Spectrophotometric color formulation based on two-constant Kubelka-Munk theory

Eric Walowit

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SPECTROPHOTOMETRIC COLOR FORMULATION BASED
ON TWO-CONSTANT KUBELKA-MUNK THEORY

by
Eric Walowit

A thesis submitted in partial fulfillment
of the requirements for the degree of
Bachelor of Science in the School of
Photographic Arts and Sciences in the
College of Graphic Arts and Photography
of the Rochester Institute of Technology

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SPECTROPHOTOMETRIC COLOR FORMULATION BASED ON TWO-CONSTANT KUBELKA-MUNK THEORY

by

Eric Walowit

Submitted to the Imaging and Photographic Science Division in partial fulfillment of the requirements for the Bachelor of Science degree at the Rochester Institute of Technology

ABSTRACT

A new approach to computer color formulation based on non-linear least-squares techniques has been developed to characterize colorants and predict their behavior in mixtures. This approach allows the optimization of absorption and scattering calculations to characterize these colorants. This same method has been used to directly match the spectral reflectance of a standard with a mixture of colorants that yields nearly the same spectral reflectance as the standard being matched. Several advantages have been gained over more traditional methods: Kubelka-Munk $K$ and $S$ has been determined without primary binary blends, the spectral reflectance of the standard and proposed formulation exhibit lower spectral difference, the use of spectrally similar colorants has been improved and, formulations can now be predicted for standards measured over wavelength regions other than the visible spectrum.
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Special thanks to Bausch & Lomb Company for funding this research.
Dedicated to Dr. Franc Grum
Title of Thesis: Spectrophotometric Color Formulation Based On Two-Constant Kubelka-Munk Theory

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II. INTRODUCTION

A. Background

For many years it has been the task of various industries to provide materials of a specific color requested by a customer. The customer provides a standard of the desired color and it becomes the job of the manufacturer to produce a product whose color matches that of the standard. For instance, in the textile industry, heather blends (fine tweeds) are made from fibers that, if each were viewed in bulk, appear to be of similar color. These fibers are blended in such a way as to yield a desired color. Similarly, a standard blend can be matched by choosing a field of colorants (the bulk fibers), which are combined in the proper proportions (concentrations) such that the mixture (blend) is of the same perceived color of the standard for specified viewing conditions. If successful, the match evokes the same perceptual response as that of the standard. One way of finding a match is the trial and error approach of mixing various colorants until the color of the mixture appears the same as that of the standard under specific viewing conditions. Alternatively, a spectrophotometer can be employed to measure reflectances over the visible range of the spectrum. Spectrophotometric measurements of the standard and the prospective colorants can be analyzed to yield further information regarding the correct colorants and their relative proportions. Since
many data points are gathered, this kind of matching operation is best performed using modern digital computers and is known as computer color formulation. The objective of computer color formulation is to find the proportions of each colorant in a set that, when mixed, have a reflectance, that appears to have the same color as that of the standard under specified viewing conditions. If a systematic prediction can be used to select the correct colorants and their relative proportions to accurately match the color of a standard, much savings in terms of time, money and, wasted material is gained over using a trial and error approach. This systematic procedure is based on the Kubelka-Munk theory and involves two steps. First, it is necessary to characterize the field of colorants (primaries) that will be used to formulate the proposed match in terms of absorption and scattering coefficients. Second, once the primaries have been characterized, the selection of the correct colorants and their relative proportions must be determined.

B. Kubelka-Munk Theory

Kubelka-Munk turbid media theory adequately explains the behavior of mixtures of colorants by quantitatively characterizing the absorption and scattering properties of the colorants and their mixtures over the visible region of the spectrum. A perfect black absorbs all of the radiation incident upon it and scatters back none of it, while a perfect white absorbs none and scatters all. Real colors
lie between these extremes, but their absorption and scattering coefficients are expressed relative to black and white. For any wavelength, reflectance $R$ and Kubelka-Munk absorption $K$ and scattering $S$ may be interchanged using the following transformations:

\[ \frac{K}{S} = \frac{(1-R)^2}{2R}, \quad \text{and} \]

\[ R = 1 + \frac{K}{S} \sqrt{(K/S)^2 + 2(K/S)} . \]

Frequently, it is not necessary to know explicitly both the absorption and the scattering of the colorants, but rather the ratio $K/S$ is enough to predict the spectral properties of mixtures. This is known as Kubelka-Munk single-constant theory [1,2]. Single-constant theory applies when the scattering of the mixture is not dependent on the colorant or its concentration or if the scattering of the colorants is negligible in comparison with that of the absorbing substrate, as in the case of dyes. Generally, scattering does depend upon colorant concentration and is not negligible in comparison with that of the substrate to which they are applied, as in the case of paints. Therefore, both $K$ and $S$ must be known explicitly and is known as Kubelka-Munk two-constant theory [1,2]. This research is confined to the case of industrial importance where two-constant theory accounts for the physical effects of turbid media. Two-constant theory is developed below as it applies to the characterization of colorants ($K$ and $S$
determination) and the calculation, of colorant concentrations (color matching).

1. K and S Determination

The conventional method for characterizing the absorption and scattering properties of colorants over wavelength has been through the preparation of special mixtures known as primary binary blends [3]. For every colorant of interest, a sample of each of the following is prepared: masstone (pure colorant), binary mixture of masstone with white, or a binary mixture of masstone with black, or both. The spectral reflectance of each sample is measured spectrophotometrically, and surface corrections, if any, are made [4]. The calculation of K and S for the colorant of interest actually requires only two samples which yield the two independent linear equations required to solve for K and S:

\[
\begin{align*}
(K/S)_m &= (1-R_m)^2 / 2R_m \\
&= C_m K_m / C_m S_m \\
(K/S)_{mix} &= (1-R_{mix})^2 / 2R_{mix} \\
&= (C_m K_m + C_w K_w) / (C_m S_m + C_w S_w)
\end{align*}
\]

Where \((K/S)_m\) (K/S of the masstone), \(C_m\) (concentration of the masstone), \(R_{mix}\) (reflectance of the binary mixture with, say, white), \(C_w\) (concentration of white), \(K_w\) (absorption
coefficient of white), $S_w$ (scattering of white) are all known. This yields two equations and two unknowns allowing the explicit solution for $K_m$ (absorption coefficient of the masstone) and $S_m$ (scattering coefficient of the masstone).

An improvement can be made through the use of the third mixture which increases the reliability of the $K$ and $S$ determination [5]. This approach uses combinations of the three mixtures taken two at a time to compute a set of $K$ and $S$ values which are then used to predict the reflectance of the third mixture not used in the $K$ and $S$ determination. This is repeated for the other combinations and the $K$ and $S$ values predicted by each combination are compared. For each measured wavelength, the methods that predict the reflectance of the third mixture most accurately are averaged to yield the $K$ and $S$ values which are then stored for future use. This entire procedure is then repeated for each colorant of interest.

This procedure becomes quite time-consuming and expensive and does not always give accurate results. Frequently, the $K$ and $S$ values produced by the different combinations do not agree very well, and the accuracy of the $K$ and $S$ values determined in this fashion must seriously be questioned [6]. The validity of this method is also questionable since masstones tend to be mixed with each other when matching, rather than mixtures of masstone with black or white. If there is any effect on the absorption and scattering properties of a colorant by the presence of
other colorants, as in the case of the blending of fibers, then the difference between the way colorants are characterized and the way they are used may be important. Furthermore, the discrepancies would be expected to grow when the nature of reflection, absorption, and scattering of the actual colorants is more complex than the simple two-flux assumption made under Kubelka-Munk theory [7].

2. Color Matching

Once the colorant characteristics have been determined, it is then desirable to know which ones are required, and in what proportions, to match the color of the standard. In practice only the ratio $K/S$ of the standard is known, while the separate $K$ and $S$ values of the prospective colorants have been previously determined. $K/S$ is calculated by dividing the sum of the products of colorant concentrations and absorption coefficients by the sum of the products of colorant concentrations and scattering coefficients for the $i$ different colorants:

$$K/S \text{ predicted} = \frac{\sum_i C_i k_i}{\sum_i C_i s_i}.$$

The object is to find the concentrations $C_i$ for each colorant such that $K/S$ predicted becomes nearly equal to the actual $K/S$:

$$K/S \text{ actual} = \frac{(1-R_{\text{actual}})^2}{2R_{\text{actual}}}.$$
When this is satisfied, actual reflectance is nearly equal to the predicted reflectance. Typically, reflectance data is taken every ten nanometers from 400nm to 700nm to represent the standard and colorants, and four colorants are used to match the standard [8]. The K and S coefficients have previously been determined for each colorant at each wavelength and the reflectance of the standard has been converted to K/S. This yields thirty-one equations in the parameters K/S, C, K, and S, where all parameters are known except the concentrations of each colorant, C. The manner in which this overdetermined system of equations is solved for colorant concentration determines the type of match performed. If the system of equations is solved for the colorant concentrations yielding minimum tristimulus difference, a tristimulus match is performed. Alternatively, if the solution is made for the colorant concentrations that yield minimum spectral difference, a spectral match is performed. These methods are discussed in detail below. Both approaches have been used based on single-constant theory, while for the more complex two-constant theory, only tristimulus matching has been reported.
a. Tristimulus Matching

Tristimulus matching involves matching a standard's tristimulus values with a set of colorants that, when mixed, yield the same tristimulus values as that of the standard being matched [9-11]. Tristimulus values incorporate the reflectance data taken over all wavelengths by a relationship of the form,

$$TSVi = k \sum \lambda R(\lambda) \times S(\lambda) \times 0(\lambda)i,$$

where $R(\lambda)$ is the spectral reflectance of the standard over wavelength $\lambda$, $S(\lambda)$ is the spectral power distribution of the reference illuminant over wavelength, $0(\lambda)i$ are the three observer color matching functions $i$ over wavelength, $k$ is a normalizing factor, and $TSVi$ is the resulting tristimulus value for each observer color matching function. A set of simultaneous equations with as many tristimulus values as colorants is created, which is then solved for colorant concentrations that yield the minimum tristimulus difference between standard and predicted match.

Given that different reflectance curves may integrate to the same tristimulus values, the predicted match may have a reflectance curve that is different from or metameric to that of the original sample even though the tristimulus values of the standard and the match are equal. Metamerism occurs when two samples have the same tristimulus values under a primary illuminant and different tristimulus values.
under secondary illuminants. The samples may look the same under one source but not the others if their spectral curves are not identical. Additionally, the color matching functions exist only over the visible spectrum, hence if spectral characteristics in a band outside the visible are of interest, tristimulus values yield no weight in the desired band. The military, for instance, is particularly interested in controlling the infrared reflectance of camouflage materials. Furthermore, tristimulus matching makes use of information of only a limited number of parameters, the tristimulus values of the standard, derived from all of the wavelength information available, and therefore may not yield the best values when the match is being made from colorants that are of quite similar color. Although changing the concentration of one of these colorants may change the predicted reflectance substantially, changing the concentrations of the other spectrally similar colorants in the set may have a nearly identical effect on the resulting tristimulus values. This poor sensitivity of the tristimulus values of the match to spectrally similar colorants frequently leads to unreasonable predicted concentrations and is typical of a class of problems where the parameters are highly correlated.
b. Spectral Matching

McGuiness proposed an algorithm that allows the reflectance spectrum of a standard to be compared directly to the reflectance produced by a set of colorants at concentration as determined using Kubelka-Munk single-constant theory [12]. Spectral matching eliminates illuminant and observer dependence in the calculations as well as the loss of sensitivity associated with tristimulus reductions. Matches generated in this manner will exhibit less spectral difference than tristimulus matches and can be performed over any spectral region.

Spectral matching, as it has been applied to the single-constant case, makes use of linear optimization to calculate the colorant concentrations that minimize the sum of squares difference between the K/S curves of the standard and predicted match at every wavelength of interest. Linear optimization is possible since by definition of Kubelka-Munk single-constant theory, K/S of the mixture is linear with the product of colorant concentration and K/S:

$$K/S = \sum_i C_i (K/S)_i.$$\n
Little has been published explicitly on spectral matching for the non-linear two-constant case. A non-linear approach for two-constant theory seems necessary since by definition K/S of the mixture is proportional to the sum of
the products of colorant concentrations and absorption coefficients but inversely proportional to the sum of the products of colorant concentrations and scattering coefficients [13].
C. Limitations of Computer Color Formulation

Computer color formulation, however helpful, is not perfect, namely because of the large number of parameters affecting successful implementation of formulated recipes [14-17]. Computer color formulation deals only with the manipulation of spectral data to yield better recipes. The production of the recipes has its associated problems, the solution of which are beyond the scope of this research. Briefly, confounding the manufacturing and industrial problems of mixing the formulae there are associated instrumental problems such as calibration as well as the problems implicit in sample preparation and presentation. Inherent complexities of turbid media theory are also a factor.

