Feb. 6, 1951 E. I. STEARNS, JR 2,540,797

METHOD AND APPARATUS FOR COLOR MATCHING

Filed Nov. 2, 1945 13 Sheets-Sheet 1

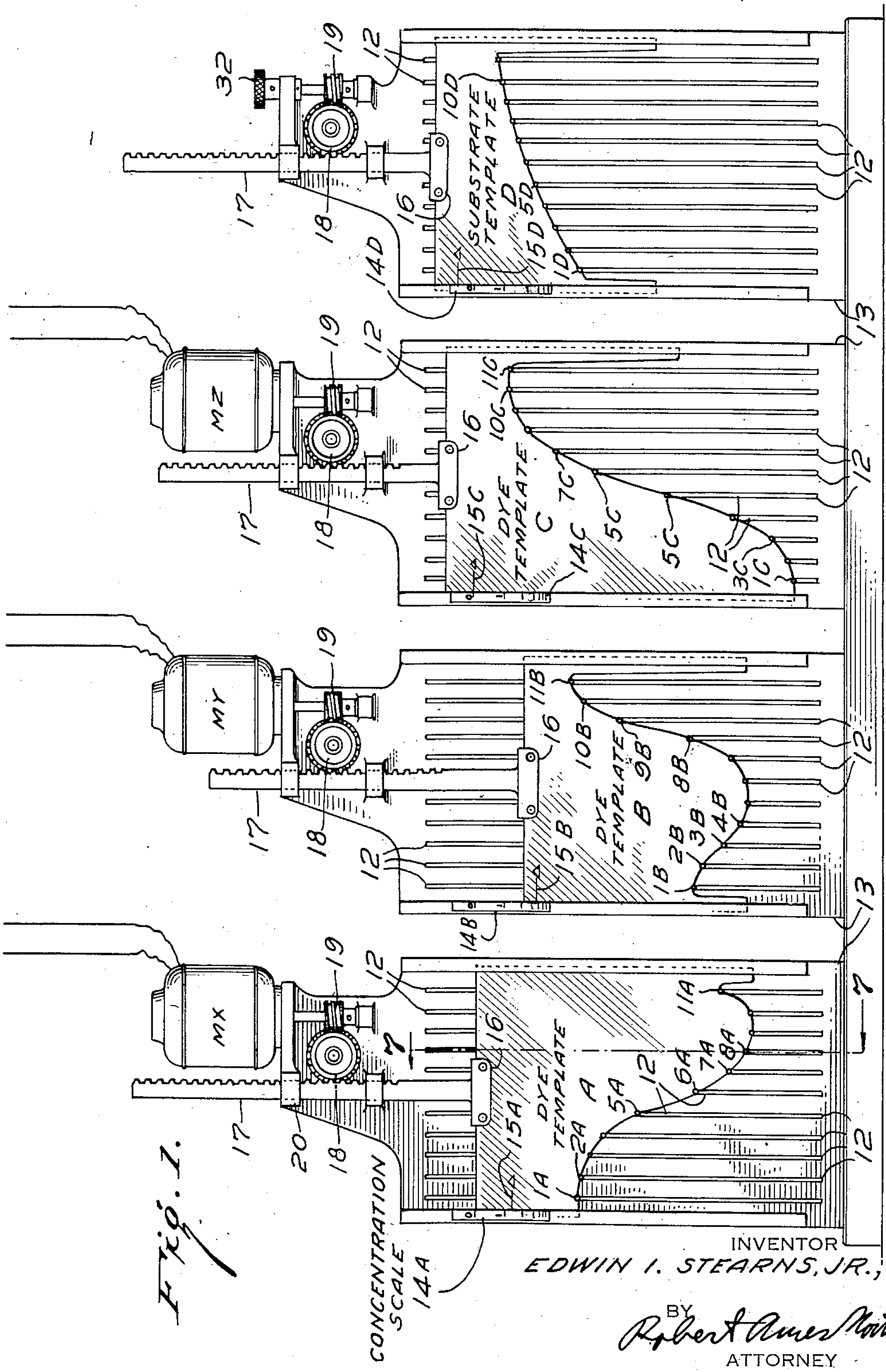

Fig. 1.

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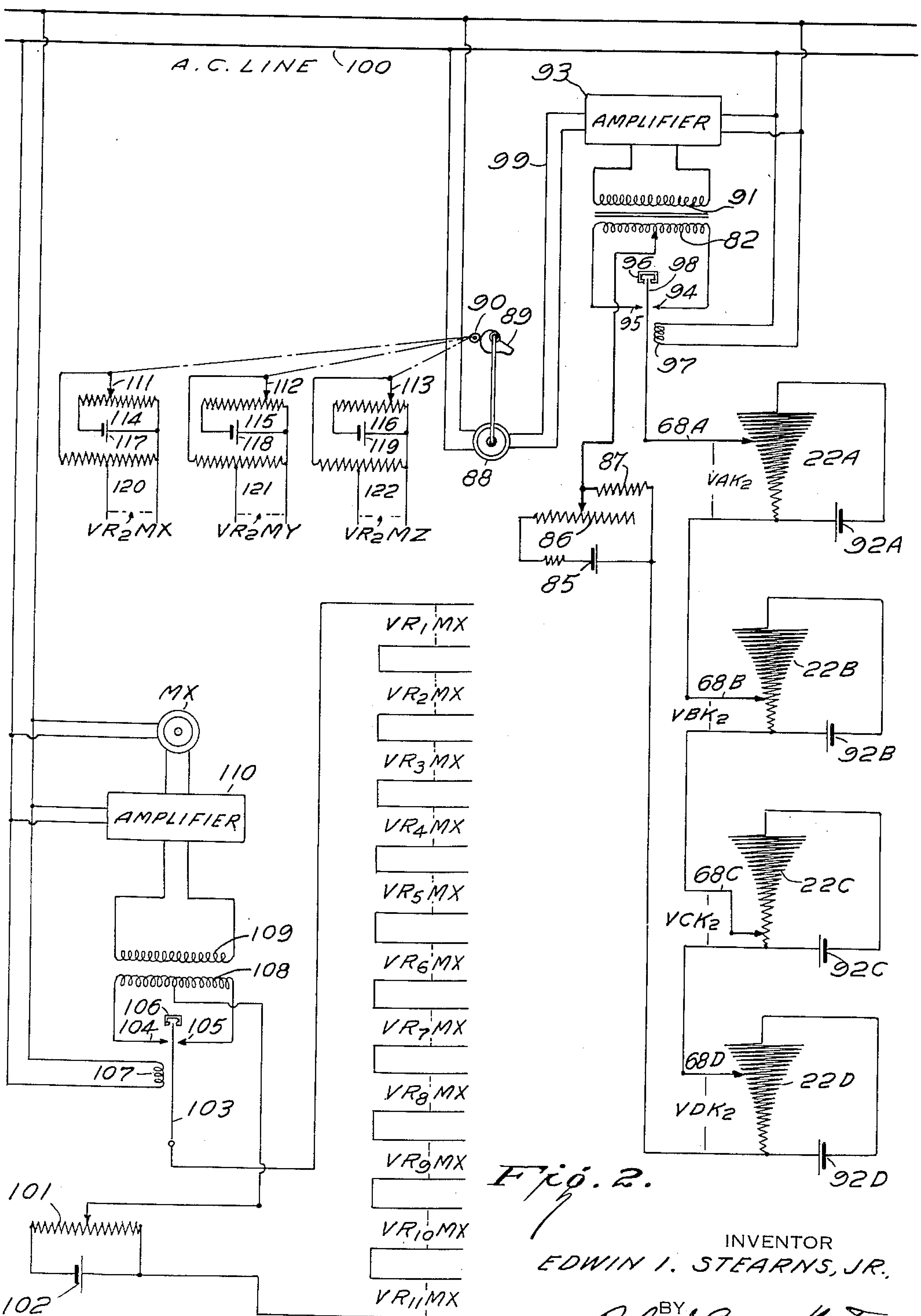

Fig. 2.

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METHOD AND APPARATUS FOR COLOR MATCHING

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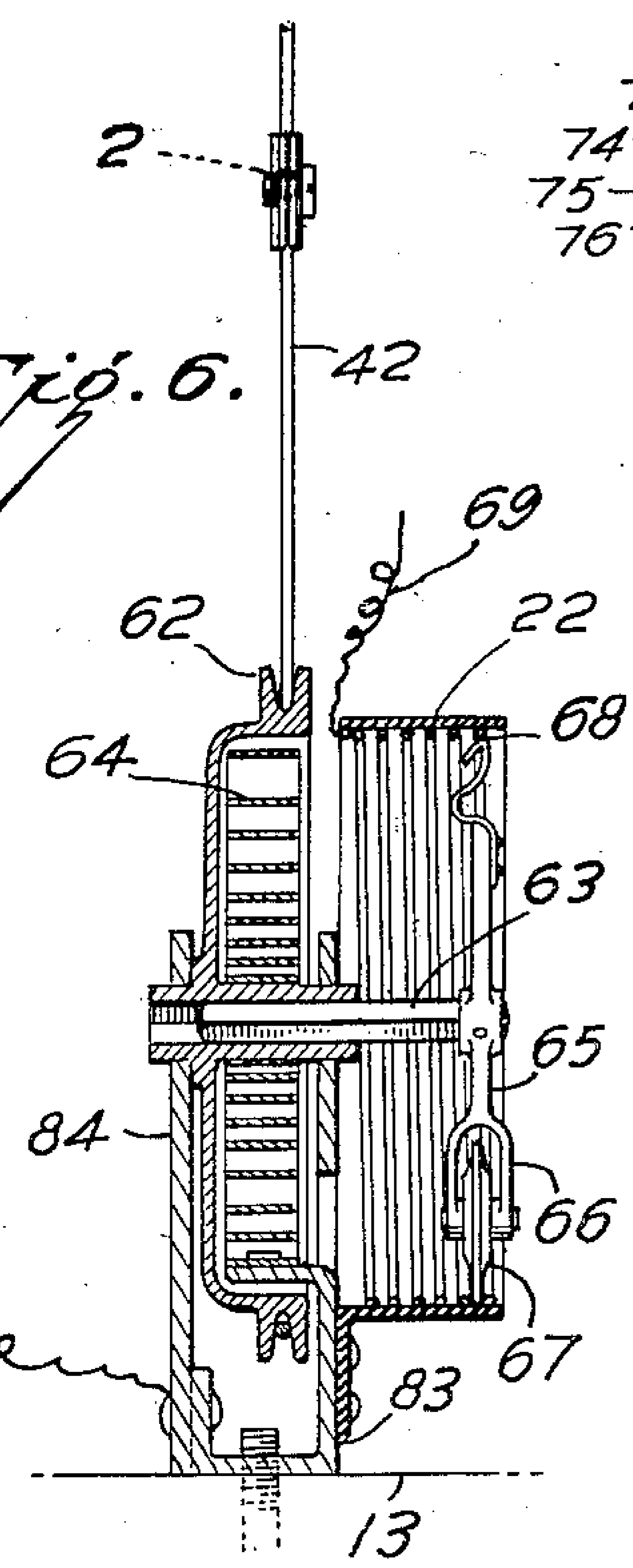
Fig. 6.



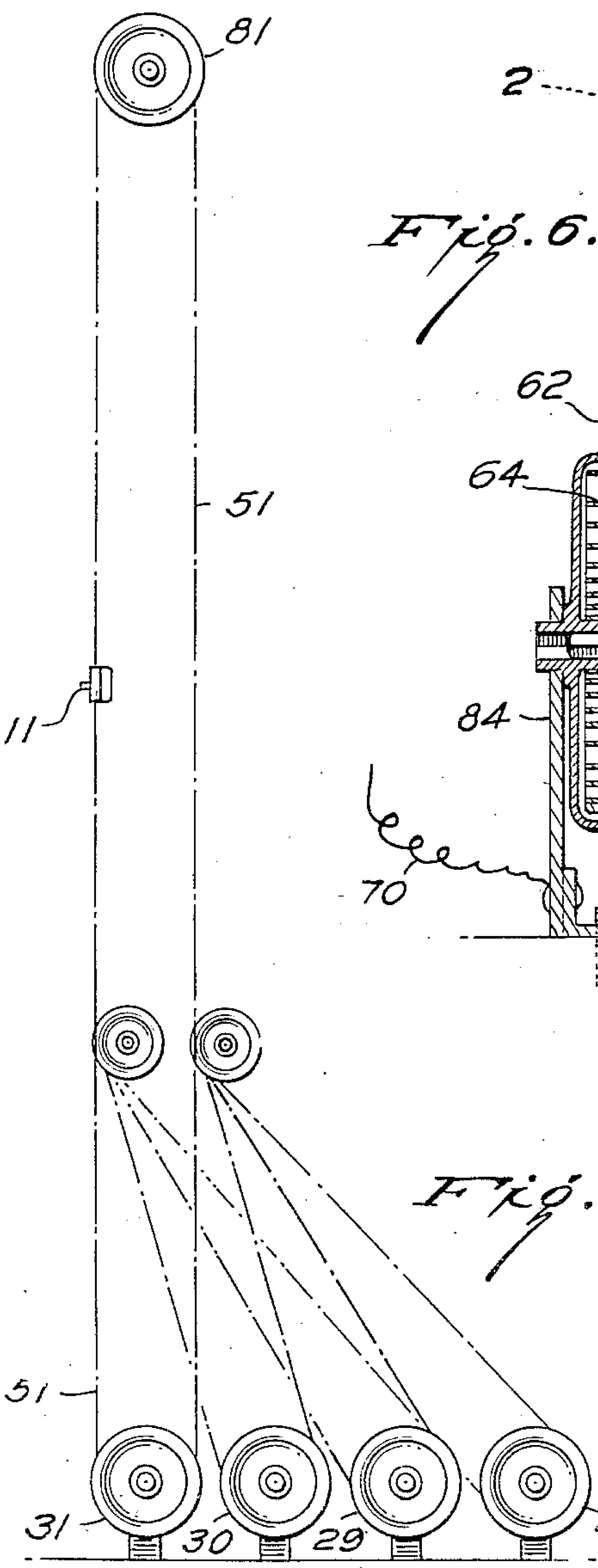


Fig. 3.

