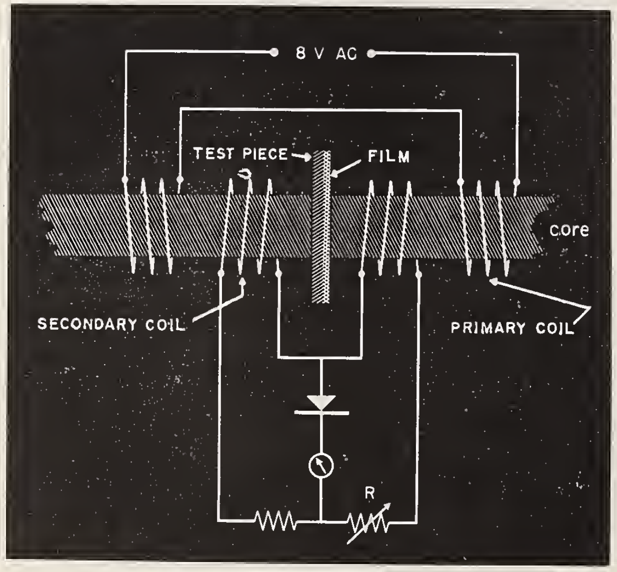


FIGURE 106. *Coating-thickness meter.*

Such devices can be made very sensitive and indicate thickness changes down to 0.01 mil.

4.6. Eddy Currents, Inductance Change. Principle: The inductance of a coil fed with a-c current decreases when the magnetic field of the coil induces eddy currents in a nonferrous conductor near the coil. Generally, two coils are used, connected in such a way that they form two legs of an electrical bridge circuit. The unbalance of the bridge is a measure of the thickness of the material in the vicinity of the coil, provided its distance from the coil is fixed. To measure the thickness of nonconducting material, a thick conducting base is provided, and eddy currents are induced in it. Under these conditions the intensity of the eddy currents depends on the distance of the coil from the base metal. The minimum base thickness necessary depends on frequency and conductivity; the higher the frequency, the thinner the base may be.

Any of the meter designs and circuits used to measure a change of inductance may be used. The frequencies used vary from 60 cps up to 1,000 kc; the design of the equipment depends upon frequency. The inductance-change effect depends very much on the frequency; for each object thickness there is a frequency that gives maximum sensitivity.

To measure the thickness of coatings or sheets from one side, two inductance coils are generally arranged in one head, the search coil being small and so built that it can be brought very close to the surface to be tested. Proximity to the metal base decreases the inductance of the test coil. To measure the thickness of metallic foils with both sides accessible, the search inductance is split into two halves and the metallic foil is passed between them, increasing the eddy-current loss and decreasing the inductance with increasing thickness of the material. When used to determine the thickness of nonconductive, nonmetallic coating on a nonmagnetic metal base, the zero position of the scale must be determined first by placing the search coil on a part of the metal free of any coating and perfectly smooth. In this condition the meter is adjusted, generally by a variable inductance. The calibration is established by placing sheets of nonconducting material of known thickness between the search coil and the base.

Magnaflux FT–400. The Magnaflux Corp manufactures an instrument of this kind, the "Magnatest FT–400," with a bridge circuit and a hand detector. Scale ranges are 0 to 2, 0 to 4, and 0 to 20 mils. The instrument operates at 60 cps and the accuracy is given as ±2 percent of the coating thickness. The measured area has to be flat, with a diameter of more than ¾ in.

4.61. ***"Filmeter"* [142] (fig. 107).** This portable battery-operated instrument, "Filmeter," developed to measure the thickness of oxide coatings on aluminum, contains two oscillators, one of them with a constant standard frequency, the other with adjustable frequency. The search coil is at the end of an insulated piston which can be moved against the pressure of a spring in an aluminum cylinder. The eddy-currents in the specimen, under the coating, change the frequency. The frequency is readjusted to the frequency of the standard oscillator by turning the dial of a variable air capacitor until the earphone detector finds frequency balance. The indications are practically independent of the conductivity of the aluminum base, but the base has to have a thickness of at least 11 mils. Surface roughness, under practical conditions, changes the indications less than 2 percent. The method could, of course, also be used to get a pointer indication of the thickness with a rectifier and a moving-coil instrument.

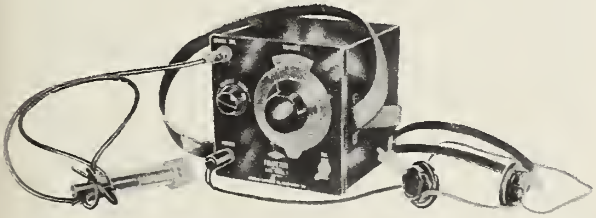


FIGURE 107. *"Filmeter" with measuring head and earphone.*

The accuracy of the Filmeter is given as ±3 percent of full scale for the range 0 to 5 mils and ±5 percent for the range 0 to 3 mils.

Manufacturer: American Instrument Co., Silver Spring, Md.

4.62. *Nash & Thompson Eddy-Current Gage* [120]. A British company has applied the eddy-current principle to the measurement of nonconducting coatings (paint, varnish, etc.) on nonferrous bases. The instrument consists of a coil which in conjunction with a variable capacitor forms the tuned circuit of an oscillator. The frequency of this is compared with that of an incorporated reference oscillator by means of a mixer circuit. The test coil, mounted in a housing and supported on three ball feet, is placed on the specimen. The variable capacitor is adjusted until the null point is indicated. The coating thickness can be read from a dial fitted to the shaft of the capacitor. Variations in the base metal are compensated by the initial adjustment on an uncoated sample. A flat area on the test piece of 1¼-in. diameter is required for the head. The range of coating thickness covered is 0 to 0.03 in.

Manufacturer: Nash & Thompson, Ltd., England.

4.63. *GE Eddy-Current Gage for Hollow Propellers.* The General Electric Co. has used the eddy-current method to measure the thickness of propeller walls. The search coil is calibrated by holding it in contact with walls of the same material and of known thickness. The measuring range decreases with increasing conductivity of the material under test. While the range is 0.25 in. for copper, it is 1.5 in. for brass. The accuracy was given as 5 percent. Production has been discontinued.

4.64. *Eddy-Current Gages for Moving Metal Sheets* **(figs. 108, 109, 110).** For this type of gage the material runs freely through an airgap between high-frequency coils. A meter, manufactured by GE but now discontinued, had an airgap of 375 mils for the material and was accurate to 0.01 mil.

Salford Gage. An instrument made by Salford Electrical Co., Ltd., England, is built for the following ranges; 1 to 5 mils, 2 to 10 mils, 5 to 25 mils, and 10 to 50 mils. The calibration, as with all these instruments, has to be made for the specific metal. Figure 108 shows the measuring head of the Salford foil-thickness meter.

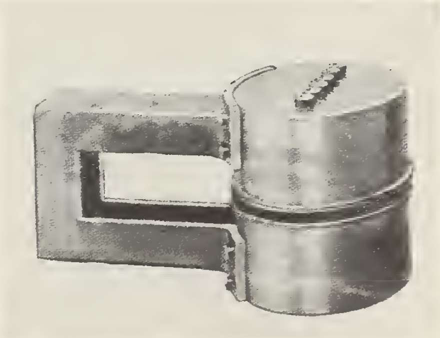
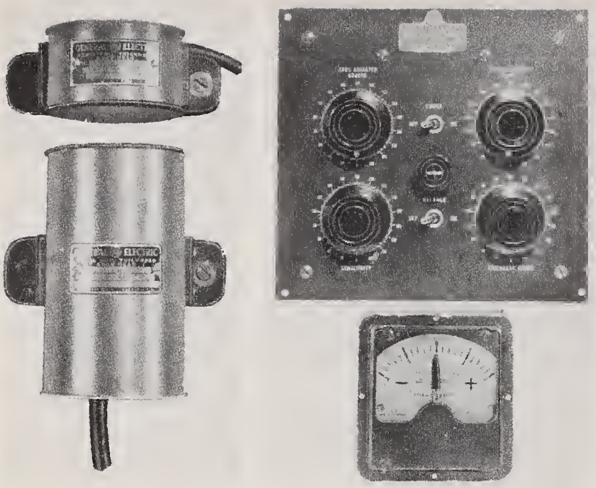


FIGURE 108. *Measuring head of the Salford foil thickness gage.*

Pratt & Whitney Gage. The foil gage of Pratt & Whitney, to be used directly with rolling mills, is shown in figures 109, 110. The gaging head consists of two parts: The lower part is under the coil in a fixed position, the upper part swings up out of the way while the mill is being threaded. The material passes between the upper and lower parts of the gage head. This gage can be used to measure foils from 0.25 to



FIGURES 109 and 110. *Pratt & Whitney foil gage.*

Gaging head. Power unit (adjustment of zero, coarse and fine sensitivity, thickness range). Indicator.

10 mils thick. The indicating meter, calibrated for the deviation from standard thickness, has two scales, 0 to 0.2 mil and 0 to 2 mils.

Magnatest FT–200. Another eddy-current gage to measure thickness of moving sheets and foils of copper, brass, or aluminum in continuous production, is manufactured by the Magnaflux Corp. under the trade name "Magnatest FT–200." It is operated on 60 cps. The thickness range may be from 30 to 80 mils. The range of the zero-centered indicator can be made ±10 percent of any nominal value between these limits. The measuring area has a diameter of 4 in.; the accuracy is given as ±0.1 percent of the nominal value.

4.65. *Gages for Lead Sheath on a Cable* [131]. Eddy-currents have been used for measuring the thickness of the lead sheath applied to cables by an extrusion process in the British Callender Cable & Construction Works in London. The method was later adopted by the Okonite-Callender Cable Company in Passaic, N. J. Here the influence of frequency is important. At 50 cps, it was found that the magnetic flux passed freely through the lead and little change of inductance took place. Up to about 500 cps a linear change of inductance took place, approximately 2.5 percent per 100 cps. The maximum change of inductance was at 1,400 cps; for higher frequencies the effect decreased and became almost negligible for more than 2,200 cps. For this reason the measurements were made at 1,400 cps. The flux was induced with four electromagnet coils mounted around the cable sheath, as it came from the press, using roller bearings to contact the sheath surface. The output after rectification was measured with a d-c instrument. Thickness measurement in this application corresponds to determination of concentricity. The trade specifications allow 18 percent eccentricity. With the gaging device it was possible to keep eccentricity within about 5 percent, or 7.5 mils for 150-mil average thickness.

4.66. ***"Probolog"* (fig. 111).** Corrosion of condenser tubing presents a problem to many power plants. The tubes have outer diameters from 0.625 to 1.250 in. and a wall thickness from 28 to 165 mils. They are of nonmagnetic metals (copper, brass, stainless steel) and they are used in bundles up to 5,000 tubes. Test equipment for this problem, called a "Probolog," has been developed by the Shell Development Co., Emeryville, Calif. The probes, with diameters of 0.313 to 1.005 in., have interchangeable Mumetal cores with an axial length of 900 mils, figure 111. Two search coils are mounted on the core, each about 300 mils long, the coil centers about 370 mils apart. The clearance between probe and tube ranges from 40 to 152 mils. The probe is first driven by compressed air to the far end of the tube, and then slowly withdrawn with a power winch at a speed of 1 or 2 fpm through the tube length, which is generally about 20 ft. As long as the tube under test is uniform in thickness, the eddy-currents induced in the tube by the two coils (the tube acting like a short-circuited winding over the coil) are identical and the balance of the bridge circuit is not disturbed. If there is, however, a thinned area ("pool") caused by corrosion, on either inner or outer surface of the tube, the bridge becomes unbalanced. The unbalance voltage is converted into a current which energizes a solenoid to rebalance the circuit. The rebalance current is recorded on a strip chart which moves in synchronism with the pulling of the probe. With proper interpretation and calibration with test pieces of the same tubes having thickness differences along their length and also holes of known diameter, the size and depth of corrosion pools and other defects can be determined with fair accuracy, reaching ±5 percent as far as the wall thickness is concerned.

For the different tube diameters, seven probe diameters are available. Recommended practice is not to test all tubes, but to make a hydrostatic test first to find defective tubes that fail under

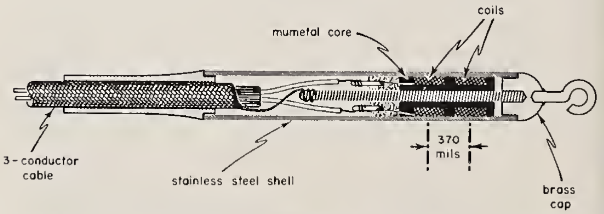


FIGURE 111. *Search-coil assembly for the "Probolog" condenser-tube tester.*

the test pressure, and after this to test all tubes in the vicinity with the electromagnetic method, as described.

Manufacturer: Shell Development Co., Emeryville, Calif.

4.67. *Gage for Ceramic Coatings on Metal* [106]. A ceramic-coating thickness gage has been developed to measure the thickness of protective coatings of metals and alloys in high temperature service. The range of this instrument is from 20 to 100 mils, with an accuracy of about ±0.2 mil for 20 mils and ±1 mil for 100 mils, i.e., about 1 percent of the indication of the moving-coil meter within this range. For this application a frequency of 500 kc is used.

4.68. *Gages for Metal Coatings on Metal* [44, 49, 209]. Conductive metallic coatings on a base of different electric conductivity can be measured by using the eddy-current principle.

One device employing this principle [44] uses a commercial type of oscillator with a high-frequency output. Two germanium diodes in opposite phase cause current to flow alternatively through the two legs of a bridge circuit, one leg including the test probe coil, the other, a variable resistance. A direct-current micro-ammeter in series with the bridge circuit receives first the current through the test probe, then the current through the variable resistor, and registers the current difference.

The probe is first placed on a reference (uncoated) surface and the meter adjusted to read zero. It is then placed on the surface to be tested and the current change noted. In practice, this current change is a direct indication of the thickness of the coating in question. The magnitude of the induced eddy current, dependent on both difference in conductivity between the base and coating metals and the thickness of the coating, in turn determines the strength of its own magnetic field. The field of the eddy current opposes the field of the inducing current, thus lowering the impedance of the probe coil and allowing proportionately more current to flow through the probe. The recorded test currents are interpreted by comparison with a calibration curve prepared by measuring samples of known thickness.

The sensitivity range and accuracy of the eddy-current instrument are dependent on such variables as the frequency used (e.g., a frequency of 2 Mc is found effective for coatings up to 1.5 mils thick, and 100 kc for coatings up to 6 mils), circuit resonance, and the differences in conductivity of the two metals.

The Boonton Radio Corp. Gage, manufactured by the Boonton Radio Corp., Boonton, N. J., and the "Dermitron" gage, manufactured by Unit Process Assemblies, N. Y., are two examples of this type of gage.

Magnatest FT–600. Magnaflux Corp. has a commercial type [49] "Magnatest FT–600 Series" with a very small contact head which forms one arm of a bridge circuit. A typical unit has a scale graduated in mils to 10 mils.

4.7. Mutual Inductance With Air Core [42, 107, 141] (fig. 112). Principle: The mutual inductance transducer consists of a primary and a secondary coil wound on the same coil form, but at separate positions on the form. A metal surface lies near the secondary coil (fig. 112). When the primary coil is excited with rf, eddy-currents are induced in the metal surface. If the metal were an ideal conductor the field of the primary coil at the surface would be just canceled by the field of the eddy-currents. When the mutual inductance transducer is placed so that the secondary coil is adjacent to the metal surface, there will be no voltage induced in it. As the transducer is moved away from the metal an increasing voltage will be picked up by the secondary coil.