D. Outlook

Present methods of computer color formulation have their inherent limitations. K and S determination using primary binary blends may not always yield accurate matching results. This happens as the nature of the colorants depart from the assumptions of Kubelka-Munk theory. Tristimulus matching is limited to the visible spectrum and to well defined colorants and frequently results in a match whose spectral curve is quite different from that of the standard. Spectral matching eliminates these problems with tristimulus matching but has only been applied to single-constant theory. For these reasons, a more robust approach to K and
S determination and color matching is needed to alleviate some of the problems associated with traditional computer color formulation based on Kubelka-Munk two-constant theory.
III. EXPERIMENTAL

The technique described below extends the principles associated with spectral matching to two-constant theory. A single approach to both K and S determination and spectral matching based on two-constant theory is referred to here as spectrophotometric color formulation. This method uses a linear simplification followed by iterative improvement using non-linear optimization techniques resulting in a spectrophotometric color formulation algorithm that will handle the non-linear two-constant situation.

A. Theoretical Development

1. Background

As discussed above, spectral matching refers to the determination of the correct colorant concentrations that results in a spectral curve least different from that of the standard. To perform a spectral match, the reflectance of the standard over wavelength is converted to K/S, and the coefficients (concentrations) of K and S of the primaries being used to match the standard are selected such that the spectral difference between standard and match is a minimum. This same idea can be extended to K and S determination. If the reflectance at any wavelength of several mixtures of colorants and the proportions of each colorant are known, then the values of K and S that yield the closest values of
the actual K/S of the mixtures can be determined.

It is possible to simplify the problem by assuming that reflectance can be accurately converted to K/S using:

\[
\text{K/S actual} = \frac{(1-R_{\text{actual}})^2}{2R_{\text{actual}}}.
\]

\(R_{\text{actual}}\) is the true reflectance value of a standard for a spectral match or a true reflectance value of a mixture for a K and S determination. Since,

\[
\text{K/S predicted} = \sum_i C_i K_i / \sum_i C_i S_i,
\]

and can be rewritten as,

\[
\sum_i C_i K_i + (\text{K/S actual}) \sum_i C_i S_i = 0,
\]

then all terms are linear. The \(K_i\) and the \(S_i\) are Kubelka-Munk absorption and scattering coefficients respectively for the \(i\) colorants at concentration \(C_i\) for a particular wavelength or mixture. \(\text{K/S predicted}\) is the quantity that must equal \(\text{K/S actual}\).

It can be seen that if the \(K_i\) and the \(S_i\) over wavelength are known then the \(C_i\) may be linearly determined to perform a spectral match. Alternatively, if the \(C_i\) are known for different mixtures then the \(K_i\) and the \(S_i\) may be computed to perform a K and S determination.
At this point it is helpful to define several matrices. These matrices are depicted below.

When calculating the K and S values of a set of primaries, several mixtures of these primaries with each other are required at known concentration levels. A matrix [KSCOEFS] has as its row elements the coefficients of K and S, namely the concentrations of the primaries for that mixture. This matrix will have as many rows as mixtures. At least two mixtures are required for each pair of K and S parameters to satisfy the degrees of freedom of the problem. The solution vector [KANDS] will have in the first half of its elements the computed values of K for the primaries and in the second half it will have the computed values of S.

When performing a spectral match, the K and S values of the primaries are known over wavelength, and it is the concentrations that need to be determined. A matrix [CCOEOFS] can be formed that has as its row elements the coefficients of concentration, namely the Ki and the Si. This matrix will have as many rows as wavelengths for which spectral data was obtained. At least as many wavelengths must be included as colorant concentrations to be determined to satisfy the degrees of freedom of the problem. The solution vector [C] will contain the computed colorant concentrations.
In both cases the vector [OBS] contains the right side of the equation, namely zeros except for a constraint. Unconstrained, these problems are indeterminate, since the observation vector would contain all zeros and there is an infinite number of solutions yielding a zero observation vector. One way of constraining the system of equations is to add a unit row to the coefficient matrices. In a K and S determination, this has the effect of forcing the sum of the absorption and scattering coefficients of a set of colorants to unity, or the sum of the concentrations to unity in the case of a spectral match.

The parameters of interest are then computed in one cycle using the well known matrix manipulation for solving an overdetermined system of linear equations [18]:

\[ [B] = \{ [X]^t[X] \}^{-1}[X]^t[Y]. \]

The solution vector [B] contains the parameters of interest, [X]^t is the transpose of the coefficient matrix [X], and [Y] is the vector of observed values for the number of observations. In a K and S determination, [B] contains a K and S value for each primary at a particular wavelength, [X] contains colorant concentrations for the different mixtures. In the case of a spectral match, [B] contains colorant concentrations, [X] contains absorption and scattering coefficients over the wavelength range of interest.
2. Explicit linear solution for K and S

In a K and S determination for, say, four colorants eight parameters need to be determined (the K and S values of each colorant at a particular wavelength). Therefore, at least eight mixtures are required to create an exactly determined system of eight equations in the eight unknowns. However, if the entire mixture history involving only these four colorants is available, then the additional mixtures can be used to define an overdetermined system of equations, thereby increasing the confidence in the calculated values of K and S. This method is outlined below:

1) K/S for a particular mixture at a particular wavelength is computed from reflectance and is known to contain the four colorants at known concentration, hence:

\[ K_{\text{mix}} = \sum_{i=1}^{4} C_i K_i \]  
\[ S_{\text{mix}} = \sum_{i=1}^{4} C_i S_i \]

2) Cross-multiplying and equating to zero yields:

\[-C_1 K_1 - C_2 K_2 - C_3 K_3 - C_4 K_4 + (K/S)_{\text{mix}} \left( C_1 S_1 + C_2 S_2 + C_3 S_3 + C_4 S_4 \right) = 0\]

3) Since the concentrations of the colorants in the mixture and the K/S of the mixture are known constants, they are the terms of a row in the coefficient matrix. Making the substitutions: \( X_1 = -C_1, X_2 = -C_2, X_3 = -C_3, X_4 = -C_4, \)
\[
X_5 = (K/S)_{\text{mix}1}, \quad X_6 = (K/S)_{\text{mix}2}, \quad X_7 = (K/S)_{\text{mix}3}, \quad X_8 = (K/S)_{\text{mix}4}
\]
and repeating for the \( j \) different mixtures at a particular wavelength yields:

\[
\begin{align*}
\begin{array}{cccccccccccc}
\text{mixture} & 1 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\text{mixture} & 2 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\text{mixture} & 3 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\text{mixture} & 4 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\text{mixture} & 5 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\text{mixture} & 6 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\text{mixture} & 7 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\text{mixture} & 8 & | & X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \\
\end{array}
\end{align*}
\]

\[
\begin{align*}
[K_{\text{SCOEFS}}] = \\
\begin{array}{cccccccccccc}
| 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & \text{constraint} \\
\end{array}
\end{align*}
\]

4) The observation vector is formed from the right side of the \( j \) equations; zeros and a constraint:

\[
\begin{align*}
\begin{array}{cccccccccccc}
\text{mixture} & 1 & | & 0 \\
\text{mixture} & 2 & | & 0 \\
\text{mixture} & 3 & | & 0 \\
\text{mixture} & 4 & | & 0 \\
\text{mixture} & 5 & | & 0 \\
\text{mixture} & 6 & | & 0 \\
\text{mixture} & 7 & | & 0 \\
\text{mixture} & 8 & | & 0 \\
\end{array}
\end{align*}
\]

\[
\begin{align*}
[OBS] = \\
\begin{array}{cccccccccccc}
| 0 & & \text{mixture} & j \\
| 1 & & \text{constraint} \\
\end{array}
\end{align*}
\]

5) The parameters of interest, the \( K \) and \( S \) coefficients for the four colorants at a particular wavelength, can now be computed:

\[
[K_{\text{ANDS}}] = \{ [K_{\text{SCOEFS}}] \cdot [K_{\text{SCOEFS}}]^{-1} \} [K_{\text{SCOEFS}}] \cdot [OBS],
\]

\[
\begin{align*}
\begin{array}{cccccccccccc}
\text{mixture} & 1 & | & 0 \\
\text{mixture} & 2 & | & 0 \\
\text{mixture} & 3 & | & 0 \\
\text{mixture} & 4 & | & 0 \\
\text{mixture} & 5 & | & 0 \\
\text{mixture} & 6 & | & 0 \\
\text{mixture} & 7 & | & 0 \\
\text{mixture} & 8 & | & 0 \\
\end{array}
\end{align*}
\]
The solution vector $[\text{KANDS}]$ has the following form:

\[
[\text{KANDS}] = \begin{bmatrix}
| K1 | & \text{absorption coefficient of colorant 1} \\
| K2 | & \text{absorption coefficient of colorant 2} \\
| K3 | & \text{absorption coefficient of colorant 3} \\
| K4 | & \text{absorption coefficient of colorant 4} \\
| S1 | & \text{scattering coefficient of colorant 1} \\
| S2 | & \text{scattering coefficient of colorant 2} \\
| S3 | & \text{scattering coefficient of colorant 3} \\
| S4 | & \text{scattering coefficient of colorant 4} \\
\end{bmatrix}
\]

6) Steps 1 - 5 are repeated for each wavelength for which spectrophotometric data is available. Normally, this is done from 400 to 700 nanometers in 10 nanometer increments yielding 31 points. This yields the four $K$ and four $S$ values for each colorant for each of the thirty-one wavelengths.
3. Explicit linear solution for C

In a spectral match from, say, four colorants four parameters need to be determined (the concentrations $C$ of each colorant required to match the standard). Therefore, at least four wavelengths are required to create an exactly determined system of four equations in the four unknowns. However, if the thirty-one point reflectance data for the standard has been measured, as above, then the additional wavelengths can be used to define an overdetermined system of equations, thereby increasing the confidence in the calculated values of $C$. This method is detailed below:

1) $K/S$ of the standard is computed from the reflectance of the standard at each wavelength. The colorants that will be used to match the standard as well as their $K$ and $S$ values have previously been determined, as above. The concentrations of each colorant required to match the $K/S$ of the standard is implicit in:

\[
\begin{align*}
K - \text{standard} &= C_1K_1 + C_2K_2 C_3K_3 + C_4K_4 \\
S &= C_1S_1 + C_2S_2 C_3S_3 + C_4S_4
\end{align*}
\]
2) Cross-multiplying, equating to zero, and rearranging the terms so they appear explicitly as coefficients of concentration yields:

\[ \begin{align*}
C_1 & \left( K_1 - S_1(K/S) \right) + C_2 & \left( K_2 - S_2(K/S) \right) + \\
C_3 & \left( K_3 - S_3(K/S) \right) + C_4 & \left( K_4 - S_4(K/S) \right) = 0
\end{align*} \]

3) Since the \( K \) and \( S \) values of the colorants, and the \( K/S \) of the standard are known constants, they are the terms of a row in the coefficient matrix. Making the substitution \( X_1 = C_1K_1-S_1(K/S), \) \( X_2 = C_2K_2-S_2(K/S), \) \( X_3 = C_3K_3-S_3(K/S), \) and \( X_4 = C_4K_4-S_4(K/S), \) and repeating for the 31 wavelengths yields:

\[
\begin{array}{cccc}
X_1 & X_2 & X_3 & X_4 \\
\text{wavelength} & \text{nm} \\
400 & \text{X} & \text{X} & \text{X} & \text{X} \\
410 & \text{X} & \text{X} & \text{X} & \text{X} \\
420 & \text{X} & \text{X} & \text{X} & \text{X} \\
430 & \text{X} & \text{X} & \text{X} & \text{X} \\
\vdots & & & \\
700 & \text{X} & \text{X} & \text{X} & \text{X} \\
1 & 1 & 1 & 1 & \text{constraint}
\end{array}
\]

4) The observation vector is formed from the right side of the 32 equations; zeros and a constraint:

\[
\begin{array}{c}
\text{wavelength} \\
400 & \text{X} \\
410 & \text{X} \\
420 & \text{X} \\
430 & \text{X} \\
\vdots & & \\
700 & \text{X} \\
1 & \text{constraint}
\end{array}
\]
5) The parameters of interest, the colorant concentrations, can now be computed:

\[
[C] = \{ [CCOefs]t[CCOefs] \}^{-1} [CCOefs]t[OBS].
\]

The solution vector \([C]\) has the following form:

\[
[C] = \begin{bmatrix}
C_1 \\
C_2 \\
C_3 \\
C_4
\end{bmatrix}
\]

- concentration for colorant 1
- concentration for colorant 2
- concentration for colorant 3
- concentration for colorant 4

4. Non-linear iterative improvement

An iterative improvement can be obtained by then performing either type of calculation in reflectance space. Once \([B]\) has been determined as above, predicted \(K/S\) and predicted reflectance can be calculated,

\[
K/S \text{ predicted } = \Sigma_i C_i K_i / \Sigma_i C_i S_i, \text{ and}
\]

\[
R \text{ predicted } = 1 + (K/S)_p \sqrt{\Sigma_i(C_i S_i)^2} + 2(K/S)_p.
\]

Evaluation of the quality of the match can be done in the highly non-linear reflectance space using a non-linear optimization algorithm. Using these equations, the non-linear optimization algorithm adjusts \([B]\) until \(R\) predicted nearly equals \(R\) actual.
The problem of determining $[B]$ in situations where Kubelka-Munk two-constant approach is necessary, is essentially an exercise in non-linear optimization. The parameter to be minimized is the sum of squares difference between the actual reflectance curve and the predicted curve as computed from $[B]$. A non-linear approach is ultimately necessary if the predicted reflectance is going to be compared with the actual reflectance since the transformation to reflectance is not linear.