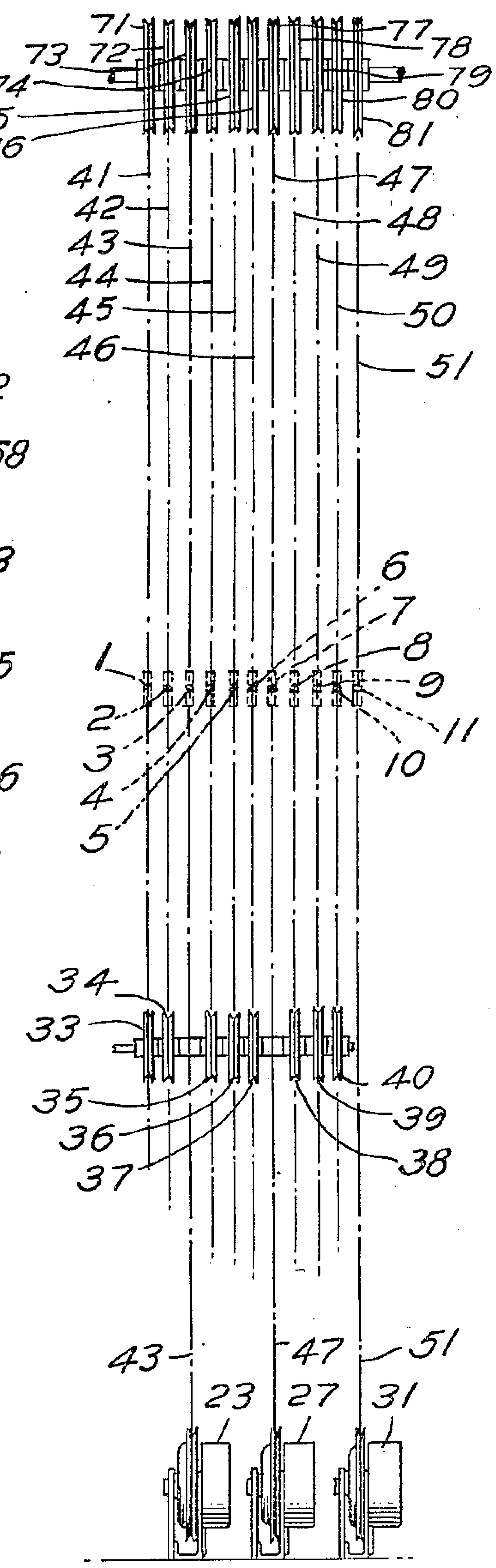
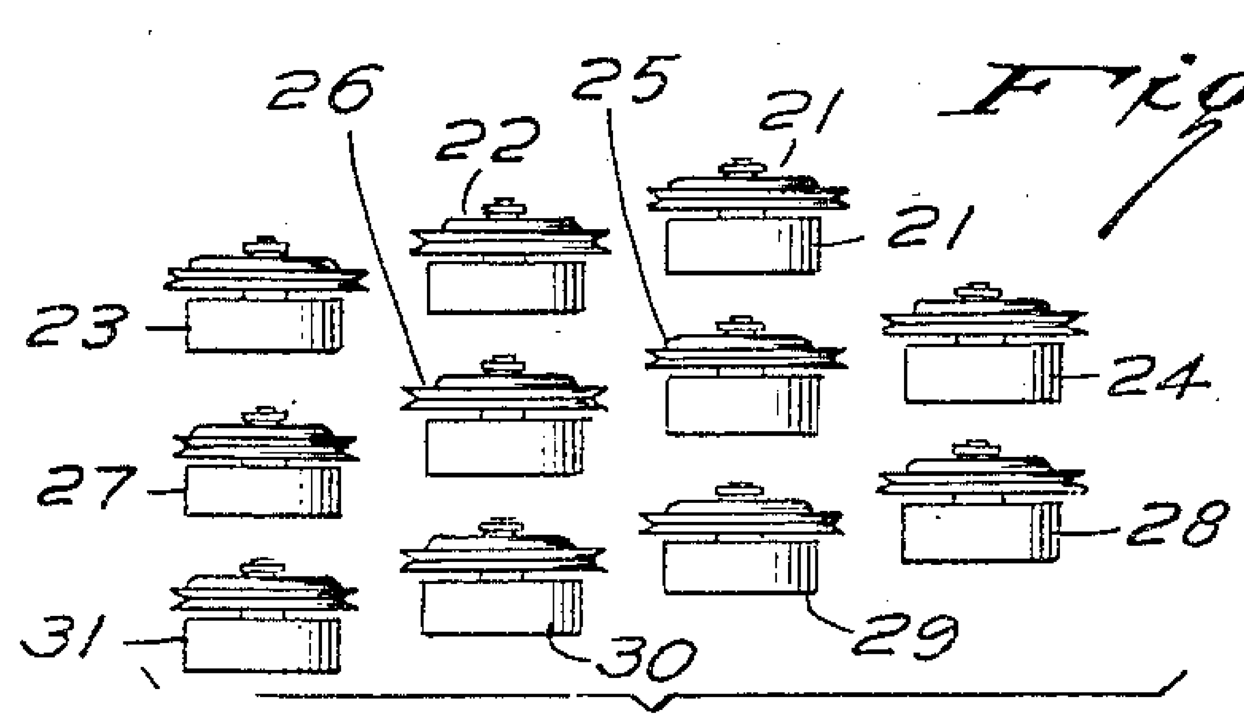


Fig. 5.

Fig. 4.



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METHOD AND APPARATUS FOR COLOR MATCHING

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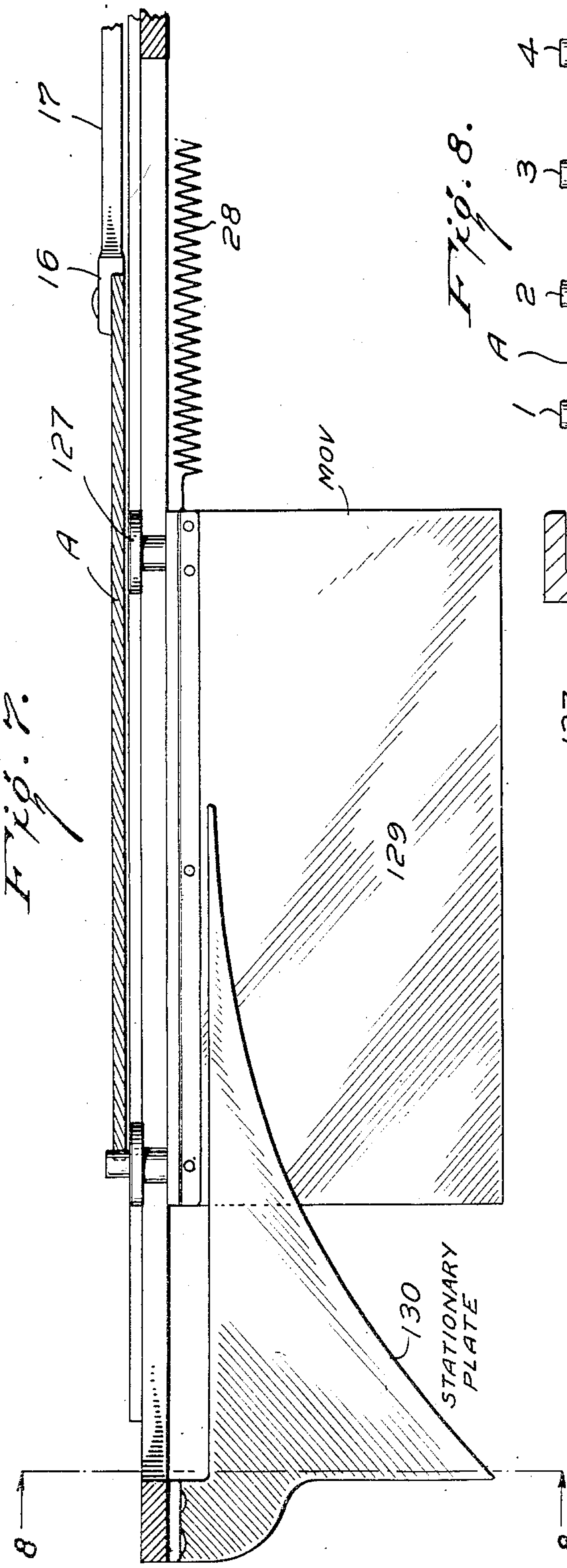

Fig. 7.

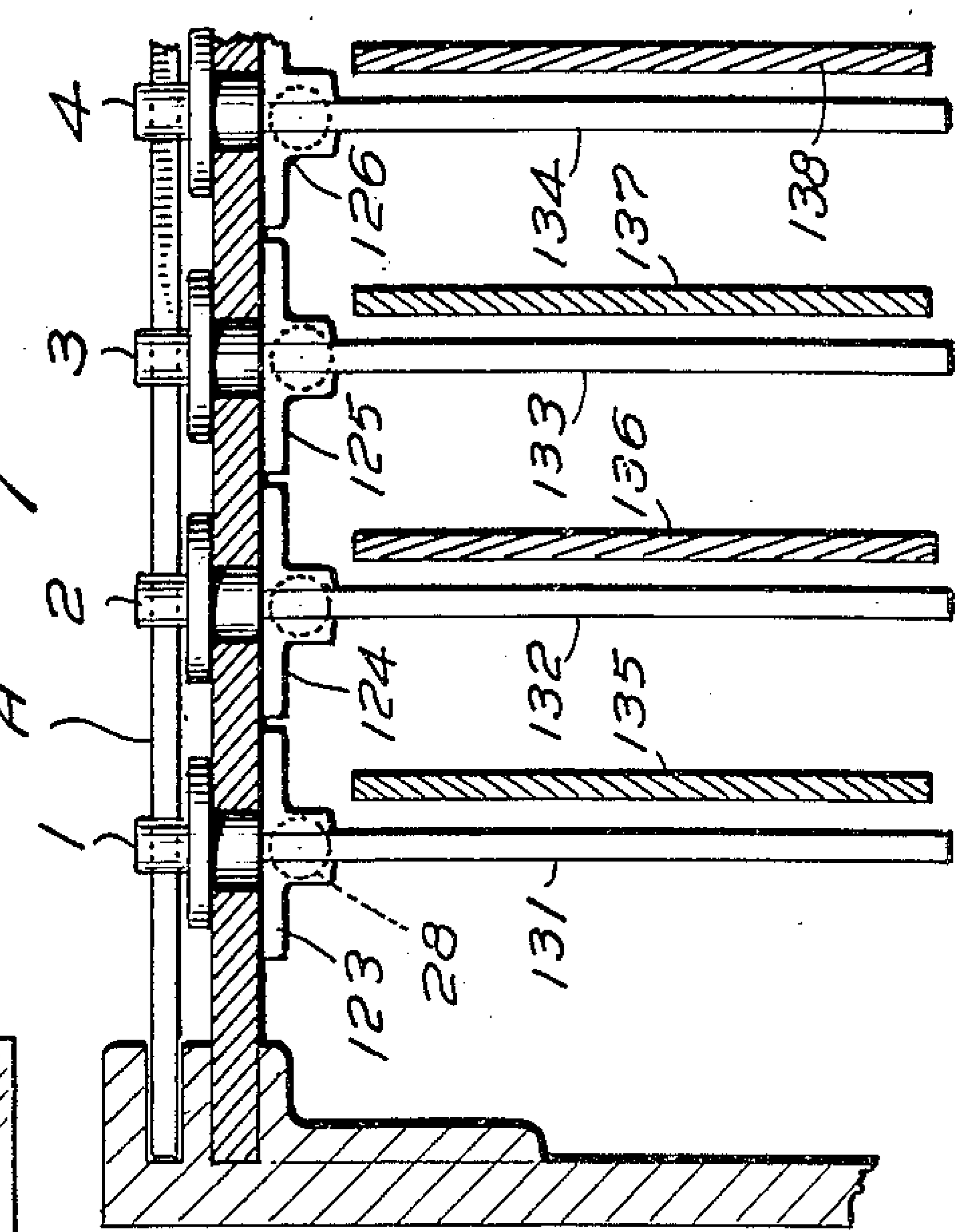

Fig. 8.

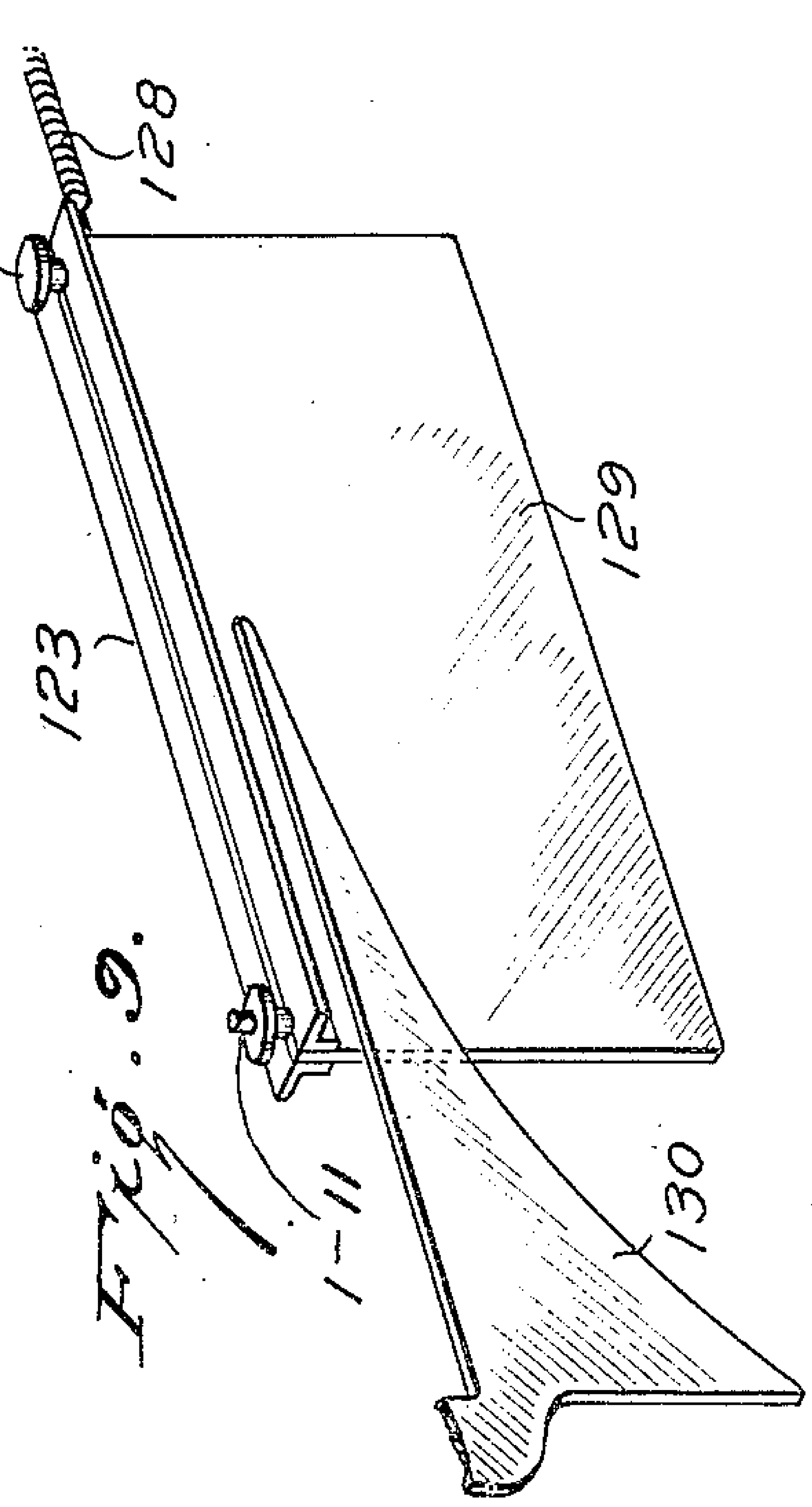

Fig. 9.

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METHOD AND APPARATUS FOR COLOR MATCHING

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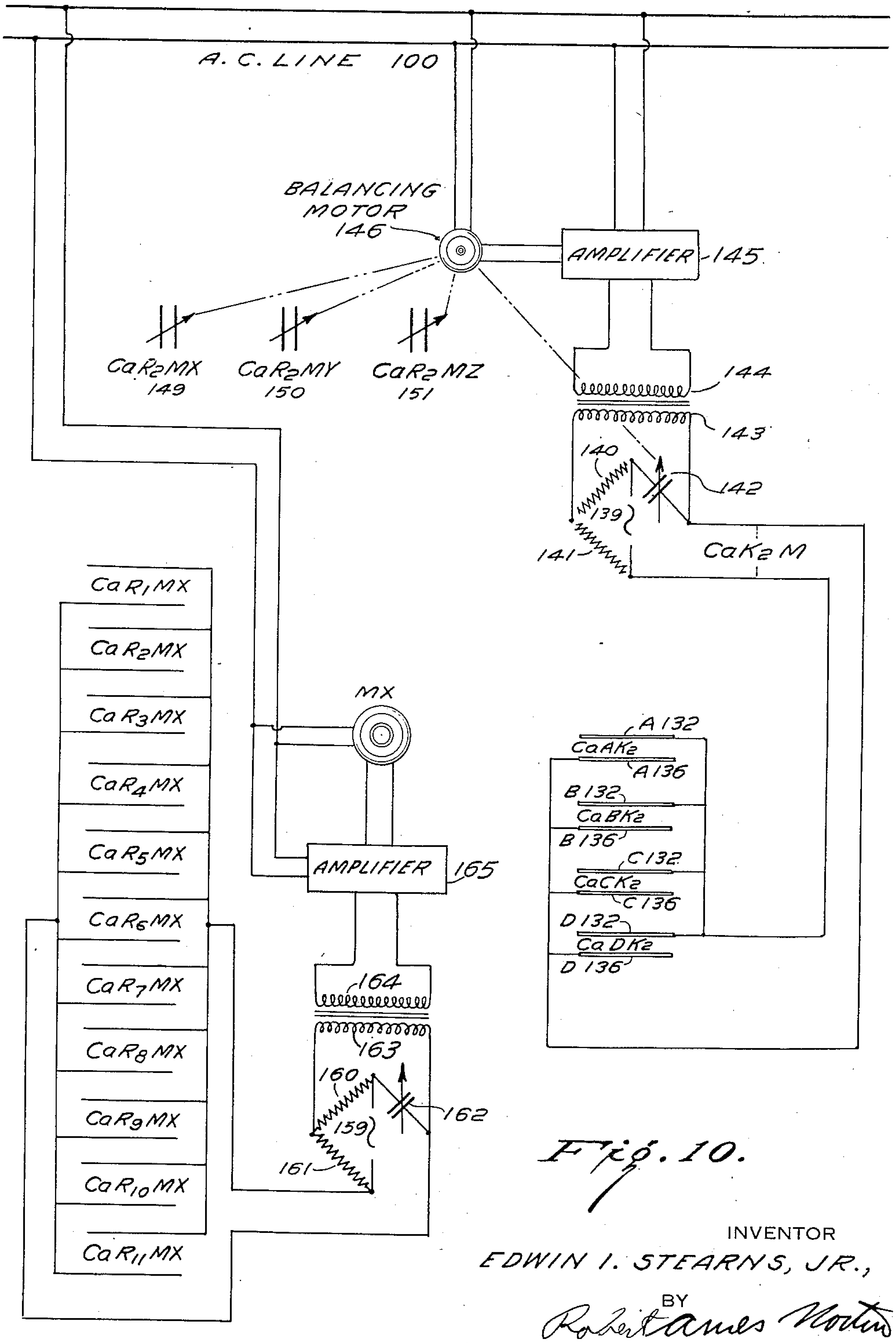

Fig. 10.

