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A MULTIPURPOSE PHOTOELECTRIC REFLECTOMETER

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ABSTRACT

The multipurpose reflectometer was developed primarily to measure apparent reflectance, specular gloss, and trichromatic coefficients. These measurements are useful in the ceramic, paint, textile, paper, and chemical industries to indicate lightness, gloss, and color of finished articles. In the reflectometer, two light beams from a single source are directed along separate paths to two barrier-layer photocells. Various types of these photocells were studied to find which could be used most advantageously. The reflectometer employs a substitution null method and requires a galvanometer to indicate equality of the currents generated by the two photocells. For each sample tested, there is a photometric adjustment to restore equality of the currents. The amounts of photometric adjustment are measured on the direct-reading scales, one of which is used for apparent reflectance and the other for specular gloss. Because of its high precision, the instrument is well suited for measuring small differences in apparent reflectance, gloss, or color of nearly identical samples. However, for greatest accuracy, it is necessary to correct the scale readings by calibration.

CONTENTS

I. INTRODUCTION

The multipurpose photoelectric reflectometer is the result of an attempt to combine in one instrument means for measuring (1) 45°,0° luminous apparent reflectance relative to a standard, (2) 45°,0° apparent reflectance relative to a standard through filters for either tristimulus colorimetry or abridged spectrophotometry, (3) four of the six listed types of gloss [27],[1] and (4) the transmission of clear liquids and optical filters having plane parallel faces.

The development of the multipurpose reflectometer, its construction, its calibration, and its applications are described in the present paper. Further information on the instrument and its use may be found in a paper by Scofield [53] and in a report by the Institute of Paper Chemistry [33].

The multipurpose reflectometer is one of a series of null-method instruments developed by the author to measure 45°,0° apparent reflectance relative to a standard. The two earlier reflectometers are briefly described herein. The first (fig. 5) was a 0°,45° visual reflectometer using a pattern mirror [25]. The aim in building this model was to make a null-method instrument that was simple, could be constructed from inexpensive and readily obtainable materials, and would take relatively large areas of test surfaces. The Committee on Standardization of Tests of the Porcelain Enamel Institute studied this instrument for possible use to measure the apparent reflectances of porcelain-enamel surfaces. They inquired if an instrument of the same character could be photoelectric rather than visual. In answer to this inquiry, two Photox barrier-layer photocells and a galvanometer were substituted for the eye and pattern mirror of the visual instrument, the result being the Photox 0°,45° reflectometer (fig. 6) [6, 26].

Following the successful development of a reflectance test [49], in which this Photox reflectometer was used, the same Committee of the Porcelain Enamel Institute turned to the development of tests of porcelain enamels for resistance to acids [50] and to surface abrasion [51]. For these tests, an instrument for measuring specular gloss was required. It was suggested that an instrument for measuring both specular gloss and 45°,0° apparent reflectance would be doubly useful. The first objective of the present project was to design an instrument meeting this dual need.

To develop apparatus suitable for certain colorimetric measurements was the second objective. In a paper on photoelectric colorimeters, Gibson [18] pointed out that a number of instruments have been developed during the past few years supposedly to measure "color" by means of an illuminant, three spectral filters—usually red, green, and blue—and some type of barrier-layer photoelectric cell. He showed how filters spectrally suitable for photoelectric tristimulus colorimetry ought to be chosen with respect to photocell and illuminant. It is possible to show that, in addition to filters which are properly chosen with respect to photocell and illuminant, a measuring technique capable of unusually high photometric precision is necessary for photoelectric tristimulus colorimetry if the resulting measurements are to identify the smallest color differences of interest. The present paper considers the problem of obtaining high precision, but the selection of proper filters and use of the data obtained therewith are left for subsequent consideration [29].

[1] Figures in brackets indicate the literature references at the end of this paper.

A third objective was to improve the methods of gloss measurement. In an earlier paper [27], six separate types of gloss were listed, four of which should be subject to photometric measurement. Measurement of specular gloss was required by the Porcelain Enamel Institute; two of the remaining three types, contrast gloss and sheen, have been measured with the multipurpose reflectometer; measurement of absence-of-bloom gloss, the fourth type, has been planned, but not actually tried.

Although not projected in the original plans, a device suitable for measuring the transmission of clear solids and liquids was obtained by making a slight adjustment of the attachment for 75°,−75° specular gloss (sheen). The spectral filters used for reflection measurements are available for transmission measurements also and make possible tristimulus colorimetry and abridged spectrophotometry of transmitting specimens. Inasmuch as many of the so-called colorimetric methods of chemical analysis are simply methods of abridged spectrophotometry, the multipurpose instrument may be used as an analytical instrument for the chemical laboratory.

II. TERMINOLOGY

In this paper, psychophysical terms are used to denote the quantities measured, even though they are properly radiometric because photocells rather than human eyes are the responding mechanisms. Instead of light, radiant energy should properly be spoken of; instead of illumination, irradiation; and so forth [35]. However, the use in the present apparatus of source-filter-photocell combinations which measure properties similar to those detected by the human eye was taken as sufficient justification for using the better known psychophysical terms in the present paper.

The term "apparent reflectance" [43] used in this paper, having come into general use only recently [1, 27, 30, 37, 45], deserves a word of explanation. Surfaces, when illuminated, usually do not appear uniformly bright from all directions. The *reflectance* of a surface is, by definition, the ratio of the total quantity of reflected light to the total quantity of incident light regardless of directions. Apparent reflectance, on the other hand, always refers to some specified condition of view. To connect the terms "reflectance" and "apparent reflectance," the concept of the ideal perfectly diffusing surface which reflects according to Lambert's law and appears uniformly bright from all directions is used. The *apparent reflectance* of a surface for the given directions[2] of illumination and viewing is defined as the reflectance which a perfectly diffusing surface would need to possess in order to appear equally bright under the same conditions. The symbol for apparent reflectance is $A_{\theta i, \theta v}$, where θi and θv are respectively the angles of illuminating and viewing measured from the normal. In the present paper, *luminous* apparent reflectance is inferred when apparent reflectance is spoken of; also, it is assumed that when both illuminating and viewing beams are unidirectional, they lie in a single plane perpendicular to the surface.

Measurements of apparent reflectance are both useful and practical. A person viewing a surface never observes it from all directions simultaneously, but from some single direction. An apparent-reflectance

[2] Multidirectional as well as single directions of illuminating and viewing may be involved in apparent reflectance designations. Thus on page 604, below, reference is made to $A_{diffuse, 0°}$ as well as to $A_{45°, 0°}$.

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value will designate the reflectance which this surface appears to have when viewed from this single direction. Moreover, apparent-reflectance measurements for many conditions, among them 45° illumination and 0° viewing, give results for most opaque surfaces so similar to the true reflectances [43] that they are often used instead. Apparent-reflectance measurements, it should be noted, are more easily made than reflectance measurements, which, for each surface measured, require either many determinations with a goniophotometer and integration to give the final result, or the use of an absolute reflectometer.

Illumination at 45° and normal viewing have been internationally adopted as standard conditions for colorimetry of opaque surfaces [54] because they represent a satisfactory average of the directional conditions under which surface colors are observed in everyday life. Values obtained for the reciprocal conditions, normal illumination and 45° viewing, are by the reciprocity law [43] equivalent to 45°,0° values for the same surfaces.

In the direction of mirror reflection and adjacent directions, the apparent reflectances of surfaces are usually much higher than in other directions. The shininess of surfaces is evidence of this high apparent reflectance.

III. PHOTOCELLS AND ELECTRIC CIRCUIT

Barrier-layer photocells possess three advantages for colorimetric and photometric apparatus: (1) The cells are simple and rugged in construction; (2) they generate an emf directly from the light flux incident upon them, so that no externally applied potentials are required for their operation; and (3) they respond more strongly to energy of the visible spectrum than to other energy. On the other hand, there are a number of recognized disadvantages of the cells. Possible methods of compensating for or of overcoming these disadvantages were made the subject of a study prior to designing the reflectometer. A number of cells of different types were investigated under the operating conditions expected in the proposed instrument.

The circuit which seems to come nearest to eliminating the undesirable types of barrier-layer photocell behavior is a null circuit in which two cells are connected with opposite polarities to the terminals of a galvanometer. The resulting current-balancing circuit has been widely used [3] and was employed by the author in the Photox reflectometer (see fig. 6, below) because of the recommendation given by Wood [59]. When the current-balancing circuit is used, the light source of the instrument may be operated directly from electrical supply lines, rather than from a special constant-voltage supply. Because of its success in the Photox reflectometer, this null circuit was adopted for the multipurpose instrument.

The examination of barrier-layer photocells for possible use in the multipurpose reflectometer was conducted under the operating conditions expected in the new instrument. Photocell current was studied in its relation to the wavelength of illumination, the amount of illumination, the duration of exposure, and the temperature. To study the effects of the first two factors, manufacturers' data describing the cells were examined. To study the effects of duration of exposure

[3] Fourteen instances of the use of this circuit, including the Photox reflectometer, are mentioned by Brice [5].

and of temperature, tests were made on cells of four types. Most of the data on photocells given herein were collected in 1936 and 1937, at the time the multipurpose reflectometer was started. They may not be characteristic of similarly named photocells manufactured at the present time.

The spectral sensitivity of a cell must be known before it can be used with confidence in an instrument to measure either luminous properties or trichromatic coefficients. Figure 1 gives the spectral responses (reported by manufacturers) for three barrier-layer photocells, each plotted approximately to unit maximum, and also the ICI standard luminosity (visibility) curve [19, 36] for comparison. It is

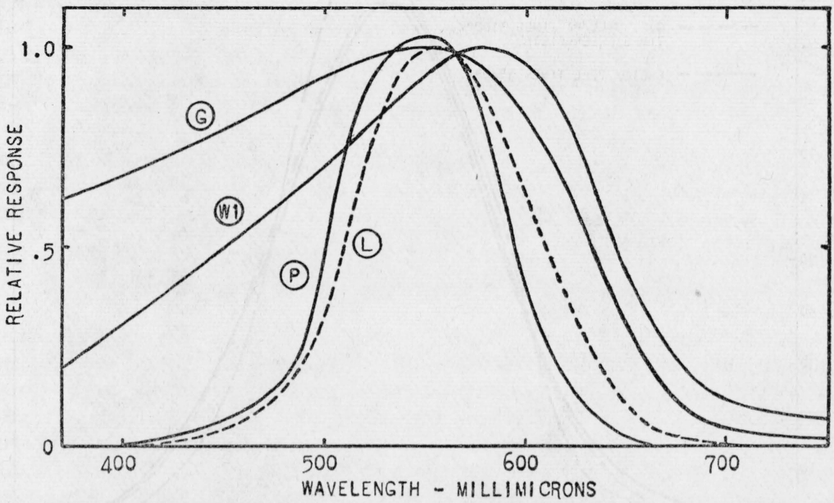

FIGURE 1.—*Spectral-response curves, reported by manufacturers, for three barrier-layer photocells together with ICI luminosity (visibility) function, L.*

G, GE light-sensitive cell; *W1*, Weston Photronic cell, type 1; *P*, Photox cell.

believed that most barrier-layer photocells are characterized by spectral-response curves similar to some one of those shown.

Thus the spectral-response curve published for the Lange photoelectric cell [41, 48] is similar to the Photronic type 1 curve [57], whereas the published curves for the Photronic type 2 cell [57] and the Electrocell [4] are similar to that of the GE cell [16, 17].