Several general optimization algorithms have appeared in the literature since 1963 and the interested reader should refer to Christian and Tucker [19-23] who discuss optimization, Bevington [24] and Marquardt [25] who discuss the Levenberg-Marquardt optimization algorithm that was implemented in this research for iterative improvements. Optimization algorithms based on several different strategies were implemented for this research. Gradient-following [24] and linearization [24] techniques similar to those found in computer statistical libraries were tried independently with only fair results. Finally, the Levenberg-Marquardt [25] strategy was used. This technique interpolates between the gradient and linearization approaches from the instantaneous position on the error hypersurface at any iteration to the predicted minimum. This error hypersurface is a map of residual error as a function of each $n$ parameter and is hence $n$-dimensional. From the current position on the error
hypersurface the gradient and linearization strategies tend to predict the position of the minimum, in the worst case, orthogonal to each other with the true minimum hopefully lying along some vector between them. The Levenberg-Marquardt algorithm attempts to compute this angle and control the descent to the true minimum by moving along this vector. Using this algorithm, convergence was rapid and reliable.
B. Verification of Theory

The research is twofold. The first is the application of optimization to \( K \) and \( S \) determination, while the second is the application of optimization to spectral matching. The testing followed this outline:

1. An optimization of Kubelka-Munk absorption coefficients \( K \) and scattering coefficients \( S \) was performed on a data set provided by Burlington Industries. From a set of twenty-five blends of blue, green, yellow and red fibers, as many as twenty four of these blends were used in a non-linear least-squares determination of \( K \) and \( S \) for the thirty-one point wavelength data. The reflectance data was measured on a Bausch & Lomb / Diano Match Scan spectrophotometer, specular component included with diffuse polychromatic illumination. This reflectance data is provided in Appendix I. The \( K \) and \( S \) coefficients determined in this fashion were used to predict the reflectance of the twenty-fifth blend, a twenty-five percent mixture of each fiber.

2. Tristimulus and spectral matches were performed for several types of matching situations. The primary \( K \) and \( S \) data had previously been determined using primary binary blends. Colorimetric differences and spectral differences were computed for both matching approaches.
a. A reflectance curve was matched that was previously synthesized from the primaries used to match it. This reflects the situation where a match is sought for a standard from the correct colorants with materials that follow Kubelka-Munk behavior closely and there is little measurement error.

b. Standard reflectance curves were matched that were synthesized with primaries other than those used to attempt to match the standard. This reflects the situation where the correct colorants are not known and a match is sought with an alternate set of colorants. These materials, however, are assumed to follow Kubelka-Munk behavior closely.

c. Fiber-blends provided by Badische Corporation were matched from the fibers used to create those blends. Colorant concentrations were computed with both spectral and tristimulus matching and compared to the concentrations actually used to prepare the original blends. This reflects the situation where there is substantial measurement error and it is known that the materials deviate significantly from Kubelka-Munk behavior [26]. The reflectances of the primary binary blends as well as the blend reflectance data and matching data is given in Appendix III.

By testing various aspects of computer color formulation, the advantages and limitations associated with spectrophotometric color formulation have been observed.
IV. RESULTS

Tables 1 and 2 pertain to the determination of K and S data for the four fibers. Although the optimized K and S data for each fiber may be found in Appendix II, Table 1 shows the difference between predicted and actual reflectance of the four-way blend. Table 2 has three items of interest. First is the color difference between predicted and actual reflectance of the four-way blend in CIELab units, two degree observer. Second is the percentages of each fiber required to match the actual four way blend as determined through the optimized K and S and using tristimulus matching. Third is the percentages of each fiber required to match the actual four way blend as determined through the optimized K and S and using spectral matching.

Tables 3, 4, and 5 pertain to color matching. Table 3 shows matches to a green standard from the primaries that were used to numerically synthesize that standard. The first match is a tristimulus match from these primaries and the related color differences while the second match is a spectral match and the related color differences. Table 4 summarizes tristimulus and spectral matches to gray standards from an alternate set of colorants. The actual matching data can be found in Appendix IV. Table 5 summarizes the tristimulus and spectral matches of the fiber blends from the fibers in the blends. The actual matching data can be found in Appendix V.
**TABLE 1**

**PREDICTION OF FOUR WAY BLEND REFLECTANCE**

<table>
<thead>
<tr>
<th>WL</th>
<th>R predicted</th>
<th>R measured</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>3.11241</td>
<td>3.10000</td>
<td>0.01241</td>
</tr>
<tr>
<td>410</td>
<td>3.19328</td>
<td>3.18000</td>
<td>0.01328</td>
</tr>
<tr>
<td>420</td>
<td>3.32346</td>
<td>3.32000</td>
<td>0.00346</td>
</tr>
<tr>
<td>430</td>
<td>3.51839</td>
<td>3.51000</td>
<td>0.00839</td>
</tr>
<tr>
<td>440</td>
<td>3.75462</td>
<td>3.74000</td>
<td>0.01462</td>
</tr>
<tr>
<td>450</td>
<td>3.93744</td>
<td>3.93000</td>
<td>0.00743</td>
</tr>
<tr>
<td>460</td>
<td>4.07171</td>
<td>4.06000</td>
<td>0.01171</td>
</tr>
<tr>
<td>470</td>
<td>4.20132</td>
<td>4.20000</td>
<td>0.00132</td>
</tr>
<tr>
<td>480</td>
<td>4.40311</td>
<td>4.40000</td>
<td>0.00311</td>
</tr>
<tr>
<td>490</td>
<td>4.66537</td>
<td>4.66000</td>
<td>0.00537</td>
</tr>
<tr>
<td>500</td>
<td>4.97179</td>
<td>4.94000</td>
<td>0.03179</td>
</tr>
<tr>
<td>510</td>
<td>5.21765</td>
<td>5.15000</td>
<td>0.06765</td>
</tr>
<tr>
<td>520</td>
<td>5.30567</td>
<td>5.17000</td>
<td>0.13567</td>
</tr>
<tr>
<td>530</td>
<td>5.16815</td>
<td>4.98000</td>
<td>0.18815</td>
</tr>
<tr>
<td>540</td>
<td>4.95634</td>
<td>4.73000</td>
<td>0.22634</td>
</tr>
<tr>
<td>550</td>
<td>4.85363</td>
<td>4.59000</td>
<td>0.26363</td>
</tr>
<tr>
<td>560</td>
<td>4.81634</td>
<td>4.52000</td>
<td>0.29634</td>
</tr>
<tr>
<td>570</td>
<td>4.84285</td>
<td>4.51000</td>
<td>0.33285</td>
</tr>
<tr>
<td>580</td>
<td>5.14202</td>
<td>4.76000</td>
<td>0.38202</td>
</tr>
<tr>
<td>590</td>
<td>5.58195</td>
<td>5.36000</td>
<td>0.22195</td>
</tr>
<tr>
<td>600</td>
<td>6.64220</td>
<td>6.18000</td>
<td>0.46220</td>
</tr>
<tr>
<td>610</td>
<td>7.22156</td>
<td>6.77000</td>
<td>0.45156</td>
</tr>
<tr>
<td>620</td>
<td>7.46222</td>
<td>7.03000</td>
<td>0.43221</td>
</tr>
<tr>
<td>630</td>
<td>7.53312</td>
<td>7.11000</td>
<td>0.42312</td>
</tr>
<tr>
<td>640</td>
<td>7.72023</td>
<td>7.30000</td>
<td>0.42023</td>
</tr>
<tr>
<td>650</td>
<td>8.22978</td>
<td>7.81000</td>
<td>0.41978</td>
</tr>
<tr>
<td>660</td>
<td>9.27334</td>
<td>8.85000</td>
<td>0.42334</td>
</tr>
<tr>
<td>670</td>
<td>10.84142</td>
<td>10.41000</td>
<td>0.43142</td>
</tr>
<tr>
<td>680</td>
<td>13.12664</td>
<td>12.68000</td>
<td>0.44664</td>
</tr>
<tr>
<td>690</td>
<td>16.19110</td>
<td>15.69000</td>
<td>0.50110</td>
</tr>
<tr>
<td>700</td>
<td>20.75672</td>
<td>20.21000</td>
<td>0.54672</td>
</tr>
</tbody>
</table>

**GOODNESS = 9.093E-06**

**NONLINEAR OPTIMIZATION OF K AND S USING TWENTY-FOUR BLENDS**
## Table 2: Match of Four-way Blend

**TRIAL IS -- 4 WAY MATCH NL24**

<table>
<thead>
<tr>
<th>STANDARD</th>
<th>TRIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>R25/G25/Y25/B25</td>
<td>4 WAY MATCH NL24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ILL</th>
<th>DE</th>
<th>LD</th>
<th>RG</th>
<th>YB</th>
<th>DC</th>
<th>DH</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>1.38</td>
<td>0.71</td>
<td>0.27</td>
<td>1.16</td>
<td>1.12</td>
<td>2.88</td>
</tr>
<tr>
<td>A</td>
<td>1.55</td>
<td>0.80</td>
<td>0.35</td>
<td>1.28</td>
<td>1.14</td>
<td>3.62</td>
</tr>
<tr>
<td>CW</td>
<td>1.54</td>
<td>0.80</td>
<td>0.15</td>
<td>1.30</td>
<td>1.23</td>
<td>3.50</td>
</tr>
</tbody>
</table>

CIELAB GOODNESS = 0.9093E-05

12-APR-85 11:51:33 ITER = 1 COMBINATION 1

COLORANT %

- BLUE (NL/24): 24.8541%
- GREEN (NL/24): 27.1974%
- YELLOW (NL/24): 22.4374%
- RED (NL/24): 25.5111%

COST = 1.0000  MI = 0.04

<table>
<thead>
<tr>
<th>ILL</th>
<th>DE</th>
<th>LD</th>
<th>RG</th>
<th>YB</th>
<th>DC</th>
<th>DH</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>A</td>
<td>0.03</td>
<td>0.00</td>
<td>-0.03</td>
<td>0.00</td>
<td>-0.03</td>
<td>0.11</td>
</tr>
<tr>
<td>CW</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

GOODNESS = 1.3095500E-06

### Colorant Percentages

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Color</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BLUE (NL/24)</td>
<td>25.62%</td>
</tr>
<tr>
<td>2</td>
<td>GREEN (NL/24)</td>
<td>26.19%</td>
</tr>
<tr>
<td>3</td>
<td>YELLOW (NL/24)</td>
<td>22.33%</td>
</tr>
<tr>
<td>4</td>
<td>RED (NL/24)</td>
<td>25.86%</td>
</tr>
</tbody>
</table>

12-APR-85 11:54:32 COMBINATION 1 AFTER 2 ITERATIONS FOR R25/G25/Y25/B25

<table>
<thead>
<tr>
<th>ILL</th>
<th>DE</th>
<th>LD</th>
<th>RG</th>
<th>YB</th>
<th>DC</th>
<th>DH</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>0.37</td>
<td>0.03</td>
<td>0.27</td>
<td>-0.26</td>
<td>-0.05</td>
<td>-2.82</td>
</tr>
<tr>
<td>A</td>
<td>0.28</td>
<td>0.04</td>
<td>0.18</td>
<td>-0.21</td>
<td>0.00</td>
<td>-1.56</td>
</tr>
<tr>
<td>CW</td>
<td>0.33</td>
<td>0.03</td>
<td>0.20</td>
<td>-0.26</td>
<td>-0.12</td>
<td>-2.49</td>
</tr>
</tbody>
</table>

CIELAB

MI = 0.10 GOODNESS = 0.2719E-06 AT A COST OF $1.0000
Table 3: Match to Green Standard

TYPE REFLECTANCE FILE RECORD NUMBER 24,1
STANDARD IS -- GREEN

OUTPUT SIZE ?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 6,1
RECORD CONTAINS YELLOW 142
COLORANT 2 ? 11,1
RECORD CONTAINS TI02
COLORANT 3 ? 13,1
RECORD CONTAINS NEW BLUE
COLORANT 4 ?