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METHOD AND APPARATUS FOR COLOR MATCHING

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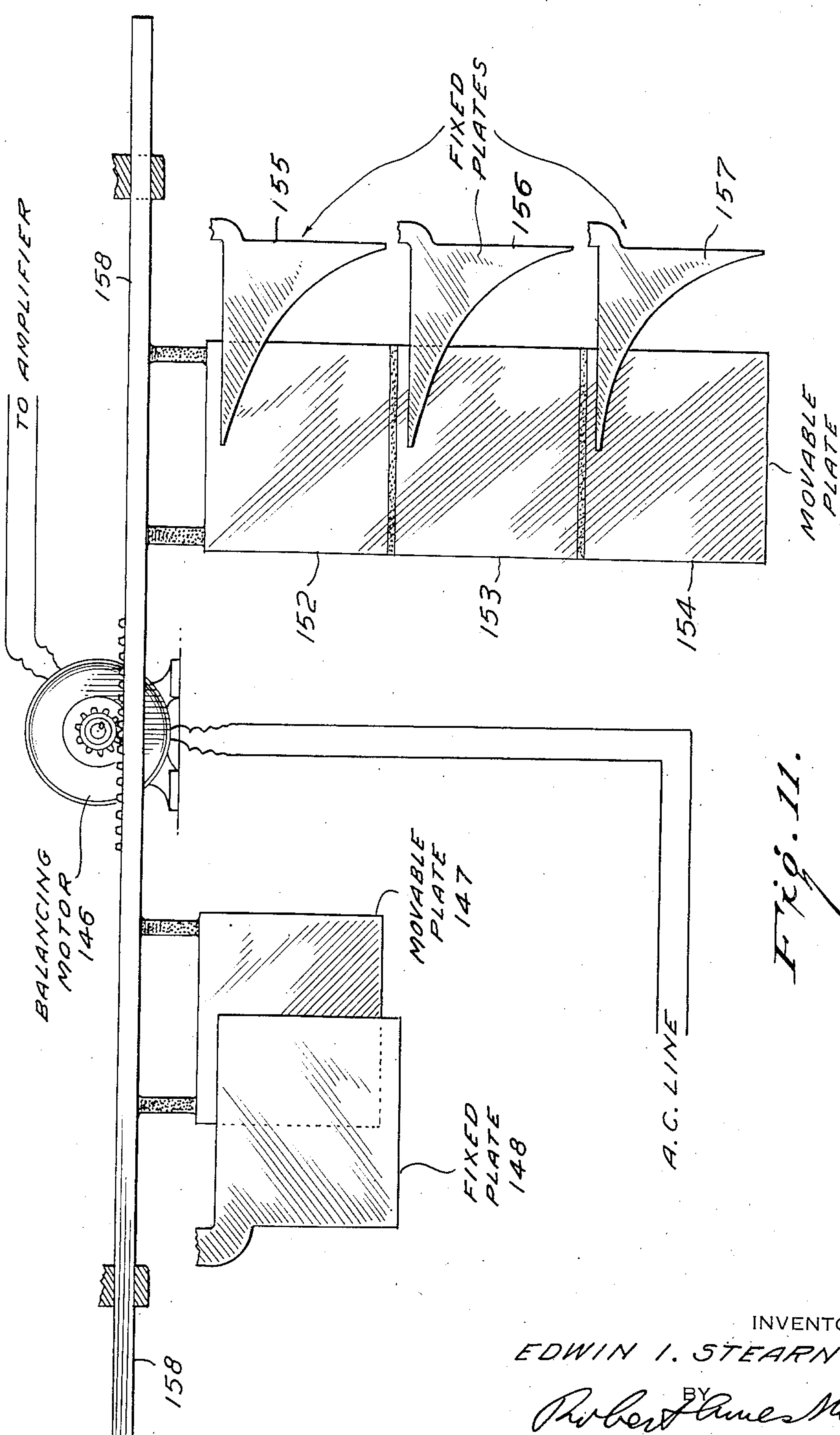

Fig. 11.

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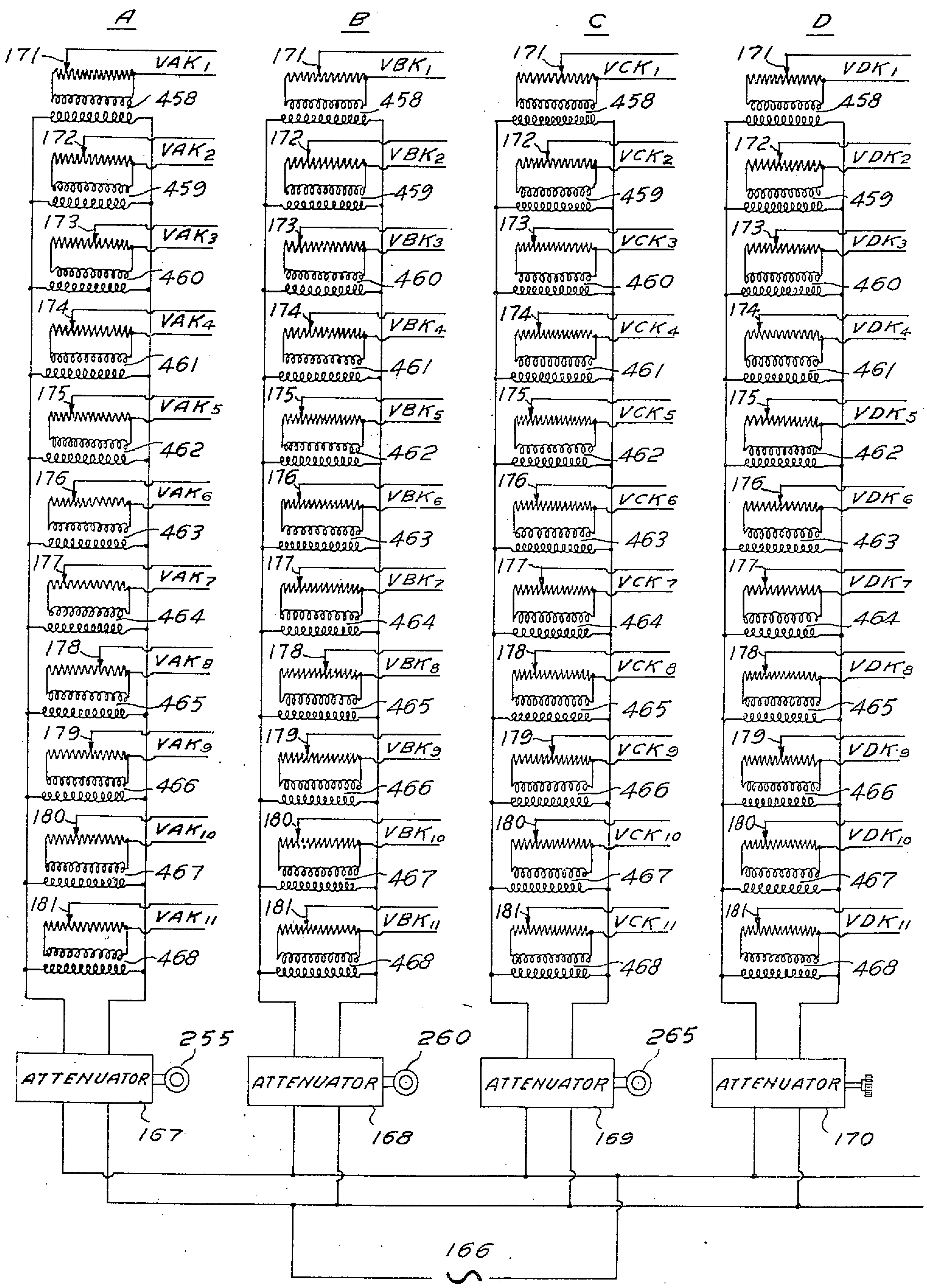

Fig. 12.

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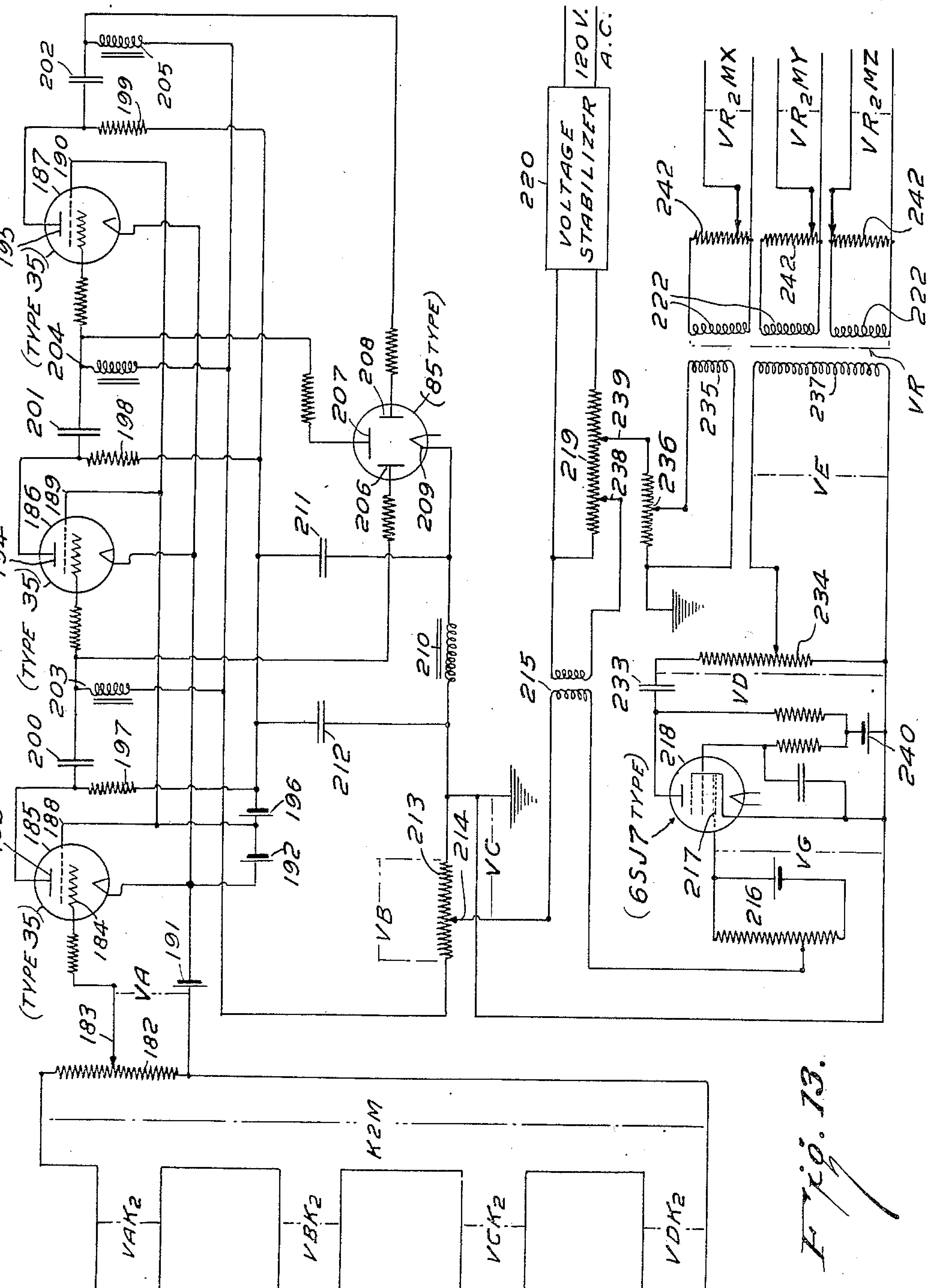

Fig. 13.

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METHOD AND APPARATUS FOR COLOR MATCHING

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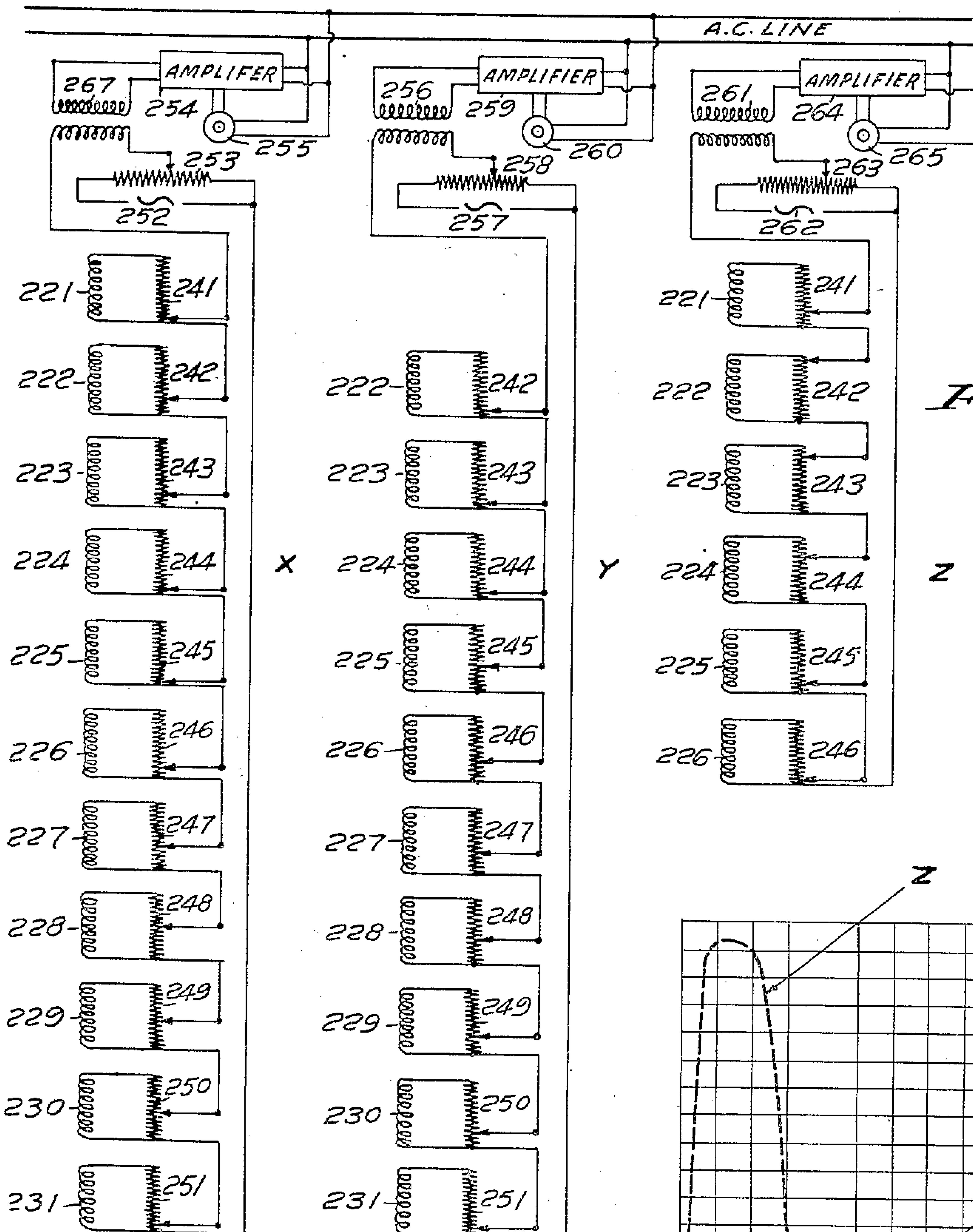

Fig. 14.