In considering uses of the multipurpose reflectometer, the present paper reports, as was noted above, only the measurement of luminous properties, such as luminous apparent reflectance, luminous transmission, gloss, and opacity. Spectral characteristics of the two combinations, which have been used in the multipurpose reflectometer to measure luminous properties, are plotted in figure 2 together with the distribution resulting from multiplying the ICI luminosity function (representing an average normal observer) by ICI illuminant *C*. ICI illuminant *C* is an illuminant [36, 54] of known spectral distribution which is representative of average daylight. The two combinations are (1) the spectral response of a GE barrier-layer photocell to light from an incandescent source at 3,100°K passed through a specified green filter and (2) the spectral response of an average Photox cell

[4] Given in a paper by Parker before the September 1940 meeting of the Illuminating Engineering Society.

to an incandescent source operating at 2,840°K. The GE cell is used in multipurpose reflectometers intended for measuring both luminous and chromatic properties. Without a filter, the spectral response of the Photox cell to a source at 2,840°K is roughly similar to that of the average human observer as represented by the standard luminosity function. Although the Photox cell without filter does not provide as satisfactory duplication of the luminosity function as does the GE cell with the green filter, it has been used with success both in the

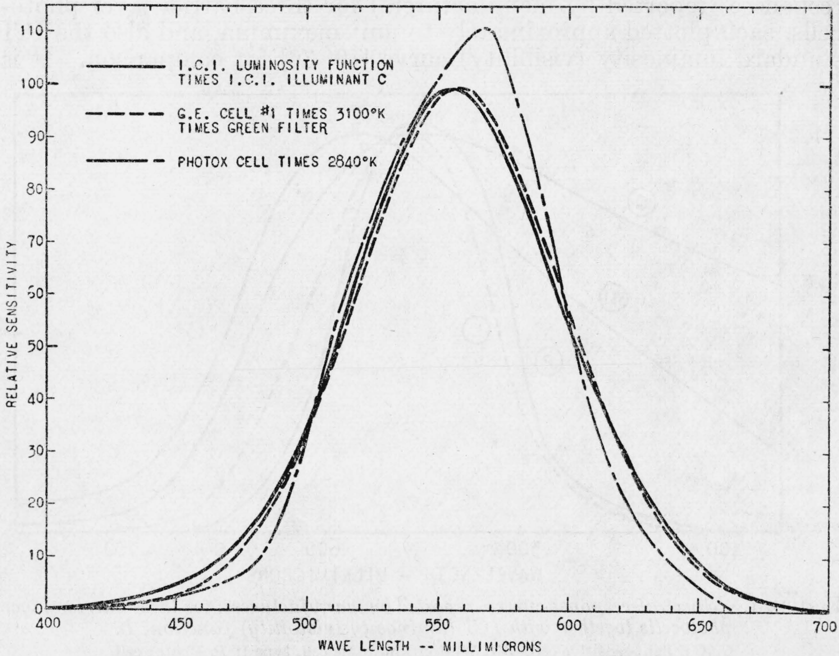

FIGURE 2.—*ICI luminosity function times ICI illuminant C compared with (1) spectral response of GE cell times spectral transmission of green filter times spectral energy of 3,100°K, and (2) spectral response of Photox cell times spectral energy of 2,840°K.*

The green filter is Corning 330 Signal Yellow, 2.7 mm of melt of 11-9-31, plus Corning 428 Light Shade Blue Green, 3.5 mm of melt of 11-2-37 [7]. (The areas under each of the three curves are equal.)

Photox reflectometer and in those multipurpose reflectometers intended only for the measurement of luminous properties.

A number of combinations of filter and barrier-layer photocell have been designed by others to measure luminous properties. The Weston Photronic type 1 cell with Viscor filter described by Gage [14, 57], the GE cell with green filter described by Barnes [3], the G–M Visitron cell with "visual correction filter" [13], have all been designed to evaluate the lightness and brightness of samples under whatever illuminant is actually present. On the other hand, the GE cell with filter specified in figure 2 and the Photox cell with no filter are each offered for use with a designated incandescent illuminant to evaluate samples for lightness as they would appear to the human eye under ICI illuminant *C*. In other words, provision is made in the multipurpose reflectometer for the simultaneous conversion from photocell response to luminosity-function response and for the change of illuminant from actual incandescent to artificial daylight. The effect of daylight illumination is thus secured without the use of a daylight filter.

In addition to their use for reporting spectral sensitivities, manufacturers' data were consulted to find the currents produced by the different photocells under a given illumination. In table 1 the photocell currents for 1 foot-candle of incandescent-lamp illumination and zero external potential are tabulated together with the dimensions of the respective cells and the current per unit area of sensitive surface. The information in table 1, showing that the well-known Weston Photronic type 1 cell gives relatively low current, and in figure 1, showing that the same cell possesses relatively low sensitivity to blue light (compared with the GE cell), eliminated this cell from consideration for possible use in the multipurpose reflectometer. The response of the Photox cell is also low, but the amount of light incident upon it need not be diminished by passage through a filter in order to measure luminous properties.

TABLE 1.—*Currents generated by barrier-layer photocells in current-balancing circuits (potential across cell terminals at zero)*

Cell name and literature	Active area		Current in microamperes per foot-candle [a]	
	Dimensions (diam.)	Area	Total	Per cm²
	cm	*cm²*		
Weston Photronic, model 594 (original, or type 1) [57]	3.8	11.4	1.43	0.12_5
Westinghouse Photox, style 836107 [56]	5.1	20.3	2.9	.14
Weston Photronic, model 594, type 2 [57]	3.8	11.4	4.2	.37
Lange photoelectric cell No. 1202, type S50 [41, 48]	3.8	11.4	4.5	.39
Electrocell No. 781 [42]	3.8	11.4	5.6	.49
GE round "Hewlett" cell,[b] [16] (removed from market, 12-37)	4.6	16.7	7.8	.47
GE light-sensitive cell [17]	3.8×1.9	7.1	3.4	.48

[a] Although not so stated in every source, it is believed that these figures refer to incandescent-lamp illumination.

[b] The round GE cell was withdrawn from the market at the end of 1937, and in its place a smaller "GE light-sensitive cell" having a rectangular face was offered. Use of the smaller cell in a multipurpose reflectometer requires a more sensitive current indicator than was needed with the large cell.

To measure the effects of temperature and duration of exposure, cells of four types were studied by the author. At the time of these studies, the GE cell was available only in the round model; the rectangular cell having similar characteristics and in wide use today had not appeared. The changes of current from five round GE cells, three Westinghouse Photox cells, three Weston Photronic type 2 cells, and three Electrocells were measured while the cells were under constant illumination of approximately 2 foot-candles. The circuit used was designed by Barbrow [2] to measure the current of a barrier-layer photocell in a current-balancing circuit. The results are shown graphically in figure 3. As a measure of fatigue, each cell was exposed to an incandescent lamp giving it an illumination of 2 foot-candles, and the current during a period of 3 minutes from initial exposure was plotted as a fraction of the current 15 seconds from the start. In demonstrating the influence of temperature, the current generated by each photocell was plotted as a fraction of the current at about 40° C.

In figure 4 are curves giving the currents from one photocell of each type at three levels of illumination. For this figure, 25° C instead of 40° C was chosen as the reference temperature.

Figures 3 and 4 show that use of the current-balancing circuit is no guarantee that the behavior of barrier-layer photocells will be

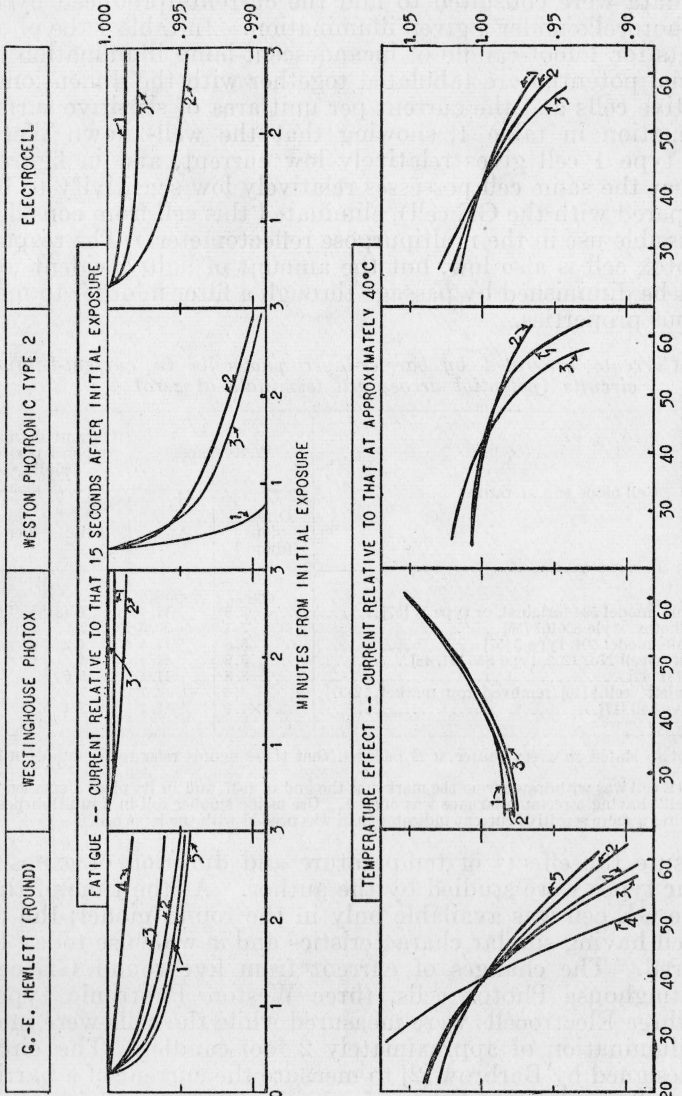

FIGURE 3.—*Currents of different barrier-layer photocells as a function of (1) duration of exposure and (2) temperature.*

Cell terminals at zero potential, incandescent source with no filters, cell illumination of 2 foot-candles. Numbers identify curves of individual cells.

automatically duplicated from cell to cell, even when the two cells are of the same type. Two photocells to be used together in a multipurpose or Photox reflectometer must have similar fatigue characteristics and similar spectral responses. If, moreover, the instrument in which they are used is to operate from ordinary electrical supply, the two cells must change response identically whenever the source changes in intensity because of a change in line voltage. If the two cells in an instrument do not meet these requirements, the device will operate in an unsteady manner and fail to give reproducible readings (see the study of errors, below).

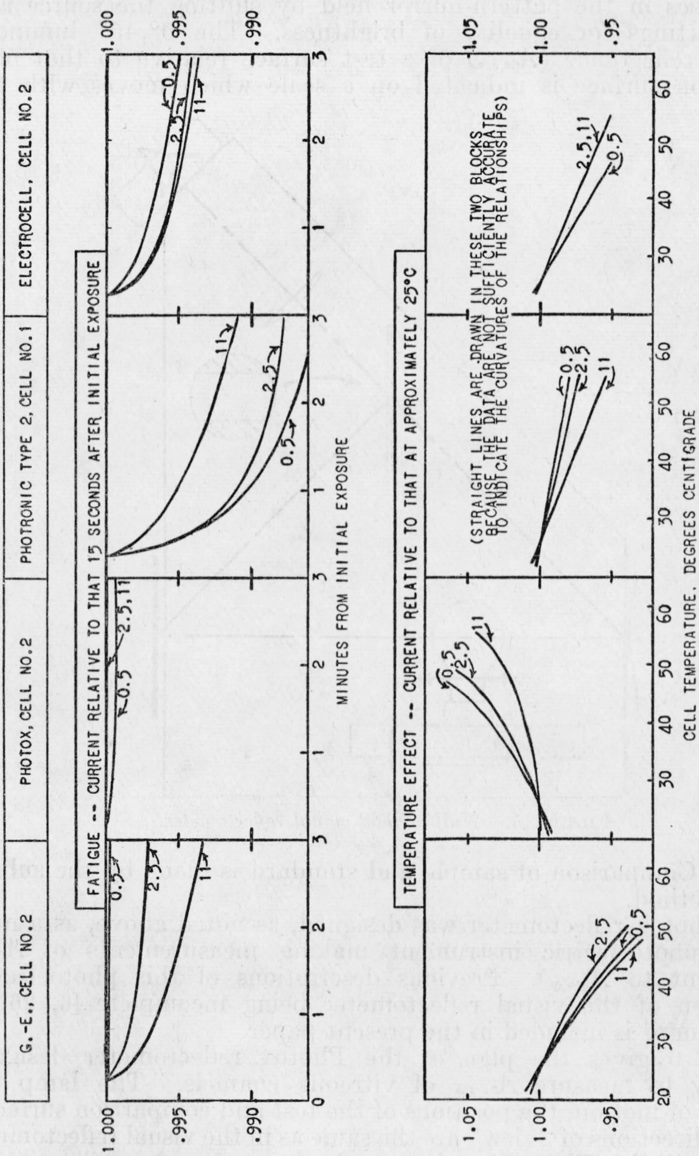

FIGURE 4.—*Currents of one of each of four types of barrier-layer photocells as a function of (1) duration of exposure and (2) temperature.*

All terminals at zero potential, incandescent source with no filters, cell illuminations of 0.5, 2.5, and 11-foot candles, as indicated on curves.

