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6—A GENERAL-PURPOSE PHOTOELECTRIC PHOTOMETER AND ITS USE IN TEXTILE LABORATORIES

By N. H. CHAMBERLAIN

INTRODUCTION

During the course of research on textile projects, it frequently happens that long series of measurements are required of some physical property of textile fibres, yarns, or fabrics, such as fibre diameter or length, yarn regularity, fabric thickness, lustre, or weight; or it may be that research in colour chemistry necessitates repeated determinations of the concentration of dyestuff solutions, or the depth of shade attained by dyed patterns. In some cases the methods available for such determinations are simple and rapid, but in others, notably fibre diameter, yarn regularity, and the reflection colorimetry of dyed fabrics, this is not so. Long series of measurements of fibre diameter with a microscope are not only tedious and time-consuming, but throw a definite strain on the operator's eyes; further, particularly in the case of fine fibres, their accuracy leaves much to be desired, owing chiefly to the difficulty of defining the edge of a cylindrical object such as a fibre with a lens of high power. (The projection method, using fibre cross-sections, is not available if the fibres to be measured have to be preserved for further work, as is nearly always the case.)

It so happens that a large proportion of these physical properties are either dimensional in character, or optical, and there seems to be no good reason why the photoelectric cell should not replace the eye with benefit both to the operator and the accuracy of his results. Some attempts in this direction have already been made, notably by Barker and Stanbury[1], who used this method for the determination of yarn regularity, McMahon[2] who determined the amount of kemp in fleece samples photoelectrically, and Cunliffe[3], who has utilised a photoelectric cell in conjunction with a valve potentiometer for absorption colorimetry. In the two former cases it is doubtful whether the apparatus described possessed the necessary degree of robustness and fool-proofness for routine use in the hands of students and semi-skilled operators.

The present paper is an account of an attempt to produce a general-purpose photoelectric photometer capable of adaptation to the measurement of at least a few of the properties mentioned, together with some of the results obtained in its use.

The Criteria of an Ideal Apparatus

Before proceeding to a discussion of the actual apparatus, it may be well to summarise the properties and qualities that were aimed at. The degree to which these have been achieved can then be the better assessed. First then, the apparatus should, if possible, be direct-reading. Null methods and compensation methods have undoubted advantages as regards absolute precision, but become tedious when long series of measurements have to be made. Second, the final instrument upon which readings are taken must be robust, quick in action, and capable of withstanding reasonable overloads for short periods without damage and without altering its calibration. Moving-coil instruments of the pivoted type such as milliammeters, millivoltmeters, or voltmeters, answer this description, and have this additional advantage, which may be given as the third desirable attribute of the apparatus, that they may be used in full daylight and without any particular precautions against vibration, stray fields, etc., such as are often necessary when reflecting galvanometers, electrometers, and the like are employed. Fourth, if at all possible the whole apparatus should be mains-driven from A.C. mains, and the inconvenience of batteries, for either high- or low-tension supply, eliminated. Fifth, the apparatus must have a stable zero and a calibration which requires checking only at infrequent intervals. Sixth, straight-line relationships between the quantity measured and the instrument reading are very desirable, as simplying calibration very considerably. Seventh, the random error of individual readings should not exceed 1 per cent. The impression gained from a study of the literature seems to be that this figure, while by no means the limit of accuracy to be obtained from photoelectric equipment under stringent conditions of control and with considerable experimental elaboration, represents just about what may be expected from careful design, a reasonable use of automatic control where possible, and commercial light sources and photocells. Most experimenters have condemned the use of the mains as a source of power if accuracy of this order is required, but the objection is largely bound up with the way in which the photocell is used, and full advantage has not been taken of the various automatic voltage- and current-controlling devices which are now commercially available.

General Considerations in Design

The principles of operation of photoelectric cells are too well known to require detailed description. Emission cells only are considered in the present connection, because this type gives the greatest precision in practice, and is the only type to which valve amplification can conveniently be applied. The emission photocell is essentially a current generator; the most sensitive type, the caesium-silver oxide gas-filled cell, gives a minimum of 75 microamperes per lumen of incident light, when the latter is that from a tungsten-filament electric lamp. Vacuum cells have sensitivities of approximately one-tenth this figure or less. Quantities of light of the order of one lumen, however, are rarely allowed to fall on the cell. In the present case, preliminary calculations confirmed by rough experiments showed that the amount of light which would be available at the cell cathode in most of the applications suggested earlier, would rarely exceed one millilumen, and might be only one-tenth of this, namely, 0·0001 lumen. The currents to be measured, to an accuracy of one per cent., will thus vary from about one-tenth to one-hundredth of a microampere. Whatever type of apparatus is used, therefore, it must be sensitive to at least 10^{-10} ampere. Now, in practice, the photocell is always made to function as a generator of voltage rather than of current, by causing the photoelectric current to pass through a large external resistance termed the load resistance, and measuring the voltage drop across this resistance. In theory, since the cell itself has an extremely high internal resistance, the load resistance also can be made very great, and thus small photoelectric currents can be made to generate large voltages in it. Thus, in the present case, if a load resistance of 100 megohms is used, a current of 0·1 microampere will give a voltage drop of 10 volts across it. The only instrument capable of measuring this voltage directly, however, would be an electrometer such as the Lindemann or Compton instrument; for since the instrument will be connected in parallel with the load resistance, its own internal resistance must be high compared with the load resistance, or the shunting effect of the instrument will reduce the effective value of the latter, and thereby decrease the sensitivity of the apparatus. The electrometers mentioned may have an internal resistance as high as 10^{13} ohms, which is quite sufficient to render the shunting effect on even a 1000 megohm load resistance negligible, but for present purposes such instruments have been ruled out as unsuitable for reasons already given. No moving-coil instrument, of course, has an internal resistance of anything approaching this figure; hence, if such instruments are to be employed, valve amplification becomes essential.

There are, broadly speaking, two policies which may be pursued in regard to valve amplification; either the steady photoelectric current obtained when light is incident on the photocell may be passed through a load resistance as already described, and the D.C. potential difference between its ends amplified by means of a D.C. amplifier; or, alternatively, the photoelectric current may be suitably interrupted so as to give an alternating current through the load resistance at audio frequency, resulting in an A.C. potential difference across it, which is then amplified by means of a standard audio-frequency amplifier. The choice has, apparently, almost universally gone to the first method; but the second possesses so many advantages that it seems remarkable that it has not been seriously considered in practice. The only published work appears to be that of Hampson and Richards[1], who used interrupted light and valve amplification with rectifier-type photocells to measure the whiteness of laundered fabrics.