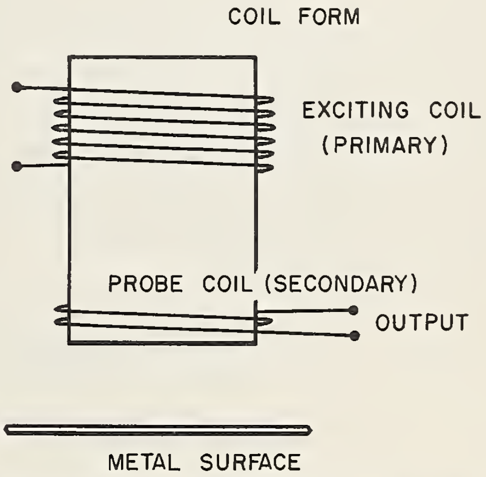


Figure 112. *Basic structure of distance-measuring element.*

Mutual inductance between two coils is varied by proximity of metallic surface.

4.71. *Measurement of Bearing Eccentricity* [107, 141, 185] (fig. 113). This instrument measures the displacement of a turbine shaft in its journal bearing. The problem is to measure the thickness of the oil film in a 6-in.-diameter bearing with a radial clearance of only about 6 mils, while running at more than 10,000 rpm submerged in lubricating oil at 200°F.

Four distance-sensitive elements are used, mounted around the shaft, immediately beyond the bearing in positions 90° apart. Each consists of two concentric coplanar coils, wound on a single bakelite form, 1 in. in diameter (fig. 113), the inner coil having a diameter of 70 percent of that of the outer coil. For such a coil system the output is linear up to a distance of about 50 mils. The shaft is electroplated with

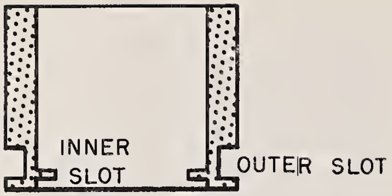


FIGURE 113. *Probe coil form used in oil-film thickness indicator.*

copper, 1 mil thick, in a band immediately under the distance-sensing coil assemblies. A frequency of 2,500 kc is used. The output from the four pick-ups is connected with the four plates of a cathode-ray oscillograph and in this way a picture of the eccentricity of the shaft in the bearing is obtained. The range is ±13 mils. One mil is represented by two lines 150 mils apart, giving a magnification of the eccentricity of 150. The over-all accuracy of the method is estimated as better than 0.5 mil.

The same principle has been used to measure and indicate the longitudinal movement of high-speed rotating shafts, such as might be caused by failure or wear of a thrust bearing [185]. A brass disk, which forms part of the electrical system, is fastened on the end of the turbine shaft. Motion of the disk towards or away from the probe changes the mutual inductance between two windings. The output voltage, indicated on a meter, shows shaft position in units of mils on a d-c instrument.

4.72. *Phase-Angle Thickness Gage for Silver Coating on Stainless Steel* [9, 220]. The phase-angle thickness gage is useful only when the resistivities of the base material differ materially from that of the coatings. The probe consists of a mutual inductance transducer which is held in proximity to the sample. A buckout transformer shielded from the sample is also located in probe head. The two elements are electrically connected and excited with rf current in opposition, producing output voltages whose phase difference is responsive to the conductance of the sample. A phasemeter is calibrated for the desired frequency ranges. The application of this device given in the references is for silver on steel. For direct reading of thickness, the phasemeter output is indicated on a meter calibrated in mils of silver which has been applied to a base of 37 mils of stainless steel. The probe is brought within ⅛ in. of the specimen in order to make a reading.

4.8. **Wattage Absorbed.** This method has been used to measure the thickness of ferromagnetic sheets or tubes (boiler tubes) from one side. Devices of this type have a pole area of 1 by 0.5 in.; they are connected to the power line, and the wattage absorbed in eddy-current losses is measured by a wattmeter. The method is reportedly satisfactory with larger tubes of considerable wall thickness. For small tubes with thin walls, the eddy-current energy at times is lower than the power consumed in the potential circuit of the wattmeter used. Changes of permeability, conductivity, or thermal history of the tubes have little influence. The average error for boiler tubes is reported as not exceeding ± 5 mils.

5.00. Optical Methods

5.1. **Measuring Microscope** [18, 167, 190]. The standard ASTM method of determining the thickness of coatings requires the use of the measuring microscope. The chemical dropping test and magnetic tests are alternatives. In ASTM 219, rules for use of the measuring microscope have been established by the American Electroplating Society cooperating with the National Bureau of Standards and the American Society for Testing Materials. This test is used for electrodeposited coatings of copper, nickel, chromium, lead, zinc, or cadmium thicker than 0.05 mil. The surface of the specimen is protected either by mounting in a plastic material such as phenolic or acrylic resin, or by electroplating it with a relatively thick coating of copper. A section produced by cutting perpendicular to the flat surface is ground and polished by regular metallographic methods, treated chemically, and/or illuminated in such a manner as to obtain maximum contrast between the coating and the adjacent materials. The thickness is measured with a filar micrometer ocular that has been selected and calibrated so that the error will not exceed 2 percent. As an example, the scale may be graduated to 0.01 mm (0.4 mil).

Alternatively, the image of the specimen may be projected at a known magnification on a ground-glass focusing plane in the camera of a metallographic microscope, where the width of the projected edge of the coating is measured with a graduated linear scale. Magnifications of 500 are feasible.

When measuring the thickness of soft materials, like paper, with a micrometer microscope, the material must be embedded in resin or a similar substance [190, p. 4, 5]. Although the micrometer microscope discloses details of the cross section, it is very difficult to get accurate results because only the edge is measured, and not anything like the average thickness or the local thickness of a well-defined area of the sheet.

5.2. **Change of Focus** [64, 196, 208] **(figs. 114, 115, 116, 117, 118, 119, 120).** This method is used to measure the thickness of large sheets of transparent material at the middle of the sheet, where mechanical micrometers cannot be used, or to measure the wall thickness of glass bulbs, accessible from only one side. Some transparent materials are so soft that the pressure of the anvil of the conventional mechanical micrometer deforms or damages them. The method is also used to measure the thickness of transparent coatings on an opaque base.

A microscope is used that can be adjusted with a micrometer screw to focus successively on the bottom and top surface of the sheet under test. With this method a focus discrimination of 0.2 mil is possible. The lower end of the microscope tube is held to the surface of the sheet. This is the zero mark on the micrometer scale. The transparent sheet is marked on the side away from the microscope with a soft pencil which leaves graphite particles that can be focused sharply in the microscope.

The readings on the barrel and thimble of this optical micrometer give the thickness of the sheet directly if the scale is calibrated for a certain refractive index n of the material under test. If the displacement of the microscope lens is h, the thickness is $x=n \cdot h$. Because most optical materials in common use have refractive indices of 1.520 ±0.015 (a variation of about 1 percent), such instruments are generally calibrated for this value. Figures 114 and 115 show micrometers of this type.

FIGURE 114. *Aireon optical micrometer.*

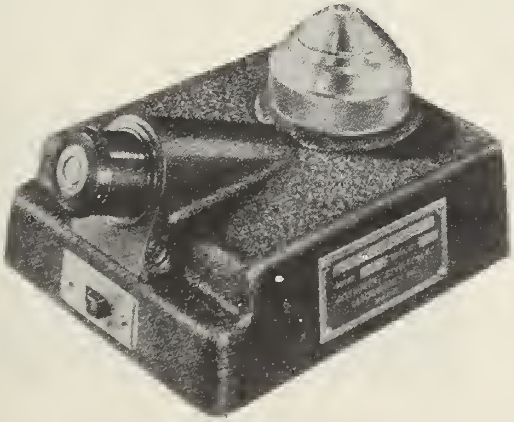


FIGURE 115. *"Opti-Mike."*
Instrument Development Labs.

"Optimike." The "Optimike," figure 115, has a built-in lamp, connected with two flashlight cells. The measuring range of this instrument is 400 mils; the accuracy is given as ±1 mil.

Manufacturer: Instrument Development Labs., Needham Heights, Mass.

Schneider instrument. The principle is used in an instrument built in Germany to measure the wall thickness of inaccessible but hollow transparent bodies. For measuring rough and optically bad surfaces, an immersion attachment is supplied with the instrument.

Manufacturer: Dr. Schneider Instrument Works, Bad Kreuznach, Germany.

The method has also been used to measure the thickness of transparent coatings of aluminum oxide, or to determine the thickness of glass mirrors. In this case the upper surface is marked with a graphite or grease pencil; the base metal of the mirror or the coating is easily recognizable from its texture by using a magnification of 500 to 1,000.

Thicknesses of very thin metal coatings on glass have also been determined in this way (fig. 116). The metal film is removed from a part of the glass plate. A beam of light from the lamp, B, (fig. 118) going through the lenses L_1 and L_2 and the filter F, projects a virtual image G′ of the grid G very near to the surface O_1 under test. The virtual reflections G'_1 and G'_2 are photographed through the miscroscope M_1. The method has been used to determine

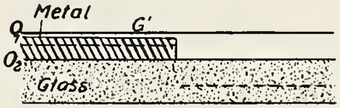


FIGURE 116. *Measuring thickness of transparent films.*

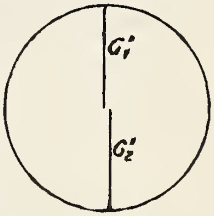


FIGURE 117. Mirror *images of a line.*

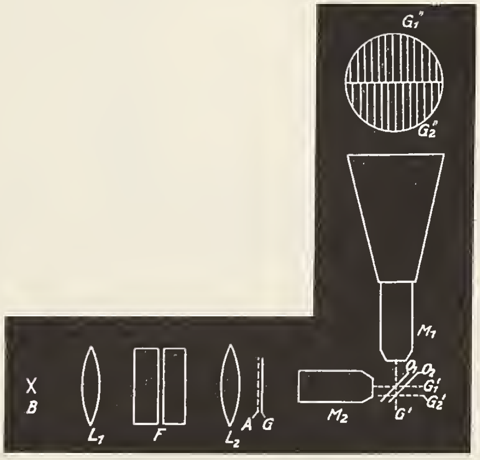


FIGURE 118. *Arrangement to measure film thickness.*

silver coatings 0.10 to 0.15 μ (4 to 6 μin.) thick. The average error of 160 measurements was ±0.008 μ.

Bausch & Lomb instrument. Bausch & Lomb Optical Co. has also used this principle in a thickness meter for glass (figs. 119, 120). The light source L projects an image of the graduated glass scale by means of the lens M on the first surface A′ of the object (such as the glass bulb shown) when held against the small elongated aperture O, which is at an angle of 45° to the beam of light. The outer surface A′ will reflect the image of the graduated scale S through the lens B and the prism P to the frosted screen Z. Only part of the light is reflected by the outer surface. The balance is refracted into the transparent material and will fall on the second surface A^2, be partially reflected to A and from there refracted into the air, giving finally a second picture of the scale S on the screen Z. The pictures are of almost equal light intensity, but the separation of the two images is proportional to the separation of the two glass surfaces, and can be measured directly by counting the divisions displacement. In the illustration the thickness is 0.018 in. The instrument is calibrated for the standard refraction index of glass, $N=1.522$. Readings on other glasses have to be corrected according to the refractive index.

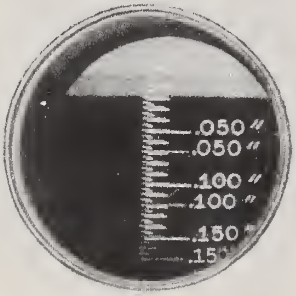


FIGURE 119. *The two scales as reflected in the eyepiece when measuring glass approximately 18 mils thick.*

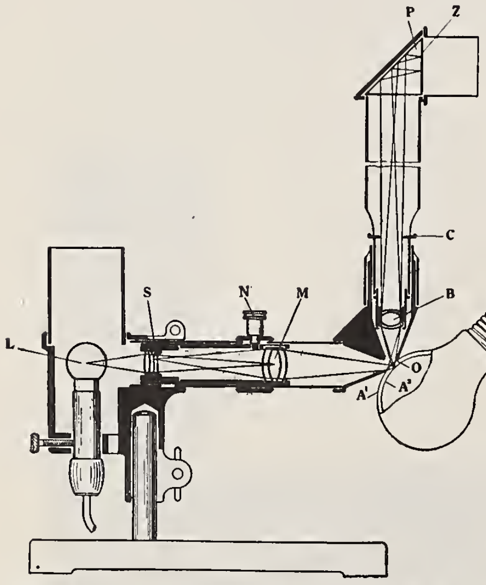


FIGURE 120. *Optical system of Bausch & Lomb thickness meter.*

5.3. Interference [128, 159]. The thickness of extremely thin reflecting metallic films is difficult to measure. The older methods of determining film thickness of the order of 1 to 0.01 wavelength of light have usually involved weighing or chemical determination of the quantity of material on a known area. These methods are difficult to apply because of the small quantities involved, and they suffer from the defect that the density of tenuous films (of atomic or molecular dimension) must be assumed to be that of solid metal. The interference methods described in this section provide measurements free from assumptions of density with precision of the order of 10 A (approximately 0.04 μin.).

5.31. ***GE Spectrophotometer*** **[2] (fig. 121).** Spectrophotometers are used to measure the thickness of transparent films, e.g., electrolytic oxide coatings on aluminum. The recording spectrophotometer (General Electric Co.) projects progressively a series of monochromatic polarized beams of light, ranging from 400 to 700 mμ, onto a sample coated with the film under test, placed over an aperture of 1 in. diameter in a small sphere. The reflectance or transmission of the sample is automatically recorded as a function of the wavelength. The reflected light obeys the laws of interference (fringes of equal chromatic order), and the curve traced by the recording spectrophotometer has variations related to the thickness and refractive index of the film (fig. 121). The refractive index must be

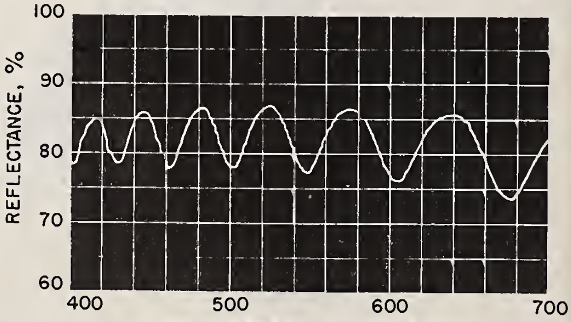


FIGURE 121. *Reflectance curve for "Alzak" reflector sheet with commercially thin oxide coating.*

determined separately. The thickness of the film is determined by the number of maxima between two wavelengths.

5.32. *Michelson Interferometer* [58]. This well-known instrument can be used to measure thickness of thin metallic films. One of the total reflecting plates of the interferometer is first coated with an opaque film of the metal by the usual evaporation process. Then, a central region, approximately one-third of the total reflecting area, is covered with a mica strip and the remaining unobstructed area is given an additional deposit of the same metal, when the film is evaporated in production. The mica strip has to be thin and in very close contact with the interferometer plate. The plate, with the mica strip removed, is placed in the interferometer and the instrument adjusted for white light fringes. A monochromatic source is then substituted, and the two fringe patterns compared. In the central region the fringes are displaced relative to the fringes in the outer portions. For a displacement of one fringe the thickness of the film deposited during the second evaporation is half the wavelength of the light used; for fractional displacements, corresponding fractions of the half wavelength. When the customary green mercury line is used for measurements, the fringe displacements for a film 20 mμ thick is less than one-thirteenth of a fringe. The fringes are sharp enough, however, for comparator measurements of displacement, or even for projection on a screen with subsequent measurement. Both methods have been used with considerable accuracy.

5.33. *Interference Microscope* [198]. The interference microscope has been found useful in measuring the thickness of decorative chromium plating. In order to use this method, a part of the coating must be stripped from the piece to be tested by suitable means leaving a distinct boundary between the coated and stripped portions. It is then placed under the interference microscope and brought into focus. Focusing in the interference microscope is much like an ordinary microscope. When the enlarged, focused image of the surface is visible in the eyepiece, a shutter is opened which allows a series of parallel light and dark bands to be superimposed on the image of the surface. The spacing and direction of the fringes can be adjusted according to need. In boundary measurements such as the one under consideration, the fringes should be perpendicular to the boundary. A fringe shift results from any surface irregularity, the amount of the shift being determined by the depth of the irregularity. A shift of one bandwidth is equal to a depth of one-half the wavelength of the light used, usually the 5460-A green line of mercury. The range of the instrument is from 2 to 100 μin. The method is considered to be extremely accurate.