IV. AUTHOR'S EARLIER REFLECTOMETERS

The first reflectometer built by the author was the 0°,45° visual reflectometer, illustrated in figure 5 [25]. The outline of the instrument is shown, and the lines of sight and directions of movement of the lamp are indicated. The two surfaces to be compared, mounted at opposite ends of the instrument, are illuminated by the source, which may be moved along the supporting rods to vary the illuminations upon them. These surfaces are viewed in a direction approximately 45° from normal, and, with the aid of a pattern mirror, they are seen in photometric juxtaposition. The observer balances their brightnesses in the pattern-mirror field by shifting the source and makes settings for equality of brightness. The 0°,45° luminous apparent reflectance ($A_{0°,45°}$) of a test surface relative to that of a comparison surface is indicated on a scale which moves with the

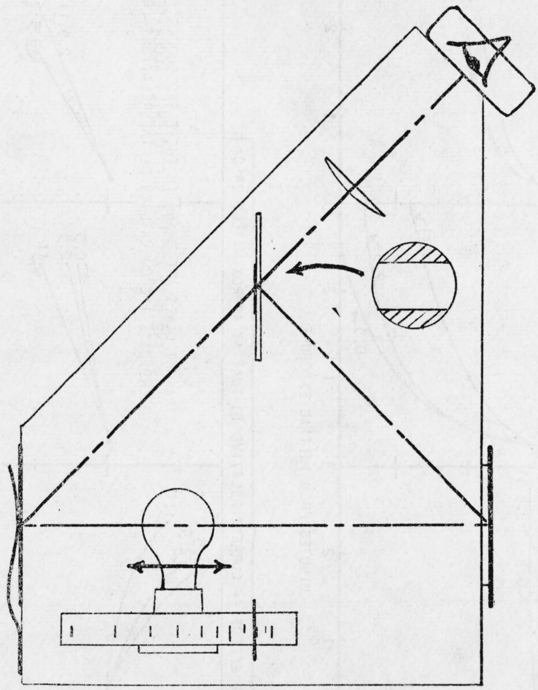

FIGURE 5.—*Null-method visual reflectometer.*

source. Comparison of sample and standard is made by the substitution method.

The Photox reflectometer was designed, as noted above, as a null-method photoelectric instrument making measurements of $A_{0°,45°}$ (equivalent to $A_{45°,0°}$). Previous descriptions of this photoelectric adaptation of the visual reflectometer being incomplete [6, 26], a short account is included in the present paper.

Figure 6 gives the plan of the Photox reflectometer designed especially to measure $A_{0°,45°}$ of vitreous enamels. The lamp, its direction of motion, the positions of the test and comparison surfaces, and the directions of "view" are the same as in the visual reflectometer just described. The comparison and test surfaces are illuminated along directions near the perpendicular by light from the movable lamp between them. Two 5-diopter, 3-in. diameter, plano-convex lenses are used to direct light reflected from each surface to its corresponding photocell. A shutter varies the proportions of light reaching the two cells by diaphragming at will either beam. The instrument is housed in a rectangular metal box—over-all dimensions, 44 by 40 by 23 cm.

As stated in section III, the two Photox cells are connected with different polarities to the terminals of a galvanometer which is deflected when currents generated by the two cells do not balance. A 60-watt, pear-shaped, Mazda lamp, operating on a 110-volt supply to give a color temperature of approximately 2,840° K is used as source of illumination. With MgO in the test position and a white

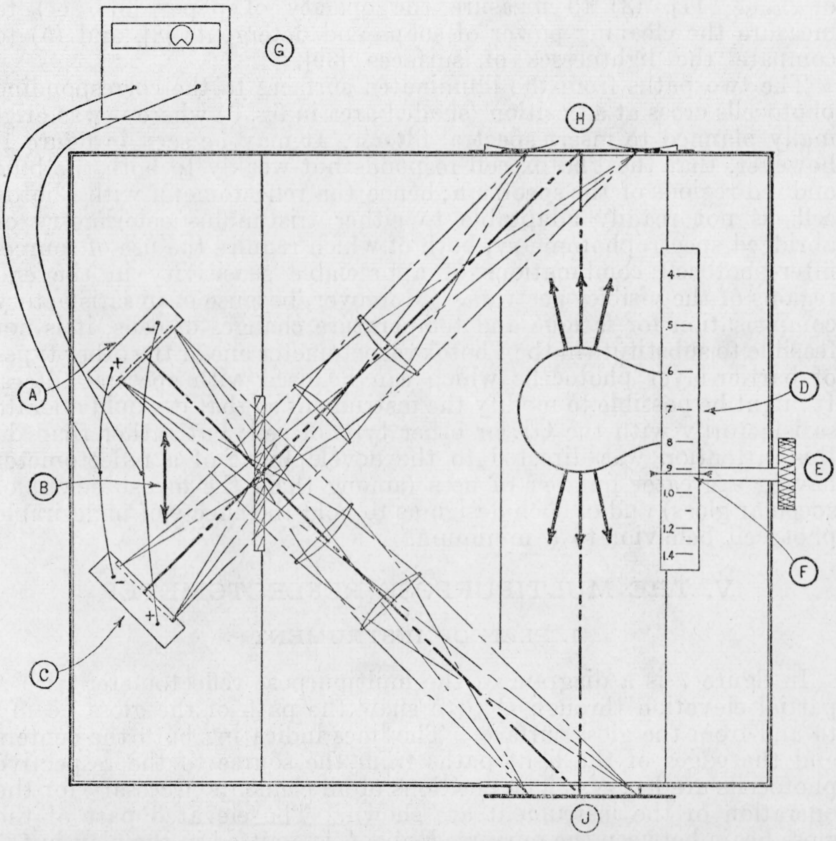

FIGURE 6.—*Diagram of Photox 0°,45° reflectometer.*

A, test Photox cell; *B*, shutter; *C*, comparison Photox cell; *D*, lamp and scale attached; *E*, knob to move lamp and scale; *F*, index; *G*, galvanometer; *H*, comparison surface; and *J*, test surface.

porcelain surface in the comparison position, the illumination upon each Photox cell, when balanced, is roughly 2 foot-candles. The box-type galvanometer used responds with 1-mm deflection to a current of 0.02 microampere through its 1,000-ohm coil.

The dimensions of the lamp and the enclosure in which the lamp operates are the same in the Photox instrument as in the visual instrument. Since the directions of view are also the same, the reflectometer scales used with the visual and Photox instruments are identical.

Settings for $A_{0°,45°}$ are made in the same manner as with the visual instrument. A standard of known value is placed in the test position; the scale is set for the luminous apparent reflectance of this standard; and the shutter is then moved to bring the galvanometer to zero. With the instrument thus adjusted, the surface to be tested is substituted for the standard; and now the lamp with scale is moved to the new position giving null deflection of the galvanometer. Luminous apparent reflectance is then read from the scale.

In addition to its use for (1) the standard porcelain-enamel reflectance test [49], the Photox reflectometer has been employed (2) to test paints for compliance with specified minimum acceptable values of $A_{0°,45°}$, [11], (3) to measure the opacity of paper [37], (4) to measure the cleaning power of soaps and detergents [8], and (5) to compare the lightnesses of surfaces [39].

The two paths from the illuminated surfaces to the corresponding photocells cross at a position (shaded area in fig. 6) where it was originally planned to insert spectral filters. It may be seen in figure 1, however, that the Photox cell responds but weakly to both the blue and red regions of the spectrum; hence the reflectometer with Photox cells is not readily adaptable to either tristimulus colorimetry or abridged spectrophotometry, both of which require the use of source-filter-photocell combinations of appreciable sensitivity in the end regions of the visible spectrum. Moreover, because of unsatisfactory compensation for fatigue and temperature changes of cells, it is not feasible to substitute in the Photox reflectometer one or the other types of barrier-layer photocells which can be used with spectral filters. It might be possible to modify the instrument so that it would operate satisfactorily with the GE or other type of cell; but rather than do this, attention was directed to the development of a reflectometer having a greater number of uses (among them the measurement of specular gloss) and of such design as to hold the effects of undesirable photocell behavior to a minimum.

V. THE MULTIPURPOSE REFLECTOMETER

1. PLAN OF INSTRUMENT

In figure 7 is a diagram of the multipurpose reflectometer with a partial elevation through Q–Q to show the path of the gloss beam [5] to and from the gloss surface. The lines indicating both the centers and the edges of the light paths from the source to the respective photocells are heavy. The positions of all elements necessary for the operation of the instrument are shown. The elevated part of the gloss beam between the mirrors, F and I, is omitted in the plan but is shown in the partial elevation.

The instrument, as has been noted, is designed to operate according to a null method. Light from the single source is divided into two paths, each of which ultimately reaches a barrier-layer photocell. The two cells are connected, with polarities opposing, to the terminals of the galvanometer, giving the current-balancing circuit described above. The paths followed by the two beams are purposely geometrically different so that different operations may be performed with them. Light diverges from the filament of the projection lamp, C, and passes through a round window in the aluminum insulating shield, B. Beyond this shield, the beam may pass through one of

[5] "Gloss beam" is used hereinafter to designate the pencil of light which is separated from the entrant beam by the small aluminum mirror, F, and which ultimately reaches the stationary photocell, N. "Gloss photocell" is used to designate this photocell and "gloss surface" to designate the surface, H, in position to receive the beam at 45° and reflect it at −45° along the path toward the gloss photocell.

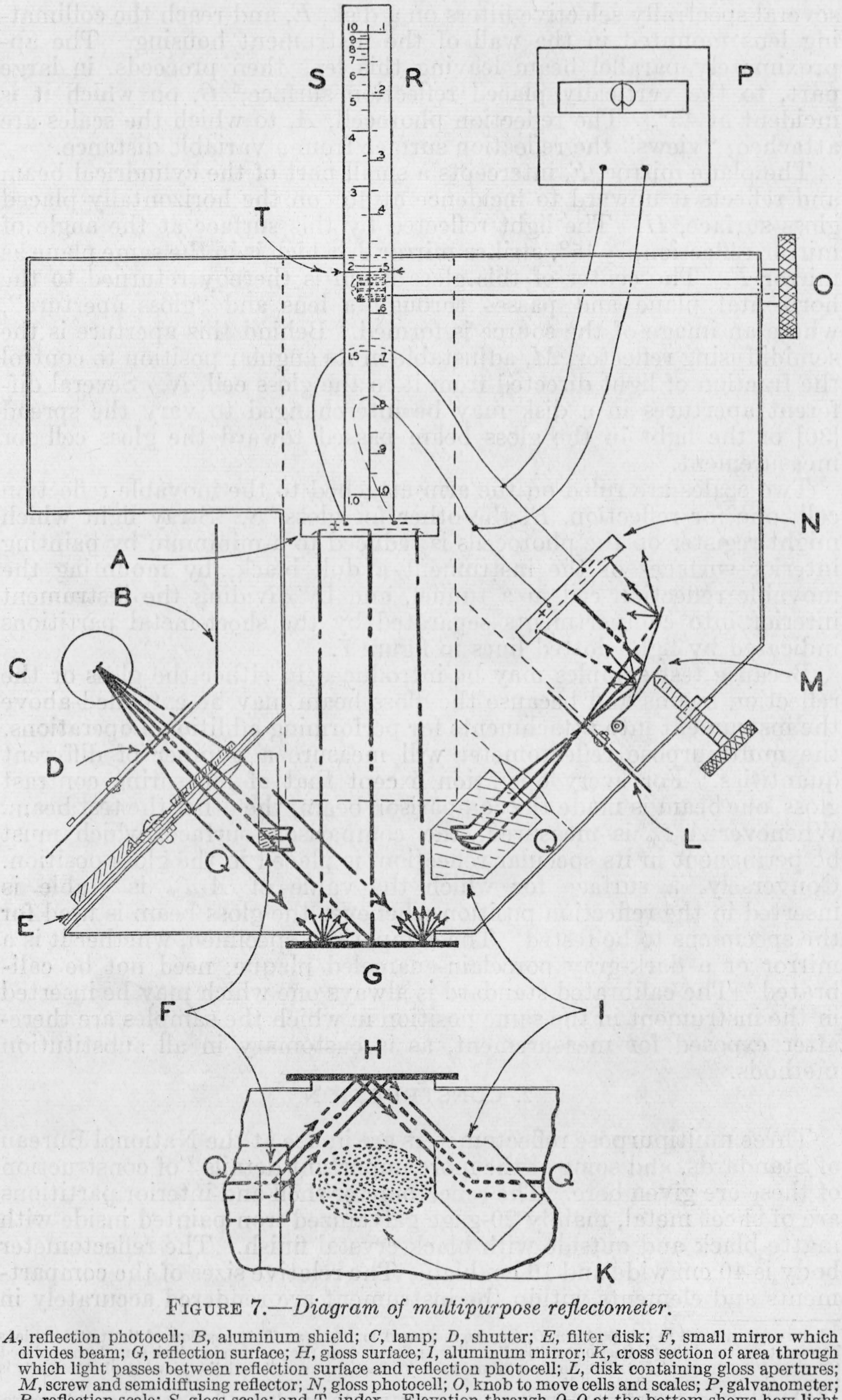

FIGURE 7.—*Diagram of multipurpose reflectometer.*

A, reflection photocell; *B*, aluminum shield; *C*, lamp; *D*, shutter; *E*, filter disk; *F*, small mirror which divides beam; *G*, reflection surface; *H*, gloss surface; *I*, aluminum mirror; *K*, cross section of area through which light passes between reflection surface and reflection photocell; *L*, disk containing gloss apertures; *M*, screw and semidiffusing reflector; *N*, gloss photocell; *O*, knob to move cells and scales; *P*, galvanometer; *R*, reflection scale; *S*, gloss scale; and *T*, index. Elevation through *Q–Q* at the bottom shows how light is directed up to the gloss surface, *H*, from the plane of the other beams of the instrument below.

several spectrally selective filters on a disk, *E*, and reach the collimating lens mounted in the wall of the instrument housing. The approximately parallel beam leaving this lens then proceeds, in large part, to the vertically placed reflection surface,[6] *G*, on which it is incident at 45°. The reflection photocell, *A*, to which the scales are attached, "views" the reflection surface from a variable distance.