D.C. amplifiers, if high gain is required, suffer from many disadvantages, of which the chief is that of instability. Unless separate insulated high-tension batteries, or their equivalent, are provided for every stage, coupling between stages occurs through the common impedance of the high-tension supply, and this cannot be eliminated by the decoupling arrangements used in A.C. amplifiers, since these are not applicable in D.C. circuits. As a result, D.C. amplifiers tend to be either elaborate as regards battery arrangements, or unstable, and the use of the mains as a source of high-tension supply is almost out of the question. Further, since slight variations in either high-tension or low-tension supplies cause exactly the same effects in the circuit as variations in the input potential which is to be measured, such supply variations are amplified together with the input voltage and superimposed upon the amplified output; while slow variations in supply voltage cause drift and an unstable zero. To this class of amplifier belongs the electrometer triode as used in valve potentiometers for the estimation of *p*H by means of the glass electrode. Here the effects mentioned are minimised by using only one stage, thereby avoiding instability due to inter-stage coupling; by supplying both high- and low-tension voltages from large-capacity accumulators, thereby minimising drift and spurious responses; and finally by using a null method with a sensitive microammeter in the anode circuit of the valve as indicating instrument. Under these circumstances a linear relation between input and output is not required, but it would not in any case be obtained except over comparatively small ranges. Cunliffe (*loc. cit.*) has recently described a method in which a photoelectric cell is used in conjunction with a valve potentiometer of the above type to measure the light absorption of coloured solutions. Finally, all D.C. amplification schemes as applied to photocells encounter the difficulties caused by stray light. The cell is quite unable to differentiate between light falling on its cathode from the source to be measured, and light coming from any other extraneous source. Consequently, stray light, whether daylight or artificial light, must be rigorously excluded, and this perhaps has not always been achieved as thoroughly as experimenters have hoped and desired. Its accomplishment generally involves either the use of a dark-room for the apparatus, or the enclosure of both the cell and the light source in a light-tight box, all manipulation being performed from outside the box, and the lid closed during observations.

When A.C. amplification is used, the position is entirely different. Suppose the light from the experimental source is interrupted periodically by some suitable mechanical arrangement. The photoelectric current will then alternate in similar fashion, and an A.C. potential difference will be set up across the load resistance. Such a potential can be amplified, providing the periodicity of the alternation is suitable, by means of an audio-frequency amplifier, and the design of such amplifiers, of high gain and perfect stability, has reached a very high level as a result of the commercial developments of broadcasting. Instability through interstage coupling is completely eliminated by means of suitable decoupling arrangements, and since the amplification is dependent mainly on the shape of the valve characteristics, and is practically independent of high- and low-tension voltages over a reasonably large range (particularly if automatic grid bias is used), drift is minimised and a stable zero obtained. As output meter, an A.C. voltmeter of the metal-rectifier type may be employed. Such instruments are robust and of high internal resistance, and will stand a reasonable amount of misuse and temporary overloading without disastrous results. The power supply to the amplifier may very well be taken from the A.C. mains, after rectification and suitable smoothing, and valves are available with indirectly-heated cathodes suitable for A.C. supply through a step-down transformer. The output from such an amplifier can very easily be made a linear function of the input. Last, but by no means least, the stray light difficulty is removed; for if the stray light falling on the cathode of the photocell is " continuous " (i.e. non-interrupted) light, while it will cause an increased *D.C.* current to flow through the load resistance, and in consequence will give rise to a D.C. potential across its ends, this will have no effect on the amplifier providing the input to the first stage is taken, as it normally is, through a condenser. In actual practice, it has been found that the cathode of the photocell can be flooded with daylight while measurements are taking place without the slightest effect on the output meter. Stray light from lamps running on A.C. circuits produces a very minute A.C. component in the load resistance, due to the fact that the filament of an electric lamp, although of relatively high heat capacity, does follow to some slight extent in temperature the alternation of the supply voltage. As a result, large amounts of stray light from such sources do have some effect on the amplifier. It is a fairly simple matter to avoid such effects, by using apparatus in daylight only, or screening any auxiliary lamps that must inevitably be used. In any event the sensitivity to stray light, even from A.C. lamps, is enormously reduced as compared with that of a photocell connected to a D.C. amplifier, and using " continuous " light.

The basic apparatus (of which Fig. 1 gives a general view), falls naturally into three parts, the amplifier, the light source and its associated interrupter mechanism, and the cell and its potential supply. These three components will therefore be described separately. Other auxiliary apparatus required for individual applications will be described as these are dealt with.

The Amplifier

The amplifier in its final form consists of a three-stage transformer-coupled circuit of conventional design. Details of construction will not be given, as they follow well-known and orthodox radio practice. Certain points arising in connection with the application of such an amplifier to quantitative work of the present character may, however, be of interest.

The chief difficulty encountered when attempts to find a suitable amplifying arrangement were first made, was that of hum in the output. All amplifiers deriving their power supplies from A.C. mains, and more particularly those employing A.C. for cathode heating purposes, generate hum,

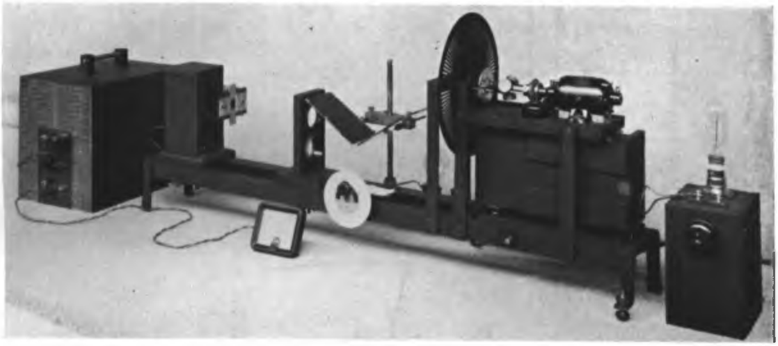

Fig. 1

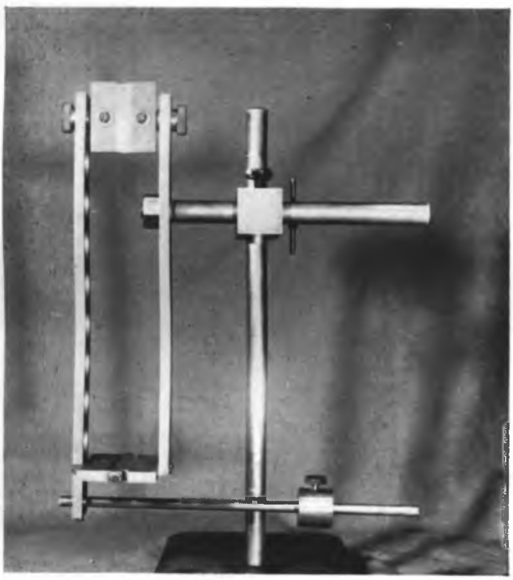

Fig. 6

Measurement of fibre diameter apparatus (p.T72).