FIGURE 122. *Step gage to measure thickness of molecular films.*

5.34. *Color Comparison* [33, 34] (fig. 122). This method is based on the comparison of interference colors reflected from white light by the film under test [33] and colors reflected from a glass surface coated with films of various thickness.

The GE step gage [34] is a plate of special glass enclosed in a plastic case (fig. 122). A film of barium stearate is deposited on the glass in a series of monomolecular layers, deposited in such a way as to build a series of steps each 1 μin. thicker than the preceding one. When illuminated by white light, each step reflects a color determined by its thickness. The steps appear as a series of colored strips. The range is from 2 to 16 μin. The readings have to be corrected for the refractive index of the plate on which the unknown film is deposited. The procedure of correction is different from materials with lower or higher refractive index than the film.

The many uses of the step gage are described in the GE instruction book, GEJ–2329 "Barium Stearate Stepgauge."

5.35. *Donaldson-Khamsavi Method* [69, 202] (fig. 123). (The material presented here is taken from the book, "Multiple beam interferometry," by S. Tolansky [202]). In the multiple-beam method of W. K. Donaldson and A. Khamsavi, the thin film to be measured (AB in fig. 123) is deposited on part of a flat glass surface, ABC. A fairly thick opaque coating of silver, PQRS, is then deposited by evaporation over both film and flat. The height, QR, then equals that of the silver film AB. A silvered flat, DE (reflectivity=0.90), is brought close to the combination of AC. When illuminated from

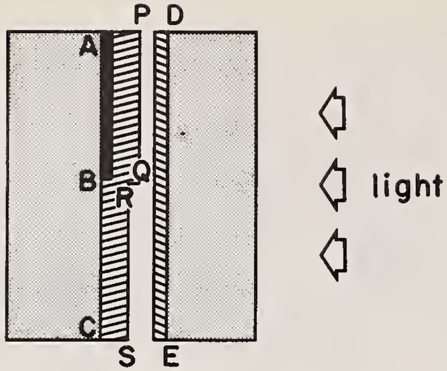


FIGURE 123. *Donaldson-Khamsavi method for very thin reflecting metallic film.*

the right, back-reflected Fizeau fringes are formed which exhibit the sharpness characteristic of multiple beam interference. The step displacement, RQ, can thus be determined with a precision down to the order of 10 A (10^{-6} mm).

It should be noted that the true metrical thickness of the film is obtained. The opacity of the silver coating PQRS automatically eliminates phase-change effects that would vitiate results if transmission fringes were used. It is not sound practice to make the coating film PQRS sufficiently thin to permit of transmission observations, for then the phase-change effect at the combination PQ may differ in an unknown manner from that at the simple film RS.

The film AB must be capable of withstanding the vacuum necessary for evaporation of the superposed coating of silver.

5.36. *Fizeau Method* [101]. This method, devised by Fizeau, is used to determine the thickness of silver film on glass, e.g., on mirrors. The film in question is supported 1 or 2 mm above a small iodine crystal. After a few minutes, the iodine vapor will react with the silver, thus forming a spot of transparent silver iodide. The area surrounding the transparent spot will be partially converted to silver iodide and will appear, when viewed by reflected light, as a series of concentric, colored rings. The number of these rings is a measure of the thickness of the silver iodide, hence of the silver film. A table is available which correlates the number of rings with the film thickness [101]. It is essential that the film be exposed to the iodine until transparency results. A longer exposure will enlarge the pattern, but will not increase the number of rings. The range of thickness usually varies from about 0.03 μ to approximately 0.2 μ.

5.4. Diffraction [126, 171, 173, 143a]. This method has been used to measure the diameter of fine wires. If a narrow beam of light is directed against an obstacle, the dimensions of which are not much more than the wave length of the light, interference fringes develop in the space behind the object. For example, diffraction patterns from a needle are parallel bright and dark lines, visible under magnification, which broaden towards the tip of the needle. The smaller the object, the wider the spacing of these lines. On this principle, a "diffraction micrometer" has been developed by the Dr. Carl Leiss Co. in Berlin-Steglitz in cooperation with the Osram Lamp Co. The method can be used for wires from 0.01 to 0.08 mm in diameter; the accuracy is given as about ±0.3 percent of the actual diameter (not of the maximum range).

The diffraction of light by a bundle of parallel fibers was employed by Thomas Young in 1824 in a simple, ingenious device (the eriometer) for the rapid, direct measurement of average diameter. McNicholas and Curtis [138a] made a new construction of Young's instrument and applied the method to textile fibers. The eriometer average diameter is in excellent agreement with comparable data obtained with the microscope.

5.5. Light Beam to Photocell [88, 118, 165, 181, 194, 218] (figs. 121, 124, 125). Optical-photoelectric thickness meters do not directly contact the object to be measured. Instead, a thickness or diameter influences the light quantity falling on a photocell. The method is not ordinarily used to measure the thickness of sheets during the process of production, but rather to measure the thickness of fine wires or, in the textile industry, fibers, threads, yarns, and slivers. In all such devices care is taken to see that variations in the light source do not influence the reading.

5.51. *"Evenometer"* [88]. This instrument is used primarily to determine unevenness (variation of diameter) of raw silk thread which is wound at a spacing of 100 threads per inch around a slotted board. A beam of light is directed to the space where the silk is over the slot and its intensity is measured in a differential arrangement. Two recordings are made, one of the average diameter, the other (by means of an integration circuit) of the deviation from the standard diameter.

5.52. *"Filometer"* [194]. This instrument developed by the Deering Milliken Research Trust in Pendleton, S. C., is similar in principle to the Evenometer, but does not use the shadow method, which may give erroneous results when the material has a tendency to band, ribbon, or twist, causing an apparent change of diameter. The Filometer employs a high-intensity beam of light, so arranged that light is actually transmitted *through* the material. In this way the change of light is a measure of the density of the material and not of its thickness alone. Different standards are required for colored yarn. The recorder has two pens, one recording the momentary thickness, the other recording long-term variations of average thickness.

5.53. *"Serc" Evenness Tester* [192], *Electron Micrometer, and "Diamatrol"* (fig. 124). These instruments are all operated on the optical-photoelectric principle. A beam of light from one source is split into two balanced equal halves, M and R (fig. 124). These beams fall on two matched photocells, P_1 and P_2, whose amplified outputs are opposed to each other, so that the total output will be zero. The yarn or wire of known diameter, say 20 mils, is placed in beam R and the corresponding photocell P_2 will receive less light. An indicating meter connected to the difference voltage will now register a certain unbalance. With a knife edge, adjustable with a micrometer screw, the amount of light in the second beam M is reduced until it equals the intensity of the beam obstructed by the 20-mil yarn and the indicator or recorder reads zero again. This position of the micrometer is marked "20 mils."

When production yarn uniformly 20 mils in diameter runs through the meter the indicator will read zero. It will show a plus indication if the yarn is larger than 20 mils, minus for thinner yarn. The electrical meter can be calibrated in mils deviation, plus or minus, from 20 mils normal diameter. The scale of the micrometer, which adjusts the knife edge in beam M, measures the base diameter, while the electric indicator indicates the deviation from the base diameter. The scale of the indicator has a length of ±4 in. and can be calibrated to read ±4 mils, to give a magnification of 1,000. Special designs of the instrument have full scale deflection for ±0.5 mils, equivalent to a magnification of 8,000. To prolong its age, the 6-v lamp is operated at only 3.2 v. Change of the light intensity caused by voltage fluctuations will cause the same percentage change of reading of deviation from base diameter. A method of compensating for changes in either amplifier or photocell is to use only one amplifier and one photocell to which both light intensities are alternately directed. A rotating disk scans the two light beams alternately and generates two alternating voltages with 180 degrees phase displacement. The difference of these voltages is indicated by the meter.

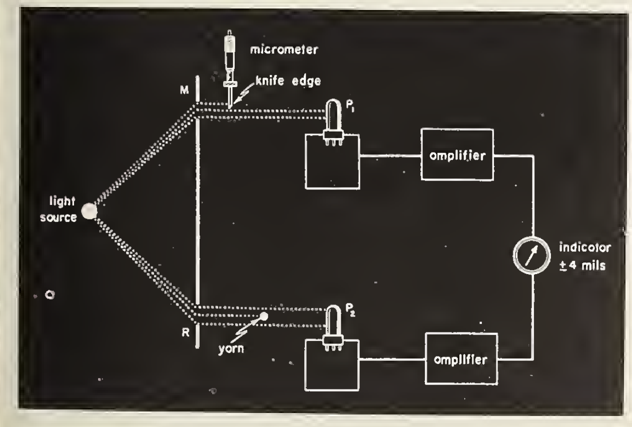


FIGURE 124. *Principle of the yarn-diameter indicator of Standard Electronics Research Corp.*

Line-voltage fluctuations up to ±5 percent, which cause light fluctuations of about ±15 percent, can be compensated by another electronic circuit. For wider line changes, constant voltage transformers have to be used. The readings of these optical-electrical thickness meters are unaffected by the composition or specific gravity of the filament under test, or by its water content.

Manufacturer: Standard Electronic Research Corp., New York City.

5.54. *"Visi-Limit" Gage* [118, 218] (fig. 125). This instrument operates with a differential system, using only one beam of light, which compares the photoelectric effects generated by the sample with the effects of specimens representing high and low limits.

Figure 125 shows the basic principle, applied to measuring the thickness of a wire. There is one light source, a scanning disk of special design, a frame with three apertures, a photocell, and an amplifier. The three apertures are illuminated in sequence by the rotating disk. The wire under test is behind the middle aperture. The light coming through the middle aperture is reduced with increasing thickness of the wire, the illuminated area of the photocell becomes smaller and with it the photocurrent. The other two apertures are adjusted to reproduce production limits, the high-limit aperture corresponding to a test wire of maximum diameter, the low limit aperture to one of minimum diameter.

The scanning disk illuminates the three apertures in such a way that the total area uncovered at any time is constant. Three a-c voltages are generated, fed to an a-c amplifier, and from there to the vertical deflection plates of a 5-in. cathode-ray oscilloscope. All three voltages appear at once in the oscilloscope as three horizontal lines. Although the voltage is connected only for one-third of each revolution of the scanning disk, the picture is persistent for the observer. The thickness indicated by the length of the middle line has to be within the

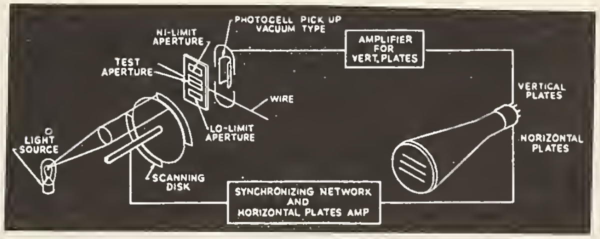


FIGURE 125a. *Schematic diagram of the "Visi-limit" gage.*

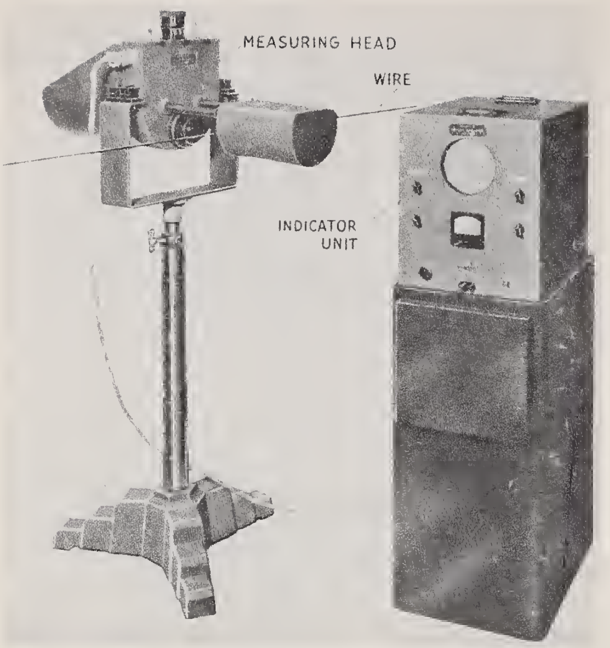


FIGURE 125b. *"Visi-limit" micrometer, measuring head, and indicator unit, as used to measure wire thickness.*

limits given by the lengths of top and bottom lines.

The magnification of the deviation from standard thickness can be adjusted up to 4,000, so that one-half mil is represented by 2 in. The resolution is constant and is given as 0.1 mil, independent of the total dimensions of the test object. The wire may vibrate as much as 400 mils. In the absence of vibration the accuracy is given as ±0.1 mil.

An adaptation of the "Visi-Limit" gage to measure the thickness of sheets belongs with the mechanical-optical-photoelectric methods. The sheet is passed over a roller, and under a straightedge placed at a known distance above the roller. The light beam passes through the space between the top of the sheet and the straightedge, forming the test aperture. The limit apertures are adjusted to the allowed tolerances.

Manufacturer: Raymond Wilmotte Co., Washington, D. C.

5.6. Electron Microscope [139]. The electron microscope has been widely used since 1939, to measure the thickness of very fine fibers or films of the order of 0.1 μ (4 μin.). New methods of measurement and of calibration with objects of known diameter have been developed here and abroad. Mahl [139] gives 36 literature references. By way of stating the limits of the electron microscope, it may be said that an object 0.02 μ thick (0.8 μin.) can be measured with an accuracy of about 0.005 μ (0.2 μin.).

6.00. X-ray Methods

6.1. Shadow Geometry [90] (pat. 1) (fig. 126). This method is used to determine the thickness of the walls of large vessels, especially the hulls of ships, where both sides are accessible but not in such a way that a gaging tool could be used. One of several test procedures is the following [90] (fig. 126): Two straight tungsten wires are cemented on the outside of the hull, about 4 in. apart. An X-ray tube with a very sharp focus is located on the same side about 8 in. from the surface. On the inside of the hull a photographic film is placed in close contact with the wall, the correct location being determined by means of an electromagnet on the outside and a compass needle on the inside. When the focal distance a and the spacing b of the wires are known, the unknown thickness of the wall may be calculated as $d=(ac/b)-a$, where c=the spacing of the shadows. Instead of using two wires at spacing b, two images of one wire may be secured by moving the X-ray tube parallel to the surface for two exposures.

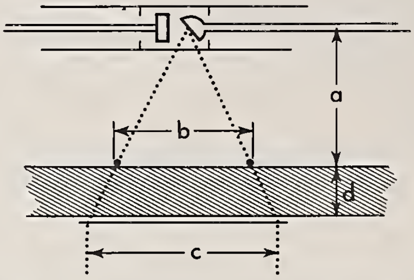


FIGURE 126. *X-ray shadow method, using two tungsten wires in the distance "b".*

6.2. Absorption, Photographic Comparison [148]. A set of blocks of known thickness of the same material as the test object, ground in steps of 20 mils over the full range of thickness likely to be encountered, is photographed simultaneously with the test object on X-ray film with fine grain and high contrast. In order to get the maximum contrast in the film, the minimum voltage capable of penetrating the object should be used. One application is the measurement of the thickness of hollow steel propeller blades. One-half of a film 7 by 17 in. is pressed by an inflated rubber bladder inside the propeller, the other half is placed under the test blocks.