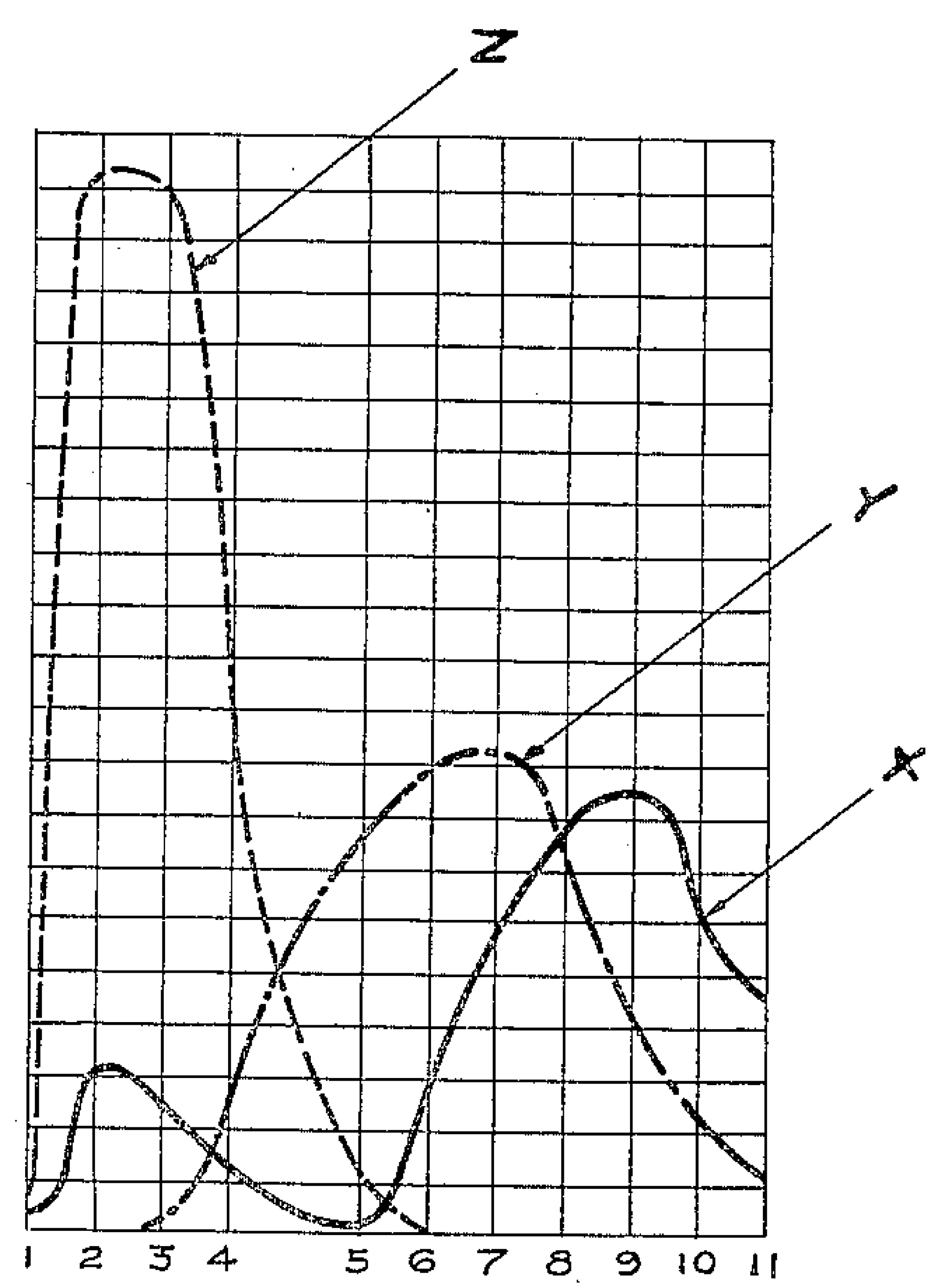

Fig. 15.

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METHOD AND APPARATUS FOR COLOR MATCHING

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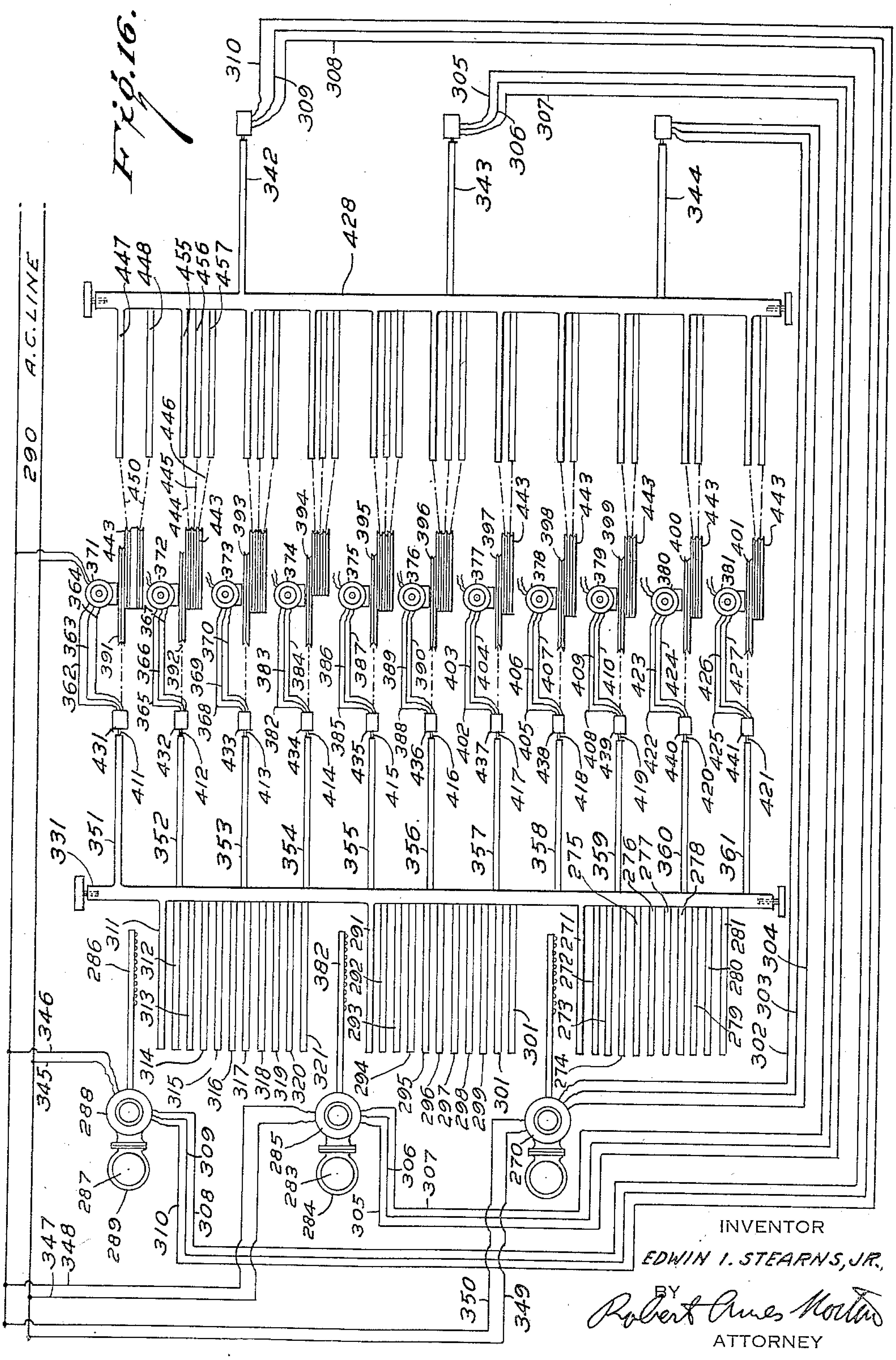

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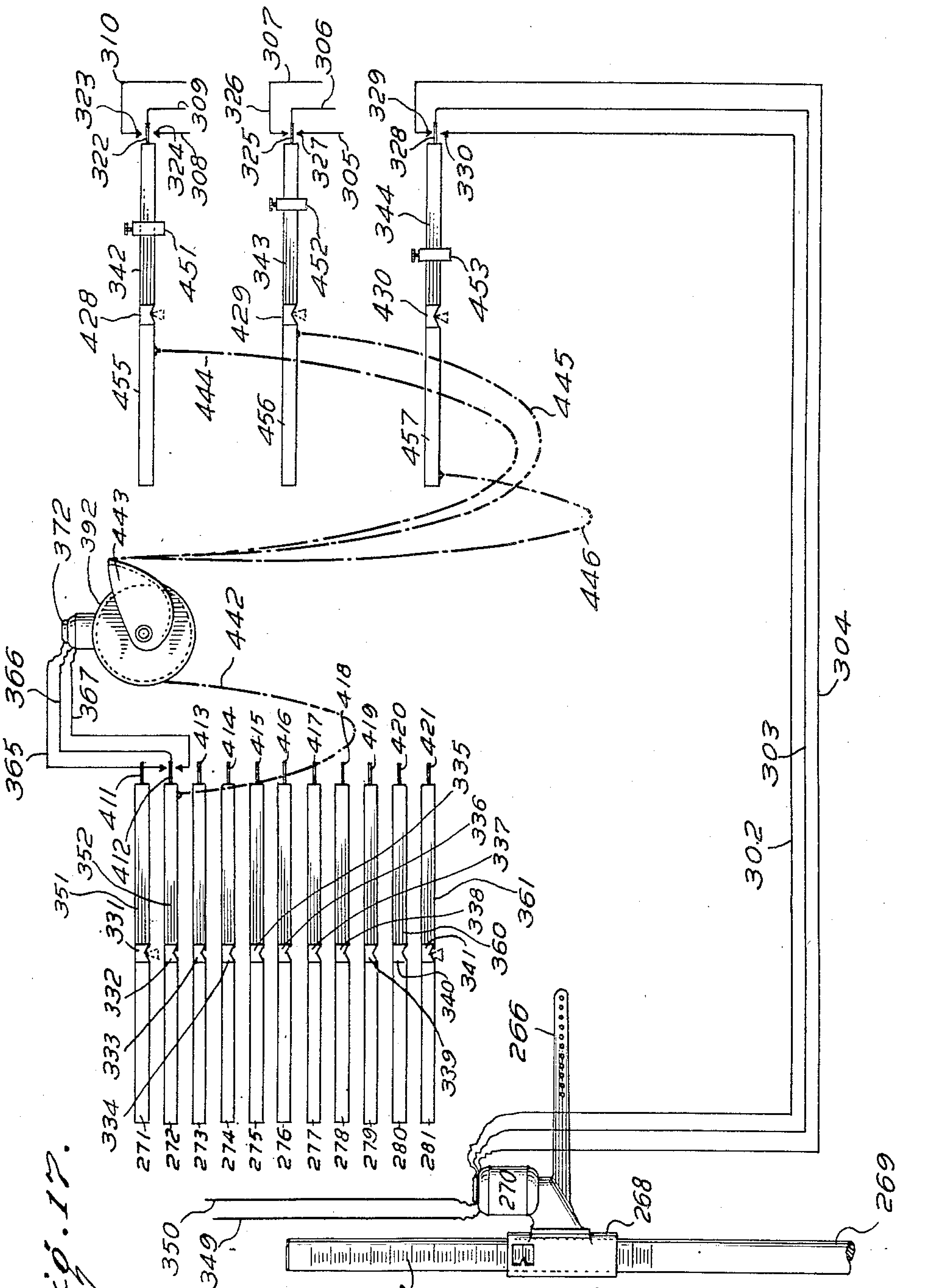

Fig. 17.

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METHOD AND APPARATUS FOR COLOR MATCHING

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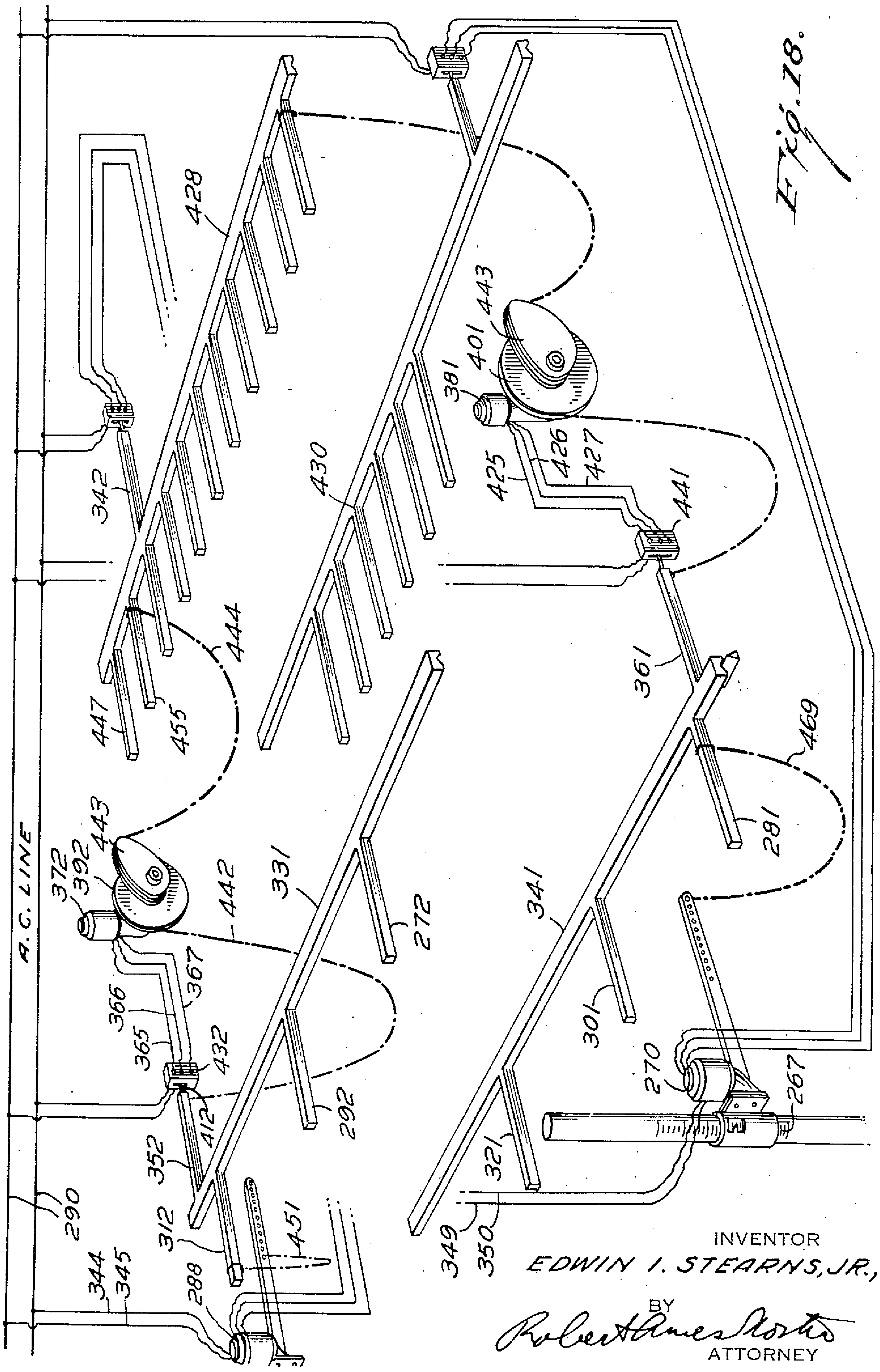

Fig. 18.