NUMBER OF COLORANTS PER FORMULA? 3
10-APR-85 14:46:16 ITER = 1 COMBINATION 1
COLORANT %
( 6U)YELLOW 142 == 19.9985
( 11U)TI02 == 60.0020
( 13U)NEW BLUE == 19.9995

CIELAB
GOODNESS = 9.5179609E-10

COLORANT PERCENTAGES

FIBER 1 YELLOW 142 20.00%
FIBER 2 TI02 60.00%
FIBER 3 NEW BLUE 20.00%

10-APR-85 14:47:09 COMBINATION 1 AFTER 1 ITERATIONS FOR GREEN

CIELAB
GOODNESS = 9.5179609E-10 AT A COST OF $0.8000
### TABLE 4

**SUMMARY OF TRISTIMULUS AND SPECTRAL MATCHES OF GRAY STANDARDS FROM ALTERNATE COLORANTS**

<table>
<thead>
<tr>
<th>STANDARD</th>
<th>Match Number</th>
<th>G tm</th>
<th>G sm</th>
<th>Delta E sm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Gray</td>
<td>1</td>
<td>4.70</td>
<td>3.44</td>
<td>2.91</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.60</td>
<td>2.06</td>
<td>8.97</td>
</tr>
<tr>
<td>Medium Gray</td>
<td>3</td>
<td>1.55</td>
<td>.80</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.93</td>
<td>1.27</td>
<td>7.70</td>
</tr>
<tr>
<td>Dark Gray</td>
<td>5</td>
<td>.31</td>
<td>.17</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>23.4</td>
<td>1.17</td>
<td>4.55</td>
</tr>
</tbody>
</table>

Reference to a tristimulus match is indicated by tm, a spectral match by sm. G is goodness, the average squared spectral difference per wavelength. Delta E is the predicted color difference between standard and spectrally predicted match expressed in CIELab units, D65, two degree observer. By definition, tristimulus matches predict zero color difference under the primary illuminant.
### TABLE 5

**SUMMARY OF TRISTIMULUS AND SPECTRAL MATCHES OF FIBER BLENDS FROM THE CORRECT FIBERS**

<table>
<thead>
<tr>
<th>BLEND</th>
<th>G tm</th>
<th>G sm</th>
<th>Delta E sm</th>
<th>Delta C tm</th>
<th>Delta C sm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.64</td>
<td>3.11</td>
<td>.45</td>
<td>1.76</td>
<td>1.54</td>
</tr>
<tr>
<td>2</td>
<td>.78</td>
<td>.61</td>
<td>.19</td>
<td>2.25</td>
<td>2.28</td>
</tr>
<tr>
<td>4</td>
<td>1.81</td>
<td>1.28</td>
<td>.20</td>
<td>.84</td>
<td>.91</td>
</tr>
<tr>
<td>6</td>
<td>6.82</td>
<td>3.26</td>
<td>.27</td>
<td>1.09</td>
<td>.85</td>
</tr>
<tr>
<td>7</td>
<td>34.7</td>
<td>12.1</td>
<td>1.25</td>
<td>1.23</td>
<td>1.14</td>
</tr>
<tr>
<td>9</td>
<td>.53</td>
<td>.42</td>
<td>.09</td>
<td>3.62</td>
<td>3.65</td>
</tr>
<tr>
<td>10</td>
<td>.56</td>
<td>.37</td>
<td>.1</td>
<td>.77</td>
<td>.91</td>
</tr>
<tr>
<td>11</td>
<td>7.75</td>
<td>2.09</td>
<td>.57</td>
<td>4.27</td>
<td>4.16</td>
</tr>
<tr>
<td>12</td>
<td>47.7</td>
<td>29.8</td>
<td>1.38</td>
<td>4.36</td>
<td>1.99</td>
</tr>
<tr>
<td>15</td>
<td>48.2</td>
<td>4.96</td>
<td>1.39</td>
<td>10.77</td>
<td>4.10</td>
</tr>
<tr>
<td>17</td>
<td>.86</td>
<td>.68</td>
<td>.06</td>
<td>1.06</td>
<td>1.07</td>
</tr>
<tr>
<td>21</td>
<td>625.</td>
<td>.98</td>
<td>.41</td>
<td>11.02</td>
<td>1.10</td>
</tr>
<tr>
<td>22</td>
<td>2.48</td>
<td>.41</td>
<td>.39</td>
<td>2.23</td>
<td>1.02</td>
</tr>
<tr>
<td>25</td>
<td>2.17</td>
<td>.27</td>
<td>.13</td>
<td>2.40</td>
<td>1.91</td>
</tr>
<tr>
<td>27</td>
<td>8.61</td>
<td>6.83</td>
<td>.33</td>
<td>1.44</td>
<td>1.55</td>
</tr>
<tr>
<td>32</td>
<td>47.3</td>
<td>.71</td>
<td>.40</td>
<td>6.59</td>
<td>3.30</td>
</tr>
<tr>
<td>33</td>
<td>.30</td>
<td>.17</td>
<td>.40</td>
<td>4.54</td>
<td>4.53</td>
</tr>
<tr>
<td>34</td>
<td>5.36</td>
<td>4.98</td>
<td>.15</td>
<td>.93</td>
<td>1.34</td>
</tr>
<tr>
<td>Ave</td>
<td>47.0</td>
<td>4.06</td>
<td>.45</td>
<td>3.398</td>
<td>2.075</td>
</tr>
</tbody>
</table>

The blend number is that reported by Burlone [28]. An H or an L indicates that when the predicted match was actually prepared it had a high or low color difference from the standard. Reference to a tristimulus match is indicated by tm, a spectral match by sm. G is goodness, the average squared spectral difference per wavelength. Delta E is the predicted color difference between standard and spectrally predicted match expressed in CIELab units, D65, two degree observer. By definition, tristimulus matches predict zero color difference under the primary illuminant. Delta C is the average difference in concentration between the predicted and actual concentrations of fiber in the blend.
V. DISCUSSION

The research had two objectives. The first was the application of optimization to $K$ and $S$ determination, while the second was the application of optimization to spectral matching.

An optimization of absorption coefficients ($K$) and scattering coefficients ($S$) was performed on the data set provided by Burlington Industries. From a set of twenty-five blends of blue, green, yellow and red fibers, as many as twenty four of these blends were used in a non-linear least-squares determination of Kubelka-Munk absorption and scattering coefficients for the thirty-one point wavelength data. The $K$ and $S$ coefficients determined in this fashion were used to predict the reflectance of the twenty-fifth blend, a twenty-five percent mixture of each fiber. The agreement between predicted and actual reflectance of this four-way blend was quite good, and improved as the number of blends used to compute $K$ and $S$ was increased from eight to twenty-four. Eight blends provide the minimum number of independent equations to solve for the four unknown absorption and scattering coefficients. This is the same number that would be required to compute $K$ and $S$ using binary blends. From Table 1, the difference between predicted and actual reflectance of the four-way blend can be observed. Goodness is defined here as the average squared absolute error per wavelength and was calculated by
summing the squared difference between the reflectance of the standard and that of the prediction and dividing by the number of data points (wavelengths). The calculated value of goodness for this prediction was 9.093E-06 or about an average of .3% difference in percent reflectance units. Although this seems quite small, from Table 2 this led to a predicted colorimetric difference of about 1.4 CIELab units for the listed conditions. Tristimulus and spectral matches of the standard four-way blend with these primaries resulted in predicted concentrations averaging 1.4% different from the nominal values. Although these kind of results would normally be considered unacceptable when dealing with homogeneous materials that follow Kubelka-Munk theory, conversations with several sources in the fiber industry indicate that these results are considered quite good in a fiber-blending situation. This stems from the fact that fiber blends appear quite heterogeneous to a human observer, and it is not known how this correlates with color differences as measured by a diffuse spectrophotometer which tends to make the sample appear homogeneous to the detector. Therefore, according to these sources, delta Es of up to two CIELab units and percentages of fiber of up to two percent difference usually yield quite acceptable matches. The advantage of this method is that no primary binary blends have to be prepared; the primary data can be computed from normally documented blend history. Further research is necessary to test the hypothesis that primaries optimized in this fashion yield better matching results than primaries
determined using binary letdowns.

Tristimulus and spectral matches were performed for several types of matching situations, where the primary K and S data have been determined using primary binary blends. Colorimetric differences and spectral differences were computed for both matching approaches.

In the first situation, a reflectance curve was matched that was previously synthesized from the primaries used to match it. This represents the situation where a match is sought for a standard from the correct colorants with materials that follow Kubelka-Munk behavior closely and there is little measurement error. From Table 3, it can be seen that both tristimulus and spectral matching resulted in perfect spectral matches indicated by the near zero values of goodness and delta Es. Additionally, the predicted concentrations is both cases were the correct values.

In the second situation, reflectance curves were matched that were synthesized with primaries other than those used to attempt to match the standard. This is indicative of the situation where the correct colorants are not known and a match is sought with an alternate set of colorants. These materials are paints and follow Kubelka-Munk behavior closely. From Table 4 it can be seen that although spectral matching resulted in curves of much lower predicted spectral mismatch, it was at the expense of a colorimetric match. When matches are sought from
colorants that are not in the standard, perfect spectral matches are not possible, hence any match will be metameric with that of the standard. Given the fact that some spectral mismatch must exist, tristimulus matching optimizes the mismatch to allow a colorimetric match. Alternatively, spectral matching optimizes the mismatch itself without regard to colorimetric difference. Unless it is necessary to specifically control spectral difference, tristimulus matching may be preferred for this type of situation. If many colorants are available, it is possible that spectral matching could produce matches of low spectral difference and acceptable colorimetric difference, although further research is necessary to test this hypothesis.

In the third situation, fiber-blends provided by Badische Corporation were matched from the fibers used to create those blends. Some of these fibers were of spectrally similar character. This reflects the situation where there is substantial measurement error, the colorants are similar, and it is known that the materials deviate from Kubelka-Munk behavior. Colorant concentrations were computed with both spectral and tristimulus matching and compared to the concentrations actually used to prepare the original blends. Significantly better results were gained with spectral matching over tristimulus matching. This improvement may be due to the increased sensitivity provided by the spectral matching approach. Where there is substantial deviation from optimal conditions associated
with computer color formulation, it appears better to avoid the tristimulus reduction and rather try to minimize overall spectral error. From Table 5 it can be seen that spectral matching resulted in much better predicted spectral difference as well as providing significantly closer concentration values while providing acceptable colorimetric differences. In fact, average spectral difference was reduced an order of magnitude, average predicted concentration accuracy was increased by 1.3 percentage points while the average predicted colorimetric difference was less than .5 delta E CIELab units. These results indicate a real matching improvement.
VI. CONCLUSIONS

Spectrophotometric color formulation is a tool that could have widespread application in the colorant formulation industry. Since this approach produces better matches under certain conditions while potentially allowing the use of more colorants without unreasonably increasing the formulation time, savings in terms of money and time could be realized by reducing the number of wasted production batch formulations.

An application for this tool is in the fiber-blending industry. Here, spectrally similar fibers are woven together on a microscopic level to yield a macroscopically different color. Traditional approaches computer to color formulation as applied to fiber-blending have suffered from low accuracy. The measurement of these heterogeneous samples is difficult and it is been hypothesized that the turbid media effects associated with fiber depart from Kubelka-Munk theory. Furthermore, spectrally similar colorants are employed in matching fiber blends. It is in the area of fiber-blending that spectrophotometric color formulation could be most useful. Perhaps the combined approach of least-squares determination of K and S coupled with spectral matching would yield an even greater improvement in match prediction.
The value of using spectrally similar primaries transcends fiber-blending, however. Frequently, production batches that were intended to match a standard are slightly off-shade and are useless unless they can be worked into another formulation. The key is to use spectrally similar off-shade materials to produce an on-shade product. If formulations from these similar waste materials could be accurately produced, substantial savings would result. In the case where alternate formulations are being sought to match a standard with colorants other than those in the standard, the substitution of a colorant that is slightly different from one that is being considered may have certain advantages. It may be true that the new colorant, or combination of several colorants, will reduce metamerism or cost. It is apparent that the ability to distinguish between, and work with, mathematically similar colorants would be an improvement.

Another area spectrophotometric color formulation could be used is for matching standards in a wavelength region where there is no tristimulus information possible. If, for instance, the ultraviolet or infrared reflectance regions of a standard need to be matched, spectrophotometric color formulation could be used, just as in the visible region. The manufacture of camouflage materials is an example of the importance of controlling reflectance outside the visible region.
It is conceivable that spectrophotometric color formulation could replace many of the existing color formulation programs designed to handle various types of specific problems.
VII. REFERENCES


6) ibid., p. 35


9) ibid., pp. 290-334.


13) V. Gugerli, "Rezeptieren auf der Basis optischer Messungen", Textil-Rundschau, 18, 266(1963).