6.3. Absorption, Radiation Detectors [55, 57, 66, 213, 219] (fig. 127, 128). This type of industrial thickness meter has received increasing use in the past 10 years, especially for measuring the thickness of continuously running sheets. With the advent of radioactive isotopes,

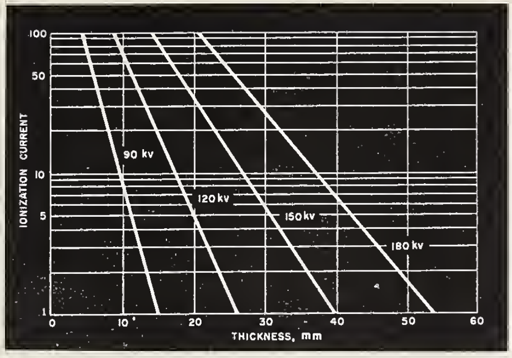


Figure 127. *Ionization current as a function of material thickness and X-ray voltage.*

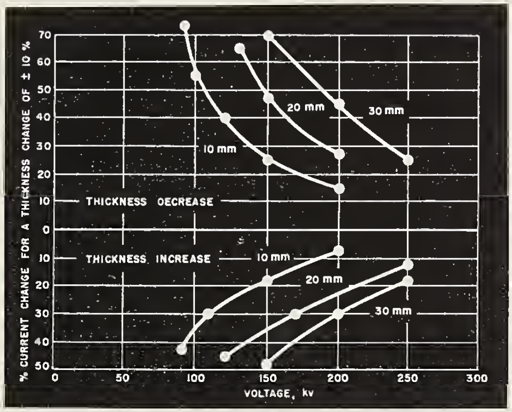


Figure 128. *Current change for a thickness change of ±10 percent for steel plates 10, 20, and 30 mm thick, as a function of voltage.*

however, it has lost some ground. The basic principle is the following: When material of unknown thickness (of any kind, but generally metallic) is placed between an X-ray tube and a radiation indicator, a part of the radiation is absorbed. The decrease of intensity is an indication of the energy absorbed and depends on both material and thickness.

Two different effects are used for measuring radiation: (a) gas ionization in ionization chambers or Geiger-Mueller counters, (b) fluorescence of a screen, measured by a light-intensity meter. The first X-ray thickness meters used ionization chambers of old design, measuring intensity with slow moving-coil instruments of high sensitivity. When suitable amplifiers were developed it became possible to use for low-intensity radiation the newer ionization chamber and Geiger counters with high-speed response needed for measurements on sheets moving with a speed up to 30 mph.

When a fluorescent screen is exposed to X-rays, high-speed photoelectrons are liberated. Since the invention of the photomultiplier tube, this detector is used more and more. Its glass envelope is mounted near a fluorescent screen of zinc-cadmium sulfide or other materials with high response speed, and is covered with black paper to exclude undesired light.

Radiation thickness meters have the great advantage that the material is not in contact with any mechanical member. They can be used when the strips are not only moving fast in a longitudinal direction, but also vibrating transversely. One design allows a transverse movement of the strip up to 18 in. In contrast to absorption meters using visible light, X-ray meters are not affected by steam or dust developed in rolling mills. Even layers of cooling water 1/16 in. thick give not more than ±1 percent error. These meters do not give absolute measurements; they have to be calibrated with standard samples. The purpose of the different designs is to eliminate as far as possible the effects of variable voltage and of changes in the emission of the X-ray tube.

In principle, X-ray thickness gages are very sensitive, 1-percent thickness change corresponding to 5- to 10-percent change of transmitted energy. It is necessary, however, to use the proper type of X-rays for each test: Soft rays for thin or slightly absorbent material like paper, plastics, or foils, and hard rays generated with high-voltage tubes for thick material. Figure 127 shows ionization current in the detector as a function of material thickness and X-ray voltage. If we plot from this the sensitivity (percentage current change for 10-percent thickness change) we get figure 128. From this it is evident that the lower the voltage the higher the sensitivity, but of course there are limits to the sensitivity of the detectors and the stability of the circuits. Low X-ray voltage is also desirable for reasons of safety and cost.

It is important to bring both the tube and the radiation receiver as close as possible to the object under test, though it may be desirable to allow the material, if coming from a rolling mill, to vibrate transversely as already mentioned. When testing unevenness of the wall thickness of containers, tubes, or bottles, it is of the greatest importance to keep the area under test as small as possible, in order to find minor flaws at the same time. On the other hand, for measuring thickness of sheets in production, an averaging effect is desirable.

6.31. *Single Tube and Beam* [203, 213]. In an early use of this method [203] steel sheets 2 in. thick were tested with 200 kv in a 2-in.^{2} area, using a Geiger-Mueller counter as the pickup. At the maximum sensitivity the response time was 0.1 sec for an instrument used with an active area of about 0.3 in.^{2}

The modern "Measuray" [213] also uses only one tube and one beam. The X-ray tube is contained within a grounded housing in the lower part of the unit, and the pickup, a photocell, may be as much as 30 in. above the base.

Manufacturer: Sheffield Corp., Dayton, Ohio.

6.32. *Absorption Differential* **[83, 84, 98, 137, 140, 219] (fig. 129, 130).** The purpose of all differential methods is to obtain higher accuracy, independent of fluctuations of the supply voltage. This is done by comparing the absorption of two beams of X-rays in a specimen of standard thickness and in the sample under test. Three schemes are possible: (a) one tube alternately irradiating the standard and the unknown, (b) one tube with a double window to split the emission into two parts, one directed to a standard thickness, the other to the test object, and (c) two tubes, operating under identical conditions. All these instruments apply mainly to the measurement of the deviation from the standard value. The accuracy at the center of the scale is almost the same as the accuracy to which the thickness of the standard has been determined.

For the first method [137] one X-ray tube is used with two ports. Two fluorescent screens are mounted so as to receive the transmitted radiation from the test and the reference object. Visible light from the fluorescent material is interrupted by a rotating shutter which allows the two beams to impinge alternately upon a photocell. A commutator mounted on the rotating shutter provides phasing information for an algebraic rectifier.

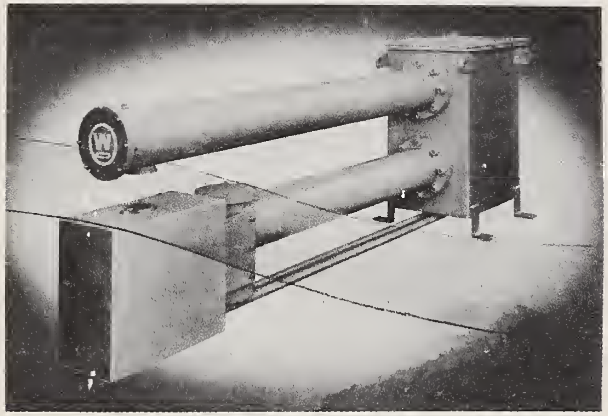


FIGURE 129. *Westinghouse X-ray thickness gage for cold-rolled steel strip.*

The second method [137, 98] involves the use of two pickup devices. The radiation pulses appear simultaneously at the output of both pickups. The difference indicates the thickness difference between reference and test material. Measuring ranges of this type of thickness meter are given by GE as follows:

Material	50 kv	100 kv
	Mils	*Mils*
Lead	1 to 6	6 to 31
Copper	3 to 25	25 to 115
Mild steel	[a]5 to 40	[b]40 to 190
Brass	5 to 25	25 to 110
Glass (hot)	60 to 500	
Aluminum	80 to 500	200 to 1,000
Rubber	187 to 1,000	

[a]Cold strip. [b]Hot strip.

The third method [140, 219] uses two sources of X-rays and one pickup device. The two tubes are so connected that they operate 180 deg out of phase, so that pulses from each source arrive alternately at the common pickup. This method is used for the Westinghouse cold-rolled-strip-steel thickness gage (figs. 129, 130). The work X-ray tube, shown above the pass line, directs its beam downward through the material to be tested. The standard X-ray tube, shown below and to the left of the pass line, directs its beam horizontally through a standard sample. The transmitted radiation in both instances strikes the pickup unit. The indicator has a scale length of ±3 in. with ±10 divisions on each side of center, to give the deviation of the rolled sheet from the thickness of the standard sample. This is part of a calibration device, and it can be

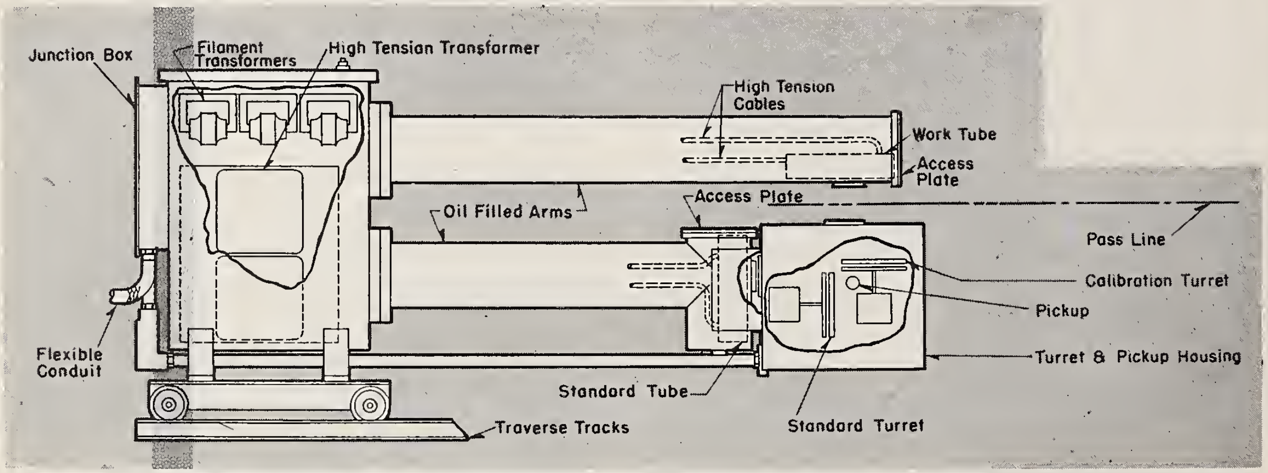


FIGURE 130. *Schematic view of Westinghouse X-ray thickness gage.*

adjusted in steps of 1 mil from 5 to 119 mils total thickness. One range of the instrument indicates ±1 mil for all standard thicknesses from 5 to 49.9 mils. In this way the full deflection of 3 in. on the meter corresponds to ±20 percent deviation in 5 mils, and one division 300 mils wide corresponds to ±2 percent or 0.1-mil deviation, a magnification of 3,000. For a standard thickness of 49.9 mils, the full scale of ±1 mil gives ±2 percent or 0.1 mil, the magnification being 300. The second range of the instrument is ±3 mils, for standard thicknesses from 50 to 119 mils, so that one division of the scale corresponds to 0.3-mil thickness difference, which is ±0.6 percent of the low limit of 50 mils and ±0.25 percent of the high limit of 119 mils for sheet thickness.

In the X-ray absorption gage of the Standard Electronics Research Corp. in New York City, developed to detect voids in artillery shells, [83, 84], the X-rays, after passing through the part under test, strike a pair of potassium iodide scintillation crystals one-eighth in. square, which emit visible light approximately proportional to X-ray intensity. The light from the crystals goes to the cathodes of secondary emission phototubes, whose output is amplified and applied to a d-c meter to indicate the difference of thickness. The device is very sensitive; a thickness difference of 0.5 mil in a sheet 250 mils thick, or a change of one part in 500, can be detected. The X-ray beams, obtained with 180 peak kv and 4 ma, have a diameter of three-sixteenths in. (190 mils).

Manufacturers of X-ray gages: General Electric Co., Schenectady, N. Y.; Industrial Gages Corp., Englewood, N. J.; Sheffield Corp., Dayton, Ohio; Standard Electric Research Corp., New York, N. Y.; and Westinghouse Co., Pittsburgh, Pa.

6.33. *Special Varieties of X-ray Gages* [127, 214]. In the manufacture of steel bottles for highly compressed gases, uniformity of wall thickness and freedom from flaws are very important. In testing the bottles the detector is inserted inside the bottle or tube by means of a cable or rod of appropriate length; the X-ray source is outside. The tube or bottle is rotated. At the same time, either the X-ray tube with the detector or the bottle alone is moved longitudinally so that the whole surface is inspected. The thickness is read on an indicating instrument. High speed is very important for this kind of testing. For large objects it may be desirable to have a recording of the uniformity of thickness, providing legal evidence of the test and saving the operator's time. A facsimile recorder [127] can be used with the intensity of the stylus marks proportional to the signal picked up by the detector. The bottle and the drum of the recorder are rotated in synchronism; likewise, the axial movement of the bottle is synchronized with the axial movement of recorder pen or chart.

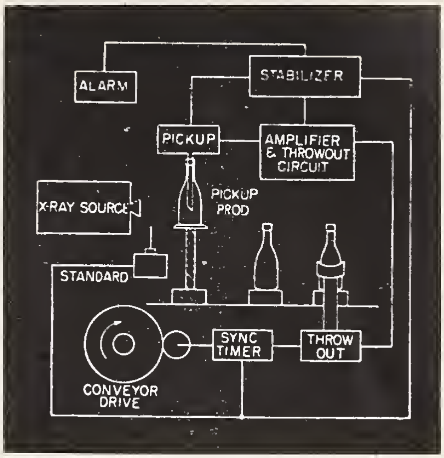


FIGURE 131. *Measuring the thickness of glass bottles in a production line with a Westinghouse X-ray gage.*

An X-ray gage to be inserted in glass containers [214] is shown in figure 131. The pickup consists of a photocell whose housing carries a small-diameter brass tube which can pass through the neck of the bottle. A fluorescent screen, mounted at the tube end at a 60° angle, is excited by the X-ray source and the pattern is sensed by the photocell. The effect of the bottle motion is that a point on the container describes a helix and the entire surface of the bottle wall is scanned. If the wall thickness is less than a predetermined value, the gaging circuits operate a mechanism to discard the defective container.

Manufacturer: Westinghouse Electric Corp., Pittsburgh 30, Pa.

6.4. Diffraction [32, 74, 95]. This method has been used to measure the thickness of electrodeposited crystalline films. Diffraction patterns of thin surface films are composed of diffraction lines from both the underlying base material and the surface layer. A comparison of the integrated intensities of the two sets of diffraction lines with a microphotometer can be used as a measure of the surface-film thickness. The theoretical investigation, made for both flat and cylindrical surfaces, was confirmed experimentally on nickel wires of 3-mm diameter, coated with barium carbonate and strontium carbonate. The usable range of the method is indicated as 0.01 to 500 μ. The experimental investigation covered the range from 1 to 60 μ [74].

In another system of measuring thin films on thick crystalline or polycrystalline backings, characteristic X-rays are reflected from the base material at one of the Bragg diffraction angles and the diffracted intensity is measured by a Geiger counter system [32, 95]. When the base material is covered by a thin coating, the

X-rays are reduced in intensity according to an exponential law. From the measured ratio of the coated and uncoated intensities, the geometry of the arrangement, and the known absorption coefficient for the coating, it is possible to compute the thickness of the coating. Measurements are made with a powder-diffraction spectrometer utilizing the focusing principle. The area tested is between 1 and 100 mm^2. Thickness was measured between 0.1 and 100 μ. The method is applicable to coatings of any material or combination of materials whose X-ray absorption coefficients are known.

The method has also been used to *identify* contaminating films less than 0.01 μ thick on electrical contacts without measuring their thickness.

6.5. Backscattering, Secondary Radiation [28, 29, 158, 205] (figs. 132, 133, 134). This technique measures the thickness of metallic coatings on a base metal. A device used by the canning industry to measure the thickness of a tin coating on hot dipped steel is used here as an example [158, 205]. A 20-kev X-ray beam is directed at an angle of 70 deg upon the surface of the sheet (figs. 132, 133), penetrating the tin coating and causing the underlying metal to emit secondary fluorescent radiation in all directions. The intensities are measured with Geiger counters during a 30-sec interval. The maximum thickness measurable is 3 lb per base box, which means 3 lb of tin on both sides of 112 sheets, each 12 by 20 in. With a count of 500 impulses per interval for uncoated sheets, the count was reduced to 200 for sheets with a 1-lb coating, 60 for sheets with a 2-lb coating, and 20 for sheets with a 3-lb coating.