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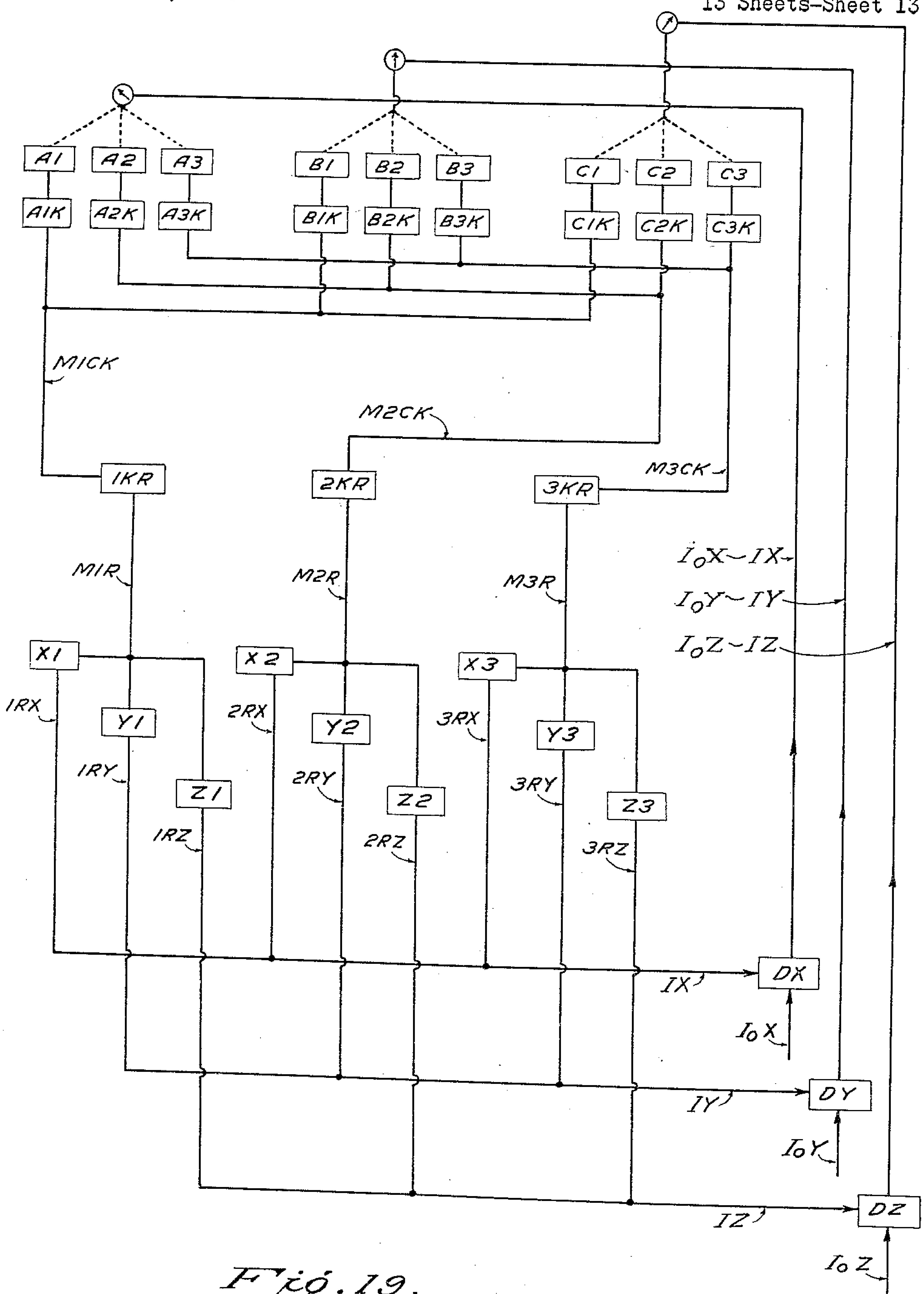

Fig. 19.

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Patented Feb. 6, 1951

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UNITED STATES PATENT OFFICE

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METHOD AND APPARATUS FOR COLOR MATCHING

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Application November 2, 1945, Serial No. 626,310

10 Claims. (Cl. 235—61)

1

This invention relates to a method of determining tristimulus values of mixtures of a plurality of colors, and particularly to methods of automatically matching the tristimulus values of dyeings with predetermined dyes. The invention includes instruments capable of carrying out the above processes.

The scientific specification of colors is in terms of tristimulus values; that is to say, the amount of each of three theoretical and imaginary colors, or stimuli, X, Y and Z, which will give the same response to the eye as the actual color. While an infinite number of sets of tristimuli are possible, including real as well as imaginary colors, in practice a unique set of imaginary colors is employed. This set is characterized by the fact that every color, even spectral colors, can be represented without using a negative amount of any tristimulus, something which would be impossible with real colors, and, further, one, Y, corresponds to the color sensitivity of the human eye. The tristimuli for different illuminants are somewhat different, and, in general, two sets are in common use, one for daylight and one for tungsten light. These are the only ones used in the vast majority of color matching. The description of the tristimulus notation appears in Chapter 1 of the Handbook of Colorimetry by Dr. Arthur C. Hardy, 1936 edition. Fig. 9 on page 8 of this book shows the spectrophotometric curves of three tristimuli for daylight illumination. This figure is reproduced in Fig. 15 of the drawings which will be described below.

In the past the problem of determining the tristimulus values of a mixture of a plurality of dyes, and particularly the matching of a dyeing with such dyes, has been a matter of importance to the dyestuff industry. It is mathematically feasible to determine tristimulus values of mixtures of dyes from the reflectance values of the separate dyes by extensive and time consuming mathematical calculations. This method of solution permits the matching of an unknown dyeing with a mixture of predetermined dyestuffs but it involves excessive time. The mathematical operations, even with the aid of new equation technique, are still slow and the operation requires the assumption of starting concentrations of the colors and then a series of cut and try solutions with various concentrations. It may require hours to obtain a satisfactory match by this method.

The present invention relates to a method of solving the problem and to apparatus for carrying out the method in which the spectral curves of the dyestuffs to be used to match a given dyeing are divided into a series of selected, or preferably weighted, ordinates. The number of wave length ordinates chosen depends on the accuracy desired in the determination of the tristimulus values of a mixture of dyes. The accuracy increases very rapidly with multiplication of ordinates chosen up to an order of magnitude of about 8 to 12 ordinates. When the dye components are sensibly chosen additional ordinates do not add to the accuracy of the result sufficiently greatly to warrant the additional complexity which they introduce in the mechanical methods of handling the data according to the present invention. For practical color matching ten or eleven properly selected ordinates give sufficient accuracy, and except for special scientific problems larger numbers do not give results which are worth the additional complication.

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The present invention gives instantaneous or substantially instantaneous registration of the tristimulus value of a mixture of any concentrations of a plurality of known dyestuffs. When a match is sought by the cut and try method the matching is not automatic. However, the enormous increase in speed of determining each trial mixture cuts the time down to a very small fraction of that now required. Broadly, therefore, the present invention might be considered as including methods and apparatus for giving a substantially instantaneous determination of tristimulus values of any mixture of a plurality of dyes in various concentrations. In a more specific aspect, however, the invention goes beyond this sub-combination of steps and provides for substantially instantaneous matching of any dyeing, the tristimulus values of which are known. In this more specific aspect the process and apparatus automatically varies the proportions of the dyes in the mixtures until one is reached which matches the unknown dyeing.

The term "substantially instantaneous" used in both of these modifications requires slight elaboration. In the sub-combination which gives tristimulus values for any mixture the results are obtained in a time interval of the order of magnitude of from a fraction of a second to several seconds. The preferred modification of the process which provides for automatic matching produces results in a time of the order of magnitude of from a second or two to from one to two minutes. The terms "substantially instantaneous" are intended to be used in this somewhat broader sense.

In order to match a given dyeing by means of the present invention, using either manual or automatic matching, it is necessary to obtain the tristimulus values of the unknown dyeing using a spectrophotometer and tristimulus integration. This is not a new procedure as an apparatus capable of performing this function is described in the patent to Hardy, No. 1,799,134. It is also possible to use the method and apparatus of the present invention to obtain these figures, but as they are obtainable by known means this particular step in the solution of the problem is not considered to form a part of the present invention, although the information obtained thereby, namely, the tristimulus values, constitutes part of the data used in carrying out the process of the present invention.

The first step of the process of the present invention involves the transformation of the ordinates selected from the spectrophotometric curve of each of the dyestuffs to be used in a mixture, and if desired the substrate such as cloth or other fabric to be dyed, into a physical force which is substantially instantaneously additive. This force must be proportional to the product of dye concentration with the additive function of the dye, which will be referred to as K. K is substantially proportional to

$$\frac{(1-R)^2}{2R}$$

where R is percentage reflectance.

The description of the development of the formula for the additive absorption function K is to be found in the United States patent to Pineo, No. 2,218,357, where it is pointed out that some of the light striking a dyed fabric is reflected from the surface; that is to say, non-selectively as far as color is concerned. The rest of the light penetrates various distances into the fabric and is selectively absorbed by the dyestuff molecules, which results in color. In the specification and claims the surface reflectance will be referred to as "*s*," and the light reflected after passing through paths of various lengths in the fabric as "*b*," the so-called "body reflectance." The Pieno patent evelops K in terms of *b*. For most fabrics, of which wool is typical, *s* is small, though not negligible. While K is substantially proportional to

$$\frac{(1-R)^2}{2R}$$

it is not exactly proportional, and the relation will vary slightly with different fabrics by the amount of the surface reflectance *s*.

In the cases of transmission samples, mixtures of fibers and other color applications, there are additive functions K but these functions differ mathematically from K for reflectance given above. Some of these other additive functions are described in the American Dyestuff Reporter, volume 33, page 177, and the patent to Pineo, No. 2,176,013, patented October 10, 1939. Thruout, the remainder of this description will deal with K for reflectance as reflectance samples constitute the most important field at the present time.

The spectrophotometric curve may be used as a physical shape in some of the modifications of the apparatus of the present invention. In other cases it, or spectrophotometer readings, may be used merely to obtain data for the chosen ordinates. In the first case it is usually necessary to have a curve which is invariant in shape with concentrations, is proportional to log K, so that linear movement will measure concentration changes on a logarithmic scale. Such a curve can be drawn with a flickering beam spectrophotometer using a varying ratio drive, as described in patent to Pineo, No. 2,218,357 referred to above. In general such a curve is a logarithmic function of the extinction coefficient of the color for the particular wave length ordinate. Where the curve is merely used to obtain the reflectance data it is desirable to use a curve plotted in terms of the extinction coefficient itself, which is additive for a plurality of dyes, whereas the logarithmic function is not.

In the modification in which the spectrophotometric curve is used as a physical entity this may be effected by transforming the chosen ordinates into fixed physical lengths by cutting in rigid material a template having the profile of the curve. This mechanical embodiment of the curve may be used with various modifications of the other steps of the process or elements of the apparatus. It presents advantages in that templates can be readily filed and are cheap to manufacture. It is thus possible to provide a library of templates for all dyes to be used in matching. There is a disadvantage in that one additional step in the process, or correspondingly additional element in the apparatus, is necessary because the lengths of the ordinates represent logarithmic functions and these have to be transformed into their anti-logarithmic equivalents in order to permit their addition, as will be discussed in greater detail below.

When the energy forms for substantially instantaneous addition are to be electrical voltages, the ordinates may be potentiometers set in accordance with the ordinates of the curve for K. These may be physically moved by templates or they may be pre-set manually. In the latter case it is also possible to design the potentiometers in the form of fixed tapped resistance which can be provided with plug-in or other quick electrical connections, and filed, one set for each dye. When the potentiometers are manually set or when tapped resistors are used, variations in concentrations are usually expressed as changes in the voltage applied to the potentiometers. In the case of templates or other mechanical forms of the spectrophotometric curve which can be used to actuate devices concentration is usually expressed, on a logarithmic scale, as linear motion of the template.

Other additive quantities may be used in the place of voltages, for example, capacities. In one of the steps of the process of the present invention the use of capacities presents an advantage that variation can be effected both by shape of the movable condenser plates and by spacings. However, condensers are more delicate and more easily deranged than potentiometers.

The additive quantities may be mechanical in their nature, for example, they may be angular torques produced by modified forms of chain balances. Other physically additive quantities may be used and the process of the present invention is not limited to voltages, capacities, angular torques, etc., described above. The process is also a multi-step process in which it is possible to use more than one type of physical quantity. Thus, for example, an electrical quantity may be used in one or more steps and angular torque in another step, one step may use capacities and another voltages, etc. This great flexibility of the process is a practical advantage.

While the process is not broadly concerned with the use of any particular means or additive physical quantity, nevertheless the different quantities present advantages and disadvantages, and for most operations there is an advantage in using voltages as the quantities. The circuits and the physical units are more rugged and in some cases more simple, and it is possible in some of the steps of the process to use electronic amplifiers to effect some of the operations. This eliminates the use of many moving parts and adds to the simplicity and reliability of the apparatus for performing the process of the present invention.

The first step of the present invention is to produce an output of the additive quantities as linear or reciprocal functions of K of the dyes and substrates for the chosen ordinates. In the case of processes or apparatus using movable templates this involves logarithmic potentiometers or specially shaped capacitors to transform the logarithmic function of K into a function which is additive. Where the data from a curve is expressed directly in the form of quantities proportional to K or its reciprocal as when potentiometers, capacities or angular torques are set in accordance with the data from the reflectance curve of a particular dye, this change of function is not necessary, but the energy fed to the step must be capable of variation with dye concentration if matching is to be effected automatically.

The additive quantity, such as voltages, capacities, weights, or the like, for each ordinate of each dye and, if desired the substrate, are then added. When these are electrical units they are arranged in circuits so that they add up in series for voltages, parallel for capacities, etc. When the quantities are weights they are attached to the same side of a balance. The addition of the ordinates for the dyes results in the production of a number of quantities equal to the number of ordinates, each quantity representing the sum of the same ordinate for all the dyes. In a typical example where three dyes and one substrate are to be used, the quantity for each ordinate represents the sum of the three dyes and the substrate. If in a typical case where there are eleven ordinates there will be eleven quantities.

The next step is to transform the physical quantities into quantities proportional to the three tristimulus value at each ordinate i. e., R times the tristimulus coefficients which will result in a number of quantities three times as great as the number of ordinates. This transformation may be effected in various ways, for example, by comparing the quantity corresponding to the sum for the dyes and substrate for each ordinate with a standard quantity in the same units. The standard quantity is varied by a motor which responds to the differential between the summed ordinate quantities and the fraction of the standard quantity produced by movement of the motor. In the case of voltages the motor operates the movable arm of a potentiometer or rheostat supplied with standard voltage and the voltage between one terminal and the movable arm is connected in opposition to the voltage corresponding to the sum for the dyes and substrate for the ordinate, preferably using a suitable relay to operate the motor. The motor will obviously turn until the movable arm of the potentiometer is set to the same voltage as that corresponding to the ordinate. Other electrical quantities such as capacities may be compared in a similar manner. In the case of mechanical weights the motor will vary the amount of the standard weight, for example, the length of a chain. The amount of movement of the balancing motors is used to set up three quantities for each ordinate which are attenuated in accordance with the tristimulus coefficient of the wave length corresponding to the ordinate. In the case of voltages three equal voltages may be generated and attenuated by three different potentiometers, or potentiometers may be equally driven across three voltages proportional to the tristimulus coefficient. In analogous methods other electrical units may be compared. In the case of mechanical weights the weight may be increased, for example, by lowering a chain from a cam shaped pulley.