VIII. Appendix I

Burlington blend reflectance data:

Reflectance data of fiber blends

Note: The next two pages are reflectances of the blends followed by their graphs.
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IX. Appendix II

K and S data for Burlington blends:

Optimized K and S coefficients for the four fibers
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X. Appendix III

Alternate matches:

Tristimulus and spectral matches of gray standards

Note: The next three pages are tristimulus matches of the gray standards followed by three pages of spectral matches to the same gray standards.
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 13,1
STANDARD IS -- LIGHT GRAY

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 10,1
RECORD CONTAINS TI02
COLORANT 2 ? 12,1
RECORD CONTAINS YELLOW PY74
COLORANT 3 ? 17,1
RECORD CONTAINS GREEN PG17
COLORANT 4 ? 28,1
RECORD CONTAINS PURPLE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 14:06:39 ITER= 3 COMBINATION 1
COLORANT %
( 10U)TI02 = 37.6942
( 12U)YELLOW PY74 = 4.1773
( 17U)GREEN PG17 = 43.1394
( 28U)PURPLE = 14.9691

COST=  1.000  MI = 1.12
ILL=D6 2 DE= 0.01  LD= 0.00  RG= 0.01  YB=-0.01  DC= 0.00  DH= 0.24
ILL=A 2 DE= 1.12  LD= 0.01  RG= 1.07  YB= 0.34  DC=-0.59  DH= 28.31
ILL=CW 2 DE= 1.24  LD=-0.36  RG=-0.38  YB=-1.13  DC= 1.18  DH=-3.61

CIELAB
GOODNESS = 4.6967864E-03

JOB CODE? 3

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 10,1
RECORD CONTAINS TI02
COLORANT 2 ? 12,1
RECORD CONTAINS YELLOW PY74
COLORANT 3 ? 29,1
RECORD CONTAINS BLUE PB60
COLORANT 4 ? 28,1
RECORD CONTAINS PURPLE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 14:07:25 ITER= 3 COMBINATION 1
COLORANT %
( 10U)TI02 = 4.5487
( 12U)YELLOW PY74 = 1.9353
( 29U)BLUE PB60 = 91.7684
( 28U)PURPLE = 1.7475

COST=  1.000  MI = 1.60
ILL=D6 2 DE= 0.02  LD= 0.01  RG= -0.01  YB= 0.01  DC= -0.01  DH= -0.39
ILL=A 2 DE= 1.59  LD= -0.02  RG= 1.58  YB=-0.22  DC= 0.03  DH= 40.64
ILL=CW 2 DE= 1.24  LD=-0.41  RG= 0.86  YB=-0.79  DC= 0.82  DH= 19.42

CIELAB
GOODNESS = 4.0000000E-02

600
ENTER
USE MATCH SCAN? [T/F]  F
TYPE REFLECTANCE FILE RECORD NUMBER 14,1
STANDARD IS -- MEDIUM GRAY

OUTPUT SIZE ?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 10,1
RECORD CONTAINS TI02
COLORANT 2 ? 12,1
RECORD CONTAINS YELLOW PY74
COLORANT 3 ? 29,1
RECORD CONTAINS BLUE PB60
COLORANT 4 ? 28,1
RECORD CONTAINS PURPLE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 14:12:30 ITER= 3 COMBINATION 1
COLORANT %
(  10U)TI02 == 1.8310
(  12U)YELLOW PY74 == 1.8817
(  29U)BLUE PB60 == 94.4009
(  28U)PURPLE == 1.8864

COST= 1.000 MI = 1.62
ILL=D6 2 DE= 0.02 LD= 0.01 RG= -0.01 YB= 0.01 DC= -0.01 DH= -0.36
ILL=A 2 DE= 1.60 LD= -0.01 RG= 1.58 YB= -0.27 DC= 0.05 DH= 33.06
ILL=AW 2 DE= 1.15 LD= -0.40 RG= 0.62 YB= -0.71 DC= 0.75 DH= 14.97

CIELAB
GOODNESS = 1.5534506E-03

JOB CODE? 3

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 10,1
RECORD CONTAINS TI02
COLORANT 2 ? 15,1
RECORD CONTAINS RED PV19
COLORANT 3 ? 17,1
RECORD CONTAINS GREEN PG17
COLORANT 4 ? 29,1
RECORD CONTAINS BLUE PB60
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 14:13:16 ITER= 3 COMBINATION 1
COLORANT %
(  10U)TI02 == 1.1843
(  15U)RED PV19 == 1.4189
(  17U)GREEN PG17 == 4.7083
(  29U)BLUE PB60 == 92.6885

COST= 1.000 MI = 0.74
ILL=D6 2 DE= 0.03 LD= 0.01 RG= 0.01 YB= -0.02 DC= 0.02 DH= 0.26
ILL=A 2 DE= 0.72 LD= 0.00 RG= 0.39 YB= 0.61 DC= -0.71 DH= 2.97
ILL=AW 2 DE= 1.25 LD= -0.25 RG= -0.23 YB= -1.20 DC= 1.22 DH= -1.75

CIELAB
GOODNESS = 1.9339784E-03
ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 15,1
STANDARD IS -- DARK GRAY

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 10,1
RECORD CONTAINS TIO2
COLORANT 2 ? 12,1
RECORD CONTAINS YELLOW PY74
COLORANT 3 ? 28,1
RECORD CONTAINS PURPLE
COLORANT 4 ? 30,1
RECORD CONTAINS BLUEGREEN
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 14:14:30 ITER= 3 COMBINATION 1
COLORANT %
( 10U)TIO2 == 6.7194
( 12U)YELLOW PY74 == 26.8751
( 28U)PURPLE == 51.0937
( 30U)BLUEGREEN == 15.3118

COST= 1.000 MI = 0.99
ILL=D6 2 DE= 0.03 LD= 0.01 RG= -0.02 YB= 0.02 DC= -0.02 DH= -0.34
ILL=A 2 DE= 0.97 LD= 0.00 RG= 0.92 YB= -0.32 DC= 0.14 DH= 17.60
ILL=CW 2 DE= 0.47 LD= -0.15 RG= 0.44 YB= -0.08 DC= 0.09 DH= 8.02

CIELAB
GOODNESS = 3.0586662E-04

JOB CODE? 3

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 11,1
RECORD CONTAINS MARS BLACK
COLORANT 2 ? 17,1
RECORD CONTAINS GREEN PG17
COLORANT 3 ? 29,1
RECORD CONTAINS BLUE PB60
COLORANT 4 ? 28,1
RECORD CONTAINS PURPLE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 14:15:09 ITER= 4 COMBINATION 1
COLORANT %
( 11U)MARS BLACK == 0.7608
( 17U)GREEN PG17 == 1.8579
( 29U)BLUE PB60 == 96.2599
( 28U)PURPLE == 1.1214

COST= 1.000 MI = 0.56
ILL=D6 2 DE= 0.04 LD= 0.00 RG= 0.02 YB= -0.04 DC= 0.04 DH= 0.35
ILL=A 2 DE= 0.53 LD= 0.00 RG= 0.12 YB= 0.51 DC= -0.52 DH= -1.38
ILL=CW 2 DE= 0.51 LD= -0.11 RG= -0.33 YB= -0.37 DC= 0.39 DH= -5.27

CIELAB
GOODNESS = 2.3436528E-02
COLORANT PERCENTAGES

FIBER 1  TI02  32.09%
FIBER 2  YELLOW PY74  2.17%
FIBER 3  GREEN PG17  53.14%
FIBER 4  PURPLE  12.60%

10-APR-85 14:26:55 COMBINATION 1 AFTER 1 ITERATIONS FOR LIGHT GRAY

ILL=D6 2 DE= 2.91  LD= -0.71  RG= -2.41  YB= 1.47  DC= 0.97  DH=-69.39
ILL=A 2 DE= 2.06  LD= -0.85  RG= -1.08  YB= 1.53  DC= -0.09  DH=-49.83
ILL=CW 2 DE= 2.72  LD= -1.09  RG= -2.47  YB= 0.26  DC= 1.23  DH=-48.51

CIELAB

MI = 1.33  GOODNESS = 0.3440E-02 AT A COST OF $1.0000

COLORANT PERCENTAGES

FIBER 1  TI02  2.18%
FIBER 2  YELLOW PY74  1.00%
FIBER 3  BLUE PB60  96.43%
FIBER 4  PURPLE  0.39%

10-APR-85 14:27:40 COMBINATION 1 AFTER 1 ITERATIONS FOR LIGHT GRAY

ILL=D6 2 DE= 8.97  LD= 0.55  RG= -8.86  YB= 1.26  DC= 7.42  DH=-73.20
ILL=A 2 DE= 7.08  LD= -0.30  RG= -7.04  YB= -0.68  DC= 6.24  DH=-44.29
ILL=CW 2 DE= 5.91  LD= -0.26  RG= -5.90  YB= -0.15  DC= 4.50  DH=-61.88

CIELAB

MI = 2.79  GOODNESS = 0.2059E-02 AT A COST OF $1.0000
COLORANT PERCENTAGES

FIBER 1  TI02  0.60%
FIBER 2  YELLOW PY74  0.84%
FIBER 3  BLUE PB60  98.29%
FIBER 4  PURPLE  0.27%

10-APR-85 14:32:58 COMBINATION 1 AFTER 26 ITERATIONS FOR MEDIUM GRAY

ILL=D6  2  DE= 10.05  LD= -0.21  RG= -9.90  YB= 1.69  DC= 7.88  DH=-77.70
ILL=A   2  DE=  7.90  LD= -1.14  RG= -7.80  YB= -0.57  DC= 6.68  DH=-46.61
ILL=CW  2  DE=  6.68  LD= -1.11  RG= -6.58  YB=  0.18  DC= 4.60  DH=-64.62

CIELAB

MI = 3.22  GOODNESS = 0.7997E-03  AT A COST OF $1.0000

COLORANT PERCENTAGES

FIBER 1  TI02  0.27%
FIBER 2  RED PV19  0.14%
FIBER 3  GREEN PG17  1.36%
FIBER 4  BLUE PB60  98.23%

10-APR-85 14:34:50 COMBINATION 1 AFTER 26 ITERATIONS FOR MEDIUM GRAY

ILL=D6  2  DE=  7.70  LD= -2.05  RG= -6.18  YB= -4.13  DC= 6.81  DH=-36.66
ILL=A   2  DE=  9.33  LD= -2.98  RG= -7.13  YB= -5.23  DC= 8.56  DH=-22.59
ILL=CW  2  DE=  8.46  LD= -2.87  RG= -4.96  YB= -6.22  DC= 7.63  DH=-24.91

CIELAB

MI = 1.73  GOODNESS = 0.1268E-02  AT A COST OF $1.0000
COLORANT PERCENTAGES

FIBER 1 TI02 5.36%
FIBER 2 YELLOW PY74 21.19%
FIBER 3 PURPLE 56.18%
FIBER 4 BLUEGREEN 17.28%

10-APR-85 14:37:18 COMBINATION 1 AFTER 26 ITERATIONS FOR DARK GRAY

ICH=D6 2 DE= 2.09 LD= -1.34 RG= 0.84 YB= -1.37 DC= 1.43 DH= 12.43
ILL=A 2 DE= 2.36 LD= -1.34 RG= 1.14 YB= -1.57 DC= 1.38 DH= 21.23
ILL=CW 2 DE= 2.25 LD= -1.47 RG= 0.90 YB= -1.44 DC= 1.51 DH= 11.83

CIELAB

MI = 0.36 GOODNESS = 0.1731E-03 AT A COST OF $1.0000

COLORANT PERCENTAGES

FIBER 1 MARS BLACK 0.26%
FIBER 2 GREEN PG17 0.51%
FIBER 3 BLUE PB60 98.67%
FIBER 4 PURPLE 0.55%

10-APR-85 14:39:40 COMBINATION 1 AFTER 26 ITERATIONS FOR DARK GRAY

ILL=D6 2 DE= 4.55 LD= -0.77 RG= 1.37 YB= -4.27 DC= 4.37 DH= 12.64
ILL=A 2 DE= 4.17 LD= -0.92 RG= 0.17 YB= -4.06 DC= 3.93 DH= 12.83
ILL=CW 2 DE= 5.21 LD= -0.99 RG= 0.88 YB= -5.04 DC= 5.07 DH= 7.28

CIELAB

MI = 1.23 GOODNESS = 0.1171E-02 AT A COST OF $1.0000
XI. Appendix IV

Badische blend reflectance data:

Reflectance data of fiber blends
August 9, 1984

Cornelius McCarthy

Dear Mickey:

Enclosed is the data you requested. Page 1 contains data on 9 solids. Pages 1 to 3 contain data on the 42 blends discussed in the Color Research and Application paper. The blend information starts at line 19. There are 8 numbers on line 190. The first four are the numbers of the colors in blend #1 and the last four are their respective concentrations in blend #1. Lines 195 and 200 are the 16 reflectances (400 to 700 nanometers, 20 nanometer intervals) for blend #1. The rest of the blends follow the same format.

Pages 4 and 5 contain information on the "Primaries". These curves were synthesized from the K and S data stored in the data file.

I am very interested in the outcome of your study. I am especially interested in your non-linear optimization routine particularly as it pertains to calculation of K and S data from blends other than the conventional binary blends with white and black. If the program is successful in accomplishing this and could be made available by itself, we would be interested in talking about a purchase.

When you are in this area, please come by to talk about our common interests. In the meantime, please let me know if there is any other information you need.