(Face page T64)

to a greater or less extent, in their output. This hum, which has the effect of causing the amplifier to show a positive output with no intentional input, is due to a variety of causes, some of which are readily eliminated, while others can be overcome only with great difficulty. In the present case hum due to insufficient smoothing of the rectified high tension supply was obviated by means of a two stage choke-capacity filter with condenser input, followed by extra resistance-capacity filters formed by the usual decoupling arrangements, to the first two stages. Cathode bias was used on all stages, and the cathode bias resistance by-passed by large-capacity electrolytic condensers (*see* Fig. 2). The input circuit of the first valve was completely screened by

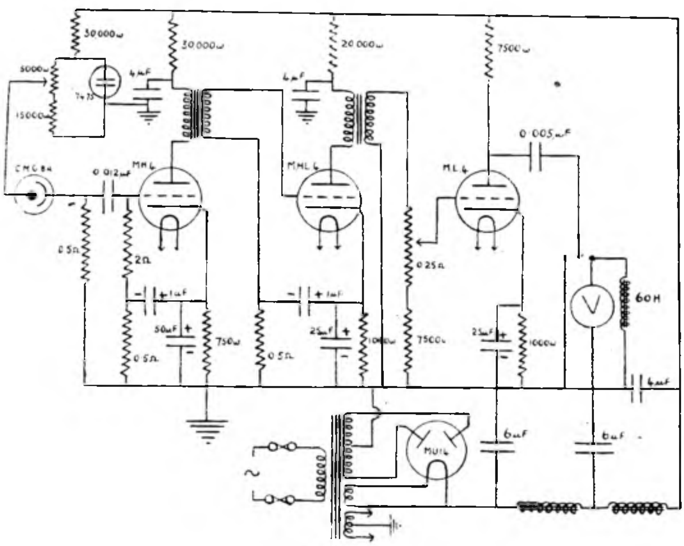

Fig. 2

enclosing it in an earthed sheet-iron box, and the lead to the grid of this valve from the photocell consisted of screened wire with the screening earthed. Transformer coupling was employed in preference to resistance-capacity coupling in order to keep the valve grids at low impedance to earth, and the grid circuits decoupled as shown in Fig. 2. The hum is approximately 0·40 volt at maximum gain, and decreases as the gain is reduced. This residual hum, which probably arises either from slight heater-cathode leakage or from capacitive coupling between heater and grid pins at the valve-holders, can be further reduced by reducing the grid-circuit impedance of the first valve, but this involves a reduction in the photocell load resistance and consequently a loss of sensitivity.

The valves (Osram) used in the amplifier are, first stage MH4, second stage MHL4, and output stage ML4, all triodes. The exact component values, together with the conventional circuit diagram, are shown in Fig. 2. The actual amplifier is built in two sections, the upper containing the power transformer, rectifier valve, and filter circuits, and the lower the amplifier proper. A sheet of soft iron covers the whole of the underside of the base-board on which the upper section is mounted, and is earthed, in order to prevent hum pick-up from the power transformer and first smoothing choke, which are also additionally screened. The whole is enclosed in a brass case which is also earthed, and the input and output are taken from opposite ends of the amplifier so as to avoid any possibility of feed-back resulting in instability.

The mains transformer is rated at 350-0-350 volts, which, after rectification, gives a smoothed high-tension voltage of approximately 360 volts at 30 milliamperes load. This voltage is adjusted by means of a resistance in series with the first smoothing choke, which happens to have a resistance (D.C.) of only 250 ohms. If a higher-resistance choke were used, this resistance might not be necessary. In any event its value must be determined by trial and error, and it is therefore not shown in Fig. 2. The load resistance of the output valve (7500 ohms) carries approximately 13 m.a., and therefore dissipates approximately 1·3 watts. In order that 1-watt type commercial resistances may be used without overloading, four 30,000 ohm resistances are connected in parallel to give the 7500 ohm load, the wattage dissipated in each being then well within its rating. This device is adopted in several other cases to avoid overheating these composition resistances, and so to ensure stable performance from them. The output of the amplifier is taken across a 60 henry choke between the anode of the output valve and earth, using a ·005μF series condenser to block the D.C. voltage at the anode; this arrangement serves as an output filter, still further reducing residual hum. A switch is arranged to short-circuit the meter during adjustments to the light-source and photocell, and so avoid accidental overloads as far as possible. The gain control of the amplifier consists of a 250,000 ohm potentiometer, in series with a 7500 ohm resistance, across the secondary of the second transformer, the moving contact of the potentiometer being taken to the grid of the third valve. With this arrangement, the 7500 ohm resistance prevents the gain from being reduced so far, even at minimum setting of the potentiometer, that the second valve grid is overloaded and linearity between input and output is upset. The range over which the voltage gain may be varied is from 500 to 16,000 (first valve grid to output meter), at 150 cycles, and the output is a linear function of input over the whole of this range.