In the case of electrical quantities it is possible to eliminate motors, as the tristimulus values can be obtained from the output of electronic amplifiers of suitable design with an accuracy sufficient for most practical purposes. Extreme, and for most purposes unnecessary, accuracy is sacrificed for a more rugged and simpler apparatus with fewer moving parts.

The final result of the above step produces three quantities proportional to the tristimulus values of each ordinate. The tristimulus values of the ordinates are then added to produce three integrated quantities, each corresponding to the sum of the particular tristimulus values of all of the ordinates. This is done in a manner similar to the addition of the quantities produced by the first step, but the addition is across the ordinates instead of the different dyes and substrate for a single ordinate.

The three integrated tristimulus values obtained almost instantaneously by the process of the present invention are useful as such. In other words, this sub-combination constitutes a useful process or machine and represents a tremendous advance over what was hitherto possible because the integrated tristimulus values of a mix are determined almost instantaneously. If these are to be compared with integrated tristimulus values of the dyeing to be matched, the comparison is immediate and the concentrations of the various dyes may be manually varied bit by bit until a match results. The speed depends on how close the original concentrations approach the final desired result and on the skill of the operator in determining what new concentrations to try. However, as the integrated tristimulus values of a new arrangement of concentration is given by the process or machine of the present invention practically instantaneously the cut and try method is speeded up by such an enormous factor that it becomes entirely practicable. Matches can be obtained under favorable circumstances manually in from five to fifteen minutes as against hours which were required before. This great increase in speed renders the modification of the present invention, which includes only the steps or elements described above, a thoroughly practical process or instrument which represents a great advance over what was hitherto possible. However, even with the substantially instantaneous determination of integrated tristimulus values for any mix the machine still requires skilled operation and the judgment of the skilled operator. It is not automatic and the process does not automatically produce a match. It merely speeds up tremendously the determination of integrated tristimulus values of mixes.

It is desirable to eliminate the skill of the operator and still further increase the speed of matching, by carrying out automatically the operations which the skilled operator has to go through in setting up successive trial mixtures, and to this further refinement of the process and machine a preferred embodiment of the present invention is directed. It will be obvious that what a skilled operator does when he uses the sub-combination of the present invention described above is to vary the concentration of the different dyes in such a manner as to bring the integrated tristimulus values closer and closer to the true integrated tristimulus values of the dyeing to be matched. In the case of the operator his judgment informs him that certain dyes will have a relatively large affect on one or other tristimulus value. For instance, the integrated tristimulus value X is affected very greatly by a blue or violet, or even to a lesser extent magenta dye, whereas it is affected much less by a yellow dye. Correspondingly a yellow dye would affect the integrated tristimulus value Z to a great degree. Therefore, the skilled operator, if he finds that the integrated tristimulus value X too low will decrease the concentration of the blue dyes. In other words, if three dyes are used to produce a mix each of the dyes may be chosen so that each affects most strongly one integrated tristimulus value.

The automatic matching then proceeds by the same method as is used in obtaining the three quantities for the original integrated tristimulus values, namely, the comparison of the quantity represented by the tristimulus value produced on the machine or produced by the process with the tristimulus value of the shade to be matched. The differential, through suitable electrical or mechanical relays if necessary, can then move the elements which determine the concentration of the particular dye which has a large effect on that integrated tristimulus value. For example, if profile templates are used, this differential may cause a motor to move the template in a direction which would correspond to increased or decreased concentration. Of course the change in concentration at any time will affect all three integrated tristimulus values, but it will have a greater effect on the one which it more nearly complements. The last step will result in a balancing which will automatically change the concentrations of the dyes bringing them closer and closer to a perfect match with the integrated tristimulus values of the dyeing. In the case of the preferred machine of the present invention the operation is very rapid and may take from a few seconds to a minute. The final result is not only produced at a speed which is almost instantaneous compared to the hours that were required by mathematical calculation, but the process and the apparatus are entirely independent of skilled operation and their accuracy is just as high with an unskilled operator as with a man who had had great experience in judging color.

There are two general ways in which integrated tristimulus values may be obtained. These are known as the selected ordinate and weighted ordinate methods. In the selected ordinate method ordinates are selected in different parts

of the spectrum for each tristimulus value, and these ordinates are then treated equally. This eliminates the question of different degrees of attenuation of values for a particular ordinate in order to obtain the tristimulus values. One step or element of apparatus is eliminated. However, it is necessary to have three times as many ordinates for each color because the ordinates for each integrated tristimulus value are different.

The weighted ordinate system utilizes a single set of ordinates properly chosen through the spectrum, and the product corresponding to each ordinate is then attenuated electrically or mechanically to produce three different quantities corresponding to the relative tristimulus values for the particular wave length. While this does involve an additional step the enormous simplification which is effected by using only a single set of ordinates for each color will ordinarily render the weighted ordinate method preferable, and in fact this is the preferred form of the present invention. The preference has nothing to do with effective operation. Just as good results can be obtained by the selected ordinate method but the latter, except in exceptional circumstances, involves more complex and more expensive apparatus.

Fig. 1 is an elevation of four template racks;

Fig. 2 is a wiring diagram of a portion of the modification shown in Fig. 1;

Fig. 3 is a side view of the potentiometer drives of one of the template racks of Fig. 1;

Fig. 4 is a bottom view corresponding to Fig. 3;

Fig. 5 is a top view of the potentiometer drives shown in Fig. 3;

Fig. 6 is a detailed enlarged vertical section through one of the potentiometers;

Fig. 7 is a section through a template rack along the line 7—7 of Fig. 1 using condensers instead of potentiometers;

Fig. 8 is a horizontal section through Fig. 7 along the line 8—8;

Fig. 9 is a perspective of the two condenser plates of Fig. 7;

Fig. 10 is a wiring diagram of a portion of the modification shown in Figs. 7 to 9;

Fig. 11 is an enlarged vertical section through the capacity matching device shown in Fig. 10;

Fig. 12 is a wiring diagram of a modification using tapped resistors instead of templates;

Fig. 13 is a wiring diagram of an amplifier for producing alternating current voltages proportionate to tristimulus coefficients;

Fig. 14 is a wiring diagram showing addition of alternating tristimulus voltages produced by the modification of Figs. 12 and 13;

Fig. 15 is a graph of three tristimulus response curves;

Fig. 16 is a diagrammatic plan view of a modification employing chainomatic balances;

Fig. 17 is a vertical elevation of the modification of Fig. 16; and

Fig. 18 is a perspective of representative portions of the modification shown in Figs. 16 and 17, and

Fig. 19 is a block diagram of the apparatus for three wavelengths and three dyestuffs.

The invention will be described generally in connection with Fig. 19 which is a block diagram for three dyestuffs and three wave-lengths.

The figure shows nine elements, one for each dyestuff A, B and C for each wavelength. The wavelengths will be referred to by numbers, so that the blocks are designated A1, A2, A3, B1, B2, etc. In these elements there are generated groups of equal physical quantities proportional to concentration of the three dyestuffs. The outputs of these elements are designated A1C, A2C, A3C, etc. A second group of elements, designated A1K, A2K, A3K, etc., are responsive to the outputs and produce outputs proportional to concentration multiplied by light additive function K of each dyestuff at each wavelength. The outputs of this second group are therefore designated A1CK, A2CK, A3CK, etc. These last outputs are summed for each wavelength to produce three quantities corresponding to the sum of the CK's for the mixture of dyestuffs, and are designated M1CK, M2CK and M3CK. Three elements, 1KR, 2KR and 3KR are actuated by the three MCK quantities respectively, and produce output quantities corresponding to the reflectance of the mixture of the dyes for each wavelength, and are designated M1R, M2R and M3R. The quantities are non-linear functions of K and the wavelength corresponding to the relation between K and reflectance:

$$R=b+s$$

and

$$K=\frac{(1-b)^2}{2b}$$

where

R is total reflectance,
b is body reflectance,
s is surface reflectance, and
K is the additive light absorption function.

The three KR elements actually generate not one MR quantity but three equal ones, each of which actuates a separate element X1, Y1, Z1, X2, Y2, Z2, etc. These elements transform the MR quantities into outputs proportional to reflectance times the tristimulus coefficient of the particular tristimulus X, Y or Z for the particular wavelength 1, 2 or 3. The outputs are designated 1RX, 1RY and 1RZ respectively. The three XR quantities are summed to a quantity IX representing the integrated tristimulus value for X, and in a similar manner, two other sums representing the integrated tristimulus value Y and integrated tristimulus value Z are obtained. Three other predetermined integrated tristimulus values I_0X, I_0Y and I_0Z are generated, corresponding to the integrated tristimulus values of a shade to be matched. The two integrated tristimulus values for X are then introduced into a differential element DX which generates an output proportional to the differential between I_0X and IX, which is designated $I_0X \sim IX$. This quantity actuates the elements A1, A2 and A3. Similarly differential element DY produces a quantity $I_0Y \sim IY$, and a differential element DZ produces a quantity $I_0Z \sim IZ$; which quantities control the elements B1, B2 and B3, and C1, C2 and C3 respectively.

The choice of the elements A1K, A2K, A3K, etc., that is to say, the choice of dyestuffs, and the phasing of the differential quantities $I_0X \sim IX$, etc., are so made that the actuation of the elements A1, A2, A3, etc., is in a direction to reduce the differential quantities. The machine operates when the proper choice of dyestuffs has been used to reduce the differentials to zero. Indicators, represented by the conventional dial and pointer, show the magnitude of the quantities proportional to concentration applied to the elements A1, A2, A3, etc. In other words, these indicators show the concentrations of the chosen dyestuffs necessary to match the predetermined shade.

Fig. 19 has been limited to three dyestuffs and three wavelengths in order to provide a clear diagrammatic showing. In practice, of course, there may be more than three dyestuffs, and there will usually be a K element corresponding to substrate. Various modifications of the invention will be described in detail in Figs. 1–18 where a larger number of ordinates, eleven, are illustrated.

The modifications of the invention using voltage or capacity addition described in Figs. 1 to 14 are shown in connection with color matching involving three colors and a substrate. As most of the elements are duplicated for each color and substrate they will bear the same reference characters, with the subscript A, B or C for the particular dye, or D for the substrate. In a similar manner elements associated with each of the three tristimulus curves of Fig. 15 will bear the subscript X, Y and Z of the corresponding tristimulus.

Figs. 1 to 6 show a modification using voltage addition and dye and substrate templates. In Fig. 1 there is shown four template guide frames 13, each provided with eleven slots 12, in which the pins 1 to 11 can move. The frames accommodate templates A, B and C for the three colors and D for the substrate, the profile of the templates corresponding to the logarithm of the additive function K of the dyes and substrates. Vertical motion of the templates results in positions of the pins 1_A to 11_A, 1_B to 11_B, 1_C to 11_C, respectively, corresponding to the logarithm of the product of K with dye concentration. The templates carry a reference mark 15 which move along scales 14 on the template frame, the scale being logarithmic and showing concentration of the dye corresponding to the particular position of the template in each frame. Movement of the template is effected by a rack 17 having a clamp 16 and moving through bearings 20 on each template frame. Each rack meshes with a pinion 18 which is driven through a worm 19 from an electric motor. The motor driving template A bears the character MX, that driving template B, MY, and that driving template C, MZ. These designations indicate that the motors are driven respectively in accordance with voltages determined by the three integrated tristimulus values X, Y and Z of the mixture of the dyes, respectively. The rack for the substrate template D is set by the hand screw 32 and does not move during any particular color match as the concentration of the substrate does not change.

The pins 1 to 11 in each frame are clamped to endless cables 41 to 51, respectively. These cables at one end run over a series of idler pulleys 71 to 81 (Fig. 5), and then around the pulleys of corresponding potentiometers 21 to 31 (Figs. 3 to 5). Three of the cables, 43, 47 and 51, run straight. The other cables are deflected down by pulleys 33 to 40 (Figs. 3 and 5) in order to permit a staggered mounting of the potentiometers 21 to 31.

The potentiometers are of a conventional logarithmic type and the drive is illustrated in Fig. 6 for the potentiometer numbered 22. The pulley is shown at 62 and turns a shaft 63 journaled in an arm 84 which is clamped to the potentiometer supporting bracket 83, the latter being in turn fastened to the main framework of the template frame. Rotation of the pulley 62 is opposed by the coiled spring 64 which tends to turn the pulley so that when there is no template in the frame the pin 2 is at the top of its slot. To the shaft 63 there is clamped an arm 65 bearing at one end a fork 66 with a sharp wheel 67 running between the coils 22 of the potentiometer. The other end carries a moving contact 68. Wires 69 and 70 connect to the two ends of the potentiometer resistance. As shown the potentiometer makes five full revolutions to cover the whole of its resistance. The resistance is of conventional coiled wire type and is, of course, non-uniform, as in all logarithmic potentiometers. The scale of Fig. 6 is too small to show this non-linearity.

Fig. 2 is a wiring diagram for the pins 2_A—2_D. The potentiometers 22_A—22_D are shown diagrammatically as logarithmic potentiometers across batteries 92_A—92_D. The voltages between the negative ends of the potentiometers and the sliding contacts 68_A—68_D are designated VAK2, VBK2, VCK2, and VDK2, the notation indicating that the voltage is proportional to K times concentration of the dye A at the wave length corresponding to pin 2, and so on.

The four voltages are connected in series and therefore added, the sum being designated VK2M, a notation indicating that it is the voltage proportional to the sum of the functions K for the mixture of dyes and substrate, and for the wave length of the spectrum corresponding to pin 2. This voltage is connected in opposition to a voltage produced by battery 85 and rheostat 86 having a sliding contact connected to the other end of the battery through a resistance 87 small in comparison to 86. The sliding arm 87 is connected to the center tap of a coil 92 of the input transformer 91 of a vacuum tube amplifier 93. The two ends of the coil 92 are connected to contacts 94 and 95 which can be successively engaged by the vibrator contact 98, which is connected to slider 68_A. Vibration is effected in the conventional manner by a magnet 96 and coil 97 connected to the A. C. line 100. The difference between the voltage from the battery 85 and the voltage VK2M is thus applied in the form of alternating potential to the amplifier 93, the output of which is led through wires 99 to a balancing motor 88, which drives the moving arm 87 of the rheostat 86 in a direction to reduce the differential. When the arm 87 has been moved to a point at which the voltage from the battery 85 is exactly equal and opposite to VK2M the motor 88 stops. This device is shown in diagrammatic form only, as its structure forms no part of the present invention and the unit is a piece of standard electrical equipment which can be purchased on the open market.

The motor 88 turns a cam 89 which carries a follower 90 driving the sliding arms 111 to 113 of three equal potentiometers 114 to 116, across batteries 117 to 119. It will be noted that since the balancing voltage generated by the battery 85 is applied through a rheostat the movement of the cam 89 is proportional not to VK2M but substantially to its reciprocal. The profile of the cam 89 is so chosen that the voltages produced from the potentiometers 114 to 116 are proportional to reflectance of the mixture of dyes and substrate at the wave length corresponding to pin 2. The transformation from reciprocal of VK2M instead of VK2M itself is chosen because at certain points the change of reflectance, R, with K, is too rapid to permit reliable operation of a cam and follower. The steepness of the cam transforming 1/K into R is sufficiently moderate so that a reliable cam action is possible.

The voltages generated by the potentiometers 114 to 116 are applied across tapped resistors 120 to 122. In order to produce a voltage which is a constant fraction of the potentiometer voltage within the accuracy of the whole method of the present invention, the resistance of the tapped resistors is very much greater than the resistance of the potentiometers. For example, they may be one thousand times as great. The resistors are tapped to give a proportion of the total voltage corresponding to the tristimulus coefficients for each of the three stimuli at the wave length corresponding to the pin number, as is shown in Fig. 15. Since these voltages are in proportion to each tristimulus coefficient for the reflection of the mixture of dyes and substrate, they are designated VR2MX, VR2MY, and VR2MZ, respectively.