Dom Burlone
D. A. Burlone
R & D Department
/ct
Enclosure
<p>| 100 | 73.92 | 75.84 | 77.34 | 78.83 | 79.97 | 80.78 | 81.62 | 81.69 |
| 105 | 82.08 | 82.01 | 81.98 | 82.11 | 82.51 | 83.11 | 83.65 | 84.14 |
| 110 | 2.84  | 2.77  | 2.91  | 3.60  | 4.58  | 5.96  | 7.56  | 9.28  |
| 115 | 12.21 | 15.10 | 17.33 | 18.49 | 19.44 | 20.12 | 20.70 | 21.56 |
| 120 | 5.25  | 3.80  | 2.98  | 3.00  | 3.98  | 7.16  | 12.18 | 16.42 |
| 125 | 22.08 | 32.80 | 46.18 | 53.26 | 57.42 | 60.38 | 62.94 | 65.52 |
| 130 | 3.32  | 3.10  | 3.56  | 5.64  | 12.15 | 19.75 | 21.61 | 17.28 |
| 135 | 12.86 | 9.96  | 8.40  | 8.20  | 8.22  | 10.30 | 17.87 | 33.20 |
| 140 | 3.70  | 3.43  | 2.82  | 2.43  | 1.95  | 1.83  | 1.78  | 2.09  |
| 145 | 2.42  | 5.09  | 12.91 | 18.41 | 20.22 | 22.81 | 26.27 | 34.63 |
| 150 | 14.23 | 10.70 | 8.53  | 8.65  | 12.36 | 21.52 | 35.74 | 45.24 |
| 155 | 53.95 | 59.43 | 63.58 | 66.34 | 68.76 | 71.34 | 74.18 | 76.86 |
| 160 | 1.88  | 1.84  | 1.77  | 1.87  | 1.81  | 1.80  | 1.65  | 1.75  |
| 165 | 1.57  | 1.53  | 1.56  | 1.58  | 1.74  | 2.28  | 5.43  | 14.13 |
| 170 | 2.94  | 2.69  | 2.46  | 2.46  | 2.45  | 2.69  | 3.01  | 3.51  |
| 175 | 3.79  | 4.24  | 4.89  | 4.60  | 6.56  | 14.61 | 29.39 | 41.23 |
| 180 | 5.63  | 6.59  | 7.50  | 7.24  | 5.56  | 4.66  | 3.74  | 3.45  |
| 185 | 2.91  | 2.66  | 2.52  | 2.51  | 2.57  | 3.20  | 6.55  | 16.43 |
| 190 | 3.94  | 1.20  | 5.0  | 15.0  | 50.0  | 53.33 |
| 195 | 20.36 | 19.37 | 19.15 | 20.25 | 23.45 | 28.08 | 31.82 | 32.35 |
| 200 | 32.34 | 32.78 | 33.27 | 33.62 | 33.96 | 35.96 | 42.28 | 53.33 |
| 205 | 8.29  | 14.3  | 33.3  | 9.5  | 42.9  |
| 210 | 10.55 | 10.43 | 10.51 | 11.13 | 11.78 | 12.86 | 14.07 | 15.31 |
| 215 | 17.11 | 18.81 | 20.23 | 20.68 | 22.00 | 25.51 | 30.09 | 34.17 |
| 220 | 2.94  | 15.0  | 15.0  | 15.0  | 55.0  |
| 225 | 14.64 | 14.74 | 15.34 | 16.68 | 18.66 | 20.60 | 21.36 | 21.14 |
| 230 | 21.01 | 20.86 | 20.75 | 20.93 | 21.23 | 22.70 | 27.35 | 35.64 |
| 235 | 8.64  | 30.0  | 30.0  | 5.0  | 35.0  |
| 240 | 13.37 | 12.07 | 11.16 | 11.39 | 12.91 | 15.68 | 18.46 | 19.79 |
| 245 | 20.58 | 21.20 | 22.03 | 21.94 | 23.89 | 31.99 | 45.15 | 55.80 |
| 250 | 7.25  | 8.5  | 10.0  | 30.0  | 55.0  |
| 255 | 2.95  | 2.73  | 2.44  | 2.42  | 2.36  | 2.57  | 2.83  | 3.31  |
| 260 | 3.72  | 4.89  | 7.14  | 7.99  | 9.53  | 15.35 | 25.08 | 33.41 |
| 265 | 8.25  | 1.56  | 11.1  | 5.6  | 77.8  |
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| Time (s) | 350  | 355  | 360  | 365  | 370  | 375  | 380  | 385  | 390  | 395  | 400  | 405  | 410  | 415  | 420  | 425  | 430  | 435  | 440  | 445  | 450  | 455  | 460  | 465  | 470  | 475  | 480  | 485  | 490  | 495  | 500  | 505  | 510  | 515  | 520  | 525  | 530  | 535  | 540  | 545  | 550  | 555  | 560  | 565  | 570  | 575  | 580  | 585  | 590  | 595  |
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XII. Appendix V

Matches of Badische blends:

Tristimulus and spectral matches of fiber blends

Note: The first match on each page is a tristimulus match to the indicated standard while the second match is a spectral match to the same standard.
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 27,1
STANDARD IS -- 190 BURLONE 1

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 3,1
RECORD CONTAINS ORANGE FIBER
COLORANT 2 ? 9,1
RECORD CONTAINS BLUE FIBER
COLORANT 3 ? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 13:59:19 ITER= 1 COMBINATION 1
COLORANT %
( 3U)ORANGE FIBER == 15.4258
( 9U)BLUE FIBER ==  4.1816
( 4U)GREEN FIBER == 16.6643
( 1U)WHITE BASE == 63.7283
COST= 1.000 MI = 0.04

ILL=D6 2 DE= 0.01 LD= 0.00 RG= 0.00 YB= 0.00 DC= 0.00 DH= -0.01
ILL=A 2 DE= 0.04 LD= 0.00 RG= 0.04 YB= -0.02 DC= -0.02 DH= -0.12
ILL=CW 2 DE= 0.02 LD= 0.00 RG= 0.01 YB= 0.01 DC= 0.01 DH= -0.03

CIELAB
GOODNESS = 5.6396066E-06

COLORANT PERCENTAGES
FIBER 1 ORANGE FIBER 15.27%
FIBER 2 BLUE FIBER 4.65%
FIBER 3 GREEN FIBER 16.14%
FIBER 4 WHITE BASE 63.94%

11-APR-85 14:19:15 COMBINATION 1 AFTER 26 ITERATIONS FOR 190 BURLONE 1

ILL=D6 2 DE= 0.45 LD= -0.10 RG= 0.17 YB= -0.40 DC= -0.43 DH= -0.27
ILL=A 2 DE= 0.40 LD= -0.10 RG= 0.10 YB= -0.38 DC= -0.37 DH= -0.41
ILL=CW 2 DE= 0.44 LD= -0.10 RG= 0.14 YB= -0.41 DC= -0.42 DH= -0.21

CIELAB
MI = 0.08 GOODNESS = 0.3119E-05 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 64,1
STANDARD IS -- 220 BURLONE 2

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 2,1
RECORD CONTAINS GINGER FIBER
COLORANT 2 ? 9,1
RECORD CONTAINS BLUE FIBER
COLORANT 3 ? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:00:07 ITER= 1 COMBINATION 1
COLORANT %
( 2U)GINGER FIBER == 19.4877
( 9U)BLUE FIBER == 14.8736
( 4U)GREEN FIBER == 14.7086
( 1U)WHITE BASE == 50.9301
COST= 1.000 MI = 0.02
ILL=D6 2 DE= 0.00 LD= 0.00 RG= 0.00 YB= 0.00 DC= 0.00 DH= 0.01
ILL=A 2 DE= 0.02 LD= 0.00 RG= -0.01 YB= 0.01 DC= 0.01 DH= 0.10
ILL=CN 2 DE= 0.02 LD= 0.00 RG= 0.02 YB= 0.00 DC= -0.01 DH= -0.10

CIELAB
GOODNESS = 7.8108275E-07

COLORANT PERCENTAGES
FIBER 1 GINGER FIBER 19.56%
FIBER 2 BLUE FIBER 14.62%
FIBER 3 GREEN FIBER 15.00%
FIBER 4 WHITE BASE 50.82%
11-APR-85 14:20:11 COMBINATION 1 AFTER 1 ITERATIONS FOR 220 BURLONE 2

CIELAB
MI = 0.04 GOODNESS = 0.6061E-06 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 62,1
STANDARD IS -- 235 BURLONE 4

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 2 ? 6,1
RECORD CONTAINS YELLOW FIBER
COLORANT 3 ? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:01:25 ITER= 1 COMBINATION 1
COLORANT
( 8U)BROWN FIBER  == 31.2510
( 6U)YELLOW FIBER  == 30.4340
( 4U)GREEN FIBER   == 4.2230
( 1U)WHITE BASE    == 34.0921
COST= 1.0000 MI = 0.00
ILL=D6 2 DE= 0.00 LD= 0.00 RG= 0.00 YB= 0.00 DC= 0.00 DH= 0.01
ILL=A  2 DE= 0.00 LD= 0.00 RG= 0.00 YB= 0.00 DC= 0.00 DH= 0.01
ILL=CW 2 DE= 0.01 LD= 0.00 RG= 0.01 YB= 0.01 DC= 0.01 DH= -0.03
CIELAB
GOODNESS = 1.8058562E-06

COLORANT PERCENTAGES
FIBER 1 BROWN FIBER  31.50%
FIBER 2 YELLOW FIBER  30.31%
FIBER 3 GREEN FIBER   3.84%
FIBER 4 WHITE BASE   34.35%

11-APR-85 14:21:12 COMBINATION 1 AFTER 2 ITERATIONS FOR 235 BURLONE 4
ILL=D6 2 DE= 0.20 LD= -0.01 RG= 0.16 YB= -0.11 DC= -0.11 DH= -0.52
ILL=A  2 DE= 0.14 LD= 0.00 RG= 0.12 YB= -0.07 DC= -0.03 DH= -0.39
ILL=CW 2 DE= 0.17 LD= 0.00 RG= 0.12 YB= -0.11 DC= -0.12 DH= -0.35
CIELAB
MI = 0.06 GOODNESS = 0.1277E-05 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 66,1
STANDARD IS -- 265 BURLONE 6

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 2 ? 2,1
RECORD CONTAINS GINGER FIBER
COLORANT 3 ? 5,1
RECORD CONTAINS RED FIBER
COLORANT 4 ? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:02:53 ITER= 1 COMBINATION 1
COLORANT %
  ( 8U)BROWN FIBER == 3.8214
  ( 2U)GINGER FIBER == 12.0393
  ( 5U)RED FIBER == 6.6154
  ( 1U)WHITE BASE == 77.5239
COST= 1.0000 MI = 0.09

ILL=D6 2 DE= 0.04 LD= 0.00 RG= 0.04 YB= 0.00 DC= 0.03 DH= -0.15
ILL=A 2 DE= 0.13 LD= 0.00 RG= 0.12 YB= -0.03 DC= 0.06 DH= -0.43
ILL=CW 2 DE= 0.08 LD= -0.02 RG= 0.07 YB= -0.02 DC= 0.02 DH= -0.36
CIELAB
GOODNESS = 6.8169243E-06

COLORANT PERCENTAGES

FIBER 1 BROWN FIBER 4.30%
FIBER 2 GINGER FIBER 11.41%
FIBER 3 RED FIBER 6.51%
FIBER 4 WHITE BASE 77.78%
11-APR-85 14:22:40 COMBINATION 1 AFTER 26 ITERATIONS FOR 265 BURLONE 6

ILL=D6 2 DE= 0.27 LD= -0.01 RG= -0.07 YB= -0.26 DC= -0.25 DH= -0.56
ILL=A 2 DE= 0.33 LD= -0.03 RG= -0.04 YB= -0.32 DC= -0.26 DH= -0.76
ILL=CW 2 DE= 0.32 LD= -0.05 RG= -0.03 YB= -0.32 DC= -0.29 DH= -0.64
CIELAB

MI = 0.07 GOODNESS = 0.3259E-05 AT A COST OF $1.0000
JOB CODE?  1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F]  F
TYPE REFLECTANCE FILE RECORD NUMBER  68,1
STANDARD IS -- 280 BURLONE 7

OUTPUT SIZE ?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ?  8,1
RECORD CONTAINS BROWN FIBER
COLORANT 2 ?  3,1
RECORD CONTAINS ORANGE FIBER
COLORANT 3 ?  5,1
RECORD CONTAINS RED FIBER
COLORANT 4 ?  1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA?  4
11-APR-85 14:04:03 ITER=  1 COMBINATION  1
COLORANT %
  ( 8U)BROWN FIBER  ==  17.5113
  ( 3U)ORANGE FIBER  ==  29.9799
  ( 5U)RED FIBER   ==  6.4078
  (1U)WHITE BASE   ==  46.1011
COST=  1.000  MI =  0.05