Regarding the input circuit of the first stage, it has already been stated that the photocell is always used in conjunction with a load resistance, which converts the current output of the cell into a voltage output suitable for application to a valve amplifier. It might be thought that sensitivity could be increased very greatly by using high values of load resistance, but in practice several considerations militate against such a procedure. In the first place, the load resistance is in parallel with the input impedance of the valve; this latter is a complex quantity depending on several factors when A.C. voltages are concerned, but with commercial valves its value is rarely higher than about 10 megohms. Consequently, there can never be any virtue in making the cell load higher, or even as high, as this figure. Apart from the valve input impedance, if the input to the grid from the cell load resistance is taken through a condenser, then the valve must have an additional grid resistance in order to carry the bias voltage developed in the cathode bias resistor to the grid, and this also is in parallel with the load resistance. Since, on account of the hum difficulty already referred to, this grid resistor must have a reasonably low value, say two megohms or so, the load resistance will be seriously shunted by the grid resistor if its value is much greater than about 0·5 megohm. There is, in addition, a further reason for keeping the load resistance down to something of this order, at least when gas-filled photocells are to be used. In these cells, the photoelectric current is never saturated, i.e. independent of the voltage applied across the cell, as it is in the case of vacuum cells. In consequence, the "signal" voltage developed across the load resistance is always subtracted from the total voltage applied to the cell and load in series, leaving a portion only of this voltage to be applied across the cell, this portion being smaller, the greater the photoelectric current taken from the cell. The result of this is, in effect, that if the signal voltage constitutes any appreciable fraction of the total applied voltage, the cell is no longer working under constant voltage conditions, and the current output is no longer strictly proportional to the incident light. Hence, if linearity is demanded, the load resistance must have such a value that the signal voltage developed across it is always a negligible fraction of the total voltage applied to the cell. For these reasons, the load resistance used in the present case is 0·5 megohm, and the grid resistor 2 megohms. The coupling condenser has a capacity of 0·012μ.F., and is a good-quality mica-dielectric one. It is essential that this condenser shall have negligible leakage, otherwise D.C. potentials developed across the load resistance as a result of stray light, photocell dark current, insulation leakage, etc., will be transferred via the leaky input condenser to the first valve grid, with unpleasant consequences as regards stability of output and drift. Campbell and Ritchie[5] recommend a load resistance of 0·25 megohm, coupling condenser 0·01μ.F., grid resistor 2 megohms, in very close agreement with these experimental values.

The output of the amplifier is a linear function of input up to the limit of the output meter scale, and the same is true at minimum gain. Maximum gain at 150 cycles is approximately 16,000, or 98 decibels (input 1 mv across 0·5 megohm, output 16 v across 20,000 ohms). Since only one fixed frequency is to be amplified in the present case, the shape of the frequency characteristic is of little importance, except in assessing what variation of frequency may be permitted in the interrupter without serious error. It is of normal shape for a transformer-coupled amplifier.

The Light Source and Interrupter Mechanism

The light source used is a gas-filled automobile headlamp bulb, rated at 36 watts at 6 volts, and is supplied from an A.C. transformer. The secondary voltage of the transformer is 12 volts, the extra 6 volts being dropped in a barretter (Philips, No. 1012) connected in series with the lamp. This barretter passes 6 amps. at any voltage between 5 and 30 volts, and serves to stabilise the light source to a very considerable extent. It is not capable of dealing with short-period fluctuations in the supply, but does ensure that long slow variations are effectively smoothed out, and so prevents zero drift due to this cause. Rapid, small fluctuations round the mean are of little importance.

The lamp is contained in a ventilated lamp-house having a condensing lens 2 in. in diameter and 6 in. focal length, so that a parallel beam may be thrown on to the interrupter disc. The latter consists of a brass disc 12 in. in diameter, pierced with 96 radial slots, each $1\frac{5}{8}$ in. long, arranged with their inner ends on a pitch circle of 3·82 in. radius. Each slot is $\frac{1}{8}$ in. wide at this end, opening out to 11/64ths in. at its outer extremity, and they are therefore separated by a solid portion of the disc equal in width to the slot. The disc rotates in front of a mask pierced with seven slots identical with those in the disc, and the light beam is directed so as to pass through the slots of the mask and disc when these are coincident. When the disc is rotated therefore, the light beam is completely interrupted 96 times per revolution, giving, at 800 revs. per minute, a frequency of about 1300 cycles/second to the A.C. component of the photocell current. The disc is mounted in ball bearings, and driven by means of a 1/40th H.P. A.C. commutator motor. Its speed is controlled by a centrifugal governor of the friction type, similar to that used for controlling electric gramophone motors. Measurements of disc speed made with the Ashdown Rotoscope indicated that the governor was capable of maintaining a speed constant within ± 5 revs./min. at 800 revs./min. for an indefinite period. The details may be seen in Fig. 1.

The periodicity of 1300 cycles/second was used in order that the amplifier should operate on as high and flat a portion of its frequency characteristic as possible; maximum sensitivity is thus obtained and minimum errors due to small variations in interrupter disc speed. The wave-form of the A.C. current generated in the photocell by light interrupted by a disc of the type described is not sinusoidal, but tends to be rather triangular. The output meter, being sensitive to wave-form as are all metal-rectifier instruments, will thus not measure accurately the RMS value of the output. This is of no consequence, however, since the wave-form is constant for a given disc at constant speed, and the output is not required in volts, but only in known arbitrary units.

The Photocell and its Potential Supply.

The photocell used is an Osram CMG8A caesium-silver oxide gas-filled cell, and is mounted in a light-tight sheet-iron box, the latter being earthed as a protection against pick-up of stray A.C. fields. The particular cell used was marked for a normal supply voltage of 80 volts, this being approximately 0·6 of the glow-discharge voltage in the dark. The cell can be run at higher voltages than 80, provided that bright lights do not fall on it when the voltage applied is high, and so initiate the glow-discharge. The cell supply voltage is taken from the rectified and smoothed H.T. supply of the amplifier as shown in Fig. 2. A 30,000 ohm fixed resistance, in series with a 5,000 ohm potentiometer and a 15,000 ohm fixed resistance, is connected between the +H.T. line and earth. The current through all three is thus approximately 7 m.a. and the voltage drop across the potentiometer and 15,000 ohm resistance 140 volts. A neon voltage regulator (Mullard 7475, 140 volts striking, 95-100 volts running) is connected across the latter combination, and thus strikes when the H.T. supply is switched on. Thereafter it maintains the P.D. across the potentiometer + 15,000 ohm resistance combination at 96 volts. One end of the potentiometer is thus at 96 volts above earth potential, the other at +72 volts approximately. The cell anode is connected to the moving contact of this potentiometer, and the cell voltage can thus be varied from 72 to 96 volts, the mid-scale value being 84 volts. The neon stabiliser was found to be extremely effective in maintaining a steady potential to the cell.