The plane mirror, *F*, intercepts a small part of the cylindrical beam and reflects it upward to incidence at 45° on the horizontally placed gloss surface, *H*. The light reflected by this surface at the angle of mirror reflection, −45°, strikes mirror *I*, which is in the same plane as mirror *F*. The center of this gloss beam is thereby returned to the horizontal plane and passes through a lens and "gloss aperture", where an image of the source is formed. Behind this aperture is the semidiffusing reflector, *M*, adjustable in its angular position to control the fraction of light directed from it to the gloss cell, *N*. Several different apertures in a disk may be interchanged to vary the spread [30] of the light in the gloss beam passed toward the gloss cell for measurement.

Two scales are ruled on the arm attached to the movable reflection cell, one for reflection, *R*, the other for gloss, *S*. Stray light which might register on the photocells is reduced to a minimum by painting interior surfaces of the instrument a dull black, by mounting the movable reflection cell in a tunnel, and by dividing the instrument interior into compartments separated by the sheet-metal partitions indicated by light dotted lines in figure 7.

Because test samples may be introduced in either the gloss or the reflection beams and because the gloss beam may be extended above the instrument into attachments for performing additional operations, the multipurpose reflectometer will measure a number of different quantities. For every operation except that of measuring contrast gloss, one beam is made the comparison beam, the other the test beam. Whenever $A_{45°,0°}$ is measured, the comparison surface, which must be permanent in its specular reflection, is placed in the gloss position. Conversely, a surface for which the value of $A_{45°,0°}$ is stable is inserted in the reflection position whenever the gloss beam is used for the specimens to be tested. The comparison specimen, whether it is a mirror or a dark-gray porcelain-enameled plaque, need not be calibrated. The calibrated standard is always one which may be inserted in the instrument in the same position in which the samples are thereafter exposed for measurement, as is customary in all substitution methods.

2. CONSTRUCTION

Three multipurpose reflectometers are in use at the National Bureau of Standards, and some of the more important details [7] of construction of these are given here. The reflectometer shell and interior partitions are of sheet metal, mainly 20-gage galvanized iron painted inside with matte black and outside with black-crystal finish. The reflectometer body is 40 cm wide and 16 cm high. The relative sizes of the compartments and elements within the instrument are rendered accurately in

[6] Surfaces inserted in this position, *G*, may be measured for $A_{45°,0°}$. This position of the test sample is hereinafter termed the "reflection position" to differentiate it from the position in which samples are placed for gloss measurement, *H*. The beam is termed the "reflection beam," and the viewing photocell, *A*, is termed the "reflection photocell."

[7] The detailed plans used in building these instruments may be consulted in the Colorimetry and Spectrophotometry Section, National Bureau of Standards.

the diagram, figure 7. The dimensions of the different photocells which may be used are given in table 1.

Concentrated-filament projection lamps of 100 to 400 watts may be used. The ventilated lamp housing must be thermally insulated from the body of the instrument, but the lamp filament must not move relative to it. In some cases the lamp socket and lamp housing have been mounted on a U-shaped bar attached rigidly through insulating washers to the instrument body. In one case, the body, insulating shield, and lamp socket were mounted on a rigid board which does not readily conduct heat.[8] However, it has been found that even though the lamp socket be rigidly located relative to the body, movement of the lamp in its socket will sometimes take place during operation. Such movement has been found in both the medium-screw-base and medium-prefocus-base sockets which have been tried. Trouble is most likely to occur during the warm-up period, when the instrument has just been turned on and heating causes changes in the parts.

Simple, double-convex lenses 42 mm in diameter are used (10 diopters for the collimating lens and 20 diopters for the gloss-beam lens). The spectral filters employed are 2 in. square. The small mirror, *F*, in the entrant beam is of chrome-aluminum, about 15 mm square, deposited by evaporation on the end of a thin strip of glass. The mirror, *I*, is large, so that its back side will block all light proceeding from the reflection surface toward the gloss photocell. This mirror may be of electrolytically brightened sheet aluminum, chrome-aluminum deposited by evaporation, or other nonselective mirror material. The small circular opening in the disk containing gloss apertures is used for specular-gloss measurements. It is 6.2 mm in diameter and provides an angular spread [9] of the gloss beam of 11.7°. For measurements of quantities other than specular gloss, bloom, and sheen, a large circular opening 25 mm in diameter is used to provide for the maximum angular spread (about 22°) possible with the present lens system. Three openings of this large size are used; two hold "neutral" filters. The 7 by 5 cm semidiffusing reflector beyond the disk is of electrolytically brightened sheet aluminum; however, a surface painted with aluminum varnish will serve the same purpose.

Both of the instrument openings upon which samples are mounted are oval, 7 cm long and 5 cm wide. The samples are placed against a brass collar raised 7 mm from the shell of the instrument to keep the instrument body and the samples from contact over extended areas. Almost the whole reflection opening is filled by the incident beam; consequently samples for measurements of $A_{45°,0°}$ are required to have flat areas at least 7 by 5 cm (unless the special device for small areas is used). The gloss beam, on the other hand, covers only a diamond-shaped area 3.8 cm long and 2.5 cm wide in the center of the gloss opening, but specimens to be tested must have a somewhat larger flat area to hold against the 7- by 5-cm elliptically shaped brass collar.

Several auxiliary features may be noted. The clamp which holds the samples during measurement is attached to the end of a spring-bronze arm through a ball and socket so that it will hold specimens of almost any shape firmly in position. It may be used interchangeably over the gloss and reflection openings. Also interchangeable is the

[8] The author is indebted to I. A. Balinkin, of the University of Cincinnati, for suggesting this second method of assembling a reflectometer.

[9] For an explanation of what is meant by the spread of a gloss beam see reference [30].

movable guide which determines the location of the test piece of the area that is measured. The work of the Porcelain Enamel Institute Committee on Standardization of Tests furnished an example of the use of this guide. It was necessary to measure the specular gloss of the same area of each test piece before and after treatment. By leaving the guide locked in position while etching or abrading a sample it was always possible to remeasure after treatment the exact area initially exposed.

The knob to move the reflection cell, the lever to open the shutter, and a key to reduce the response of the galvanometer are located close together on the rear right side of the instrument, where they may be easily reached by the right hand. A reading lens and mirror enable the operator to read the scales while seated in front of the instrument. The semidiffusing reflector is turned by a thumbscrew conveniently placed in the position indicated by figure 7. A thumb nut on the shank of this screw enables the operator to lock the reflector in any position desired.

Except when the reflectometer is used for abridged spectrophotometry or with the small rectangular GE photocells, a galvanometer with which one may detect a current of 0.003 microampere is suitable. If, however, the smaller rectangular cells are used with a projection lamp of less than 400 watts, the galvanometer must respond visibly to a current of 0.001 microampere. For abridged spectrophotometry, a galvanometer which will detect with certainty the presence of a current of 0.0001 microampere is needed because of the necessarily low transmission of some of the filters used; the coil of the galvanometer should have a resistance of about 1,000 ohms.

3. ATTACHMENTS FOR SPECIAL OPERATIONS

The first of the several attachments built to adapt the instrument to special problems is a stand (not illustrated) to lift the reflectometer about 8 in. above the table top and mount it in a vertical instead of a horizontal position so that dry powders or opaque liquids in open pans may be introduced for 45°,0° measurements. When the reflectometer is used in this position, the lamp mounting must be turned, because projection lamps must always be operated with base down.

Figure 8 (*A*) illustrates a device which is used with nonflat surfaces or with surfaces too small in area to fill the full reflection opening. The device consists of a simple lens (20 dipoters, 42 mm diam) which converges the incident beam to three-eighths inch in diameter at the plane of the reflection surface. During the use of this attachment, a major portion of the incident beam departs significantly from 45° incidence. Since, moreover, nonflat surfaces and surfaces too small to measure in the usual manner are difficult to accurately position for measurement, the apparent reflectances obtained with this attachment are not as accurate as those obtained in the usual manner.

To measure specular gloss at angles other than 45°, attachments of the type shown in figure 8 (*B*) are mounted on top of the reflectometer and test specimens are placed upon them. By changing the dimensions and the angles of the two mirrors, the type of device may be designed for specular-gloss measurements at any angle desired. Measurements at both 60°, figure 8 (*B*), and at 75°, figure 12, have been made with the multipurpose reflectometer. Used with the small gloss aperture, the 60° attachment has been found to give gloss values

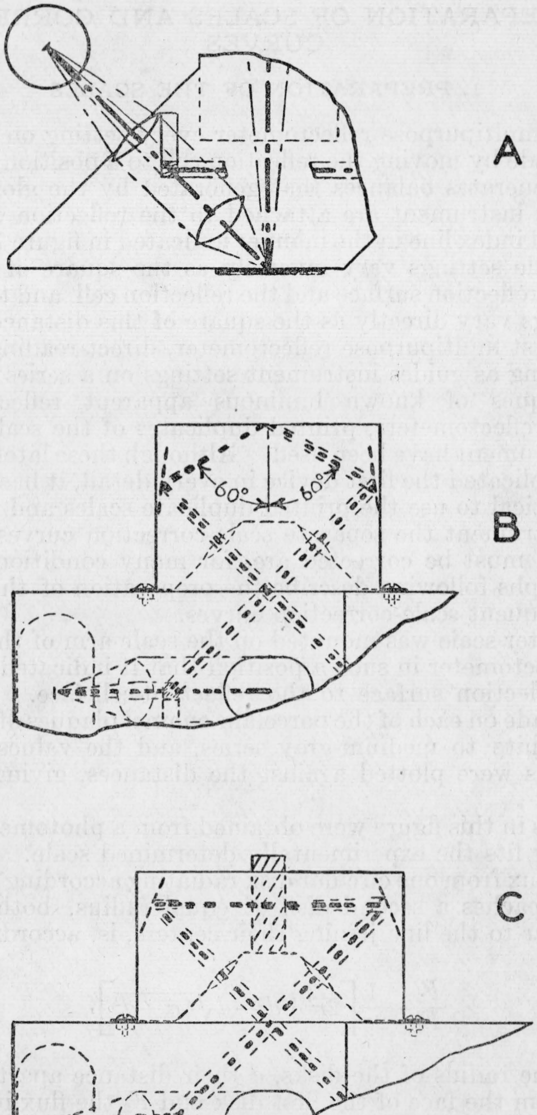

FIGURE 8.—*Three reflectometer attachments for special functions.*

A, For approximate values of $A_{45°,0°}$ of nonflat surfaces and surfaces of small area; *B*, for 60°, −60° specular gloss; *C*, for transmission.

of painted surfaces in fairly good accord with those derived according to the ASTM Tentative Method of Test for Specular Gloss of Paint Finishes [1, 30].

For transmission, figure 8 (*C*), the gloss beam is directed horizontally through the top of the same type of device. Clear liquids in glass cells and clear solids with polished parallel faces are then inserted for measurement.

VI. PREPARATION OF SCALES AND CORRECTION CURVES

1. PREPARATION OF THE SCALES

With the multipurpose reflectometer every setting on an unknown sample is made by moving the reflection cell to a position at which the current it generates balances that generated by the gloss cell. The scales of the instrument are attached to the reflection cell and pass under a ruled index line in the manner indicated in figure 7. Roughly, the gloss-scale settings vary inversely as the square of the distance between the reflection surface and the reflection cell, and the reflection-scale readings vary directly as the square of this distance.

For the first multipurpose reflectometer, direct-reading scales were prepared using as guides instrument settings on a series of porcelain-enamel plaques of known luminous apparent reflectances. For subsequent reflectometers, printed duplicates of the scales drawn for the first instrument have been used. Although these later instruments have not duplicated the first device in every detail, it has nevertheless proved practical to use the printed duplicate scales and then prepare for each instrument the separate scale-correction curves. The scale errors which must be corrected are, for many conditions, not large. The paragraphs following describe the preparation of the first scales and of subsequent scale-correction curves.

A centimeter scale was mounted on the scale arm of the first multipurpose reflectometer in such a position that it indicated the distance from the reflection surface to the reflection-cell face. Null settings were then made on each of the porcelain-enamel plaques of a previously measured white to medium-gray series, and the values of $A_{45°,0°}$ of these plaques were plotted against the distances, giving the dots in figure 9.