The design shown in figure 134 uses two X-ray heads to measure the thickness of the plating on both sides of the sheet at the same time. The test area is 4 in.^{2}; the sheet is measured in 12 spots by moving it by hand under the detector assembly. The equipment is also used for checking the plating thickness in continuous production, using averaging circuits for the 30-sec measuring period. The count can be indicated (usually scaled down in multiples of 2) or recorded either graphically or digitally. The range for tin coatings is from 0 to 200 μin., too small for magnetic or electromagnetic methods. The accuracy is given as 2 percent of the measured thickness, which is about the same as is

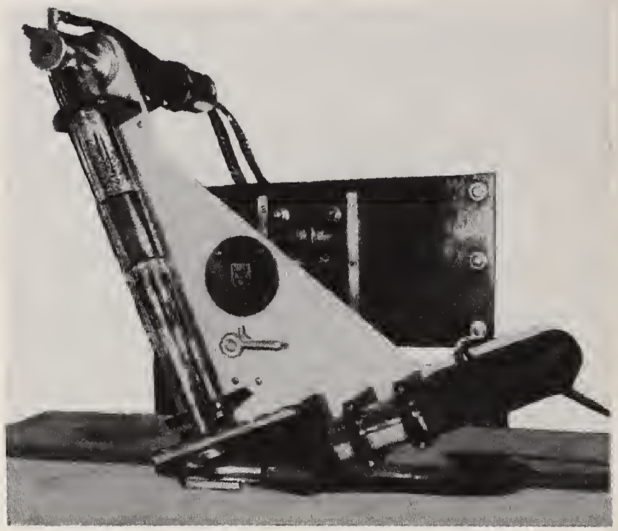


FIGURE 133.

Measuring head consists of the X-ray tube (at top) and a lead-lined brass collimating tube designed to produce uniform radiation over a circular area of 4 in.^{2} The Geiger tube at right measures the secondary emission after it has been reflected back through the tin coating at an oblique angle.

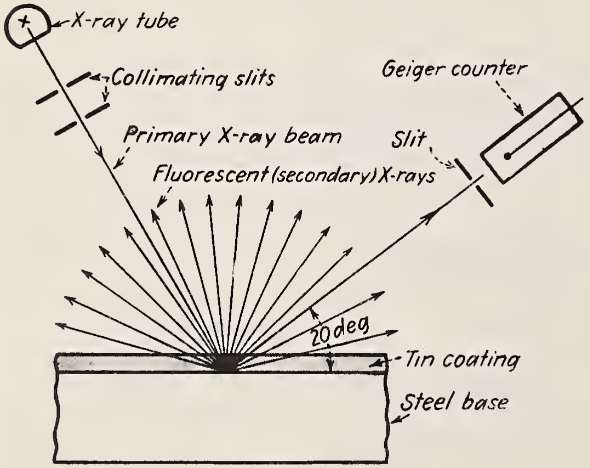


FIGURE 132.

Secondary fluorescent emission at the iron-tin boundary is measured from an acute angle; absorption by the tin coating reduces the intensity in proportion to the thickness of the tin coating.

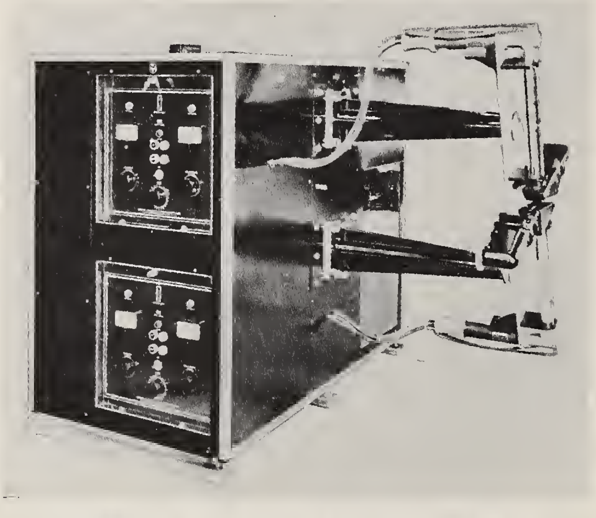


FIGURE 134. *X-ray tin coating thickness meter.*

Twin equipment, to measure the thickness of the coatings on both sides of the plate.

obtainable with the chemical method used for calibration [29].

The method can also be used to determine the thickness of metallic coatings on metals other than steel. It is, however, necessary that the coating material have an appreciably higher atomic number than the base metal. There are limits for both the maximum and the minimum thickness measurable: Very thick layers absorb all radiation before it can enter the counter, very thin coatings cause too little change compared with unplated material.

A similar method has been developed by H. F. Beegley, Jones & Laughlin Corp. [28].

Manufacturer: North American Philips Co., Mount Vernon, N. Y.

6.6. Spectrometry, For Depth of Cold-Working [87] (fig. 135). When the surface of a metal is cold-worked, as by sandblasting, the crystal structure of a thin layer is altered [87]. Figure 135 shows a special fixture, used to position a flat specimen at the Bragg angle and also to rotate the specimen about an axis normal to its flat surface, so that the entire surface is scanned. The output of the Geiger counter varies as the specimen is rotated. The variation of intensity recorded by the potentiometer is a function of the grain size of the specimen. Small grain gives small intensity variation, large grain gives large intensity variation. The method is most sensitive to grain sizes larger than 1 μ.

After a first recording of the X-ray spectrogram under slow rotation of the specimen, the surface is etched to remove a known thickness of the cold-worked layer, after which a new spectrogram is taken. This is repeated until the variation of the intensity from the Geiger counter becomes negligible.

The advantage of this method is said to be in the higher speed of testing. Using five etching steps, only 1½ hours were needed, compared with 10 hours when determining cold-work thickness by X-ray diffraction photographs.

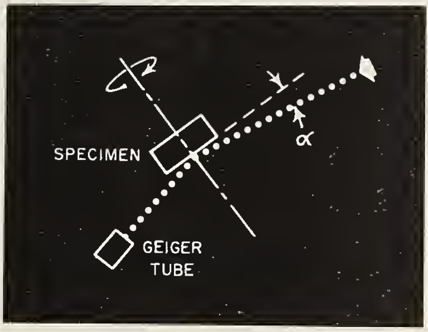


Figure 135. *Measuring cold-work thickness with the X-ray spectrometer.*

7.00. Radioactivity

Nuclear radiations useful for measurement of thickness include alpha rays, beta rays, gamma rays, and neutrons [24, 48, 67, 93, 163, 184, 193]. The different radiations vary in ability to penetrate materials. Many devices are now available to measure the amount of radiation transmitted, absorbed, or reflected. These measurements can be interpreted in terms of the thickness of the material irradiated.

At this writing alpha rays are not known to have been employed in thickness gages. Their limited penetration power restricts their use to only the thinnest of materials. (Their maximum range in air is only about 4 in.; a sheet of paper can stop them.)

Nuclear radiations find extensive use in applications where contact with the material being measured is undesirable; they are especially useful in measuring the thickness of sheet material, either metallic or nonmetallic, in production. Electrostatic charges on the moving sheets do not affect thickness measurements made with gamma radiation or neutrons.

Radioactive materials which are sources of nuclear radiations are either naturally occurring radioactive isotopes such as radium, thorium, uranium, and actinium, or artificially produced radioactive isotopes. The many artificially produced radioactive isotopes, which have recently become available through the extensive operation of nuclear reactors, have given impetus to many industrial measurement techniques based on their use.

Selection of Radioactive Material [48, 86, 152, 182, 193]. The choice of a radioactive source for a particular application is based on its half life and the type and energy of the emitted radiation. Half life is defined as the time required for the activity of the source to fall from an initial value to half that value. It is desirable that a radioactive source have a sufficiently long half life so that frequent recalibration of the instrument will not be necessary. On the other hand, long half life means a lower particle emission rate and consequently slower measurements.

Correction for emission loss is made in some modern industrial instruments by periodic standardization with a sample of known thickness. Other instruments avoid this by using a split beam of radiation and passing one part through air or a calibrated sample, the other through the material under test and comparing outputs.

Of the naturally occurring radioactive elements useful as sources of radiation for thickness measurement, radium has the longest half life, 1,600 years. This means that only 1 percent of its atoms will decay in 20 years. Of the artificially produced isotopes only carbon-14 has a comparable half life, actually greater, of about 6,000 years. For industrial purposes, cobalt-60 is most widely used as a source of gamma rays. The emission of cobalt-60 corresponds very closely to the effective energy of a 2,000-kv X-ray machine. This isotope has a half life of 5.2 years and a specific activity of approximately 20 curies/cm^3, 10 times that of the usual radium sources. As a result, the dimensions of a cobalt-60 source can be very small, thus giving very clear radiographic pictures. The cost is also lower than that of radium.

The type of radiation and its energy determine the nature of the reaction with matter. Alpha particles, being ionized helium atoms, consist of two protons and two neutrons. They have a positive charge equal numerically to twice the change of a beta particle (high speed electron) and a mass 7,400 times that of a beta particle. Because of their relatively great mass and charge, alphas have very low powers of penetration.

The depth to which either an alpha or beta particle will penetrate a substance depends not only on the mass, charge, and energy of the incident particle, but also on the density of the medium. For a given path length, a medium's stopping power is given by the mass per unit area presented to the incident beam. As the incident particles pass through a medium, they collide and interact with its atoms causing pairs of ions to form. At each such ionization the incident particle loses energy. If the density and thickness of the medium are great enough, the particle will lose all of its energy and come to a stop.

Because of their lack of charge, gamma rays and neutrons do not interact with matter in the same way as do alpha and beta particles. Gamma rays are high-energy photons akin to X-rays but of shorter wavelength. In matter, they lose energy by producing secondary beta particles. They do this in any of three ways: (1) The photoelectric effect, where the gamma photon completely transfers its energy to a single existing electron which is then ejected. (2) The Compton effect, which is the result of an elastic collision. Part of the photon's energy is lost to an existing electron, and the photon of reduced energy and frequency bounces off at an angle, much like a particle. (3) Pair formation where the energy of the gamma photon must be greater than about 1 million electron volts (1 Mev) in order to penetrate the cloud of electrons surrounding the nucleus. In the field of the nucleus it loses all of its energy in the production of a "pair," one positive and one negative electron.

Neutrons react only with the nuclei of atoms. They effect their energy transfer either by elastic collision or by absorption. The result of an elastic collision is direct transferal of energy. The result of neutron absorption is either (a) the emission of high energy alpha particles, (b) fission, (c) the emission of beta or gamma rays, or (d) some combination of a, b, and c.

For a given application, greatest sensitivity is attained when the range of the radiation most nearly approximates the thickness of the material to be measured. For example, if a steel beam 4 in. thick were to be measured, alpha and beta radiation would be useless since ¼ in. of steel stops all such radiation. Gamma rays, on the other hand, will penetrate as much as 12 in. of steel. A high energy gamma ray of 1.2 Mev is reduced to only one-sixteenth of its original intensity by 4 in. of steel whereas a low-energy gamma ray, 0.3 Mev, is reduced to one-two-hundred-fiftieth by the same thickness. The latter would be preferable in this case.

Unlike the other types of radiative absorption, there is no simple relationship between neutron absorption and the density of the medium. Neutrons are absorbed in a selective fashion, depending not only on the density of the absorber, but also on its composition. What may otherwise be a drawback proves useful in determining relative proportions in a mixture of substances. In some cases, irradiation with neutrons causes the elements in the absorber to develop reaction products by which their relative proportions can be determined. Thus, if the absorber consists of a coating and a base, it may be possible to determine the proportion of coating to base and hence the coating thickness.

Instrument Types. Thickness-measuring instruments are of three types, transmission, reflection, or absorption-activation, according to specific needs. Transmission instruments are, on the whole, the simplest and most common type. The source and detector are on opposite sides of the material to be measured. The attenuation of the detected rays is a direct indication of the thickness of the measured material.

A reflection instrument has the source and detector on the same side and measures the radiation reflected back through the material. It is inherently a less sensitive instrument than the transmission gage due to difficulties in shielding the detector from the direct rays from the source, but is invaluable in the measurement of materials accessible from one side only, such as closed tanks and pipes or paper or rubber on the roll during calendering. A shield is used in these gages to prevent the detector from "seeing" the direct rays from the source. This is a simple matter with beta gages, but the gamma ray's greater penetration requires very heavy shielding.

Absorption-activation instruments make use of the behavior of neutrons. The sample is bombarded, then measured for induced radioactivity as previously described. The nature and intensity of the resulting radiation is a good indication of the kinds and amounts of material involved.

Radiation Detectors [22, 24, 93, 153, 171, 182, 186]. The detector chosen for any measuring instrument employing radiation is as vital to the success of the instrument as the source and method used. Three types of radiation detectors are commonly used in industrial gages. They are the scintillation counter, the Geiger-Mueller counter, and the ionization chamber. Photographic emulsions are also employed to a much lesser extent.

The first type, the scintillation counter, usually consists of a phosphor and a photomultiplier combination in conjunction with a counting circuit. The particles to be detected strike the phosphor and expend their energy to produce photons. These are, in turn, detected by the photomultiplier and counted.

The choice of phosphor (organic, inorganic) and its form (shape, thickness, etc.) depend on the particle to be detected. The short-range alpha particle, for example, requires only a thin layer of material for energy absorption. Beta particles require thicker layers. Large blocks of phosphor of high stopping power may be used for gamma rays.

A photomultiplier tube consists of a photosensitive surface, the photocathode, a number of dynodes, and an anode. Photons, which are small bundles of light energy, strike the photocathode, causing electrons to be emitted. These electrons are directed toward the dynodes where they cause further emission. The process is repeated many times. Each time the electrons strike a new surface, multiplication takes place, i.e., each electron causes two or more electrons to be emitted. After striking a series of dynodes, the final stream of electrons is collected by the anode. The output current from the anode is, for a given photomultiplier, an indication of the photon input.

The photomultiplier varies according to prospective source and use. The variants in this case are the photocathode, which determines the efficiency of light collection from an extended source; the signal/noise ratio, which determines the particle energies to be detected; and the multiplication factor, which determines the amount of subsequent amplification necessary.

The scintillation counter is noted for its high sensitivity (ability to detect very low energy radiations) and counting efficiency (ratio of the number of ions counted to the total number produced). It is about 50 times more sensitive to gamma radiations than ion chamber instruments and is capable of speeds approximately 400 times as great as the Geiger-Mueller counter. It also has the advantage of not suffering from the limited lifetimes due to gas dissociation of ion chamber instruments. The chief disadvantage of the scintillation counter is its need for a highly stable power supply for the photomultiplier tube. The scintillation counter is most commonly used in rapid scanning devices or for picking up low radiation fields such as those found in some reflection-type gages.

The other two main types of radiation detectors, known generally as ion chambers, are essentially two electrodes in the presence of a gas. Should the gas be ionized by radiations when the electrodes are uncharged, most of the ions will recombine to form neutral atoms and very few will strike the electrodes. If a potential difference is introduced, the electrons will be accelerated in the direction of the anode, the positive ions toward the cathode. As the potential difference is increased, the number of ions collected per unit time will increase until they are being collected at a maximum rate. This potential difference is called the saturation voltage.

The Geiger-Mueller (G-M) tube is a special form of ion chamber in which the applied voltage is higher than saturation voltage, and accelerates the electrons to such an extent that they cause further ionization of the gas molecules they strike. These ions in turn ionize other molecules, etc. The result is an avalanche effect and is called gas amplification. This multiplication of the initial ions causes a discharge along the length of the anode.

The G-M tube has three important properties. They are: (1) The output pulse at a given applied voltage is constant in amplitude and independent of primary ionization, i.e., an alpha and a beta particle of any energy would give a pulse of the same amplitude. (2) The output pulse is sufficiently large to be shown with little or no amplification. (3) The sensitivity is such that a count is obtained when a single ion is produced in the chamber.