The photocell housing has an aperture in the side facing the cell cathode, and over the aperture is fitted an ebonite extension chamber with removable lid, and grooved internally so that light filters or a ground-glass diffusing screen can be inserted in the path of the light reaching the cathode. This extension terminates in an adjustable slit defined by two pairs of overlapping metal plates so that it is adjustable both in width and length. In this way rough adjustments to the amount of light falling on the cell may rapidly be made.

Constancy and Linearity of the Apparatus

It is above all necessary that a direct-reading instrument shall be constant, i.e. both give reproducible readings under a standard set of conditions, and be free from zero drift. It is also a great convenience if the final calibration curve, relating the quantity to be measured to the output reading of the instrument, is a straight line. Calibration need only then be performed at one or two points instead of over the whole range to be covered.

In the present case the constancy of the apparatus was tested by allowing a small amount of light from the source to fall on the cell cathode through an aperture approximately 1·0 × 0·1 mm., a ground-glass diffusing screen being used in front of the cell to prevent the light from being concentrated on one tiny spot on the cathode, and an output reading of 10 volts was obtained by adjusting the amplifier gain. Leaving the conditions unchanged, the reading was observed every day for several hours over a period of several days, the amplifier, light, and motor being switched off each night. It was found that the whole apparatus required about 1½ hours after switching on from the cold to attain steady working conditions. This is by no means unusual, as a steady voltage output cannot be expected until valves, transformers, chokes, resistances, the barretter in the light supply, etc., have achieved their steady working temperatures. After this initial period, the reading was found to remain steady, apparently indefinitely, within ±1·0 per cent., i.e. the voltmeter reading remained between 9·9 and 10·1 volts.

Very occasionally an excursion of as much as 0·5 volt was observed, but such variations were invariably of short duration, a few seconds at most, and were attributable to the fact that the building in which the apparatus was used contained a large number of induction motors driving heavy machinery, which were started and stopped fairly continuously during the period of the observations. If constancy is to be maintained, lenses, lamp-bulb, and the photocell itself must be kept free from dust, finger-marks, and the peculiar translucent film that is apt to deposit on glass surfaces exposed to the air of many laboratories, particularly these containing a miscellaneous assortment of chemicals.

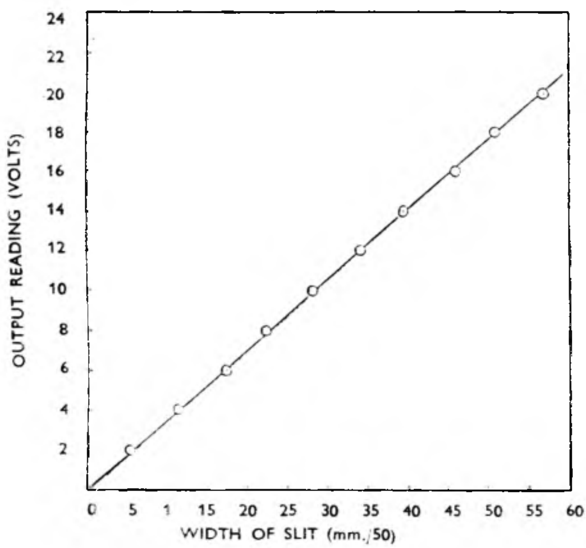

Fig. 3

As regards linearity, it is not of course possible to ensure that a linear output is obtained under all possible circumstances. Provided that the phenomenon or property to be measured can be made to modify the incident light beam in a linear manner, then linearity of output is possible; but if this is not the case, as, for example, in determining the concentration of solutions of coloured substances which do not obey the Lambert-Beer Law, then linearity is not to be expected. In the present case all that was sought was to show that the output reading was a linear function of the total amount of light falling on the photocell cathode. In order to test this point, a Brown and Sharpe vernier caliper was used. This instrument was set up in front of the photocell, its jaws being used as a parallel slit whose width could be adjusted at will and determined accurately from the vernier of the instrument. This slit was illuminated by throwing upon it an enlarged image of the centre slit of the interrupter mask. Evenness of illumination over the range to be covered was ensured by using only the centre slit of the mask, and only the centre portion of this slit. Readings of output voltage against slit width were taken, using as before a ground-glass diffusing screen to spread the light over the whole of the photocell cathode, and thus avoid errors due to varying sensitivity from point to point of the photoelectric surface. The results obtained are shown in Fig. 3 and indicate that the output is a linear function of the light input, and the straight line obtained passes through the origin. According to Campbell and Ritchie (*loc. cit.*), doubt has been cast by some workers on the possibility of true linearity between light input and electrical output in the case of gas-filled photocells; while it is possible that when such cells are used in bright lights and near the glow-discharge point linearity may not be obtained, it is plain that in the present case, using very feeble lights and an anode voltage well removed from the glow-discharge potential, perfect linearity is found. As Campbell and Ritchie remark, experiments in which linearity is achieved have greater evidential value than those in which it is not, because the cause of such departure from linearity may lie not in the photocell but in the way it is used. In addition to too high a potential and too bright a light, other possible sources of non-linearity lie in the use of too high a load-resistance, or a non-linear amplifier, and in stray light effects.

Applications of the Apparatus

(1) *As Nephelometer or Absorption Colorimeter.* The apparatus is readily adapted for use as a nephelometer.

As an example may be quoted the results obtained in the determination of sulphuric acid in a sample of A.R. perchloric acid. A calibration curve was first obtained using a solution of A.R. potassium sulphate made acid with hydrochloric acid, suitably diluted, and precipitated with barium chloride solution in a plane-parallel glass cell placed in the light beam. 10 c.c. of the sulphate solution were placed in the test cell, and 1 c.c. of 5*N* HCl was added. The output reading was then adjusted in all cases to 20 volts. 5 c.c. of 10 per cent. barium chloride solution were added, the mixture stirred rapidly with a glass rod, and the new reading taken as soon as it became steady, usually after about 2 minutes. Table I and Fig 4 show the results obtained.