The voltages for each tristimulus are connected in series, as is shown for tristimulus X in Fig. 2. The sum of the voltages corresponding to tristimulus X is connected in opposition to the voltage from a battery 102 and potentiometer 101. This potentiometer is set manually in accordance with the integrated tristimulus value X of the color shade to be matched. The slider of potentiometer 101 is connected to the center tap of coil 108 of the input transformer 109 of a vacuum tube amplifier 110 of the same design as amplifier 93. In a similar manner the differential between the sum of the tristimulus voltages X and the voltage from the potentiometer 101 is applied onto a vibrator arm 103 which is vibrated by the A. C. coil 107 and magnet 106 to alternately strike contacts 104 and 105, which are respectively connected to the ends of the coil 108. The differential of the voltage is therefore applied to the amplifier 110 in the form of an alternating voltage in precisely the same manner as the differential voltage was applied to the amplifier 93.

The output of the amplifier 110 drives the motor MX (Fig. 1), which moves the template for dye A. The motor turns in a direction to decrease the differential input to the amplifier 110. In a similar manner the voltages VR1MY—VR11MY, and VR1MZ—VR11MZ are matched with potentiometers set to the tristimulus values Y and Z and drive motors MY and MZ through amplifiers, the circuits of which are the same as amplifier 110. As these circuits duplicate the one shown in Fig. 2, they are not illustrated in the drawings.

In the operation of the modification just described in connection with Figs. 1 to 6 dyes A, B and C are chosen of suitable general colors, and the integrated tristimulus values X, Y and Z of the mixture of dyes and substrates are opposed by the three voltages set on potentiometer 101 and the other two corresponding potentiometers (not shown) in accordance with the integrated tristimulus values of the shade to be matched. Amplified differential voltages turn the motors MX, MY and MZ in directions to decrease these differentials, and finally the motors come to rest at positions of templates A, B and C, which will produce a perfect match of the shade desired. The concentration of the dyes A, B and C is read by the pointers 15_A to 15_C on the scales 14_A to 14_C, respectively.

Figs. 7 to 11 illustrate a modification in which condensers are used in place of potentiometers or other voltage generators. The pins of the template frames instead of being clamped to cables are fastened to movable plates 129 (Figs. 7 and 9) which are provided with a second supporting button 127, and which are moved by the templates against the tension of springs such as 128. The movable condenser plates 129 are provided with fixed condenser plates 130 of a shape such that the capacity varies in accordance with the additive function K as the plate 129 moves in accordance with log K.

Fig. 8 shows four pins, 1 to 4, attached to movable plates 131 to 134, which cooperate with fixed plates 135 to 138. The movable plates are provided at the top with flanges 123 to 126 which keep the plates accurately in alignment. As far as the frames and templates go the operation proceeds precisely as described in conjunction with Figs. 1 to 6 where voltages were generated.

Fig. 10 shows a capacity wiring diagram for the pin 2 analogous to Fig. 2. The movable plates 132_A—132_D are connected in parallel as are the corresponding stationary plates 136_A—136_D. The capacities, in accordance with the notation used for voltages, are designated CaAK2, CaBK2, CaCK2, and CaDK2. These four capacities in parallel add up to the capacity CaK2M, and this capacity is impressed across one arm of a Wheatstone bridge circuit, which is provided with a conventional source of alternating potential 139, resistance arms 140 and 141, and a variable condenser arm 142. The junction point of the resistance arms of the bridge is connected to one end of the input coil 143 of the input transformer 144 of an amplifier 145, and the junction point of the two capacitative arms is connected to the other end of the same coil. An alternating current input signal is, therefore, impressed on the amplifier, which is proportional to the ratio between CaK2M and capacity of the variable condenser 142. The output of the amplifier feeds a balancing motor 146, which in turn drives the variable condenser 142. The shape of the plates of this condenser may be so chosen that the rotation of the motor 146 is proportional either to K or to a reciprocal thereof, and of course the capacity of the condenser is changed in a direction to match CaK2M. At match the bridge is balanced and the motor 146 stops.

The same motor 146 drives three variable condensers 149, 150 and 151, the plate shape and spacing of which is such that the capacities are proportional to reflectance of the mixture of dyes and substrates times the tristimulus coefficient for the wave length of the spectrum corresponding to the pin. In accordance with the notation chosen for voltages these capacities are designated as CaR2MX, CaR2MY, and CaR2MZ, respectively. The capacities corresponding to the coefficient for tristimulus X for the various pins are shown added in parallel in the same figure.

The sum of the capacities for tristimulus X forms one arm of a second Wheatstone bridge provided with a source of alternating potential 159, two resistance arms 160 and 161 and a manually adjustable variable condenser 162. The latter is adjusted to a capacity corresponding to the integrated tristimulus value X of the shade to be matched, the procedure being analogous to the setting of the potentiometer 101 in Fig. 2. The junction points of the resistance arms and the capacitative arms of the bridge are connected to the two ends of a coil 163 of the input transformer 164 of amplifier 165. The circuit operates precisely as does the amplifier 145 but is based on an input signal which is the ratio between the sum of the X tristimulus capacities and the capacity of the condenser 162. The output of the amplifier 165 drives motor MX, just as the output of the amplifier 110 drove the same motor in the modification using additive voltages.

Fig. 11 shows in a schematic form the condensers 142, 149, 150 and 151 appearing in the wiring diagram of Fig. 10. The motor 146 is shown as driving a toothed bar or rack 158. This bar carries a movable plate 147 of the condenser 142 which cooperates with the fixed plate 148. The same bar moves three movable plates 152, 153 and 154, which cooperate with fixed plates 155, 156 and 157, to form the three condensers 149, 150 and 151. The fixed plates 155 to 157 are shown as being the same shape and possessing the profile which will transform the chosen function of K into R. The relative proportion of the capacity corresponding to each tristimulus coefficient for the wave length of pin 2 is determined by the relative spacing of the plates in condensers 149, 150 and 151.

If desired, the whole of the transformation from K to R need not take place in a single condenser plate. A fixed plate 148 of non-uniform shape may be used. Fig. 11 is purely schematic and representative of the method. In practice, of course, it is undesirable to use condensers with so few plates, as errors due to edge effects would be too high and, therefore, multiplate condensers will normally be used. For simplicity, however, Fig. 11 is shown in a purely schematic form with two plate condensers.

Instead of employing template frames and templates, the profile of which is proportional to the log of K, it is desirable in many cases to employ a system in which a set of eleven tapped resistors are provided for each dye, the tap being so placed as to correspond to K for the particular point of the spectrum corresponding to positions 1 to 11 in Fig. 15. A set of tapped resistors for three dyes, A, B and C and a substitute D, are shown in Fig. 12, the tapped resistors being designated by the numbers 171 to 181 corresponding to points 1 to 11 in Fig. 15, or pins 1 to 11 in the preceding modifications. The tapped resistors are across secondaries of a series of identical transformers 458 to 468, the primaries of which are connected in parallel and plug into attenuators 167, 168, 169 and 170. The first three attenuators are driven by motors 255, 260 and 265 and the attenuator 170 may be adjusted manually for a particular substrate. All of the attenuators receive voltage from a source of alternating voltage 166. The attenuators which are of conventional design and provided with the usual dials (not shown) have output impedances which are very low compared to the resistance of any of the tapped resistors 171 to 181. For example, the attenuators may have output impedances from about $^1/_{1000}$ to $^1/_{10,000}$ of the resistance of a tapped resistor.

The setting of the attenuator multiplied by the factor determined by the tap on each resistor results in the production of voltages which are proportional to K times concentration for each of the eleven ordinates for each dye and substrate i. e., C. K. In accordance with the voltage notation used before, these voltages are designated as VAK1 to VAK11; VBK1 to VBK11; VCK1 to VCK11; and VDK1 to VDK11. The voltages for a particular ordinate or pin position are connected in series. For clarity in Fig. 12 the wires are not drawn out in full.

Fig. 13 shows an amplifier for the ordinate corresponding to position No. 2 which transforms voltages proportional to the CK's for the ordinate, into separate voltages proportional to R times tristimulus coefficient. Similar amplifiers are provided for each of the other ten positions. The amplifiers may be of various designs. The figure illustrates a two-part amplifier. The sum of the voltages corresponding to K for position 2 is impressed across the input resistance 182 of a logarithmic amplifier. This amplifier, which is of conventional design, and described in the Review of Scientific Instruments, vol. 4, pages 672–675, is shown as provided with three tetrodes of the "35" type, 185, 186 and 187, the grid of the first tube receiving a portion of the input signal determined by the setting of the potentiometer arm 183. A bias battery 191 is provided to bring the voltages within the range for which the amplifier is designed. Plate and screen supply voltages are obtained from two *b* batteries 192 and 196. The former supplies the screen grids 188, 189 and 190, and the latter the plates 193, 194 and 195, through plate resistors 197, 198 and 199. Coupling for the tube outputs is through condensers 200, 201 and 202 in series with chokes 203, 204 and 205. A triple plate rectifier tube 209, of the "85" type, the plate and grid of the triode section being connected together to form a third diode plate. The plates being numbered 206, 207 and 208 receive alternating potential through suitable resistors from the input from chokes 203, 204 and 205. The cathode of the rectifier is connected to ground through a filter including choke 210 and condensers 211 and 212. A potentiometer

nected to the grounded cathode as usual. The plate is coupled to a potentiometer 234 through a condenser 233. From the latter alternating current is applied to the coil 237. This coil is the primary of a transformer provided with three equal secondary coils 222 leading to potentiometers 242 set in accordance with the tristimulus coefficient X, Y and Z for point 2 on Fig. 15.

A source 220 of stabilized A. C. voltage of suitable magnitude is applied across a double potentiometer 219 one sliding arm of which, 238, impresses a voltage across the other coil of the coupling transformer 215. A second sliding arm 239 connects a potentiometer 236 in series to ground and the sliding arm of this potentiometer impresses a voltage of 0.017 volt across the coil 235 in opposite phase to the voltage in coil 237.

For convenience in tabulating the operation of the eleven amplifiers for the eleven ordinates the input voltage to the potentiometer 182 will be designated V2KM, the attenuated input to the grid 184VA, the output of the logarithmic amplifier VB, the attenuated voltage from the potentiometer arm 214VC, the input voltage to the grid of tube 218VG, the output voltage of this tube VD, the voltage across the coil VE, and the differential voltage between coils 235 and 237VR. These designations are indicated on the diagram. The following table shows the results of the amplifier for values of K from .01 to 98.1, the extreme range thru which K is usefully measured. Most shade matching involves measurements from a K of .5 to 98.1.

V_K2M	V_A	V_B	V_C	V_G	V_D	V_E	V_R	Desired	100× Error
0	0	(0)	0	−3.72	----	----	----	----	----
.01	.0001	7.00	5.15	1.43	2.42	.960	.943	----	----
.05	.0005	8.90	6.56	2.84	2.05	.812	.795	.80	−.5
.12	.0012	9.92	7.31	3.59	1.80	.713	.696	.70	−.4
.27	.0028	10.90	8.03	4.31	1.52	.603	.586	.60	−1.4
.50	.0051	11.60	8.54	4.82	1.28	.509	.492	.50	−.8
.90	.0092	12.28	9.04	5.32	1.05	.416	.399	.40	−.1
1.63	.0166	12.95	9.52	5.80	.82	.324	.307	.30	+.7
3.20	.033	13.75	10.12	6.40	.57	.225	.208	.20	+.8
8.10	.083	14.81	10.92	7.20	.32	.127	.110	.10	+1.0
18.05	.184	15.74	11.58	7.86	.17	.067	.050	.05	0
48.02	.490	16.88	12.42	8.70	.07	.028	.011	.02	−.9
98.01	1.000	17.70	13.02	9.30	.02	.008	.009	.01	----

V_K2M=voltage to be converted.
V_A=output of unit A (attenuator)=0.0102 V_K.
V_B=output of unit B (log amplifier)=2.66 log V_A+17.70.
V_C=output of unit C (attenuator)=0.737 V_B.
V_G=grid bias on unit D=V_C−3.72.
V_D=output of unit D=$f(V_G)$ see tube characteristics.
V_E=output of unit E (attenuator)=0.396 V_D.
V_R=converted voltage=V_E−0.017.

213, thru a movable arm 214 connects ground to the bias battery and potentiometer 216. It is a property of an amplifier of the type described that the output across the potentiometer 213 is proportional to the logarithm of the input voltage. In other words, the output is proportional to log VK2M. The constants are so chosen that this output voltage equals 2.66 log input voltage on grid 184 plus 17.70.

The slider 214 produces an attenuated voltage across one coil of a coupling transformer 215. The setting is such that this voltage is 0.737 times the voltage across the potentiometer 213. The voltage is fed to the grid 217 of a "6SJ7" tube 218, a bias of plus 3.72 volts being provided by the battery and potentiometer 216. The screen grid and plate of the tube 218 are supplied through separate resistors from a B battery 240, giving about 300 volts on the plate and 125 volts on the screen. The suppressor grid is con-

It will be noted that the extreme error is only 1.4% and within the range of most practical operation the maximum error is 1%. Since the errors vary from plus to minus they tend to cancel out and the average error is very small.

The alternating current voltages, modified in accordance with various tristimulus coefficients are added. This is shown in Fig. 14 where the output coils 221_X to 231_X, 222_Y to 239_Y, and 221_Z to 226_Z are shown for the amplifiers, corresponding to all eleven ordinates.

From Fig. 15 it will be apparent that the tristimulus coefficient is zero for Y at point 1 and for Z at points 7 to 11. Therefore, the output coils 221 to 231 and their potentiometers 241 to 251 are missing at these points for the particular tristimuli.

The sum of all the X voltages is impressed across the primary of an input transformer 267 of an amplifier 254 in opposition to an alternating potential from a source 252 across a potentiometer 253. In a similar manner the sum of the voltages corresponding to tristimulus Y is applied across the input transformer 256 of an amplifier 259 in opposition to an alternating potential from a source 257 across a potentiometer 258, and the voltages corresponding to tristimulus Z are applied to the input transformer 261 of an amplifier 264 in opposition to alternating potential from source 262 across potentiometer 263. The potentiometers 253, 258 and 263 are set to correspond with the integrated tristimulus values of the shade to be matched. The amplifiers therefore operate on the differential voltages between the summed tristimulus voltages and the integrated tristimulus values set on the three potentiometers. The outputs of amplifiers 254, 259 and 264 operate respectively motors 255, 260 and 265 (see Figs. 12 and 14). These motors drive the attenuators 167, 168 and 169 (Fig. 12) in a direction to bring the differential input into the respective amplifiers to zero. When this condition has been brought about the motors 255, 260 and 265 stop and the concentrations of the three dyestuffs A, B and C are read off on the dials of the attenuators 167, 168 and 169.

The method and apparatus employing the vacuum tube amplifiers has the advantage that it reduces the number of moving parts to the three motors 255, 260 and 265. While this modification requires careful initial adjustment it operates reliably, and because of its simplicity and few moving parts constitutes a preferred modification.

Figs. 16 to 18 illustrate a method and apparatus which operates on purely mechanical principles employing the well known chainomatic balances. Because of the large number of parts in the drawings some of the chains are not illustrated and the method is shown for three dyes only, without a substrate.

Eleven chainomatic balances 331 to 341 are provided, one corresponding to each of the eleven points of Fig. 15. Each balance is provided with three left hand arms and the eleven balances therefore show thirty-three left hand arms arranged in three sets of eleven. These three sets are numbered 271—281, 291—301, and 311—321, respectively.

Fig. 17 shows one set of left hand arms 271 to 281. This group of arms is associated with a rack 269 carrying scales 267 and a framework 268 provided with an arm 266 and a motor 270, the operation of which moves the frame 268 up and down the rack by means of the conventional pinion (not shown). The arm 266 carries eleven pins from each of which a chain extends to one of the arms 271 to 281 of the balance. For clarity only one representative chain is shown in the perspective view, Fig. 18. The others are connected to their respective arms in the same manner. The position of each chain on its arm as is shown in Fig. 18 for the representative chain 469, is determined by the relative value of K for the dyestuff corresponding to the arm 266. Figs. 16 to 18 are diagrammatic in nature and Fig. 18 merely shows the chains 454 and 469 with a stirrup at the desired point on the arm. In an operating device the conventional micrometric weight shifting mechanism of a chainomatic balance is used for each arm. As this mechanism is purely conventional it is omitted for sake of clearness in the schematic drawings.