CIELAB
GOODNESS =  3.468683E-05

CIELAB
GOODNESS =  3.468683E-05

COLORANT PERCENTAGES

FIBER 1  BROWN FIBER  19.28%
FIBER 2  ORANGE FIBER  31.59%
FIBER 3  RED FIBER   3.45%
FIBER 4  WHITE BASE  45.68%

11-APR-85 14:23:44 COMBINATION  1 AFTER 26 ITERATIONS FOR 280 BURLONE 7

CIELAB
GOODNESS =  3.468683E-05

MI =  0.17 GOODNESS =  0.1213E-04 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 70,1
STANDARD IS -- 310 BURLONE 9

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1? 3,1
RECORD CONTAINS ORANGE FIBER
COLORANT 2? 5,1
RECORD CONTAINS RED FIBER
COLORANT 3? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:04:43 ITER= 1 COMBINATION 1
COLORANT %
( 3U)ORANGE FIBER == 15.5397
( 5U)RED FIBER == 27.4856
( 4U)GREEN FIBER == 9.7287
( 1U)WHITE BASE == 47.2460
COST= 1.0000 MI = 0.03
ILL=D6 2 DE= 0.01 LD= 0.00 RG= -0.01 YB= 0.01 DC= 0.00 DH= 0.03
ILL=A 2 DE= 0.04 LD= 0.00 RG= -0.01 YB= 0.04 DC= 0.02 DH= 0.07
ILL=CW 2 DE= 0.07 LD= 0.00 RG= -0.05 YB= -0.05 DC= -0.07 DH= 0.06
CIELAB
GOODNESS = 5.2538650E-07

COLORANT PERCENTAGES
FIBER 1 ORANGE FIBER 15.40%
FIBER 2 RED FIBER 27.48%
FIBER 3 GREEN FIBER 9.83%
FIBER 4 WHITE BASE 47.29%
11-APR-85 14:24:42 COMBINATION 1 AFTER 2 ITERATIONS FOR 310 BURLONE 9

ILL=D6 2 DE= 0.09 LD= -0.01 RG= -0.07 YB= -0.05 DC= -0.09 DH= 0.06
ILL=A 2 DE= 0.09 LD= -0.01 RG= -0.08 YB= -0.05 DC= -0.09 DH= 0.06
ILL=CW 2 DE= 0.16 LD= -0.01 RG= -0.10 YB= -0.12 DC= -0.15 DH= 0.07
CIELAB
MI = 0.01 GOODNESS = 0.4177E-06 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 72,1
STANDARD IS -- 325 BURLONE 10

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 2 ? 2,1
RECORD CONTAINS GINGER FIBER
COLORANT 3 ? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:05:17 ITER= 1 COMBINATION 1
COLORANT %
( 8U)BROWN FIBER == 24.4210
( 2U)GINGER FIBER == 20.7237
( 4U)GREEN FIBER == 14.0196
( 1U)WHITE BASE == 40.8357
COST= 1.000 MI = 0.01

ILL=D6 2 DE= 0.00 LD= 0.00 RG= 0.00 YB= 0.00 DC= 0.00 DH= 0.01
ILL=A 2 DE= 0.01 LD= 0.00 RG= 0.01 YB= 0.00 DC= 0.01 DH= -0.04
ILL=CW 2 DE= 0.01 LD= 0.00 RG= 0.00 YB= 0.01 DC= 0.01 DH= -0.01

CIELAB
GOODNESS = 5.5642658E-07

COLORANT PERCENTAGES

FIBER 1 BROWN FIBER 24.24%
FIBER 2 GINGER FIBER 21.11%
FIBER 3 GREEN FIBER 13.94%
FIBER 4 WHITE BASE 40.72%

11-APR-85 14:25:48 COMBINATION 1 AFTER 2 ITERATIONS FOR 325 BURLONE 10

ILL=D6 2 DE= 0.10 LD= 0.00 RG= 0.05 YB= 0.08 DC= 0.08 DH= -0.21
ILL=A 2 DE= 0.12 LD= 0.01 RG= 0.06 YB= 0.10 DC= 0.11 DH= -0.13
ILL=CW 2 DE= 0.11 LD= 0.01 RG= 0.04 YB= 0.10 DC= 0.10 DH= -0.19

CIELAB
MI = 0.02 GOODNESS = 0.3742E-06 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 74,1
STANDARD IS -- 340 BURLONE 11

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 2 ? 5,1
RECORD CONTAINS RED FIBER
COLORANT 3 ? 9,1
RECORD CONTAINS BLUE FIBER
COLORANT 4 ? 3,1
RECORD CONTAINS ORANGE FIBER
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4

11-APR-85 14:05:49 ITER= 1 COMBINATION 1

COLORANT %
( 8U)BROWN FIBER == 17.8965
( 5U)RED FIBER == 12.1552
( 9U)BLUE FIBER == 23.4975
( 3U)ORANGE FIBER == 46.4508
COST= 1.000 MI = 0.06

ILL=D6 2 DE= 0.01 LD= 0.00 RG= 0.01 YB= 0.00 DC= 0.01 DH= -0.03
ILL=A 2 DE= 0.07 LD= 0.00 RG= 0.07 YB= 0.00 DC= 0.04 DH= -0.12
ILL=CW 2 DE= 0.09 LD= -0.02 RG= 0.03 YB= -0.08 DC= -0.06 DH= -0.11

CIELAB
GOODNESS = 7.7493642E-06

COLORANT PERCENTAGES

FIBER 1 BROWN FIBER 21.07%
FIBER 2 RED FIBER 10.10%
FIBER 3 BLUE FIBER 22.15%
FIBER 4 ORANGE FIBER 46.68%

11-APR-85 14:27:33 COMBINATION 1 AFTER 6 ITERATIONS FOR 340 BURLONE 11

ILL=D6 2 DE= 0.57 LD= 0.06 RG= -0.46 YB= 0.34 DC= 0.12 DH= 1.19
ILL=A 2 DE= 0.40 LD= 0.02 RG= -0.32 YB= 0.24 DC= 0.05 DH= 0.71
ILL=CW 2 DE= 0.50 LD= 0.03 RG= -0.40 YB= 0.29 DC= 0.16 DH= 0.98

CIELAB
MI = 0.18 GOODNESS = 0.2093E-05 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 76,1
STANDARD IS -- 355 BURLONE 12

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 2 ? 2,1
RECORD CONTAINS GINGER FIBER
COLORANT 3 ? 5,1
RECORD CONTAINS RED FIBER
COLORANT 4 ? 9,1
RECORD CONTAINS BLUE FIBER
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 15:46:38 ITER= 1 COMBINATION 1
COLORANT %
( 8U) BROWN FIBER == 28.0516
( 2U) GINGER FIBER == 30.6591
( 5U) RED FIBER == 16.5835
( 9U) BLUE FIBER == 24.7058

COST= 1.000 MI = 0.22

CIELAB
GOODNESS = 4.7703379E-05

COLORANT PERCENTAGES

FIBER 1 BROWN FIBER 18.52%
FIBER 2 GINGER FIBER 32.57%
FIBER 3 RED FIBER 17.50%
FIBER 4 BLUE FIBER 31.40%

10-APR-85 15:55:10 COMBINATION 1 AFTER 6 ITERATIONS FOR 355 BURLONE 12

ILL=D6 2 DE= 1.38 LD= 0.17 RG= -0.16 YB= -1.36 DC= -0.98 DH= -3.61
ILL=A 2 DE= 1.48 LD= 0.10 RG= -0.28 YB= -1.45 DC= -1.16 DH= -2.74
ILL=CW 2 DE= 1.54 LD= 0.10 RG= -0.12 YB= -1.53 DC= -1.26 DH= -3.77

CIELAB
MI = 0.16 GOODNESS = 0.2976E-05 AT A COST OF $1.0000
USE MATCH SCAN? [T/F]  F
TYPE REFLECTANCE FILE RECORD NUMBER 80,1
STANDARD IS -- 400 BURLONE 15

OUTPUT SIZE ?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 2 ? 2,1
RECORD CONTAINS GINGER FIBER
COLORANT 3 ? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ? 6,1
RECORD CONTAINS YELLOW FIBER
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA?  4
10-APR-85 15:47:31 ITER=  2 COMBINATION  1
COLORANT %
( 8U) BROWN FIBER   ==  0.8215
( 2U) GINGER FIBER   ==  54.5400
( 4U) GREEN FIBER    ==  7.5223
( 6U) YELLOW FIBER   ==  37.1162

COST=  1.000     MI =  0.28
ILL=D6  2  DE=  0.01  LD=  0.00  RG=  0.00  YB= -0.01  DC= -0.01  DH=  0.00
ILLE=A  2  DE=  0.29  LD= -0.02  RG= -0.19  YB= -0.22  DC= -0.26  DH=  0.18
ILL=CW  2  DE=  0.41  LD=  0.06  RG=  0.33  YB=  0.24  DC=  0.26  DH= -0.46
CIELAB
GOODNESS =  4.8211752E-04

COLORANT PERCENTAGES

FIBER 1  BROWN FIBER   13.60%
FIBER 2  GINGER FIBER   36.11%
FIBER 3  GREEN FIBER    2.20%
FIBER 4  YELLOW FIBER   48.10%

10-APR-85 15:57:53 COMBINATION  1 AFTER  5 ITERATIONS FOR 400 BURLONE 15

ILL=D6  2  DE=  1.39  LD= -0.03  RG=  0.25  YB= -1.37  DC= -1.33  DH= -0.66
ILLE=A  2  DE=  1.25  LD= -0.05  RG=  0.07  YB= -1.24  DC= -1.18  DH= -0.63
ILL=CW  2  DE=  1.46  LD= -0.05  RG=  0.20  YB= -1.45  DC= -1.43  DH= -0.43
CIELAB
MI =  0.21 GOODNESS =  0.4959E-05 AT A COST OF $1.0000
USE MATCH SCAN?  [T/F]  F
TYPE REFLECTANCE FILE RECORD NUMBER  84,1
STANDARD IS -- 430 BURLONE 17

OUTPUT SIZE ?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 3,1
RECORD CONTAINS ORANGE FIBER
COLORANT 2 ? 6,1
RECORD CONTAINS YELLOW FIBER
COLORANT 3 ? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA?  4
11-APR-85 14:07:21 ITER= 1 COMBINATION  1
COLORANT %
(  3U)ORANGE FIBER == 16.5451
(  6U)YELLOW FIBER == 23.9363
(  4U)GREEN FIBER == 10.5822
( 1U)WHITE BASE == 48.9364
COST=  1.000 MI = 0.02
YB= 0.00 DC= 0.00 DH= 0.00
CIELAB
GOODNESS =  8.5976313E-07

COLORANT PERCENTAGES
FIBER 1 ORANGE FIBER  16.60%
FIBER 2 YELLOW FIBER  23.88%
FIBER 3 GREEN FIBER  10.53%
FIBER 4 WHITE BASE  48.99%
11-APR-85 14:30:51 COMBINATION  1 AFTER 14 ITERATIONS FOR 430 BURLONE 17
CIELAB
GOODNESS = 0.6807E-06 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 82,1
STANDARD IS -- 490 BURLONE 21

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 7,1
RECORD CONTAINS BLACK BASE
COLORANT 2 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 3 ? 5,1
RECORD CONTAINS RED FIBER
COLORANT 4 ? 3,1
RECORD CONTAINS ORANGE FIBER
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:07:55 ITER= 1 COMBINATION 1
COLORANT %
( 7U) BLACK BASE == 15.3451
( 8U) BROWN FIBER == -2.0423
( 5U) RED FIBER == 27.1909
( 3U) ORANGE FIBER == 59.5063
COST= 1.000 MI = 0.15
IILL=D6 2 DE= 0.03 LD= 0.01 RG= 0.01 YB= 0.03 DC= 0.03 DH= 0.01
IILL=A 2 DE= 0.13 LD= -0.02 RG= -0.12 YB= -0.05 DC= -0.10 DH= 0.10
IILL=CW 2 DE= 0.42 LD= 0.01 RG= 0.42 YB= 0.00 DC= 0.14 DH= -0.59
CIELAB
GOODNESS = 6.2492618E-04

COLORANT PERCENTAGES

FIBER 1 BLACK BASE 3.50%
FIBER 2 BROWN FIBER 21.42%
FIBER 3 RED FIBER 20.78%
FIBER 4 ORANGE FIBER 54.30%

11-APR-85 14:32:18 COMBINATION 1 AFTER 26 ITERATIONS FOR 490 BURLONE 21
IILL=D6 2 DE= 0.41 LD= 0.04 RG= -0.39 YB= -0.12 DC= -0.29 DH= 0.44
IILL=A 2 DE= 0.33 LD= 0.00 RG= -0.25 YB= -0.21 DC= -0.31 DH= 0.13
IILL=CW 2 DE= 0.41 LD= -0.01 RG= -0.33 YB= -0.24 DC= -0.34 DH= 0.35
CIELAB
MI = 0.18 GOODNESS = 0.9836E-06 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 86,1
STANDARD IS -- 505 BURLONE 22

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 2? 7,1
RECORD CONTAINS BLACK BASE
COLORANT 3? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 4? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 5?