Table I

mg. Sulphate (as H_2SO_4) present	Output reading 2 min. after adding $BaCl_2$
0·0	20·0
0·05	18·5
0·10	17·3
0·15	15·5
0·20	13·4
0·25	11·8
0·30	11·0
0·35	9·8

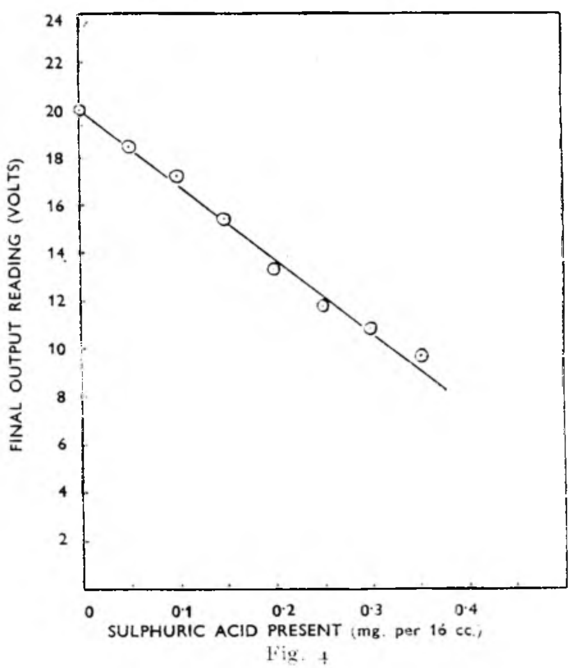

Fig. 4

The reduction in output reading is a linear function of the sulphate present up to 0·35 mg H_2SO_4 (after which readings became irregular owing to settling and flocculation). 10 c.c. of A.R. perchloric acid were then placed in the cell and treated exactly as before. The reduced reading was 18 volts, indicating a sulphuric acid content of 0·06 mg. in 16 c.c., or approximately $0{\cdot}6 \times 10^{-3}$ per cent. (w/v). It is difficult to see how such a quantity could be estimated with the same accuracy by any gravimetric or volumetric method.

The apparatus can obviously be used as an absorption colorimeter for the determination of dissolved coloured substances such as dyestuffs. In many cases light filters will be required in order to obtain maximum sensitivity. Cunliffe's paper (*loc. cit.*) gives an excellent account of the technique, which can be applied in the present case. The CMG8A photocell is not the best type to use in this connection, its maximum sensitivity lying in the red and near infra-red. The KMV6 potassium-silver oxide cell has some sensitivity over the whole of the visible spectrum and is better adapted to colorimetric measurements. This is not to say that satisfactory measurements cannot be made with the CMG8 cell, despite its inordinate sensitivity in the infra-red, as the following example shows.

Alizarin Light Blue RG (Sandoz) is a level-dyeing acid colour which is practically transparent to infra-red in aqueous solution; if the infra-red is filtered from the incident light by means of a copper chloride filter, the filtered light is blue, the dyestuff does not absorb strongly in the blue, and in any event the photocell is insensitive to blue light. Hence, the determination of this dyestuff with the caesium cell presents possibly as difficult a case as could be found. The difficulties were overcome to an extent sufficient to make an accurate determination possible by screening the majority of the infra-red out of the incident beam, using a green filter which still left a yellow or orange component of reasonable magnitude in the filtered light. For this purpose a green glass filter of unknown origin was used (possibly a glass coloured with copper compounds), but a dilute solution of 50 per cent. basic chromium sulphate used as a liquid filter was found to be equally effective. The results obtained in calibrating the apparatus with standard solutions of the above dyestuff and light filtered in this manner are given in Table II and Fig. 5.

Table II

Concentration of dyestuff (% w/v) (C)	Transmitted light (volts) (I)	Transmitted light (corrected volts) ($I - I_R$)	$\log(I - I_R)$
0·0	20·0	12·8	1·11
$0{\cdot}2 \times 10^{-3}$	18·6	11·4	1·06
0·4	16·5	9·3	0·97
1·0	13·7	6·5	0·81
2·0	11·0	3·8	0·58
3·0	9·5	2·1	0·32
4·0	8·6	1·4	0·15
6·0	7·6	0·4	−0·40

The absorption equation $I - I_R = I_0 e^{-kC}$ is obeyed by these results, as Fig. 5 shows, I_0 being the total intensity of incident light, I that of the transmitted light, and I_R that of the non-absorbable component of the incident light; while C is the concentration of the dyestuff in solution.

(2) *Measurement of Fibre Diameter.* The principle adopted for the measurement of wool fibre diameter is that of inserting the fibre to be measured between the edges of a pair of jaws, which otherwise meet so

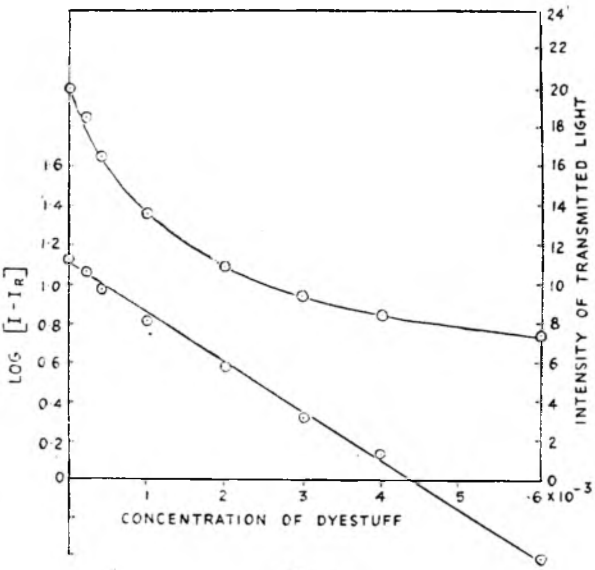

Fig. 5

accurately as to prevent any light passing through at the line of junction. The fibre thus holds the jaws apart, forming a narrow slit whose width is equal to the fibre diameter. Through this slit light is allowed to pass on to the cell, and the output thus obtained is a linear function of the fibre diameter. The actual apparatus is shown in Fig. 6.

The two stainless steel jaws are rectangular in shape, ¼-inch thick, chamfered to a thickness of approximately 1 mm. along the contact edge. A narrower contact face was not considered advisable, since even with light loading, the pressure on the fibre would become high, and distortion of the cross-section might result. Each jaw is mounted at the end of a rigid arm, and is adjustable in all directions so that accurately parallel setting is possible. The arms are pivoted together on steel needle-point bearings at a distance of 9 inches from the jaws, pivot friction being so small as to be negligible. One arm is clamped rigidly in a vertical position, and the other carries, at right angles to itself and attached below the pivot, a counter-balance arm with a sliding bobweight by means of which the pressure between the jaws when they are closed can be accurately adjusted. The jaws themselves are precision ground and lapped by hand into optical contact. A small semi-circular notch is filed in each jaw 1 mm. below its top edge, and the fibre is always inserted between this notch and the edge of the jaw. It is necessary that the point of insertion shall always be the same within narrow limits, owing to the fact that the slit obtained is not parallel, and the same fibre inserted, say at the bottom edge of the jaws, would open a wider slit than when inserted at the top edge. With the safeguard described, the possible variation of the position of insertion is not more than 1 mm., and the possible error due to this cause is limited to less than 0·5 per cent. with a pivot-to-jaw distance of approximately 230 mm.