The ionization chamber is a form of ion chamber operated at saturation voltage. It is essentially a central collecting electrode encased in a cylinder which acts as the second electrode. The kind of gas and amount of pressure used in the cylinder are determined by the particle to be detected. A hydrogen-filled chamber, for example, will be sensitive to fast neutrons, a boron trifluoride-filled chamber, to slow neutrons. Other gases are sensitive in varying degrees to different forms of radiation.

For saturation conditions it is necessary to have as high an electric field as possible. Thus the electrodes should be closely spaced to avoid the need for high voltages and the subsequent strain on the insulation. On the other hand, sensitivity is increased by allowing for a large gas volume around the collecting electrode in which the particles may dissipate much of their energy. This requires that the electrodes be widely spaced. In some instances, high-pressure ionization chambers as well as some liquid and solid chambers have been found to be effective. Guard rings are often used to avoid fringing fields and to help in defining the sensitive volume.

If alpha and beta particles are to be measured, their lower penetrating power requires that a window be provided in the ionization chamber.

The properties of the ionization chamber are: (1) The size of the output current varies with a high degree of linearity as the energy of the incoming radiation. (2) Because the gas amplification is unity, the signal usually requires considerable amplification before it is useful. (3) The recovery time is negligible compared with that of a G-M tube, hence much higher activity can be successfully recorded. (4) The design of the ionization chamber is varied according to the particle type to be measured and the sensitivity desired.

Because of its adaptability and sensitivity, the ionization chamber is used in most modern radiation thickness gages.

Photographic emulsions are made developable by the passage of charged particles. The density of the image varies with the intensity of incident radiation and therefore the thickness of the object.[4]

Radiation Hazards [163]. Should one of the radiation methods of thickness measurement be adopted, care should be taken to protect the workers from the radiation. The shielding of any instrument should be checked with the manufacturer and, in cases where a certain amount of exposure is unavoidable, badges or personal counters should be worn by the workers involved and periodically checked.

The following isotopes have been used for thickness measurement; data from [48, 193]:

Bismuth, Bi–210	Half life, 5.0 days; beta radiation, 1.17 Mev; gamma radiation, none (to study the deposition of thin films of bismuth).
Carbon, C–14	Half life, 5,740 years; beta radiation, 0.154 Mev; gamma radiation, none (measuring thickness of plastic films).
Cerium, Ce–144	Half life, 290 days; beta radiation, 3.0 Mev; gamma radiation, 0.085 Mev (thin sheets of intermediate grade steel).
Cesium, Cs–137	Half life, 33 years; low-energy beta rays (for gaging light materials).
Cobalt, Co–60	Half life, 5.2 years; beta radiation, 0.31 Mev; gamma radiation, 1.17 and 1.33 Mev (measuring thickness of thick portions of metal; equivalent to 2,000-kv X-rays).
Gold, Au–198	Half life, 2.69 days; beta radiation, 0.97 Mev; gamma radiation 0.411 Mev (measuring thickness of films deposited by high temperature vaporization of gold).
Gold, Au–199	Properties similar to Au–198.
Iodine, I–131	Half life, 8.0 days; beta radiation, 0.60 Mev; plus gamma radiation (measuring rubber films of one micron thickness).
Iridium, Ir–192	Half life, 75 days; gamma radiation, 0.35 Mev (plate, pipe, and tank wall thickness).
Phosphorus, P–32	Half life, 14.3 days; beta radiation, 1.712 Mev; gamma radiation, none (measuring film thickness of printing ink).
Platinum, Pt–197	Half life, 18 days; beta radiation, 0.65 Mev; gamma radiation, none (measuring thickness of platinum plating on ceramic ware).
Radium, Ra–226	Half life, 1,600 years; gamma radiation, 0.8 Mev (pipe wall thickness).
Ruthenium, Ru–106	Half life, 1.0 years; beta radiation 0.041 Mev; gamma radiation, none.
Strontium, Sr–90	Half life, 25 years; beta radiation, 0.537 Mev; gamma radiation, none (for a number of thickness gages).
Thallium, Tl–204	Half life, 2.7 years; beta radiation, 0.8 Mev; gamma radiation, none (for thickness gages in general).
Yttrium, Y–90	Half life, 62 hours; beta radiation, 2.16 Mev; gamma radiation, none (decay product of strontium–90).
Yttrium, Y–91	Half life, 57 days; beta radiation, 1.537 Mev; gamma radiation, none (for thickness gages in general).

7.1. Beta-Ray Absorption [51, 56, 57, 92, 119, 132, 182, 189].

7.11. *Tracerlab Gage* [182] **(figs. 136, 137).** Radioactive strontium-90, with a half life of 25 years, is enclosed with proper safety devices in a hermetically sealed capsule in a cast-aluminum mount, at the end of a C-frame with a 19.25-in. throat and an opening of 2 in. between source and ionization chamber. The latter, with the preamplifier, is located above the material. The indicator, max 20 μa, is so set that normal thickness appears at the center of the scale with plus-minus indication of thickness, weight per unit area, or percent deviation from unit weight. The possible ranges of weight and thickness with this meter run from 0.1 to 2,000 mg/cm^2, i.e., from 0.015 mil in aluminum to 100 mils in steel. Standard maximum ranges are: Paper,

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[4] For the most recent developments in the use of radiation, see Nucleonics 13, 76, 77, 82-88 (1955).

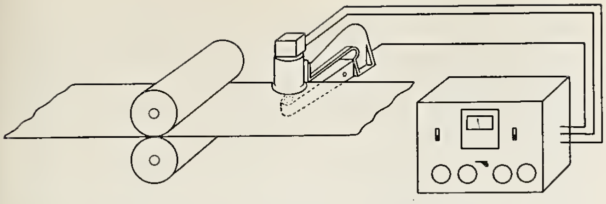

FIGURE 136. *Typical application of absorption gage.*

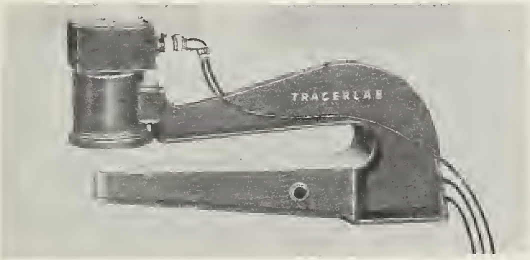

FIGURE 137. *"Tracerlab" absorption gage.*

600 mg/cm^2; steel, 30 mils; aluminum, 90 mils; plastics, 200 mils; rubber, 250 mils. The accuracy is given as ±2 percent; in special cases ±0.5 percent is obtainable. For moving sheets measurements have been made at 3,000 fpm, which is about 30 mph. Generally it is desirable to get the average thickness of the sheet by adjusting the time-constant of the indicating circuits by electrical means.

Tracerlab has also developed a beta-ray thickness meter to measure the wall thickness (or eccentricity) of vertically mounted tubes of small or large diameter, beginning with 0.1-in. inner diameter. A source of strontium-90 is mounted inside at the tip of a long rod. Two detector units (ionization chambers) are mounted 180° apart near the source, which is held fixed inside the tubing while the tubing is moved past the source. Then the tubing is rotated 90° and returned to its original position. The wall thickness is recorded with two pens on a recorder. The response time of the gaging units can be made as short as 0.1 sec, and wall thicknesses up to 30 mils of steel or 80 mils of aluminum can be measured. Tubings of greater wall thickness can be measured with gamma radiation. The average tube speed is about 30 in./min. With higher testing speed the averaging of peaks and depressions would be more pronounced.

Manufacturer: Tracerlab, Inc., Boston, Mass.

7.12. *"Accuray" Gage* **[92, 119].** The radiating source, strontium-90, and the operating principle are the same as in 7.11. The standardization is automatic, compensating for decay of source, change of characteristics of electronic components, accumulation of dirt on the housings, or changes in the density of the air path between source and receiver because of variation in temperature, pressure, or humidity. This gage is mainly used in metal, rubber, textile, and plastics industries. Four throat openings of the mount are available: 24, 36, 48, 60 in.; the position of the source is adjustable across the sheet.

A special design has been developed to measure the thickness of abrasive-coated sheets running at 350 fpm. Five beta-ray gages are used for this application, each one feeding a strip chart recorder: (1) weight of the backing material, (2) weight of the backing material plus adhesive, (3) weight of the backing material plus adhesive plus abrasive after oven treatment (curing), (4) total weight after partial cure, and (5) final weight including final adhesive.

Manufacturer: Industrial Nucleonics Corp., Columbus, Ohio.

7.13. *GE Gage* **[56, 57] (fig. 138).** In this gage a beam of beta rays (emitted by 2.5 millicuries of ruthenium-106 or 10 millicuries of strontium-90) is chopped 90 times per second by a motor-driven rotating disk before it passes through the material. An ionization chamber receives the energy of the beam and produces a 90-cps signal which is compared with a 90-cps reference signal from a small generator on the same shaft as the chopper disk. Any difference between the beta-ray signal and the reference signal indicates a deviation of the thickness from the standard value. To adjust the nominal thickness reading, the reference signal is adjustable by a voltage divider. The applications of this gage are the same as for others of the same principle. Under normal conditions a recalibration is recommended every 4 hours. The normal time constant of these gages is 1.5 sec, but by changing one resistor in the control cabinet, the minimum may be made as low as 0.3 sec. Ranges are 5 to 150 oz/yd^2 with a strontium source and 50 to 300 oz/yd^2 with a ruthenium source. The accuracy is given as ±1 percent with strontium, ±2 percent with ruthenium.

Manufacturer: General Electric Co., Schenectady, N. Y.

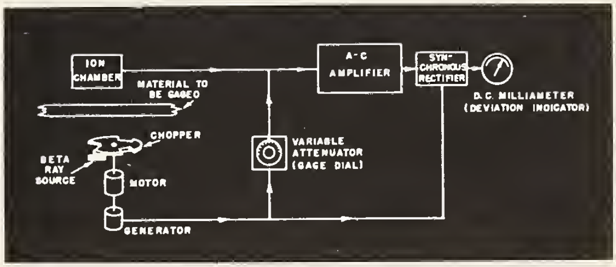

FIGURE 138. *Block diagram of beta-ray thickness gage, GE.*

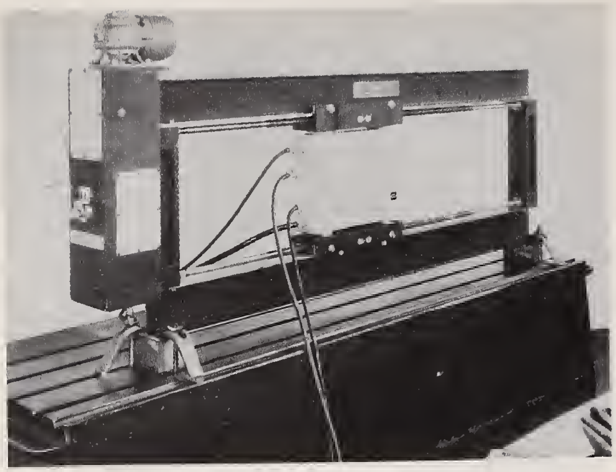

FIGURE 139. *Scanning beta-ray gage, Pratt & Whitney.*

7.14. ***Pratt & Whitney Gage*** **(fig. 139).** This company manufactures two designs of beta-ray gages, one in the usual arrangement of a deep-throated narrow C-frame (like fig. 137), and a special design of a scanning gage as shown in figure 139. In the latter, there are two boxes, one containing the radiating source, strontium-90, and the other the ionization chamber and preamplifier. These are oscillated automatically at the rate of 20 in./min across the width of the material, up to 54 in. One of the applications of this gage is the measurement of the entire thickness of tinplated sheets. The output can be used in the usual way to feed an indicator, a recorder, or alarm or control signals. The thickness (weight) range is approximately 2 to 200 oz/yd^2.

Manufacturer: Pratt & Whitney, Hartford, Conn.

7.15. ***"Betameter"*** **[132].** In this beta-ray gage, errors caused by the decay of the radiation source are eliminated by using a second source of radiation and a second ionization detector. The second chamber is mounted in a box attached to one arm of the frame, and is known as the balance chamber. It is also used to adjust the instrument to any weight-range of the material under test. The calibration operation is the following: When the instrument is set to "operate," the signals from the two chambers are fed to the input. They are of opposite polarity, and by adjustment of the balance controls they can be made of equal magnitude. Then, with the material in the gap and the balance chamber correctly adjusted, there will again be zero signal on the input, and the meter and recorder will remain in the center of their scales. Changes in weight of the material in the gap will cause a signal and a deviation of the pointer from the scale center. As the two sources are similar, they both decay at the same rate, which gives equal signal changes in the two chambers, preventing any error in standard weight due to source decay.

As a source, 20 millicuries of either strontium-90 or thallium-204 are used. The weight ranges of this instrument are:

SR–90	Tl–204
oz/yd^2	*oz/yd^2*
0 to 60	0 to 12
50 to 120	10 to 24
110 to 190	22 to 38

The time constant is 10 sec. The influence of a 10 deg F change in temperature is 0.025 oz/yd^2, and the influence of atmospheric pressure is 0.06 oz/yd^2 per inch Hg.

Manufacturer: Isotope Products, Ltd., Oakville, Ont.

7.16. ***"EKCO" Gage*** **[155, 197].** There are two different designs of this instrument. One has a single channel, comparing the output of the detecting head with an adjustable voltage derived from a stable d-c source. In the other design there are two radioactive sources and two detecting heads connected in opposition in a bridge circuit. One set is applied to a sample of known constant absorption, the other to the material under test. The indicator is a meter with zero in the center. For this instrument the ionization current is measured with a vibrating capacitor electrometer [155, 197] across a high resistance of 10^{12} ohms. The oscillation frequency of the capacitor is 550 cps. An a-c voltage of the same frequency, representing the unbalance, is generated, amplified, and rectified for indication on a d-c instrument with a scale length of 6 in.

Radiation sources are either strontium-90 or thallium-204. The ranges of measurement are from 5.8 to 160 oz/yd^2 for strontium, and from 0.29 to 43 oz/yd^2 for thallium. The accuracy is given as ±1 percent when using the instrument for time constants of sufficient length, adjustable from 0.25 to 60 sec.

Manufacturer: E. K. Cole, Ltd., London. Representative for United States: American Tradair Corp., New York, N. Y.

7.17. *Goodyear Corp. Film Gage* [105]. This gage, developed by the Goodyear Research Laboratories, uses carbon-14 as a source of beta radiation, which presents no shielding problem on account of its softness. It has a half life of about 5,700 years. Measurement is made during production, on plastic films with a weight of only 20 mg/cm^2 (5.8 oz/yd^2). For material with a specific gravity of 1.0 (like Pliofilm and vinyl films) this corresponds to a thickness of 0.2 mm (8 mils). Such a film thickness is gaged to an accuracy of ±1 percent.

7.2. Beta-Ray Backscattering [59] (figs. 140, 141a, b, 142, 143, 144). To measure the thickness of sheets with the foregoing absorption methods, the sample has to be accessible from both sides and the measurement of coating thickness is not practicable. To measure from one side only, a method using beta-radiation backscattering has been developed by Tracerlab.

In this case (fig. 140), the radiation source is located in the same instrument head as the radiation detector, but it is outside the window and shielded in such a way that radiation emitted from it cannot directly reach the detector. When a layer of the material under test is placed in or passed through the measuring position, the radiation detector (here an ionization chamber) is actuated by the beta rays diffusely reflected from the material, and the resulting chamber current indicates the thickness. The window is thin, to permit the entrance of beta particles. The ability of a material to backscatter beta rays is a function of the atomic number. Increasing thickness of the material produces lessening increments of detector response until an asymptotic value of chamber current is reached. Figure 141a is a typical curve obtained when the maximum beta-ray energy can no longer penetrate to the far surface of the material, and still return by scattering to the chamber. The thickness at which this saturation occurs is frequently referred to as "infinite thickness" and depends on the maximum beta-ray energy emitted by the source. The saturation value of detector response is a function of the scattering properties of the material under test.