NUMBER OF COLORANTS PER FORMULA? 4
10-APR-85 15:51:03 ITER= 1 COMBINATION 1
COLORANT %
( 1U)WHITE BASE == 8.4071
( 7U)BLACK BASE == 27.1426
( 8U)BROWN FIBER == 23.3644
( 4U)GREEN FIBER == 41.0859

COST= 1.000 MI = 0.17

ILL=D6 2 DE= 0.04 LD= 0.00 RG= -0.02 YB= 0.03 DC= 0.04 DH= -0.05
ILL=A 2 DE= 0.15 LD= 0.00 RG= 0.14 YB= -0.05 DC= -0.11 DH= -0.61
ILL=CW 2 DE= 0.09 LD= -0.02 RG= -0.03 YB= 0.09 DC= 0.09 DH= -0.12

CIELAB
GOODNESS = 2.4840026E-06

COLORANT PERCENTAGES
FIBER 1 WHITE BASE 9.13%
FIBER 2 BLACK BASE 28.84%
FIBER 3 BROWN FIBER 21.89%
FIBER 4 GREEN FIBER 40.14%

10-APR-85 16:03:42 COMBINATION 1 AFTER 7 ITERATIONS FOR 505 BURLONE 22

ILL=D6 2 DE= 0.39 LD= -0.08 RG= 0.15 YB= -0.35 DC= -0.36 DH= 0.57
ILL=A 2 DE= 0.43 LD= -0.08 RG= 0.15 YB= -0.39 DC= -0.41 DH= 0.41
ILL=CW 2 DE= 0.35 LD= -0.09 RG= 0.11 YB= -0.32 DC= -0.32 DH= 0.49

CIELAB
MI = 0.04 GOODNESS = 0.4141E-06 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 88,1
STANDARD IS -- 550 BURLONE 25

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 7,1
RECORD CONTAINS BLACK BASE
COLORANT 2 ? 8,1
RECORD CONTAINS BROWN FIBER
COLORANT 3 ? 9,1
RECORD CONTAINS BLUE FIBER
COLORANT 4 ? 6,1
RECORD CONTAINS YELLOW FIBER
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:09:17 ITER= 1 COMBINATION 1
COLORANT %
( 7U)BLACK BASE == 11.4922
( 8U)BROWN FIBER == 14.5036
( 9U)BLUE FIBER == 5.6965
(6U)YELLOW FIBER == 68.3076
COST= 1.0000 MI = 0.03
ILL=D6 2 DE= 0.00 LD= 0.00 RG= 0.00 YB= 0.00 DC= 0.00 DH= 0.01
ILL=A 2 DE= 0.03 LD= 0.00 RG= -0.03 YB= 0.00 DC= -0.01 DH= 0.06
ILL=CW 2 DE= 0.01 LD= 0.01 RG= 0.01 YB= 0.01 DC= 0.01 DH= -0.02
CIELAB
GOODNESS = 2.1747298E-06

COLORANT PERCENTAGES
FIBER 1 BLACK BASE 10.47%
FIBER 2 BROWN FIBER 15.48%
FIBER 3 BLUE FIBER 6.19%
FIBER 4 YELLOW FIBER 67.86%
11-APR-85 14:33:37 COMBINATION 1 AFTER 4 ITERATIONS FOR 550 BURLONE 25
ILL=D6 2 DE= 0.13 LD= -0.02 RG= 0.11 YB= -0.06 DC= -0.07 DH= -0.23
ILL=A 2 DE= 0.09 LD= -0.01 RG= 0.08 YB= -0.03 DC= -0.02 DH= -0.17
ILL=CW 2 DE= 0.10 LD= -0.01 RG= 0.08 YB= -0.06 DC= -0.07 DH= -0.15
CIELAB
MI = 0.04 GOODNESS = 0.2715E-06 AT A COST OF $1.0000
ENTER STANDARD DATA
USE MATCH SCAN? [T/F]  F
TYPE REFLECTANCE FILE RECORD NUMBER  92,1
STANDARD IS -- 580 BURLONE 27

OUTPUT SIZE ?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ?  7,1
RECORD CONTAINS BLACK BASE
COLORANT 2 ?  6,1
RECORD CONTAINS YELLOW FIBER
COLORANT 3 ?  4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ?  1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA?  4
11-APR-85 14:13:01 ITER= 1 COMBINATION 1
COLORANT %
(  7U) BLACK BASE  ==  7.9211
(  6U) YELLOW FIBER == 19.4315
(  4U) GREEN FIBER ==  4.7713
(  1U) WHITE BASE  ==  67.8761
COST=  1.000  MI =  0.05

ILL=D6 2 DE=  0.00  LD=  0.00  RG=  0.00  YB=  0.00  DC=  0.00  DH=  0.00
ILL=A 2   DE=  0.05  LD=  0.00  RG=  0.05  YB= -0.01  DC= -0.01  DH= -0.21
ILL=CW 2 DE=  0.03  LD= -0.01  RG=  0.00  YB= -0.03  DC= -0.03  DH=  0.04
CIELAB
GOODNESS =  8.6077580E-06

COLORANT PERCENTAGES

FIBER 1 BLACK BASE  8.13%
FIBER 2 YELLOW FIBER 19.26%
FIBER 3 GREEN FIBER  4.51%
FIBER 4 WHITE BASE  68.10%

11-APR-85 14:35:26 COMBINATION 1 AFTER 26 ITERATIONS FOR 580 BURLONE 27

ILL=D6 2 DE=  0.33  LD= -0.12  RG=  0.15  YB= -0.26  DC= -0.30  DH= -0.27
ILL=A 2   DE=  0.30  LD= -0.12  RG=  0.13  YB= -0.24  DC= -0.24  DH= -0.54
ILL=CW 2 DE=  0.35  LD= -0.13  RG=  0.11  YB= -0.31  DC= -0.33  DH= -0.14
CIELAB
MI =  0.03 GOODNESS = 0.6826E-05 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA

USE MATCH SCAN? [T/F] F

TYPE REFLECTANCE FILE RECORD NUMBER 94,1

STANDARD IS -- 655 BURLONE 32

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT

COLORANT 1 ? 7,1

RECORD CONTAINS BLACK BASE

COLORANT 2 ? 8,1

RECORD CONTAINS BROWN FIBER

COLORANT 3 ? 9,1

RECORD CONTAINS BLUE FIBER

COLORANT 4 ? 3,1

RECORD CONTAINS ORANGE FIBER

COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4

10-APR-85 15:51:46 ITER= 1 COMBINATION 1

COLORANT %

( 7U)BLACK BASE == 3.5402
( 8U)BROWN FIBER == 25.0229
( 9U)BLUE FIBER == 18.1472
( 3U)ORANGE FIBER == 53.2898

COST= 1.000 MI = 0.07

ILL=D6 2 DE= 0.05 LD= 0.00 RG= 0.05 YB= -0.01 DC= 0.00 DH= -0.10

ILL=A 2 DE= 0.10 LD= 0.02 RG= 0.08 YB= 0.05 DC= 0.08 DH= -0.10

ILL=CW 2 DE= 0.13 LD= 0.00 RG= -0.10 YB= -0.08 DC= -0.10 DH= 0.17

CIELAB

GOODNESS = 4.7329424E-05

COLORANT PERCENTAGES

FIBER 1 BLACK BASE 7.76%
FIBER 2 BROWN FIBER 18.46%
FIBER 3 BLUE FIBER 18.15%
FIBER 4 ORANGE FIBER 55.64%

10-APR-85 16:04:51 COMBINATION 1 AFTER 20 ITERATIONS FOR 655 BURLONE 32

ILL=D6 2 DE= 0.40 LD= 0.10 RG= -0.32 YB= 0.20 DC= 0.10 DH= 0.74

ILL=A 2 DE= 0.38 LD= 0.08 RG= -0.34 YB= 0.16 DC= 0.01 DH= 0.66

ILL=CW 2 DE= 0.36 LD= 0.12 RG= -0.28 YB= 0.19 DC= 0.13 DH= 0.59

CIELAB

MI = 0.05 GOODNESS = 0.7064E-06 AT A COST OF $1.0000
JOB CODE? 1

ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 96,1
STANDARD IS -- 670 BURLONE 33

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 7,1
RECORD CONTAINS BLACK BASE
COLORANT 2 ? 6,1
RECORD CONTAINS YELLOW FIBER
COLORANT 3 ? 4,1
RECORD CONTAINS GREEN FIBER
COLORANT 4 ? 9,1
RECORD CONTAINS BLUE FIBER
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:13:38 ITER= 1 COMBINATION 1
COLORANT %
( 7U) BLACK BASE == 29.0686
( 6U) YELLOW FIBER == 9.2246
( 4U) GREEN FIBER == 8.8616
( 9U) BLUE FIBER == 52.8451
COST= 1.000 MI = 0.08
ILL=D6 2 DE= 0.04 LD= 0.00 RG= 0.03 YB= -0.03 DC= 0.01 DH= 0.60
ILL=A 2 DE= 0.12 LD= 0.00 RG= 0.10 YB= -0.07 DC= 0.02 DH= 1.48
ILL=CW 2 DE= 0.03 LD= -0.01 RG= 0.03 YB= 0.01 DC= -0.02 DH= 0.22
CIELAB
GOODNESS = 3.0129013E-07

COLORANT PERCENTAGES
FIBER 1 BLACK BASE 29.06%
FIBER 2 YELLOW FIBER 9.42%
FIBER 3 GREEN FIBER 8.03%
FIBER 4 BLUE FIBER 53.49%

11-APR-85 14:39:55 COMBINATION 1 AFTER 26 ITERATIONS FOR 670 BURLONE 33

ILL=D6 2 DE= 0.40 LD= -0.10 RG= 0.30 YB= -0.25 DC= 0.08 DH= 5.54
ILL=A 2 DE= 0.35 LD= -0.09 RG= 0.25 YB= -0.23 DC= 0.11 DH= 4.15
ILL=CW 2 DE= 0.33 LD= -0.10 RG= 0.22 YB= -0.22 DC= 0.11 DH= 3.56
CIELAB
MI = 0.05 GOODNESS = 0.1746E-06 AT A COST OF $1.0000
ENTER STANDARD DATA
USE MATCH SCAN? [T/F] F
TYPE REFLECTANCE FILE RECORD NUMBER 98,1
STANDARD IS -- 685 BURLONE 34

OUTPUT SIZE?

ENTER RECORD NUMBER FROM K&S FILE FOR EACH COLORANT
COLORANT 1 ? 7,1
RECORD CONTAINS BLACK BASE
COLORANT 2 ? 6,1
RECORD CONTAINS YELLOW FIBER
COLORANT 3 ? 2,1
RECORD CONTAINS GINGER FIBER
COLORANT 4 ? 1,1
RECORD CONTAINS WHITE BASE
COLORANT 5 ?

NUMBER OF COLORANTS PER FORMULA? 4
11-APR-85 14:14:25 ITER= 1 COMBINATION 1
COLORANT %
( 7U) BLACK BASE == 4.2252
( 6U) YELLOW FIBER == 13.9194
( 2U) GINGER FIBER == 21.1464
( 1U) WHITE BASE == 60.7091
COST= 1.000 MI = 0.03
ILL=D6 2 DE= 0.01 LD= 0.00 RG= 0.01 YB= 0.00 DC= 0.00 DH= -0.02
ILL=A 2 DE= 0.04 LD= 0.00 RG= 0.01 YB= -0.03 DC= -0.03 DH= -0.05
ILL=CW 2 DE= 0.04 LD= 0.00 RG= 0.03 YB= 0.03 DC= 0.03 DH= -0.08
GOODNESS = 5.3586587E-06

COLORANT PERCENTAGES
FIBER 1 BLACK BASE 4.02%
FIBER 2 YELLOW FIBER 13.27%
FIBER 3 GINGER FIBER 21.74%
FIBER 4 WHITE BASE 60.97%
11-APR-85 14:40:56 COMBINATION 1 AFTER 26 ITERATIONS FOR 685 BURLONE 34

ILL=D6 2 DE= 0.15 LD= 0.02 RG= 0.14 YB= -0.06 DC= -0.04 DH= -0.47
ILL=A 2 DE= 0.14 LD= 0.03 RG= 0.12 YB= -0.06 DC= -0.02 DH= -0.39
ILL=CW 2 DE= 0.14 LD= 0.03 RG= 0.14 YB= -0.01 DC= 0.00 DH= -0.40
GOODNESS = 0.4978E-05 AT A COST OF $1.0000
XIII. VITA

Eric Walowit received the B.S. degree in Imaging and Photographic Science from the Rochester Institute of Technology in May, 1985.

He has been employed by Bausch and Lomb Company, Analytical Products Division, Rochester, NY working on color software development since March, 1984. As of June 3, 1985 he is employed by Burlington Industries, Corporate Research and Development, Greensboro, North Carolina, as a Color Scientist. His research interests are least-squares solutions of non-linear problems associated with computer color formulation.