The performance of the apparatus was checked against the microscope as follows:—Two uniform metal wires were available, one of steel with an optical diameter of 18 to 18·5 eyepiece micrometer divisions; the other, and rather more uniform, of tungsten with a diameter of 12 eyepiece divisions. A length of the tungsten wire was inserted between the jaws as standard, and the output adjusted, for comparative purposes, to 12 volts, giving 1 volt per eyepiece division. The steel wire was then found to give 18-18·5 volts output, i.e. the calibration curve is linear, and either wire can be used for setting purposes. Next, four individual wool fibres of varying diameter, 5 cm. long, were measured with the microscope at 10 points along their length, and also 10 readings were taken on each with the photometer. The means of these results are given in Table III.

Table III

Fibre	Microscopic diameter (eyepiece divisions)	Photometric diameter (volts output)
Tungsten wire (standard)	12·0	12·0
Steel wire	18·0–18·5	18·0–18·5
Human hair (minor axis)	16·0	16·39 } repeat 16·41 } determination
Cotswold	10·75	10·30
Lincoln	7·95	7·88
Merino (64's)	4·60	4·51

All micrometers involving the jaw principle tend preferentially to select the minimum diameter if the fibre to be measured is slightly elliptical in cross-section; whereas the microscopic method, in which the fibre is in effect mounted between transparent jaws (slide and coverslip) but measured at right angles to them, tends to do the reverse. Hence, in general, the diameters as measured microscopically tend to be slightly higher than when measured photometrically. In the extreme case of human hair, a smooth fibre having an elliptical cross-section of considerable eccentricity, the photometer will not measure the major axis at all, but invariably selects the minor axis, as the results indicate. With the microscope, it is generally difficult to measure the minor axis at all, unless the fibre has several turns of twist deliberately inserted into it before examination. This procedure is open to objection on the ground that the cross-section may be distorted by the strain imposed on the fibre, and focusing difficulties are increased, but was used in the present case to obtain the minimum diameter of the human hair measured.

As the difference between the photometric and microscopic diameter is greatest in the case of human hair, a further test was carried out, in which fifty hairs were measured photometrically, and fifty others of the same sample had their diameters determined microscopically, by cutting cross-sections and measuring the major and minor axes from the sections. The results are given in Table IIIA.

Table IIIa

	Mean diameter (μ)	Standard deviation σ	$\frac{2\sigma}{\sqrt{n}}$ (n=50)
Photometrically ...	55·8	10·3	1·54
Microscopically ...	54·9 (minor axis)	11·6	1·57

Since the difference between the two mean values for diameter is less than twice the standard error of either, the values do not differ significantly.

The actual value of one eyepiece division, determined by stage micrometer calibration, was $4{\cdot}27\mu$. The diameter of the tungsten wire used as standard is thus $51{\cdot}24\mu$. If the output is set to 17·08 volts with the standard in the jaws, the output meter will read $3{\cdot}0\mu$ per volt; set to 12·8 volts with the standard, $4{\cdot}0\mu$ per volt, and set to 10·25 volts, $5{\cdot}0\mu$ per volt. If a suitable standard is available the ultimate sensitivity can be increased to about $1{\cdot}0\mu$ per volt by using maximum amplifier gain. The accuracy of individual readings is considerably greater than that obtainable microscopically, since the voltmeter scale is easily read to 0·1 volt, whereas the eyepiece mcrometer can rarely, on account of the focusing difficulties already referred to, be read to a closer accuracy than 0·5 division. The apparatus is also directly applicable to the measurement of the thickness of films, metal foils, paper, etc., and, with the addition of suitable contact surfaces of greater area, to that of fabrics under known and controllable pressure.

(3) *Use as Optical Density Meter for X-Ray Photographs.* In order to adapt the photometer to the estimation of the position and intensity of the spots on X-ray fibre photographs, a narrow slit was constructed by cementing two safety-razor blades side by side on to a glass slip, leaving a gap of approximately 0·05 mm. between their edges. The length of the slit was defined by means of two pieces of opaque paper gummed to the opposite side of the glass, leaving a clear slit 2 mm. long. A mechanical microscope stage having verniers reading to 0·1 mm. was used to hold the X-ray plate in a vertical position in front of the photocell, the slit being fixed in front of the plate so that the razor-blades slid over the film side of the plate as the latter was traversed behind it; this arrangement ensured that the photo-

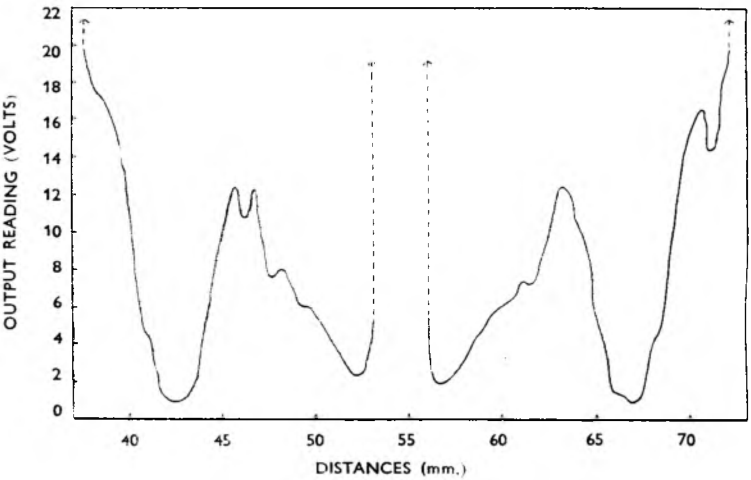

Fig. 7

graphic image and the slit opening were very approximately in the same plane. The position of the plate could be read from the verniers of the mechanical stage, while the slit, illuminated by forming an image of the lamp filament upon it with an auxiliary lens, passed light to the photocell in proportion to the density of that part of the photographic image which it covered at any particular moment. Fig. 7 shows the curve obtained in travelling along a centrally-situated part of the meridian of a fibre photograph. The whole of the plate cannot be examined at one amplifier setting unless detail is sacrificed near the centre, because the outer parts of the photograph are generally much less dense than the central zone where the important spots are often situated.