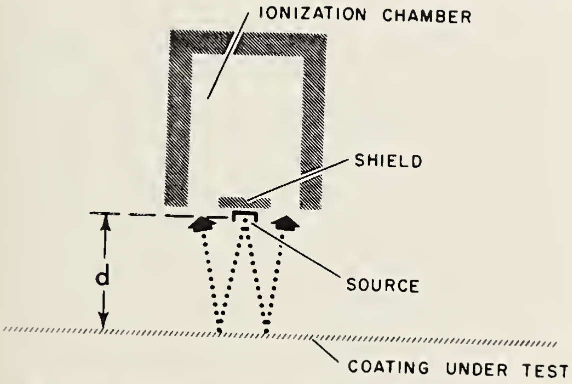

FIGURE 140. *Source and chamber mounting.*

Thickness measurement through backscattering of beta rays.

If now a layer of another material of different atomic number is present on the scattering surface of the base material, the detector response decreases or increases accordingly, as the change is to lower or higher atomic number. Figure 141b shows an increase, indicating a change to a higher atomic number. The chamber current continues to increase with additional thickness of the coating material until a new saturation value is reached, depending on the atomic number of the coating. To make useful measurements of the thickness of a coating, the thickness of the base material has to be "infinite" so that its variation in weight per unit area does not affect the readings, while the thickness of the coating has to be such that it lies in the initial approximately linear region of the characteristic curve. This requires the proper selection of isotopes, and of course it is necessary that the atomic number of coating and base be sufficiently far apart.

In figure 140 the distance *d* of the detector from the surface of the material under test is very important. For distance zero, no reflected beta particles can enter the chamber. As the distance increases, more and more radiation enters until a maximum is reached (at a distance of 400 mils for the design, fig. 142). For larger distances the radiation falls again. The curve is a function only of design; it is independent of the material under test and of the

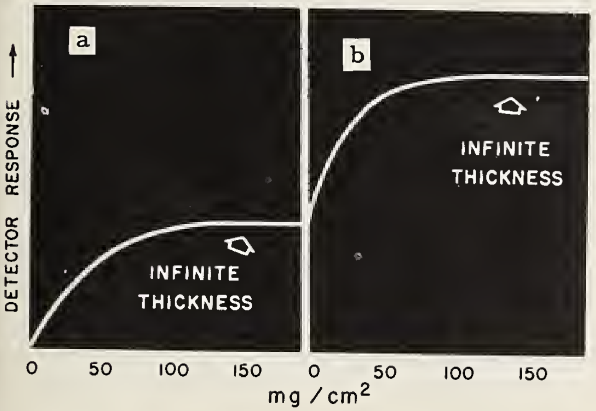

FIGURE 141. *Backscattering absorption curves for two types of material, each absorber of higher atomic number than the backing material.*

Thickness measurement through backscattering of beta rays.

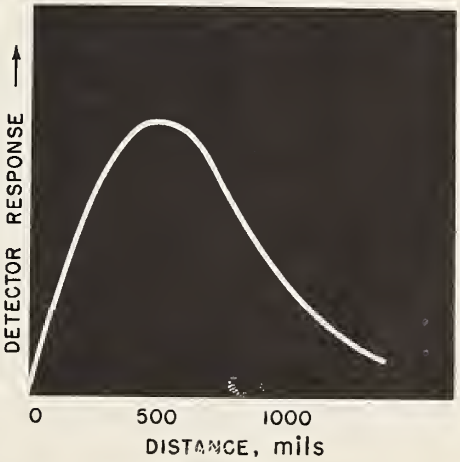

FIGURE 142.

Thickness measurement through backscattering of beta rays.

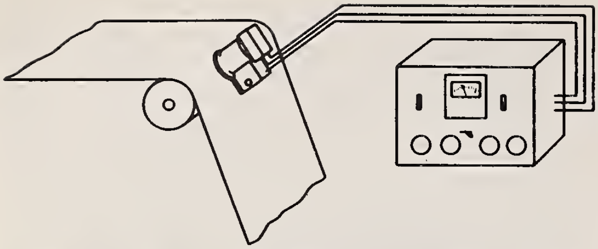

FIGURE 143. *Typical application of backscatter gage.*

Thickness measurement through backscattering of beta rays.

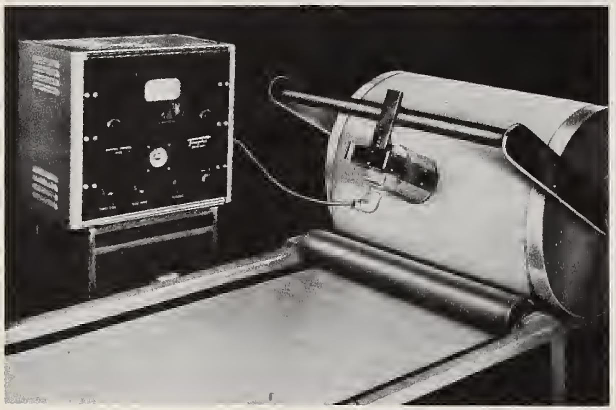

FIGURE 144. *Backscatter beta gage measuring the thickness of rubber film on demonstration calender roll.*

isotopes used. A typical application of the backscatter gage is given in figure 143. Figure 144 shows an installation to measure the thickness of rubber film on a calender roll.

The reading error for these gages has been found practically to be ±0.3 mg/cm^2, divided by the difference of atomic number units, or ±1 percent of full-scale meter reading. For a difference of 30 between the atomic numbers (tin or steel), measurements can thus be made to ±0.01 mg/cm^2.

7.3. Neutron Bombardment, Measurement of Beta-Ray Emission [212]. This method has been developed by Armour Research Foundation to replace destructive methods of measuring silver coatings about 1 mil thick on the internal surface of 50-mil brass (90 Cu, 10 Zn) waveguides. The entire waveguide is bombarded for about 140 sec with neutrons emitted by a 200-millicurie Ra-Be fast-neutron source in a cylindrical steel water tank. After this the object is immediately brought to the counting station with a special handling tool. Beta rays are emitted by the base metal as well as by the silver coating; however, the nuclear cross sections, half lives, and beta-ray energies of the individual elements involved are such that the resulting emission is largely due to the silver coating. Further, in the range of interest (0.1 to 1 mil) the net counting rate is proportional to the amount of silver on the surface under examination. The total time for one thickness measurement over an area of 1 cm^2 is about 5 minutes, and the result is accurate to better than ±0.01 mil.

7.4. Gamma-Ray Absorption and Backscattering [12, 13] (figs. 145, 146, 147, 148). The main application of gamma rays, which are far more penetrating than beta rays or X-rays, in thickness measurement, is in the measurement of thickness of heavy steel objects. Where X-ray equipment using 1,000 kv or more would be needed to penetrate 8 in. of steel, 200 mg of radium furnishes sufficient gamma-radiation. Thus, the gamma-ray instrument is not only smaller (more mobile), but is also less expensive.

To measure the thickness of very heavy steel plates or coatings the same photographic methods for measuring the absorption can be used as with X-rays. The radium pill corresponds to the focus of the X-ray tube. The amount of radium needed depends on the thickness of the object.

The *Penetron* (fig. 145) is used for measuring the thickness of the walls of pipes, containers, or vessels, from one side only and is based on the backscattering of gamma rays. The source of gamma radiation is 1 mg of radium in the form of a commercially available salt, surrounded with a shield containing a window, which directs the beam of gamma rays as desired. The shaded layers 1-2-3 represent adjacent layers of a homogeneous wall. Gamma rays emerge from the source S, impinge on the wall, and penetrate into it. Rays emerging on the other side serve no useful purpose, as it is the backscattered portion of the radiation which is utilized for measuring wall thickness from one side. The intensity of this backscattered radiation is a function of the wall thickness. To prevent radiation from falling directly on the detector D, the block SH is used as a shield. Figure 146 shows the calibration of the instrument for a flat iron plate. Up to 0.2 in. thick, the deflection of the gamma meter is approximately linear with the thickness.

Another device using reflected gamma rays for the indication of the thickness of metal sheets is described in (pat. 6). Radioactive cobalt is positioned in a body of lead a predetermined distance from the surface of the material under test, so that the rays are directed towards the face of the sheet. A detector, which is shielded from the direct radiation from the cobalt source, is positioned in the same block of lead. It receives only reflected radiation from the material.

Special heads are used in the measurement of tubes from both the outside and the inside. For measuring straight tubes from the outside, the

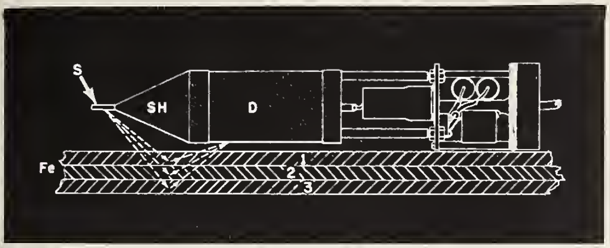

FIGURE 145. *Diagramatic illustration of the "Penetron."*

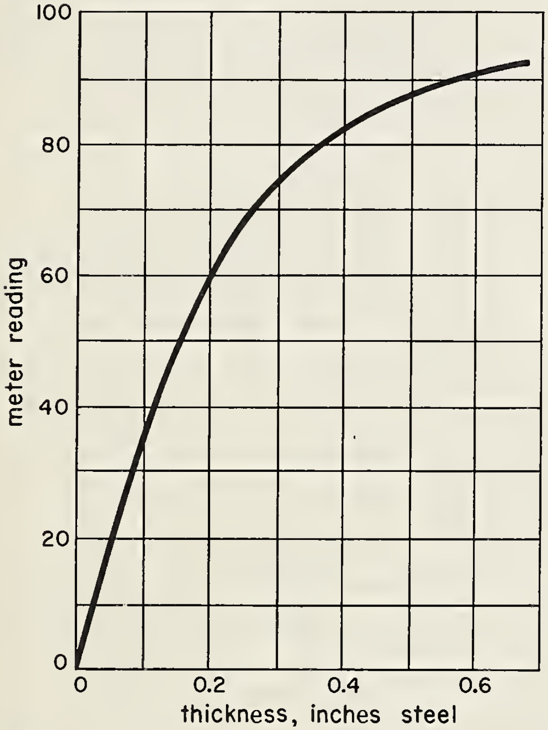

FIGURE 146. *Calibration curve of the "Penetron" for a flat iron plate or a tube measured from the outside.*

standard head, a steel tube 2.5 in. in diameter and 13 in. long is placed in a holder with permanent magnets, which serve both to support the head and to hold it onto the surface of the metal object. To measure the inside of tubes, a pneumatic holder is used.

The tangential head (fig. 147) is a special auxiliary device which was developed to measure boiler tubes. With this instrument, tubes up to 12.75 in. in diameter with a wall thickness up to 2.5 in. can be measured. The calibration curve of this instrument (fig. 148) is different from figure 146. The meter gives maximum reading with zero thickness of the tube under test. The accuracy of these meters is given as ±3 percent.

Manufacturers: (a) United Engineers, Inc., Tulsa, Okla., with the trade name "Penetron"; (b) Instruments, Inc., Tulsa, Okla., with the trade name "Rad-O-Thik."

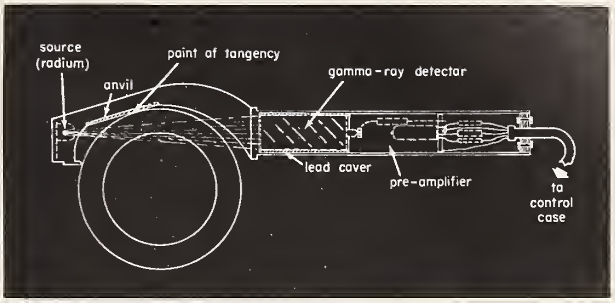

FIGURE 147. *Principle of measurement, "Penetron" tangential head.*

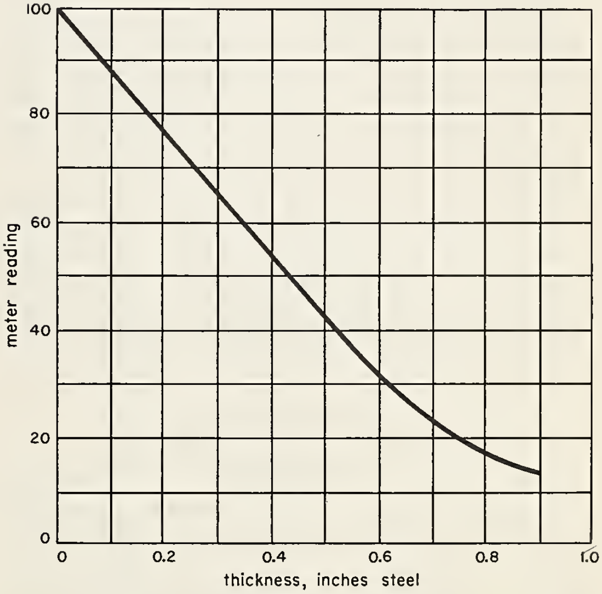

FIGURE 148. *Calibration curve for the tangential head of the "Penetron."*

7.5. Reduction of Thickness By Wear, Autoradiography [121, 162] (pat. 9). Some difficult problems in measuring the removal of material by wear have been solved by the use of radioactive tracers. Typical examples are: Piston rings, bearings, gears, rubber tires, cutting tools, polishes, automotive finishes, floor waxes.

To measure the wear of piston rings or bearings, the metal is first exposed to neutrons in a reactor and the radioactivity is measured before the part is placed in a testing engine. The quantity of metal worn off is determined by measuring the radioactivity in the lubricating oil.

Actual transfer of the radioactive metal can be detected by autoradiographing the part that has been in contact with the activated component. Tracerlab, Inc., and the Massachusetts Institute of Technology have worked on this method.

8.00. Thickness Meters For The Blind

To make it possible to employ blind people in production, a number of thickness meters, especially of the mechanical type, have been adapted for nonvisual use. Devices such as dial micrometers and other pointer instruments and watches have been modified to be read by touch. The standard Starrett micrometer, for example, has been modified for fingernail reading. All graduations on the sleeve have been deepened; the barrel graduations have been deepened and varigated raised indications attached. The operator can quickly determine in which 25-mil division the measurement falls and, according to instruction, can determine the final measurement within ¼ mil.

Auditory devices for thickness indication vary either the intensity or the frequency (pitch) of sound. The hearing ability of the blind operator being more highly developed than in others, these devices often provide the same speed of operation as the conventional devices.

The catalog "Aids for the Blind," published by the American Foundation for the Blind, New York 11, N. Y., lists many of the adaptations developed by manufacturers for thickness measurement. The Foundation will assist in duplicating earlier designs of such meters or in developing new ones.

9.00. ASTM Acceptance Tests

Thickness measurements for acceptance tests on many different objects have been standardized by the American Society for Testing Materials; the methods are listed by number below. In all these specifications, which can be found in the ASTM Standard or its periodical revision, thickness is only one of a number of properties of the objects under test. The thickness meter in most cases is a mechanical micrometer, but the preparation of the sample is different.

A. Ferrous Materials

90. Weight of zinc coatings.
166. Electrodeposited coatings of Ni and Cr.
219. Local thickness of electrodeposited coatings.
239. Uniformity of Zn coating.
267. Lead alloy coating.
309. Weight and composition of coatings, spot test.
361. Zn coating roofing sheets.
363. Zn coating ground wire strand.