The circles in this figure were obtained from a photometric equation which nearly fits the experimentally determined scale. The fraction of the total flux from one circular disk radiating according to Lambert's law which reaches a second disk of equal radius, both disks being perpendicular to the line joining their centers, is, according to Walsh [55],

$$\frac{F_2}{F_1}=\frac{1}{2r^2}\left[2r^2+d^2-d\sqrt{4r^2+d^2}\right],$$

where r is the radius of the disks, d their distance apart, F_1 the flux radiating from the face of the first disk and F_2 the flux incident upon the second disk. For an instrument fulfilling the ideal conditions, this equation would serve for spacing the rulings on the scales;[10] in the present case it proved valuable as a check against the experimental calibration. Setting $r=2.5$ cm, a series of values of F_2/F_1 were computed relative to that at 33.8 cm (the distance corresponding to a scale setting of 1.0). The reciprocals of these numbers were plotted in figure 9 as a function of d. The reflection-scale curve was then drawn through the experimentally determined dots, using the

[10] Failure of this function to apply to the actual instrument arises, in major part, from the presence of stray light, which it is impossible to eliminate entirely, and, to a lesser degree, from the fact that the reflection surface and, in some cases, the reflection photocell are not circular. This failure of the scale to fit Walsh's function is noted in the study of a multipurpose reflectometer by the Institute of Paper Chemistry [33]. They mistakenly assumed in their study that it was intended to have the reflectometer scale fit such a photometric relationship. Actually, in using Walsh's equation, it was intended only to verify in an approximate manner the experimental calibration for interpolation purposes.

circles to guide in locating the interpolated and extrapolated parts of the curve.

The curve for gloss, also plotted in figure 9, is the locus of points whose ordinates are reciprocal to the corresponding ordinates of the reflection-scale curve. In measuring gloss, it will be remembered, test sample and comparison surface positions are reversed, hence the inverse relation of the gloss scale and the reflection scale.

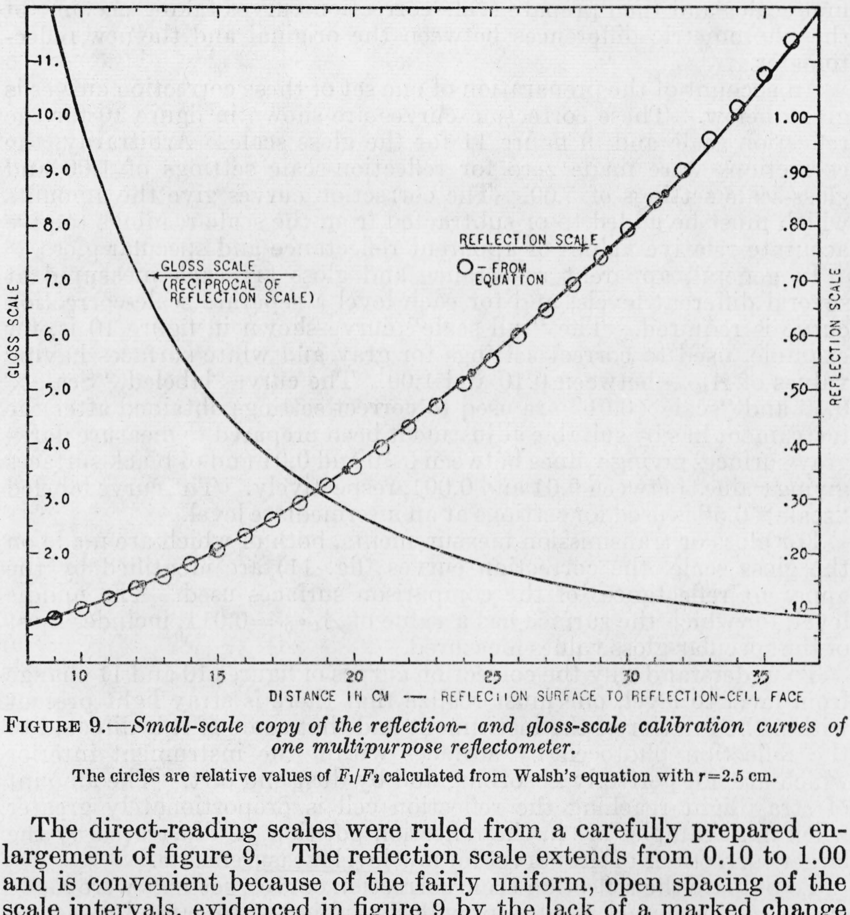

FIGURE 9.—*Small-scale copy of the reflection- and gloss-scale calibration curves of one multipurpose reflectometer.*

The circles are relative values of F_1/F_2 calculated from Walsh's equation with r=2.5 cm.

The direct-reading scales were ruled from a carefully prepared enlargement of figure 9. The reflection scale extends from 0.10 to 1.00 and is convenient because of the fairly uniform, open spacing of the scale intervals, evidenced in figure 9 by the lack of a marked change of slope of the corresponding curve. The gloss scale extends from 1.00 to 10.0, but the scale intervals are not so uniformly spaced;[11] in fact, the close spacing between 5.0 and 10.0 makes it often advisable to use a scale setting between 4.0 and 6.0, instead of 10.0, as the 100 percent setting for transmission measurements. From the carefully ruled pair of direct-reading scales, a zinc etching properly reduced in size was made, and from this etching the scales used in the instruments have been printed.

[11] It will be found that $-\log_{10}T$, into which transmission (T) is frequently transformed, is more nearly a linear function of scale distance than is T.

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2. CORRECTION CURVES

Minor mechanical differences in construction and differences in the behavior of different pairs of photocells cause variations in the photometric calibrations of instruments. Ideally, a new calibration should be prepared and a new pair of scales ruled for each reflectometer built. Preparing new scales is, however, difficult and tedious. It has proved practical merely to install in each new device a printed duplicate of the first scales and then prepare scale-correction curves taking account of the photometric differences between the original and the new reflectometer.

An account of the preparation of one set of these correction curves is given below. These correction curves are shown in figure 10 for the reflection scale and in figure 11 for the gloss scale. Arbitrarily, the corrections were made zero for reflection-scale settings of 1.00 and gloss-scale settings of 5.00. The correction curves give the amounts which must be added to or subtracted from the scale readings to give accurate relative values of apparent reflectance and specular gloss.

In general, apparent reflectance and gloss are each measured at several different levels, and for each level a separate scale-correction curve is required. The "full scale" curve shown in figure 10 is, for example, used to correct settings for gray and white surfaces having values of $A_{45°,0°}$ between 0.10 and 1.00. The curves labeled, "Scale$\times$0.1" and "scale$\times$0.01" are used to correct settings obtained after the instrument has by suitable adjustment been prepared to measure dark-gray surfaces giving values between 0.10 and 0.01 and of black surfaces giving values between 0.01 and 0.001, respectively. The curve labeled "scale$\times$0.5" is used for settings at an intermediate level.

For gloss or transmission measurements, both of which are made on the gloss scale, the correction curves (fig. 11) are identified by the apparent reflectances of the comparison surfaces used. The middle level, for which the surface has a value of $A_{45°,0°}=0.011$, includes most of the specular-gloss values measured.

To understand why the correction curves of figures 10 and 11 change from level to level, one must realize that there is stray light present within the interior of the instrument and that some of it is directed to the reflection photocell by surfaces within the instrument interior which are not perfectly absorbing and by dust and dirt. The amount of stray light reaching the reflection cell is proportionately greater when dark samples are in the reflection position, as illustrated by the larger corrections of the curves for low-level measurements.

To prepare the reflection-scale correction curves, settings were made on porcelain-enamel plaques previously subjected to careful measurement for 45°,0° luminous apparent reflectance; to prepare the gloss-scale curves, "neutral" filters of known luminous transmission were used. From the group of calibrated specimens available, several settings at each level were made. From each setting, the correction required to give the proper known value was computed and plotted on one of the pieces of coordinate paper from which figures 10 and 11 were drawn. There were relatively few points for each level, however, and therefore trustworthy correction curves could not be drawn because of uncertainty regarding the courses of the curves between the plotted points. To interpolate between the points representing the known amounts of correction, and to extrapolate at the ends of the curves, pairs of settings were made with a piece of clear glass having a transmission of 0.924 alternately introduced into and removed from the gloss beam to provide a photometric interval of known magnitude. All the scale ranges ordinarily used were covered with pairs of settings, and the departures of the scale-assigned ratios from 0.924 were the

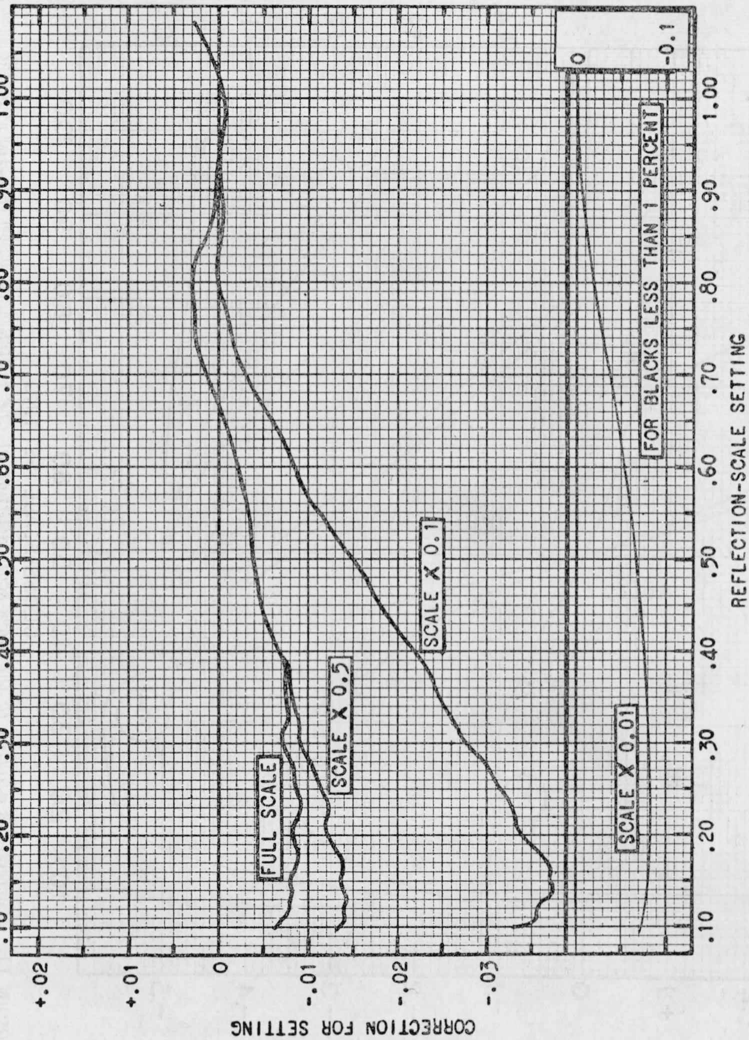

FIGURE 10.—*Corrections applied to the reflection-scale settings of one instrument when the values of $A_{45°,0°}$ of the samples measured are roughly 1.0, 0.5, 0.1, or 0.01 times settings.*

bases of corrections for interpolating and extrapolating the correction curves. As the semidiffusing reflector was adjusted to give different scale settings in this work, the samples in gloss and reflection position were frequently changed so that they were always similar in reflecting characteristics to the samples met in actual operation of the instrument in the same scale range. Approximately 30 additional points for each correction curve were obtained by making settings with this piece of clear glass.

