Project title: Real-Time Data Acquisition, Theoretical Modeling and Adaptive Control of Batch Dyeing Processes.

Project Number: S9210
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Goal:

The goal of this project is to enhance the economic competitiveness of the U.S. dyeing and finishing industry. This goal can be achieved by improving the control of batch dyeing processes through closing the control loop, and by developing new and effective control algorithms and strategies. The control algorithms should be based on the best available theoretical and process models.

Abstract:

We have continued to make good progress in all the diverse components of our research effort. Closed-loop control of dyeing processes requires real time monitoring of dyebath concentrations. Significant advances have been made in the use of both visible region absorption spectrophotometry, and flow-injection analysis (F.I.A.), for real-time dyebath analysis. Methods were developed for handling spectrophotometric interactions of dyes in complex dye mixtures. A second data acquisition system has been developed, featuring conformity to public standards, and modularity for flexibility, with robust and accurate data collection. Kinetic and equilibrium process models, based both on the diffusion equations, and on Langmuir kinetic models, have been developed and tested, with consideration of dye interactions in some cases. In addition to strictly parametric approaches to real-time adaptive control, a fuzzy logic controller has been developed to simulate the decision-making activities of an experienced dyer. Process models based on dimensionless groups of process variables have been developed, with particular emphasis on ionic dyeing systems. Our Ahiba Texomat dyeing machines have now been joined by an Ahiba Colormat dyeing machine for package dyeing studies.

Current progress:

The progress achieved is summarized in the following sections of this Annual Report

Absorotion spectrophotometry:

An adjustable path-length, flow-through transmission junction has been fitted in our dyebath circulation system to allow higher concentration dye solutions to be measured. Deviations of the spectra for dye mixtures from spectral additivity have been corrected using regression analyses, and neural networks. The neural network gave the best data fit, but the regression analysis provided spectrophotometric interaction parameters for the dyes. These parameters may correlate with the kinetic and equilibrium interactions of the dyes, as discussed later in this report. Kinetic and thermodynamic studies are being conducted to determine the influence of solution aggregation of dyes on the rates and final extents of dye uptake.

Dye concentrations can be obtained from spectrophotometric data by multiple regression methods, or by neural network methods. When no dye interaction occurs, the multiple regression matrix is equivalent to a matrix of the individual dyes' absorptivities at three specified wavelengths. At the high dye concentrations used in our study (1-4% dye owf. at a 40:1 liquor ratio), simple additive absorptivity models could not be used.

The sensitivity of reactive dyes to salt concentration was determined for each dye; in some cases, there was little effect on aggregation from 50 to 100 g/L of NaCl, but in others, there was a decrease in absorptivity with increased salt concentration. Our predictive equations for dye concentration require measurement of the electrolyte concentration, and use a linear model to account for changes in absorptivity with salt concentration. Calibration for dye mixtures requires absorbance spectra for multiple mixtures of known dye concentrations, and the development of a weight matrix which converts concentration to absorbance. Inversion of this matrix allows conversion of absorbance to concentration.

A similar treatment of the data using neural networks yielded a good predictive concentration model, but lacks the parametric modeling value of the weight matrix. Comparison of the weight matrix with the absorptivities of the individual dyes indicates to what degree the dyes in the mixture interact.

A determination of the extent of aggregation, or interaction of the dyes with other dyes or auxiliaries in solution, is useful for the determination of the effect of dye interaction on the rate and extent of dyeing. Interacting dye mixtures have lower strike rates, and possibly lower final exhaustions than the individual dyes, when applied to fabric.

Using real-time measurement of dye concentration, we are currently determining the rates of dye uptake during dyeings with individual dyes, and mixtures of dyes. Our on-line measurements give valuable information about the state of the dyeing system at intervals of 10 seconds, permitting close study of all stages of the process. This will lead to a better understanding of the kinetics of dyeing, and the role of solution interaction of dyes in the dyeing process. The degree of final exhaustion of the dyes, applied alone and in admixture, will lead to a better understanding of the effects of dye interactions on the thermodynamics of dyeing. Reflectance measurements on the dyed fabrics may give additional information on the aggregation of dyes in the dyed fiber.

Plow Injection Analysis:

During the past three years, a flow injection analysis (FIA) system which can automatically dilute and buffer dyebath samples, before making absorbance measurements, has been developed. With this FIA system the dynamic range of the spectrophotometer is extended and some of the limitations in spectrophotometer performance imposed by Beer's law are overcome. The FIA system consists of a diode-array spectrophotometer, gradient mixing chamber, sampling valve and loop, syringe pump, and laboratory dyeing machine. The sampling valve, syringe pump, and spectrophotometer are connected to an IBM-compatible computer which controls data acquisition, and performs absorbance-to-concentration conversions using partial least squares (PLS). The valve and the syringe pump are controlled by separate programs, which were written in BASIC, to carry out each step in the analysis. Data acquisition and data reduction are done within LabCalc, a commercial software package which uses the Array Basic programming language. The data acquisition software was modified, to link the valve and syringe pump control programs with LabCalc, and to incorporate LabCalc's own PLSplus prediction routines. The prediction output was modified to provide detailed, real-time printed

output, including statistics, and to save only the concentration data in a text file, which can then be imported into a spreadsheet to display the exhaustion graphs for each component.