The second dye is represented (Fig. 16), by a rack 283, frame 284, motor 285, and chain arm 282 and, similarly, a third dye has a rack 287 with a frame 289, motor 288 and chain arm 286, a representative chain 454 being shown in Fig. 18. Chains from the arm 282 go to the balance arms 291 to 301, and from the chain arm 286 to balance arms 311 to 321. The movement of the frames carrying the chain arms on their racks adds the same amount of weight to each balance arm, the effect of each chain depending on its position on the arm, which in turn is proportional to K. In other words, the movement up and down on the racks and reading on the rack scale produces an effect on the balances proportional to concentration times K. Since each balance carries three arms, the total effect is to add the K's for each of the eleven positions mechanically as they were added in the form of voltages or capacities in the modifications described in the Figs. 1 to 14.

The eleven balances 331 to 341 carry right hand arms 351 to 361, respectively. Fig. 16, being schematic, shows these arms spaced at different parts of the balance. The arms 351 to 361 carry at their ends switch members 411 to 421 respectively (Fig. 17), connected to wires 363, 366, 369, 383, 386, 389, 403, 406, 409, 423 and 426 respectively (Fig. 16). Each arm also carries a chain, one of which, 442, is illustrated in Fig. 17 for arm 352. These chains correspond to pulleys 391 to 401 respectively, which in turn are driven by motors 371 to 381.

Each of the switch members 411 to 421 is capable of making contact with electrical contacts connected to one of two wires. For the arms 351, to 361 the wires are respectively 362, and 364, 365 and 367, 368 and 370, 382 and 384, 385 and 387, 388 and 390, 402 and 404, 405 and 407, 408 and 410, 422 and 424, and 425 and 427. The switch members 411 to 421 are housed in switch boxes 431 to 441. It will be seen on Fig. 16 that from each of these switch boxes three wires run to one of the motors 371 to 381, one wire going from the switch members and the other two wires from the contacts. In the diagram shown on Fig. 16 the motors illustrated are conventional shaded pole motors, the movement of the switch arms resulting in short circuiting one of the shading coils. In other words, the motor runs in one direction when a switch arm makes contact with one contact, and in the reverse direction when it makes contact with the other. All motors are fed from the common A. C. line 290, the motors 270, 285 and 288 being fed through the wires 349 and 350, 347 and 348, and 345 and 346, respectively.

The phasing of the motors 371 to 381 is so chosen that they rotate the pulleys 391 to 401 in a direction to counteract the movement of the corresponding balance arms 351 to 361. In other words, considering the arm 352 in Fig. 17, if the turning movement of the left hand arms of the balance 332 is greater than that of arm 352, the latter will rise, making contact between the switch member 412 and the wire 365. As the switch member connects to one end of both shading coils in the motor 372 in the usual manner, this will result in short-circuiting one of the coils, which will cause the motor to turn in a direction to unwind more of the chain 442. The motor will continue to run until the additional weight of the unwound chain 442 causes the balance arm 352 to drop to a neutral position, at which time the motor will stop. If thereafter the weight decreases on the left hand arms of balance 332, arm 352 will drop, making contact between the member 412 and wire 387, which will result in short-circuiting the other shading coil in the motor causing it to reverse and wind up the chain 442 until a balance is again reached, at which point the motor will again stop. A similar operation is constantly taking place with the other ten balances 331, and 333 to 341.

The shafts of the motors 371 to 381 carry multiple cam shaped pulleys 443. Motors 371 and 377 to 381 carry double pulleys and the remainder triple. Each cam shape of the multiple cam shaped pulleys winds or unwinds a chain connected to an arm of one of the balances 428 to 430. These chains are designated generally on Fig. 16 by the reference character 450. For clarity, the reference character is shown with lead lines only to the two chains from the pulleys of the first motor 371. Each of the balances 428 to 430 corresponds to one of the tristimuli, balance 428 corresponding to tristimulus X, balance 429 to tristimulus Y, and balance 430 to tristimulus Z. Since the ordinates are chosen so that there is a tristimulus coefficient for X at each point, balance 428 carries 11 left hand arms, the one for point No. 1 on Fig. 15 being designated 447. Balance 429 carries only 10 arms, the arm for point No. 1 bearing the reference numeral 448 because the tristimulus Z coefficient corresponding to point 1 is substantially zero. Balance 430 carries only 6 arms as the coefficient for points 7 to 11 is substantially zero.

Fig. 17 shows, in more detail, the operation of motor 372 corresponding to point No. 2 on Fig. 15. The rotation of the shaft of the motor 372 is proportional to the sum of the K's for the concentration of each dye for point 2. The motor shaft carries a triple cam shaped pulley 443, which is capable of winding or unwinding chains 444, 445, 446 respectively. The shape of these cams is such that they wind out chain in proportion to the ratio between R and K. These three chains lead to left hand balance arms 455, 456, and 457, respectively, of balances 428, 429 and 430. The location of the chains on the arms is in proportion to the tristimulus coefficients for point 2 for tristimuli X, Y and Z respectively. In other words, a turning moment is applied to the balances 428, 429 and 430 in proportion to R times the tristimulus coefficients X, Y and Z for the mixture of the three dyes at point 2.

The balances 428, 429 and 430 are provided respectively with right hand arms 342, 343 and 344 carrying adjustable weights 451, 452, and 453. The positions of these weights are adjusted in accordance with the integrated tristimulus values X, Y and Z of the shade to be matched. The same right hand balance arms also carry switch members 322, 325 and 328 connected by wires 309, 306 and 303 to motors 288, 285 and 270. The switch member can contact pairs of points 323 and 324, 326 and 327 and 329 and 330. The points are connected to wires 308 and 310, 305 and 307, 302 and 304 respectively, leading to the three motors 288, 285 and 270. The circuit is similar to that described in connection with motor 372, the motors, 270, 285 and 288 also being shaded pole motors. Movement of the right hand balance arms of the balances 428, 429 and 430 will therefore cause the motors 270, 285 and 288 to wind up or unwind chains to the various left hand arms of the balances 331 to 341 in a direction to bring the balances 428, 429 and 430 back to balance again. When this finally occurs the motors 270, 285 and 288 stop and the concentrations of the dyes providing a match may be read off on the scales on the racks 269, 283 and 289.

As stated above, for the sake of simplicity Figs. 16 to 18 show only three dyes and do not show any substrate. If a substrate is present an additional set of eleven left hand arms must be provided on the balances 331 to 341. These arms do not have to be of the chainomatic type as the weight added at each point by the substrate does not change during any match, and these arms may carry adjustable weights similar to the weights 451, 452 and 453 of the balances 428 and 430, except, of course, that the weights are much smaller in magnitude than the latter, which have to balance the sum of from six to eleven tristimulus turning moments. The pulleys which wind up the chains run to the balances 331 to 341, and those which run to the balance 428, 429, and 430, can both be cam shaped. This will permit the use of shapes which are less steep than if the whole transformation is to be effected by a single cam shaped pulley.

In the drawings modifications have been shown which are either all-electric or all-mechanical. It is, of course, possible to combine electrical and mechanical devices. Thus, for example, the production of quantities proportional to the sum of the K's for each point may be effected electrically and the addition of tristimulus values effected mechanically, or vice versa. Such a combination presents some advantages over an all-mechanical operation. Three balances, 428 to 430, operate simply, but the complexity of eleven balances in the addition of the K's for each of the eleven points introduces considerable mechanical complexity and for this step, at least, the electrical methods present advantages. In a similar manner one of the integrations may be effected by means of voltages and the other by means of capacities. The possibility of using different physical methods to produce the desired quantities is an additional advantage of the present invention and renders it more flexible.

While the accuracy of the various modifications, when properly operated, is comparable, the superior ruggedness of the methods using electrical voltages make them preferable to methods using capacities or purely mechanical methods. This preference is not due to their superior accuracy but to economic considerations.

The detailed descriptions in connection with the drawings relate to modifications of the process and apparatus, in which a color match is obtained. Such modifications require that the physical quantities proportional to the three tristimulus values of the mixture of dyes and substrate be used to drive means which vary the concentration of the dyestuffs. In the case of electrical modifications employing templates these are the motors MX, MY and MZ. In the case of the modification of Figs. 12 to 14 they are the motors 255, 260 and 265, which drive the attenuators, which are moved in proportion to changes of concentration, and finally, in the mechanical modification illustrated in Figs. 16 to 18 they are the three motors 270, 285 and 288.

If it is desired to use only a portion of the preferred form of the invention, namely, an instantaneous recording of tristimulus values, the quantities corresponding to the three tristimulus values are actually measured. In the modification described in Figs. 1 to 6 this would require matching the sums of the tristimulus voltages for X, Y and Z with three other voltages, using a matching potentiometer of the same type as is described in connection with the addition of the voltages VKA2, VBK2, VCK2, and VDK2 described above. The motors which would be driven by the amplifiers corresponding to 110 would drive a balancing potentiometer, as does the balancing motor 88, and the setting of this balancing potentiometer would then be read on its dial. In a similar manner the output of the capacity amplifier corresponding to 165 would operate motors driving the matching condensers 162, and when a match was obtained the amount of capacity in the condenser 162 would appear on its dial. In the modification described in Figs. 12 to 14 the alternating current tristimulus values are matched in the same way. Where voltages are used it is also possible to read the three tristimulus value sums on suitable volt meters.

In a similar manner the angular torques corresponding to the right hand arms of the balances 428 to 430 can be read.

Since automatic matching in most cases represents such a great saving in time over cut and try methods, it will usually be preferable to utilize the preferred modifications of the present invention, which lead to direct matching without the necessity of cut and try procedure. These preferred process and apparatus are the ones illustrated in the drawings.

The process and apparatus of the present invention has been described more particularly in conjunction with the matching of shades for which three tristimulus values were available for a predetermined illuminant, such as for example, sunlight or a particular kind of artificial light. Change of the illuminant, of course, changes the tristimulus coefficients at the selected ordinates. Therefore, if it is desired to obtain a match for more than one illuminant it is necessary to produce as many sets of three integrated tristimulus values as there are to be illuminants.

In most machines the color matching is concerned solely with producing shades which will appear the same to the human eye, and therefore for most machines the ordinates will be chosen only in the visual spectrum. For certain purposes it is desirable to determine reflectance beyond the visible spectrum, for example, it is of importance to determine photographic infrared response, and in such cases the ordinates or usually additional ordinates may be selected in the near infrared, or in certain cases, in the ultraviolet. Of course for photographic response it is not necessray to have three tristimulus values. One is sufficient because the photographic emulsion responds according to its sensitivity curve and the response results in a difference in density and not a difference in color. The photographic response to a single coefficient function throughout the spectrum, while not identical with the eye's response to the three tristimulus coefficients, operates in the same manner in the same process and in the present device, and therefore the term "tristimulus" in the claims will be used in a broader sense to include sets of tristimulus values for different illuminants in the case of the eye and the analogous quantities determining photographic response. The photographic response is directly tied up with the color perception in such cases as military camouflage where it is necessary to produce visual matches that will not show great reflection difference in the infrared.

I claim:

1. An apparatus for producing a physical quantity corresponding to the reflectance of a plurality of dyestuffs which comprises in combination means for generating at a plurality of wavelengths a group of equal physical quantities, each quantity corresponding to one of the plurality of wavelengths and being proportional to the concentration of one of the dyestuffs, means for generating other such groups having quantities corresponding to the concentrations of the other dyestuffs, means responsive to the quantities generated in each group at each wavelength for generating a second group of quantities proportional to the product of concentration and additive light absorption function K of each dyestuff at the same wavelength, K being a non-linear function both of the dyestuff and of wavelength, means for summing the quantities of the second groups for each wavelength, means responsive to each of said sums for generating at least one physical quantity proportional to reflectance being a non-linear function of the sums and related thereto by the predetermined non-linear function which relates reflectance to KC.

2. An apparatus according to claim 1 for producing physical quantities corresponding to integrated tristimulus values in which a plurality of equal physical quantities proportional to reflectance are generated, means responsive to each of said quantities for each wavelength for generating physical quantities proportional to reflectance multiplied by each tristimulus coefficient for that wavelength, and means for summing the last physical quantities for each tristimulus for all of the wavelengths to produce summed quantities proportional to integrated tristimulus values.

3. An apparatus according to claim 2 comprising means for generating physical quantities proportional to the integrated tristimulus values of a predetermined shade, means responsive to the differential between the said physical quantities and the summed physical quantities for the corresponding tristimulus to vary the quantities generated corresponding to concentration of the different dyestuffs in a direction to reduce the value of the differentials, and means for indicating the concentrations of the dyestuffs.

4. An apparatus according to claim 3 for producing a physical quantity corresponding to the reflectance of a plurality of dyestuffs dyed on a predetermined substrate in which means are provided for generating an additional group of physical quantities proportional to a predetermined fixed concentration of substrate.

5. An apparatus according to claim 1 for producing a physical quantity corresponding to the reflectance of a plurality of dyestuffs dyed on a predetermined substrate in which means are provided for generating an additional group of physical quantities proportional to a predetermined fixed concentration of substrate.

6. An apparatus for producing an electrical quantity corresponding to the reflectance of a plurality of dyestuffs which comprises in combination means for generating at a plurality of wavelengths a group of equal physical quantities, each quantity corresponding to one of the plurality of wavelengths and being proportional to the concentration of one of the dyestuffs, means for generating other such groups having quantities corresponding to the concentrations of the other dyestuffs, means responsive to the quantities generated in each group at each wavelength for

generating a second group of electrical quantities proportional to the product of concentration and additive light absorption function K of each dyestuff at the same wavelength, K being a non-linear function both of the dyestuff and of wavelength, means for summing the electrical quantities of the second groups for each wavelength, means responsive to each of said sums for generating at least one electrical quantity proportional to reflectance being a non-linear function of the sums and related thereto by the predetermined non-linear function which relates reflectance to KC.

7. An apparatus for producing a voltage corresponding to the reflectance of a plurality of dyestuffs which comprises in combination means for generating at a plurality of wavelengths a group of equal physical quantities, each quantity corresponding to one of the plurality of wavelengths and being proportional to the concentration of one of the dyestuffs, means for generating other such groups having quantities corresponding to the concentrations of the other dyestuffs, means responsive to the quantities generated in each group at each wavelength for generating a second group of voltages proportional to the product of concentration and additive light absorption function K of each dyestuff at the same wavelength, K being a non-linear function both of the dyestuff and of wavelength, means for summing the voltages of the second groups for each wavelength, means responsive to each of said sums for generating at least one voltage proportional to reflectance being a non-linear function of the sums and related thereto by the predetermined non-linear function which relates reflectance to KC.

8. An apparatus according to claim 6 in which the electrical quantities are capacities.

9. An apparatus according to claim 7 in which the means for generating physical quantities proportional to dyestuff and substrate concentration comprises a plurality of frames, one for each dyestuff, said frames being adapted to receive

rigid templates having profiles proportional to the logarithm of K of the dyestuffs and said frames being provided with slots at the plurality of wavelengths, each slot carrying a pin movable therein and capable of contacting the profile of the template, the frames being provided with guides and driving means for moving the templates longitudinally of the slots, and logarithmic potentiometers driven by each pin capable of generating voltages proportional to the product of concentration and K of the dyestuff corresponding to the template at the wavelength corresponding to the pin.

10. An apparatus according to claim 7 in which the means for producing physical quantities corresponding to dyestuff concentration comprises a source of A. C. potential and an attenuator provided with means for indicating voltage changes produced thereby, and the means for generating quantities proportional to dyestuff concentration and K comprising a plurality of series of potentiometric attenuators, one for each dyestuff, the number of attenuators in each series corresponding to the number of wavelengths, and each attenuator comprising a transformer fed by the A. C. voltage attenuated in proportion to dyestuff concentration for the particular dyestuff, and a potentiometric attenuator, the attenuation for each wavelength being proportional to K of the particular dyestuff at that wavelength.

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