Although the resulting scale-correction curves in figures 10 and 11 apply to only one instrument, the curves and the description of the manner in which they were obtained may be helpful for preparing similar ones. The correction curves of other instruments which have

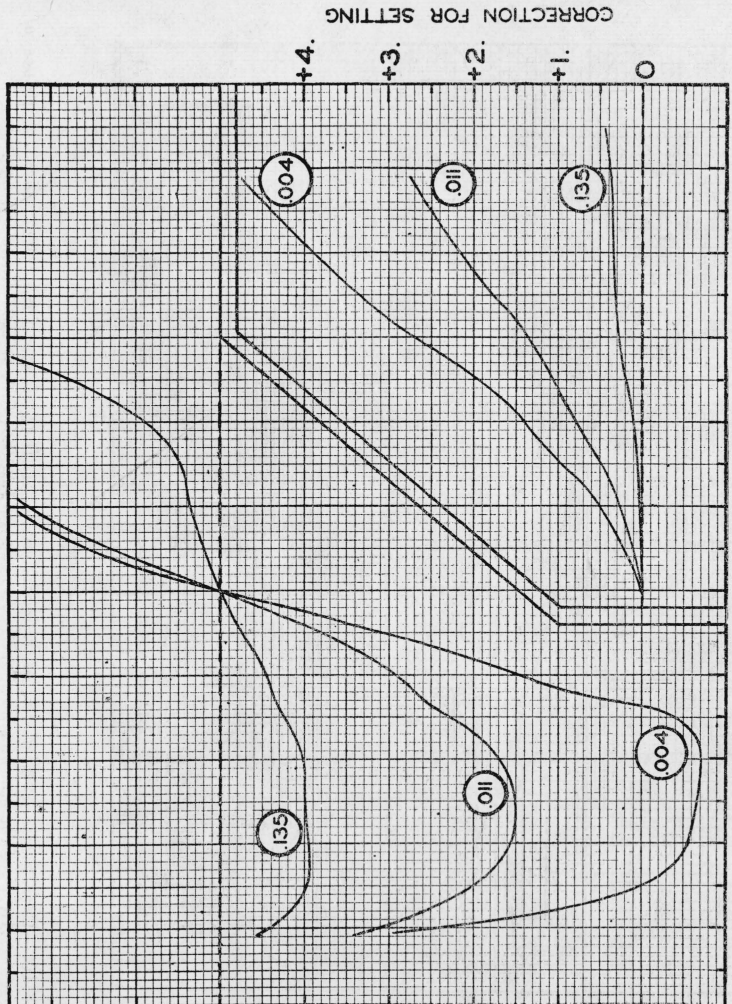

FIGURE 11.—*Corrections applied to the gloss-scale settings of one instrument when the $A_{45°,0°}$ of the comparison surface is 0.135, 0.011, or 0.004.*

scales printed from the same etching should have irregularities in the same places as those in figures 10 and 11, because these irregularities (though not the general shape of the curves) are thought to result chiefly from inaccuracies in the preparation of the original drawing.

VII. ELIMINATING OR MINIMIZING ERRORS

Eighteen potential errors in multipurpose reflectometer measurements are listed in table 2, together with the evidence by which the presence of each is detected and the procedure employed to minimize or eliminate each. The 18 are divided into a group of 12, identified by inconstant operation of an instrument, and a group of 6, the presence of which can only be established by the failure of one instrument to check results from another. Since the cause, the evidence of presence, and the cure for each of the 12 errors of inconstancy are indicated in the table, no further discussion of them is given.

TABLE 2.—*Errors in multipurpose reflectometer measurements, their causes and control*

Evidence of presence of error	Cause of error	To minimize or eliminate the error
A. ERRORS EVIDENCED BY INCONSTANT OPERATION OF SINGLE INSTRUMENT		
FROM CHARACTERISTICS OF THE PHOTOCELLS		
1. Change of settings with temperature of instrument.	Change of photocell current with temperature.	Allow instrument to warm up to equilibrium and check with standard frequently to detect drift.
2. Galvanometer drift after opening shutter.	Change, with time, of current from one photocell relative to that from the other (fatigue).	Use photocells paired for equal rate of drift and thus eliminate residual drift.
3. Galvanometer response to change of line voltage.	Change with source intensity of current from one photocell relative to that from the other.	Use photocells paired for like changes of current with identical changes of illumination.
4. Persistent failure of instrument to reproduce readings made shortly before; galvanometer drift.	Failure of contacts within photocells.	Renew electrical contacts within cells, or replace cells.
FROM DESIGN OF THE INSTRUMENT		
5. Galvanometer response to movement of a light past cracks and openings in the instrument.	Light leakage	Make housing light tight, or use instrument in a darkened room.
6. Galvanometer response to pressure on, or movement of, instrument during a setting.	Lack of structural rigidity	Build instrument rigidly; handle carefully during use.
7. Erratic operation	Dirt on optical parts	Clean parts affected.
FROM CHARACTERISTICS OF THE SAMPLE		
8. Galvanometer response to change of line voltage only when instrument beams have markedly different spectral composition.	Marked spectral difference of samples in two beams.	Operate source at constant voltage when beams have markedly different spectral composition.
9. Change of instrument reading with change of area of surface exposed.	Nonuniformity of surface of the sample in the quality being measured.	Designate area of surface measured.
10. Change of instrument reading with wobble of surface over opening.	Nonflatness of surface of sample	Flatten surface or designate exact position during measurement.
11. Change of instrument reading with rotation of sample surface.	Variation of apparent reflectance of surface with rotation in its own plane.	Make and average four readings of sample rotating it 90° between each pair of readings.
12. Change of reading with exposure of sample to light, time, humidity, or other treatment.	Impermanence of characteristics of sample.	Treat sample so affected with care and give history prior to measurement.

TABLE 2. *Errors in multipurpose reflectometer measurements, their causes and control*—Continued

Evidence of presence of error	Cause of error	To minimize or eliminate the error
B. ERRORS IDENTIFIED BY USE OF SEPARATE INSTRUMENTS		
13. Failure of reflectometer to check accurate results from separate instruments.	Inaccurate scales	Prepare and use scale-correction curves following instructions.
14. Do	Inaccurate calibration or change of standard.	Remeasure standard.
15. Failure of reflectometer to check accurate results from separate instruments (frequently appears when results are compared with those from instrument of different type).	Inexact duplication of specified directional conditions of measurement.	Examine angular conditions of measurement of both instruments involved. (Do not expect accurate duplication of results if there are differences.)
16. Failure of reflectometer to check accurate results from separate instruments. (Penetration of light is often visible at edges of sample.)	Loss of light by lateral passage after penetration into translucent sample.	Measure on instrument having negligible penetration loss. (See text.)
17. Failure of reflectometer to check accurate results from separate instruments.	Failure of spectral response of source-filter-photocell combinations to duplicate those required.	Use standards spectrally similar to samples measured.
18. Do	Fluorescence of samples	Samples must be measured on instrument not subject to fluorescence error.

Errors of the last six types are harder to identify and eradicate. Scale errors, type 13, are handled by the procedure involving preparation and use of scale-correction curves, which has just been described. Type 14 does not require extended consideration here because references to the different primary standards and to suitable secondary standards are part of the study, described below, of applications of the multipurpose reflectometer. The multipurpose reflectometer itself measures only relative values and is therefore dependent for accuracy upon the standards used for the different quantities it measures.

Disagreements attributable to error 15 appear when two instruments, which are geometrically the same according to their descriptions, possess undisclosed geometric differences. One must, of course, expect lack of agreement in results from two instruments of disclosed differences; for instance, a device designed to measure $A_{45°,0°}$ will in general give results which differ from those by another designed to measure $A_{\text{diffuse},0°}$, or a device to measure 60° specular gloss will in general give results which differ from those by any device measuring 45° specular gloss.

This error 15 appears most frequently in gloss studies, because gloss measurements always involve directions adjacent to or including the direction of mirror reflection for which the apparent reflectance of most surfaces changes markedly with small changes of angle.[12] To describe adequately the geometry of a gloss measurement, one should give not only the central directions of illuminating and viewing (as, for example, 45° and −45° for specular gloss with the multipurpose reflectometer) but he should give in addition the spreads [30] of the beams. These latter quantities give the amounts of departure from the central directions of illuminating and viewing which the gloss measurement encompasses. The total spread, for example, of

[12] For illustrations of these changes see the goniophotometric curves in references [27] and [43].

the multipurpose gloss beam with small aperture is, as was stated above, roughly 11.7°.

If two gloss instruments are identical in central directions and spreads and if the gloss beams are accurately centered about the central directions, the devices should give identical results. However, a small difference in the geometry of the devices, which might result merely from the inexact construction of some part in one, may cause significant disagreement between results given by them.

In connection with errors involving the geometry of measurements, it seemed desirable to find whether the amount of light reflected in directions other than those subject to measurement might not on some occasions affect instrument settings. When, for example, a shiny black surface is exposed in reflection position, the amount of light specularly reflected into the interior of the instrument is much greater than that going directly from the test surface to the reflection photocell. It was suspected that some of the specularly reflected light might indirectly reach the reflection photocell from the walls of the instrument interior and cause the setting to be in error. To find whether such an effect existed, a shiny black porcelain-enamel plaque and a piece of matte black velvet were measured with first the goniophotometer, not subject to the error, and then with the multipurpose reflectometer. On the former instrument both were found to have a value of $A_{45°,0°}=0.004_2$; on the latter they measured 0.004_5 and 0.004_3, respectively. Considering the difficulty of obtaining accuracy in the measurement of such low apparent reflectances, one can see that any effect of gloss of test surfaces on measured values of $A_{45°,0°}$ is negligible.[13]

With further reference to errors of geometry, it should be remembered that different types of photocells have sensitive areas of different shapes and sizes. Changing the type of photocell in a reflectometer makes necessary the recalibration of the instrument by the preparation of new correction curves.

A piece of white architectural glass will furnish an example of the type of sample subject to error 16. Whenever a sample being measured in an instrument is translucent enough to permit some of the incident light to penetrate to a depth which is an appreciable fraction of the diameter of the area illuminated, part of the penetrating light will spread laterally within the sample and return to the surface outside the area illuminated. This laterally displaced light emerging from such a sample exposed in the reflectometer cannot reach the reflection photocell, because the area of the surface exposed to the photocell is only as large as the area illuminated. Because the 5- and 7-cm diameters of the elliptical opening of the multipurpose reflectometer are large relative to the depths of light penetration into most materials, translucency errors are usually small. However, this error was easily demonstrated in the case of a white opal-glass plate into which an appreciable fraction of the incident light penetrated the full 0.9 cm of its thickness. This plate, measured on the multipurpose reflectometer, was found to have a value of $A_{45°,0°}=0.909$ relative to MgO; whereas the McNicholas goniophotometer [44], in which this error is eliminated, gave $A_{45°,0°}=0.913$.

[13] Possible exceptions occur with settings at the end of the scale when the photocell is very near the reflection surface, and with settings when the converging lens described above is used to measure surfaces of small area. In each of these instances, there is possibility that specularly reflected light from the reflection surface will reach the reflection photocell to cause error.

The present discussion of error 17 will consider only its effect on measurements of luminous properties. In the forthcoming paper [29] there will be an extended discussion of this same error as it applies to photoelectric tristimulus colorimetry.

Figure 2 shows graphically the spectral disparity between the standard luminosity function and both the Photox cell with incandescent source at 2,840°K and the GE cell with green filter and incandescent source at 3,100°K. The error arising from either one of these disparities will, in general, increase as the spectral differences between the standard and samples increases. When high accuracy is required, one usually has available a standard spectrally similar to the samples and in such instances the errors are small.

Table 3 will give one an idea of the amounts of error which may result when the multipurpose reflectometer with GE cell and green filter is used to measure plaques of different color against a white plaque as standard. Values of $A_{45°,0°}$ for 10 porcelain-enamel plaques computed from spectrophotometric data [14] are compared with values for the same plaques measured with the multipurpose instrument. The reflectometer readings have been corrected for scale errors, and 0.023 has been subtracted from each of the apparent reflectance values computed from the spectrophotometric data to compensate as well as possible for the geometric differences between the two instruments. The maximum disagreement remaining is seen to amount to 0.012 (for the maize plaque) and is probably chiefly attributable to spectral disparity between the true luminosity function and the combination of source, green filter, and G. E. photocell.

TABLE 3.—*Luminous apparent reflectance ($A_{45°,0°}$) for 10 porcelain-enamel plaques chosen as master standards for colors of kitchen and bathroom accessories [46, 47] measured with (1) a multipurpose reflectometer using GE cell and green filter and (2) a spectrophotometer [23] by computation*

Color designations of plaques	$A_{45°,0°}$ relative to MgO for ICI illuminant *C*	
	Measured on multipurpose reflectometer with GE cell and green filter	Computed from spectrophotometric data on ICI luminosity basis
White	0.743	0.734
Bath green	.312	.318
Kitchen green	.341	.343
Orchid	.331	.325
Ivory	.587	.576
Maize	.556	.544
Bath blue	.238	.244
Delphinium blue	.165	.170
Royal blue	.045	.050
Kitchen red	.081	.080

For the measurement of samples which fluoresce appreciably, error 18 may be serious. When light from a sample which is fluorescing is evaluated by a receptor which is not corrected to respond as the human eye does, the result may differ from that which the eye would give. An instance in which the error occurred may be cited. Gibson and Keegan [20] found a certain piece of pink plastic material to be fluorescing strongly in response to yellow-green radiant energy, which

[14] The spectrophotometric curves for these plaques, together with those for the green luminosity filter, were obtained with the General Electric recording photoelectric spectrophotometer [23] by H. J. Keegan.

the green filter of the multipurpose reflectometer readily transmits. The yellow-green radiant energy was transformed by fluorescence of the sample into energy of an orange color which would be largely absorbed if directed through the green filter. Since, however, the green filter in the multipurpose instrument is located between the source and the sample, this orange light was not absorbed and the response of the cell was larger than it should have been. For this sample, the multipurpose instrument gave $A_{45°,0°}=0.220$, whereas a visual reflectometer, not subject to the error, gave $A_{45°,0°}=0.193$.