B. Nonferrous Metals

33. Tinned electric copper wire.
101. Lead-coated copper sheets.
110. Dielectric method for anodically coated aluminum.
128. Sleeves and tubing for radio tube cathodes.
136. Sealing of anodically coated aluminum.
137. Weight of coating on anodically coated aluminum.
141. Electrodeposited coating of Ni and Cr on Cu.
142. Electrodeposited coating of Ni and Cr on Zu.
189. Lead-coated electric copper wire.
200. Lead coat on steel by electrodeposition.
205. Weighing method for fine wires.
219. Testing fine round and flat wire.
244. Thickness of anodic coatings measured with "Filmeter."
246. Hard-drawn electric copper wire.

C. Ceramics, Concrete, etc.

167. Thermal insulating materials.
220. Flat asbestos cement sheets.
221. Corrugated asbestos cement sheets.
222. Roofing shingles.
223. Siding shingles.

D. Miscellaneous Materials

27. Rubber-insulated wire and cable.
39. Woven fabrics.
69. Electric friction tape.
76. Textile testing.
119. Rubber insulating tape.
120. Rubber insulating gloves.
146. Felted and woven fabrics for roofing.
178. Rubber matting, 3,000 v.
202. Paper for electric insulation.
229. Sheets and plates for electric insulation.
295. Varnished cloth and tape for electric insulation.
351. Mica testing.
353. Rubber on wire and cable.
354. Tubular sleeving and braids.
374. Solid electric insulation.
376. Holland cloth.
378. Flat rubber belting.
380. Rubber hose.
395. Vulcanized rubber.
414. Cotton fibers.
418. Pile floor covering.
419. Fineness of wool.
461. Felt.
468. Lime-glass insulators.
527. Bulking thickness of paper.
545. Expansion-joint fillers.
574. Ozone-resistant wire insulation.
578. Glass yarn.
580. Woven glass tape.
634. Laminated sheets, uniformity.
645. Paper and paper products.
652. Mica stampings.
668. Rigid tubes for electric insulation.
733. Compressed asbestos sheet packing.
734. Insulated wires and cables.
751. Rubber-coated fabrics.
754. Heat-resisting rubber-insulated wires and cables.
755. Synthetic rubber-insulated wires and cables.
823. Paint films on test panels.
898. Weight per unit area of adhesive solids.
899. Weight per unit area of liquid adhesives.
902. Varnished glass fabrics and tape.
1000. Pressure-sensitive adhesive tape for electric insulation.
1005. Dry film thickness of paint, etc.
1048. Rubber insulating blankets, 16,000 v.
1049. Rubber insulator hoods, 20,000 v.
1050. Rubber-insulated line hose, 20,000 v.
1051. Rubber insulating sleeves, 10,000 v.
1055. Latex foam rubber.
1056. Sponge and cellular rubber products.
1186. Dry-film thickness of nonmagnetic coatings.
1212. Wet-film thickness of nonmagnetic coatings.
1233. Twine made from bast and leaf fibers.

Literature References

The following items cover a wide variety of methods for thickness measurement. However, completeness cannot be expected, since articles on the subject are scattered over a tremendous number of technical magazines.

Where the method described is not adequately indicated by the title of the article, this information has been added. As far as possible the company affiliation of the author has been given. References are indicated thus [ ] in the text.

In the following list, italicized figures are volume numbers of journals.

[1] H. Abramson (C. E. Johansson Co., Sweden), The Mikrokator amplifying mechanism and its use in measuring lengths and loads, Instrum. Pract. *3*, 397-400 (1949).

[2] E. Q. Adams and L. S. Ickis, Jr. (General Electric Co.), Determining film thickness with the recording spectrophotometer, Gen Elec. Rev. *42*, 540-51 (1939). Transparent coatings on aluminum. Interference method.

[3] Albrecht, R., Elektrische Dickenmesser, Die Messtech. (Halle) *10*, 165-169 (1934). Various methods of thickness measurements using electrical methods and the combination of electric and pneumatic.

[4] Albrecht, R., Die Bestimmung linearer Abmessungen mittels Druckluft, Die Messtech. (Halle) *10*, 81-85 (1934). Early disclosure of pneumatic measurements.

[5] Albrecht, R., Elektrische Laengenmesser, Helios (Leipzig) 38th year, 209-10 (July 1932). Mechanical-electrical-inductive, mechanical-electrical-capacitance, and electric-magnetic reactance methods.

[6] W. F. Aller (Sheffield Corp.), Essentials of air gaging. Amer. Mach. *91*, 69-72 (1947). Describes basic principles of air gages.

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[8] S. Anderson and R. W. Manuel (Crane Research Labs.), An electrolytic chromium plate thickness tester, Trans. Electrochem. Soc. *78*, 373 (1940).

[9] Anon., Three electronic thickness gages for metallic coatings, NBS Tech. News Bul. *38*, 127-132 (Sept. 1954).

[10] Anon., Methods of measuring case depth of steel, SAE Journal *58*, 51-54 (1950). See also SAE Handbook, Methods of measuring case depth.

[11] Anon., Thickness of aluminum oxide coatings, Bell Lab. Record *21*, 278 (1942). Breakdown test.

[12] Anon., "Penetron" measures thickness and density with gamma rays, Electronics *18*, 154 (Aug. 1945), also Electronic Inds. *36*, 101 (1945).

[13] Anon., Measuring wall thickness by gamma rays, Iron Age *156*, No. 9, 36N (1945). "Penetron" gage.

[14] Anon., Sigma electro-pneumatic gage, Instrum. Pract. *2*, 202-203 (1948). Rate of flow is measured by cooling a heated wire and measuring resistance change.

[15] Anon., Measuring to 0.025 mils without pressure, Elec. Mfg. *27*, 80-84 (1941). Describes Carson gage.

[16] Anon., Thickness of tin coatings, Sheet Metal. Inds. *17*, 625-627 (1943). Chemical-mechanical and chemical-visual method. Action of diverse chemicals.

[17] Anon., The Cornelius Scalimit Dimensional Comparator, Instrum. Pract. *4*, 148 (1950). Mechanical-electric-capacitive meter.

[18] ASTM Standard A219, Local thickness of electrodeposited coatings. Describes microscopic test, spot test, dropping test, magnetic method.

[19] ASTM Standard B110, Dielectric strength of anodically coated aluminum. Method of test for thickness by measuring the dielectric strength.

[20] ASTM Standard D374, Thickness of solid electrical insulation. Covers electric insulation except insulating rubber tape and friction tape. Permissible errors. Procedures: (a) ratchet micrometer, (b) "feel micrometer" without ratchet, (c) dead-weight dial micrometer.

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List of Manufacturers

An attempt was made to effect a complete survey of thickness meters built in the United States. Unfortunately, completeness is next to impossible, as a number of our letters requesting information were not answered, although many manufacturers were extremely cooperative. No attempt has been made to list the many sources of simple thickness meters like slide calipers or screw micrometers.

In many cases only a prototype thickness meter has been built. In clear cases of this sort no "manufacturer" is mentioned. Some devices that are not now manufactured are included because many times an old method is taken up again years later, either for a special problem or with components that had not been originally available.

Aireon Mfg. Co., Burbank, Calif.	Optical micrometer.
American Instrument Co., Silver Spring, Md.	Capacitive thickness meters — *Filmeter*, *Compressometer*, *Magne-Gage*, *Magne-Probe*.
American Tradair Corp., New York, N. Y.	EKCO nucleonic gages.
Ames Co., B. C., Waltham, Mass.	Caliper gages; comparator gages; dial gages, micrometers; dead-weight gages; screw micrometers.
Amthor Testing Instr. Co., Brooklyn, N. Y.	Dead-weight gages; dial micrometers.
Anderson Machine Shop, Inc., Needham Heights 94, Mass.	*Pacific* evenness testers.
Ateliers de Normandie, Paris 8e, France.	*Etamic* pneumatic gages for rolling mills.
Automatic Temperature Control Co., Philadelphia, Pa.	Thickness meters with differential transformers.
Bausch & Lomb Optical Co., Rochester, N. Y.	Optical thickness meters.
James G. Biddle Co., 1316 Arch St., Philadelphia 7, Pa.	Tinsley thickness gage (for metallic coatings).
Boeckler Instrument Co., Tulsa, Okla.	Screw micrometers.
Boonton Radio Corp., Boonton, N. J.	Metal film gauge.
Branson Instrument Co., Stamford, Conn.	*Audigage* (ultrasonic); *Vidigage* (ultrasonic); *Coatingage* (electromagnetic); *Sonigage* (ultrasonic).
Browne & Sharpe Mfg. Co., Providence, R. I.	Comparator gages; dial micrometers; electronic calipers; screw micrometers.
Brush Development Co., Cleveland, Ohio.	Textile uniformity analyzer.
Cleveland Trust Co., Cleveland, Ohio.	Half-millionth microcomparator.
Commercial Research Laboratories, Detroit, Mich.	Cylinder - wall thickness gage.
Decker Aviation Corp., Philadelphia 25, Pa.	Comparator micrometer; ionization transducer.
Dice, J. W. Co., Englewood, N. J.	*Carson* electronic thickness gage; ultrasonic thickness gages.
DoAll Co., Des Plaines, Mich.	Comparator gages, electromagnetic; dial micrometers; *Mauser* vernier calipers, slide calipers; *Tumico* screw micrometers.
Eastman Kodak Co., Rochester, N. Y.	Optical comparators.
Electric Eye & Equipment Co., Danville, Ill.	*Hurletron* gage.
Electronic Control Corp., Detroit, Mich.	*Bathytrol* paint thickness gage.
Federal Products Corp., Providence, R. I.	Calipers; comparator gages; dial gages; *Dimensionaire* pneumatic gages; *Electricator* mechanical-electric gages; electronic gages; recording gage; ring thickness gages; roller gages; screw micrometers.
Fielden Instruments Division, Philadelphia, Pa.	Capacitive thickness gage; evenness recorder for textiles.
Foxboro Co., Foxboro, Mass.	*Verigraph* thickness recorder.
Gardner, Henry A., Inc. Bethesda, Md.	*Elcometer;* "Interchemical" roller gages; penetrating needle gages.
General Electric Co., Schenectady, N. Y.	Beta-ray thickness meters; eddy-current thickness meters; electromagnetic thickness meters; step gage; X-ray thickness meters.
Graydon Smith Prod. Corp., West Concord, Mass.	*Metrisite* thickness gages.
Gustin-Bacon Manufacturing Co., Kansas City, Mo.	*Measurematic* gage.
Haskins Turner Co., Jackson, Mich.	Scale thickness meter for boiler tubes.

O. Hommel Co., 209-213 Fourth Ave., Pittsburgh, Pa.	OHCO miniature layer thickness meter (probably similar to the Elcometer).
Industrial Electronics Inc., Detroit, Mich.	Electromagnetic thickness meters, *Dyna-Myke*.
Industrial Gauges Corp., Engelwood, N. J.	X-ray gages.
Industrial Nucleonics Corp., Columbus, Ohio.	Abrasive coating gages; *Accuray* (beta ray) thickness gages.
Instrument Development Laboratories, Needham Heights, Mass.	*Optimike* for flat surfaces.
Instruments, Inc., Tulsa, Okla.	*Rad-O-Thik* gamma-ray gage.
Isotope Products, Ltd., Oakville, Ont.	*Betameter* beta-ray thickness gage.
Johansson, C. E., Gage Co., Detroit, Mich.	Dial micrometers; *Mikrokator, Minikator* gages; screw micrometers.
Koehler Instrument Co., Jamaica 33, N. Y.	*Pfund* paint film thickness gage.
Kokour Co., Chicago, Ill.	Dropping testers; electronic thickness testers.
Krouse Testing Machine Co., 573 East Eleventh Ave., Columbus 3, Ohio.	Krouse magnifying micrometer (permanent magnet type for plated coatings).
Lea Manufacturing Co., Waterbury 20, Conn.	*Lectromag* (Lipson) thickness gage.
Lufkin Rule Co., Saginaw, Mich.	Calipers; dial micrometers; screw micrometers.
Magnaflux Corp., Chicago 31, Ill.	Ultrasonic thickness gages *(Sonizon)*; electromagnetic thickness gages *(Magnatest)*.
McGlynn Hays Industries, Inc., Belleville 9, N. J.	*Optimike* for internal measuring.
Merz Engineering Co., Indianapolis, Ind.	Electromagnetic comparator gages.
Metron Instrument Co., Denver, Colo.	Electromagnetic comparator gages.
Metzger, F. F., & Son, Philadelphia, Pa.	*Pileometer* thickness gage.
Micrometer Pneumatique, SOLEX, Courbevoie, Seine (France).	Continuous pneumatic micrometers.
Moore Products Co., Philadelphia, Pa.	Pneumatic comparator gages.
North American Philips Co., Mt. Vernon, N. Y.	X-ray coating thickness gage.
Photoconn Research Products, Pasadena, Calif.	*Metroscope* ultrasonic thickness gage.
Platers Research Corp., 59 East Fourth St., New York 3, N. Y.	Pocket Handigage (permanent magnet type for plated coatings).
Poole Instruments, Inc., Dallas, Texas.	
Pratt & Whitney, Inc., Hartford, Conn.	Beta-ray gages; eddy-current foil gages, *Electrolimit* gages; *Magnetic* gages; magnetic *Schuster* gage; millionth comparator gages.
Precision Thermometer & Instrument Co., Philadelphia, Pa.	Calender micrometers, *Princo*.
Radium Elecktrizitäts-gesellschaft m.b.H in Wippenfüth, Germany.	
Record Electrical Co. Ltd., England.	Resistance method for intricate castings.
Rimat Machine Tool Co., Glendale, Calif.	Dial gages.
Salford Electrical Co., Ltd., England.	Eddy-current gage.
Schaevitz Engineering Co., Camden, N. J.	Thickness meters with differential transformer.
Scherr, George, New York, N. Y.	*Projectometer.*
Sheffield Corp., Dayton, Ohio.	*Electrigage; Measuray* X-ray gages; *Precisionair* pneumatic gages; reed gage; *Visual* gage.
Shell Development Co., Emeryville, Calif.	*Probolog* tube thickness meter.
Siemens & Halske	
Siemens New York, Inc., 350 Fifth Ave., New York 1, N. Y. (distrib.)	
Sigma Instrument Co., Letchworth, Hertfordshire, England.	Pneumatic comparators; foil thickness meters.
Sperry Products, Inc., Danbury, Conn.	*Reflectogage* ultrasonic thickness meters.
Standard Electronic Research Corp., New York, N. Y.	*Diamatrol* photoelectric thickness gages; electron micrometer; X-ray thickness gage.
Standard Gage Co., Poughkeepsie, N. Y.	Comparator gages; dial micrometers; *Micronar* indicator.
Starrett, L. S. Co., Athol, Mass.	Calipers; dial micrometers, comparators, indicators; portable gages; sheet gages.
Stevens Arnold, Inc., Boston, Mass.	Electronic micrometer.
Streeter Amet Co., Chicago, Ill.	Dial gages; *Guyer* gages; micrometers.
Swedish Gage Co. of America. See Johannsson Gage Co.	
Tinsley Industrial Instr. Ltd., London NW 10, England	Pencil thickness gage.
Ti-Pi Co., Kansas City, Mo.	Ti-Pi floating-caliper gage.
Tracerlab, Inc., Boston, Mass.	Beta-ray thickness gages; isotopes.
Tubular Micrometer Co., St. James, Minn.	*Tumico* screw micrometers.
Union Tool Co., Orange, Mass.	Calipers; dial gages.
Unit Process Assemblies, 75 East 4th St., New York, N. Y.	*Dermitron.*
United Engineers, Tulsa, Okla.	*Penetron* gamma-ray thickness gages.
Van Keuren Co., Watertown 72, Mass.	Light-wave screw micrometers.
Westinghouse Co., Pittsburgh, Pa.	X-ray thickness gages.
Wilmotte Raymond Co., Washington, D. C.	*Visi-Limit* thickness gages.

WASHINGTON, January 23, 1957.

Index of Gages, Methods, and Applications

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