It is not suggested that the present example represents the ultimate sensitivity and resolution to be obtained from the photometer in this application. A more refined optical system, focusing a narrow image of an illuminated slit actually in the plane of the photographic image, would doubtless give greater resolution in complex spots, and experiments are proceeding in this direction. The figures suffice to show, however, the applicability of the apparatus in this connection.

(4) *Use as Glossmeter and Reflection Colorimeter.* The surface reflectivity and lustre of textile fabrics have been examined by means of a slight modification to the optical system of the apparatus. The parallel beam from the

interrupter disc is received on an inclined plane mirror, and directed downward at an angle of approximately 30° to the vertical to fall upon the sample to be examined, lying on a horizontal table, as shown in Fig. 1. Reflected light from the sample is received on a second inclined mirror, which directs it horizontally to an auxiliary lens, by which it is focused on the photocell cathode. The table holding the sample can be rotated about an axis passing through its centre, horizontally and at right angles to the direction of the light beam. A graduated dial indicates the angle through which the sample table is displaced from the horizontal.

If a high-reflecting surface, such as a mirror or sheet of glass, is placed on the specimen table, then, with the table horizontal, the reflected beam is directed into the photocell; but if the table is rotated either way from horizontal through an angle θ the reflected beam is rotated through an angle 2θ,

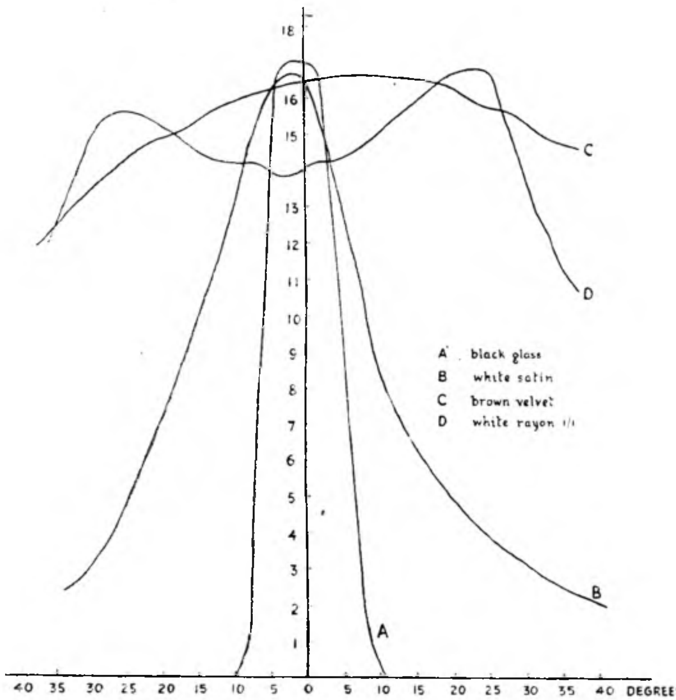

Fig. 8

and no longer falls on the cell. Instead, the cell receives any light diffusely reflected from the surface at an angle 2θ on one side of the specular direction, or position of the reflected beam. Thus, by plotting photometer output against angle of rotation of the specimen, a curve is obtained showing the intensity of the reflected light along the specular direction, and also at increasing angles on either side of it. Some curves for different materials obtained in this way are shown in Fig. 8. (These curves are not comparable as regards the axis of ordinates, the sensitivity of the amplifier having been adjusted in each case to give approximately the same output reading at maximum reflectivity.) The curve for the black glass should theoretically consist simply of a straight vertical line coincident with the axis of ordinates. In practice, however, the finite size of the light beam (which is necessary if an average sample of the surface is to be surveyed), and of the photocell cathode cause a spread of the kind shown. This curve is included for comparison purposes, as showing the order of selectivity to be expected with a highly-reflecting surface. The curve for white satin, a typical fabric of high lustre, shows well-marked reinforcement of the reflected light along the specular direction, as would be expected, whereas that for brown velvet (upright mohair pile, and therefore non-lustrous), shows very little reinforcement, but an almost flat distribution of diffusely-reflected light on each side of the specular direction. It is suggested that the ratio between the height of the peak and the spread of the curve can be used as a relative measure of lustre in a fabric. The remaining curve is interesting as illustrating one effect of fabric structure on surface reflectivity. It was obtained from a rayon fabric in which the weft was straight, whereas the warp threads did most of the necessary bending as the fabric was woven. The reflection curve shows two peaks symmetrically placed at an angle of $\pm 12^{\circ}$ from the specular direction, the fabric being illuminated along the direction of the warp. There is no doubt that the peaks are caused by the inclined floats of the warp threads, which become horizontal when the fabric is suitably tilted, and then constitute a set of reflecting planes with a specular direction of their own, inclined to that of the fabric in general. From the positions of the two peaks, it is possible to deduce the angle through which the warp threads in the fabric bend. The "shot" effect in bicolour shot silk fabrics is probably of this nature.

An obvious extension of this type of measurement is the determination of the depth of colour of dyed patterns. For this purpose the sample is laid on the specimen table and the diffusely reflected light measured at some considerable angle to the specular direction, so as to avoid the effect of lustre. Generally, the table is tilted backwards until the specimen is illuminated normally; the light diffusely reflected at an angle of approximately 40° from the normal then falls on the photocell. It is not claimed that fabrics differing widely in structure and material, say satin and velvet, could be examined as to their colour in this manner, but the necessity frequently arises for determining the relative depths of shade of a number of samples, generally of identical material and dyed with the same dye; for example in the testing of resist processes, or the measurement of fading. Here the method is rapid and convenient.

SUMMARY

A general-purpose photoelectric photometer suitable for routine use in textile laboratories is described, and some constructional details given.

Typical results are quoted, which have been obtained in using the photometer as nephelometer, absorption colorimeter, fibre diameter micrometer, glossmeter, and photographic density meter.

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Textile Chemistry Laboratory,
Leeds University.

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On the Existence of a Critical Temperature for Milling. By J. B. Speakman, J. Menkart and W. T. Liu.

Page T44, line 14: for "20" read "28".
,, ,, line 15: for "20" read "28".
,, ,, line 16: for "4·2" read "5·2".