Regarding the 18 sources of error listed in table 2, we may say, in brief, that the multipurpose reflectometer must frequently be checked for possible effects of errors 1 to 12, that data must be corrected to eliminate the effect of errors 13 and 14, and that results must be examined for the possible presence of errors from sources 15 to 18, inclusive. In spite of the formidable array of sources of error, a well-built instrument used with appropriate and accurately calibrated standards and with suitable scale-correction curves will usually yield apparent reflectances in error by not more than two-tenths of 1 percent of the incident light.

VIII. APPLICATIONS OF THE MULTIPURPOSE REFLECTOMETER

1. COMPARISON OF SAMPLES VERSUS ACCURATE MEASUREMENT OF EACH, THE SUBSTITUTION METHOD

The multipurpose reflectometer has high precision and will identify small differences in apparent reflectance, color, gloss, and other properties; but it furnishes only relative, not absolute values. The solution of many problems met in practice requires, however, that the samples of a group merely be exposed for readings from the instrument and then be arranged in order according to the property in question. When this is the case and the samples of a group are similar, the last six sources of error which are so difficult to eliminate may often be ignored. Calibrated standards are not needed. A great saving of labor, in comparison with the amount required for accurate work, is therefore possible.

For quantitative results, a working standard representing the property being measured must be available. This standard should have an assigned value near those of the samples being measured. A substitution method, in which the samples are substituted for, rather than compared with, the standard, is employed. Of the two light paths the one not used for the samples being tested becomes the comparison beam; in it a single uncalibrated specimen is used.

The standard employed for an operation with the multipurpose reflectometer is seldom the primary standard of the property measured, but instead is usually a secondary or working standard which has been carefully calibrated in terms of the proper primary standard. In order to make the variety of measurements possible with the multipurpose device and to have available for any group of samples a standard of similar specifications, a large variety of working standards is needed. In the following description of the operations of the instrument, both the primary standard for each operation and the types of secondary standards most frequently employed are mentioned. These standards are noted in table 4.

TABLE 4.—*The measuring operations of the multipurpose reflectometer, some applications of each, arrangements for operation, and the standards used*

Quantity measured	Applications (The references are to papers illustrating each type of measurement, not in the majority of cases to use of the multipurpose reflectometer.)	Arrangements for operation					Standards	
		Position of sample	Scale used	Comparison surface	Gloss aperture	Spectral filters	Primary	Working
Luminous apparent reflectance, $A_{45°,0°}$.	To test paints, etc. for compliance with $A_{45°,0°}$ specifications [11]. To measure opacity and hiding power [37] To measure cleaning power of soaps and detergents [8]. To determine lightness of surfaces (for Munsell value) [22]. To measure $A_{45°\ 0°}$ of blacks [25].	Reflectance.	Reflectance.	Aluminum mirror.	Large	Luminosity (green); (none with Photox cell).	MgO	White, gray, or black porcelain-enamel or other ceramic surface.
Tristimulus colorimetry (of surfaces), $A_{45°,0°}$, through three filters.	To furnish trichromatic coefficients [29] To measure amount and indicate character of color differences [28, 29, 39]. To measure whiteness, yellowing, fading, bleaching, amount of bluing, tinting strength, etc. [53].	do	do	do	do	Green, blue, and amber tristimulus filters.	do	Porcelain-enamel or other ceramic surface similar in color and spectral character to samples.
Abridged spectrophotometry (of surfaces), $A_{45°,0°}$, through filters.	To supply approximate spectral-reflection curves [32]. To supply apparent reflectances for selected wave lengths [4].	do	do	do	do	Selected filters transmitting narrow spectral bands.	do	Ceramic plaque of known spectral 45°,0° apparent reflectance.
Specular gloss, $G_{s(45°)}$	To indicate shininess of surfaces [24] To furnish a measure of the resistance of surfaces to abrasion, acid attack, weathering, wear, etc. [50, 51]. To classify paints and other materials for gloss [30].	Gloss	Gloss	Black plaque	Small	Luminosity (green)	Perfect mirror.	Polished black glass or surface of liquid of known refractive index.
Contrast gloss, $\frac{A_{45°,-45°}}{A_{45°,0°}}$	To determine the glossiness of surfaces of low gloss [27]. To measure papers for power to produce glare [34].	Reflectance.	Gloss or reflectance.	None	Large	do	Mirror	Matte surface measured on goniophotometer.
Bloom, $A_{45°,-45°\pm 3}$	To measure the bloom of surfaces of high gloss [40].	Gloss	Gloss	Black plaque	Special	do	Perfect mirror.	Polished surface of opaque white glass.
Sheen, $G_{sh(75°)}$	To measure sheen, or the shininess of surfaces at near-grazing angles [31].	On special attachment.	do	Gray plaque	Small	do	do	Polished black glass or surface of liquid.
Transmission	To measure luminous transmissions [21] To measure abridged spectral transmissions [10]. To furnish trichromatic coefficients for transmitting specimens [29]. To supply data for chemical analyses ("chemical colorimetry") [10, 52].	do	do	Light-gray plaque.	Large	All filters (Choice depends on use).	Air, or solvent in cell.	Air, solvent in cell, standard solution, or spectral filter of known spectral transmission.

Plaques for secondary standards are, of course, chosen from stable materials. Ceramic materials, because of their relative permanence, are widely used as working standards for apparent reflectance, gloss, and trichromatic coefficients. In certain cases, surfaces of lacquer, paint, plastic, paper, or dry powder are also satisfactory as standards;

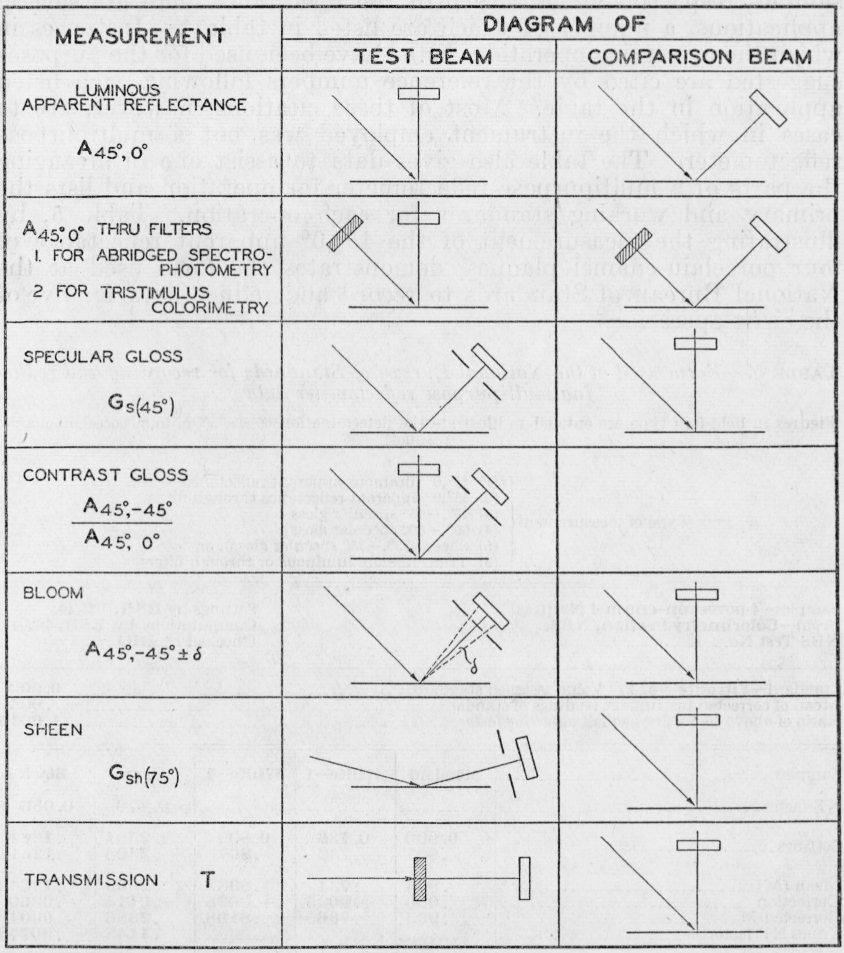

FIGURE 12.—*Different operations of the multipurpose reflectometer showing functions of both the test and comparison specimens for each operation.*

(The green filter, required with the GE cell for all measurements according to the luminosity function, is not shown.)

but specimens of any of these latter materials must be checked for permanence before use as standards. Moreover, since several porcelain enamels and ceramic tiles have been found to change color significantly with time, exposure to light, contact with water, or with other treatment, it may be said that each ceramic as well as nonceramic material must be suspected of uncertain permanence until it has proved to be otherwise. However, most porcelain-enamel plaques, blocks of opaque glass, and vitreous tiles used as standards have proved to be stable.

Considering abridged spectrophotometry and tristimulus colorimetry in separate categories, eight different measuring operations can be performed on the multipurpose reflectometer. These are shown schematically in figure 12 by the directions in which the test and comparison beams strike and leave the test and comparison samples respectively. For each of the operations there are several applications, a number of which are listed in table 4. Instances in which the measuring operations listed have been used for the purposes suggested are cited by the reference numbers following each listed application in the table. Most of these citations, however, are to cases in which the instrument employed was not a multipurpose reflectometer. The table also gives data to assist one in arranging the parts of a multipurpose reflectometer for operation and lists the primary and working standards for each operation. Table 5, by illustrating the measurement of the 45°,0° apparent reflectance of four porcelain-enamel plaques, demonstrates the form used at the National Bureau of Standards to record and reduce data for five of the eight operations.

TABLE 5.—*Form used at the National Bureau of Standards for recording and reducing multipurpose reflectometer data*

Figures in bold-face type are entered to illustrate the determination of $A_{45°,0°}$ of four porcelain-enamel plaques]

Type of measurement:
- x(1) 45°,0° luminous apparent reflectance
- (2) 45°,0° apparent reflectance through filters
- (3) 45°,−45° specular gloss
- (4) 60°,−60° specular gloss
- (5) Sheen (75°,−75° specular gloss), or
- (6) Transmission, luminous or through filters

Samples—**4 porcelain-enamel plaques.**
From—**Colorimetry Section, NBS.**
NBS Test No. ____________

Settings by **RSH, 5/25/40.**
Computations by **RSH, 5/25/40.**
Checked by **DBJ.**

Standard—**Vitrolite No. 1.** Value assigned standard	**0.909**
Mean of corrected instrument readings of standard	**.905**
Ratio of above two values equals *adjusting factor*	**1.0045**

Samples	Standard	**White—1**	**White—2**	**Gray**	**Black**
NF factor				**0.479**	**0.086**
Settings	**0.909** **.901**	**0.736** **.732**	**0.809** **.807**	**.2504** **.2495**	**.1264** **.1264**
Mean (M)	**.905**	**.734**	**.808**	**.2500**	**.1264**
Correction	**.000**	**+.0025**	**+.0028**	**−.0114**	**−.0360**
Corrected M	**.905**	**.7365**	**.8108**	**.2386**	**.0904**
Times NF factor				**.1148**	**.00778**
Times adjusting factor	**.909**	**.740**	**.814**	**.115**	**.0078**

Spectral filters used—green (luminosity)

Neutral-filter (NF) factors when green filter used: Refl. scale ________ 0.479, 0.086; Gloss scale ________ 2.09, 11.6

To extend the 1-to-10 range of the scales of the instrument for any measurements in which the small aperture is not used, one of two neutral filters is inserted in the gloss beam by turning the disk containing gloss apertures. With the insertion of either filter, the values of $A_{45°,0°}$ measured from the scale are multiplied by, or the values of transmission or gloss are divided by, the transmissions of the filters.

For the two filters in the instrument in the Colorimetry Section, National Bureau of Standards, the transmissions are:

Nominal transmissions of "neutral" filters	Exact transmissions of "neutral" filters		
	For green tristimulus filter (giving luminosity function)	For blue tristimulus filter	For amber tristimulus filter
0. 5	0. 479	0. 427	0. 480
. 1	. 086	. 065	. 088

These two filters were used in the operation illustrated in table 5 (where they are identified by "NF factors"), in which a gray and a black plaque together with two white plaques were measured for $A_{45°,0°}$ relative to a white standard. Instead of following the procedure illustrated, the gray and black plaques could have been measured against gray and black standards, respectively, and the neutral filters would not then have been required. There are many instances, however, where these filters are necessary. In tristimulus colorimetry, for instance, selective samples are frequently encountered which cannot be measured without the use of one or both of them. An orange-colored sample, as an example, might require that the reading for amber light be made with no filter, the reading for green light be made with the "five-tenths" filter, and the reading for blue light be made with the "one-tenth" filter.

2. LUMINOUS APPARENT REFLECTANCE, $A_{45°,0°}$

In illustrating the measurement of $A_{45°,0°}$ in figure 12, no spectral filter is shown, although the green filter is required if the GE cell is used. The freshly smoked surface of magnesium oxide is the primary standard [45] to which values of $A_{45°,0°}$ usually refer. Suitable working standards are white, gray and black ceramic plaques, which, when properly calibrated in terms of the standard MgO surface, may be used for the measurement of white, moderately reflecting, and black surfaces, respectively [15].

The interest in 45°,0° luminous apparent-reflectance measurements springs from widespread use of specifications for minimum apparent reflectance of paints and porcelain enamels, from the increased use of thin applications of high-opacity coatings of porcelain enamel and the resultant need for measurements of opacity, from the interest in light-reflecting properties of paints, ceramic tiles, and other materials and from the growth of specifications for opacity, blackness, and other properties. The multipurpose-reflectometer form for the measurement of $A_{45°,0°}$ is illustrated in table 5 and shows the settings and computations for determining the apparent reflectances of four porcelain-enamel plaques. The corrections entered on the form were read from the curves in figure 10. The first and second lines of settings were taken in opposite order to minimize the effect of any drift. The reader will realize in studying this form and the data thereon that in cases where less accuracy is required, certain of the indicated steps may be omitted; conversely, in cases where the highest accuracy is required, greater care would be taken to eliminate drift by more frequent settings upon the standard.

Judd ([37] p. 311, and [37a] p. TS10) has measured the TAPPI opacity of paper, $C_{0.89}$ by using settings of $A_{45°,0°}$ employing as white backing a matte surface of $A_{45°,0°}=0.89$ and as black backing a piece of black velvet.

It may be of interest for one not familiar with the lightness scale to learn that a midgray surface diffusely reflects only about 18 percent of the incident light. Lightness varies roughly as the square root [22] of apparent reflectance, and therefore surfaces reflecting only 50 percent are sometimes called white.

3. TRISTIMULUS COLORIMETRY

Successive settings with the green, blue, and amber filters are used for each measurement of the tristimulus coefficients of a sample. Most tristimulus measurements with the multipurpose reflectometer are 45°,0° measurements of samples having opaque surfaces. For such determinations, the magnesium-oxide surface is the primary standard and secondary standards of ceramic and other materials are calibrated and used in the same manner as for measurements of $A_{45°,0°}$. In addition to the colors of opaque samples studied by 45°,0° measurements, the colors of samples viewed by light specularly reflected from them or by light transmitted through them are sometimes of interest. Tristimulus measurements of gloss and transmission with the multipurpose reflectometer will give data about these latter properties.

Tristimulus measurements may be used (1) to find the approximate trilinear coordinates of a surface color, (2) to measure the amount and direction of a color change in a specimen, (3) to measure the amount and direction of a color difference between two samples, and (4) to furnish numerical measures of whiteness and yellowness. A more detailed account of the method and its applications is being prepared for presentation in the above-mentioned, forthcoming paper [29].

4. ABRIDGED SPECTROPHOTOMETRY

Abridged spectrophotometry is performed with filters which transmit spectral bands of more or less narrow wavelength range, and this differentiates it from tristimulus colorimetry. The instrument is capable of abridged spectrophotometry with any of the angular conditions which it employs, whether 45°,0°,45°,—45°, transmission, or other. The standards are those employed for other measurements having the same angular conditions. For "chemical colorimetry" the standard is an absorption cell filled either with the solvent or a standard solution of known composition.

The type of measurement made with photocell apparatus and filters isolating spectrally narrow bands is properly called abridged spectrophotometry because only a few filters (usually three to seven), and consequently only a few effective wavelengths, are used [32, 52]. Furthermore, only in rare instances do the filters restrict the spectral bands of energy employed for individual settings to the narrow wavelength ranges employed in true spectrophotometry. Spectral curves obtained by way of abridged spectrophotometry are neither complete nor accurate enough to be used for primary colorimetric specification, unless additional information concerning the spectral reflective or transmissive properties of the measured material is available. In many instances, however, an abridged spectrophotometric measurement is useful because it is known that some particular property may be studied by using a single spectral range or several ranges each isolated by spectral filters. One or two wavelength regions are most commonly found to be sufficient for chemical analysis by photometric means ("chemical colorimetry") [10, 52, 58].

Several manufacturers supply spectral data for their filters [7, 9, 12]. Only rarely however (as for instance in [52]), have builders of abridged spectrophotometers published adequate data on the spectral characteristics of the filters offered for use with their instruments. Before ordering a set of filters for abridged spectrophotometry, the spectral ranges which the filters are to cover should be decided upon. The manufacturers' data on the spectral characteristics of filters should be consulted to find those best suited. Glass filters rather than dyed gelatines are generally to be recommended, because they are less subject to deterioration from wear and fading. Adjustments of spectral transmission may be made by combining different filter components and, with glass components, by grinding to suitable thicknesses. Instructions prepared by Gage [14] are useful for determining the thicknesses of glass components required to give filters having prescribed transmissions.

5. SPECULAR GLOSS, G_s

The specular gloss, G_s, of a surface is usually expressed as the fraction of incident light specularly reflected by it. The primary standard of specular gloss is thus the perfectly reflecting mirror which, however, is physically unattainable. Working standards of specular gloss may, nevertheless, be prepared and accurately calibrated. By using Fresnel's equation [24], it is possible to compute for any optically smooth, nonmetallic surface of known refractive index the fraction of the incident light which will be specularly reflected at a given angle. Polished pieces of black glass and plaques having matte black surfaces on which has been spread a layer of monochlorobenzene[15] or other volatile liquid of known refractive index are found to be suitable as specular-gloss standards.

Specular-gloss measurements are frequently used for studies of paint, ceramic, and paper products; in addition, polished metal surfaces and metallic coatings are sometimes examined because of interest in their shininess or reflecting power. Recently there has developed a tendency to associate certain angles with the specular-gloss measurement of certain materials. Ceramic surfaces, for example, are usually measured at 45°, paint and lacquer surfaces at 60°, and paper surfaces at 75°. The different angles chosen correspond to the viewing conditions giving the best gloss differentiation of each type of product.

During measurements of gloss with the multipurpose reflectometer it is necessary to reduce the intensity of the reflection beam to correspond to the reduction of the gloss beam, because surfaces of nonmetallic materials specularly reflect only 0.2 to 6 percent of the light incident upon them at 45° instead of roughly 75 percent as does the aluminum mirror used in gloss position during apparent-reflectance operations. This reduction is accomplished by using black plaques

[15] The technique of flowing monochlorobenzene onto a clean sand-blasted surface of black porcelain enamel and quickly making a setting for specular gloss was worked out by D. G. Moore, of the Enameled Metals Section of the National Bureau of Standards, and is to be described in a forthcoming publication. Such a surface has proved in practice to be a better specular-gloss standard than one of black glass, because it is perfectly clean and optically smooth.

having values of $A_{45°,0°}=0.011$ or 0.004 as comparison surfaces in reflection position. As is shown in figure 11, the gloss-scale corrections become inconveniently large when these dark surfaces are used in reflection position. It will, however, be possible to rule a new gloss scale not requiring these large corrections whenever there is a demand for it.

6. CONTRAST GLOSS, G_c

A contrast-gloss device measures the amount of light reflected specularly by a surface relative to that reflected diffusely from the same spot at the same time. If the mirrors *A* and *B* (see fig. 7) are swung out of the light paths, the reflectometer will furnish approximate relative values of

$$G_c(\text{type 1}) \equiv \frac{A_{45°,-45°}}{A_{45°,0°}}.^{16}$$

However, contrast gloss at 45° is more frequently

$$G_c(\text{type 2}) \equiv \frac{A_{45°,-45°}-A_{45°,0°}}{A_{45°,-45°}},^{16}$$

[27, 30], or one minus the reciprocal of G_c(type 1).

There is no single primary standard of contrast gloss. Any good mirror or piece of polished black glass for which $A_{45°,0°}$ is zero will have a contrast gloss of infinity for type 1, or of unity for type 2. A working standard of contrast gloss is usually calibrated on a goniophotometer with which the ratio of the apparent reflectances for the two directions may be measured directly. A matte, white porcelain-enamel plaque is especially suitable.

Contrast gloss is generally used to describe the extent to which low-gloss surfaces depart from mattness. For instance, measurements of it correlate well with the tendency of pages of printed paper to produce glare from light specularly reflected by them toward the eyes of a reader.

Correction curves for contrast-gloss settings would be difficult to prepare. Contrast gloss is defined in terms of a ratio of amounts of reflection, whereas amount of scale correction depends chiefly upon the quantity of light passing from the reflection surface to the reflection-cell face. When suitable contrast-gloss standards are used, accurate values of contrast gloss may, however, be computed from apparent reflectances for the two directions separately measured and corrected.

7. BLOOM, G_b

No experience in the measurement of bloom has been gained at this writing. However, it should be practicable to develop a control method in the following manner. A gloss aperture would be prepared with a baffle centrally located to absorb the image of the source formed when a mirror is the gloss surface. Surrounding the centrally located baffle would be openings to pass any light which might be reflected by test specimens in directions adjacent to that of mirror reflection. Light reflected by surfaces in these adjacent directions indicates bloom of surfaces. Because the readings given with such a device would vary as the test surfaces varied in lightness and as the opening was changed

[16] Note that the values of $A_{45°,-45°}$ are apparent reflectances for 45° illumination and −45° viewing which are much greater than specular gloss values, $G_s(45°)$.

in shape, it seems safer to say that the reflectometer would compare otherwise similar surfaces for bloom rather than that it would measure them. A goniophotometer is needed for the latter task.

8. SHEEN, G_{sh}

A measure of sheen, G_{sh}, is merely a measure of specular gloss at a near-grazing angle, such as 75°. The device which is attached to the reflectometer for this measurement has been described above in section V, part 3. If values for the new angle are assigned to the standards for specular gloss at smaller angles, they may also be used as standards of sheen.

Papers and paper products have for many years been examined for gloss by inspection at near-grazing angles. It is not surprising therefore that an instrument which makes measurements at 75° is widely used in the paper industry [31]. In addition to interest in the sheen of papers, there is interest in the sheen of matte and semimatte paints, especially when these paints are to be used as interior finishes.

9. TRANSMISSION, *T*

It is possible, by merely turning each of the mirrors 7.5° in the attachment which measures sheen, to provide an attachment which measures transmission, *T*. Filters and clear solutions in glass-walled cells may be studied with this attachment. No material standard is needed, since comparisons may be made directly with the clear beam of the glass cell filled with the solvent used. Because it is sometimes possible to obtain filters of known spectral transmission when similarly measured opaque plaques are not available, transmission studies have, on occasion, been used to check the accuracy of the multipurpose instrument for tristimulus colorimetry and abridged spectrophotometry.

IX. SUMMARY

The design, construction, calibration, and use of a reflectometer having a wide variety of applications have been described. This multipurpose reflectometer is used to measure factors related to the appearance of ceramic products, paints, textile materials, papers, chemicals, and so on. The quantities most often evaluated are luminous apparent reflectance (indicative of lightness), trichromatic coefficients (indicative of chromaticity), and specular gloss (indicative of shininess). In addition, however, transmission, three other kinds of gloss, and abridged spectrophotometric values may be obtained with the apparatus.

The design of the reflectometer is based on the null principle. Light from a single source is directed along two separate paths. The beam reaching one cell is reflected specularly from one specimen; that reaching the second cell is reflected diffusely from the other. A galvanometer is used to indicate when the amounts of light in the beams have been adjusted so that each cell is generating the same current. By using the null method and beams which are geometrically different, a number of measuring operations are possible. However, the nonuniform photoelectric properties of manufactured barrier-layer photocells make it necessary to select from large groups of cells pairs which are suitable for use together in an instrument.

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Typical of the applications of the multipurpose reflectometer are the following: Measurement of the apparent reflectance, hiding power, and opacity of paints, papers, and porcelain enamels; measurement of the cleaning power of soaps and detergents; measurement of the magnitude and character of color difference between paint, cloth, ceramic, paper, or plastic samples of nearly the same color; measurement of whiteness, yellowing, fading, bleaching, blueing, and of tinting strength; determination of approximate spectral reflection curves; measurement of shininess of surfaces; classification of paints and other materials for specular gloss; measurement of luminous transmissions and approximate spectral transmissions of transparent solids and liquids. These last measurements are useful in chemical analyses.

When necessary precautions are taken, the multipurpose reflectometer may be made to operate with high precision; when proper standards are used and corrections applied, accurate results may be obtained. It is believed that the instrument will prove especially well suited for the measurement of small differences in lightness, color, and gloss between samples which are nearly identical.

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