After the system components were assembled, and the programming completed, the system components were transferred to Ciba in Greensboro for field testing. Cycle time and integration time for the spectroscopic measurements were adjusted to yield the lowest % rsd, and fastest sampling time possible. The cycle time and integration time were fixed at 0.6s and 0.2s, respectively, which means a spectrum was measured every 0.6s, and the diode array was exposed to the source for 0.2s. Three types of manifolds (coiled tubing, knotted tubing, and gradient chamber) were evaluated to determine which manifold produced the highest dispersion (or dilution ratio), with a sampling rate of 1 sample/minute. A calibration curve which encompassed 0.1 to 5.0 g/L of each dye was constructed from a factorial design of three dyes at 0.1, 1.0, 3.0, and 5.0 g/L. Using data obtained from these calibration measurements, adherence to Beer's Law was confirmed.

The spectrophotometer does have one limitation, which was discovered with the validation set. Very small amounts of blue dye in mixtures with concentrated red or yellow dye, are hard to detect and quantify separately, because of the high noise level caused by the low energy of the deuterium source at longer visible wavelengths. The accuracy of the calibration was also reduced because not all of the dye sample passed through the system in one minute. With these problems in mind, a wash cycle was added to clear the chamber between measurements, and the FIA system was recalibrated using two separate sets of mixtures - a dilute set with concentrations of each component less than 1 .O g/L, and a concentrated set with concentrations from 1.0 to 3.0 g/L. Using these solutions, the system was found to have a standard error of calibration <= 0.02 g/L. Spectra obtained from measuring a calibration solution are shown in the **Figure,** together with the exhaustion data for the laboratory package dyeing experiment discussed below.

CALIB1 #11 #6

1.51mL/min;mixing2:.6s/.2s:calibmix1   Res= 2 nm

Exhaustion Curves for Brown Shade
Dyed on Texomat

YelCRD1 — RedC2G — NavyC8

Once the system was calibrated properly and verified, it was attached to a laboratory package dyeing machine at Ciba. Three shades - navy, burgundy, and brown - were dyed with mixtures of three dyes, and the concentrations were tracked in real-time with the FIA system. After each dyeing was complete, exhaustion graphs were created. There was some noisiness, which was presumed to be caused by machine noise, in the exhaustion curves. In order to confirm this explanation, the brown and navy shades were repeated on fabric samples dyed in a laboratory Texomat. The exhaustion curves from these experiments were much smoother, which substantiated the idea that machine noise was the primary cause of noise in the package machine exhaustion curves.
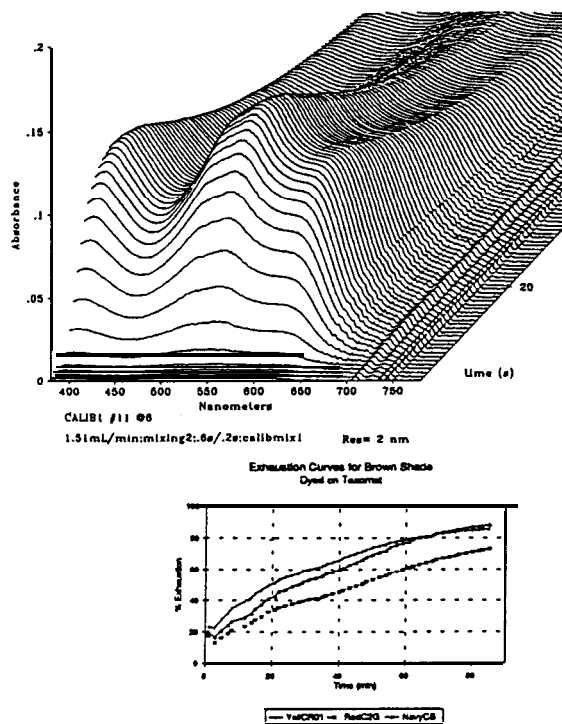
Since then, the **FIA** system has been improved by data acquisition program refinements, which calculate exhaustion in real-time, print that information, and save the time and exhaustion data to the disk The original mixing chamber, which was specially made, has been replaced by a variable-volume, commercially-available model with a self-contained, four-speed **stirring** motor. Improvements in the calibration procedure are being made to shorten the amount of time required to carry out a calibration, and to automate that process. Preparations are being undertaken to connect the **FIA** system to a **Colormat** laboratory package machine in the DARG lab.

A portable **FIA dyebath** monitoring system is being developed as part of the associated technology transfer program **S94TT-** 1.

Monitoring and Control:

To enhance our abillity to monitor and control the batch dyeing process, a second data acquisition system was designed and implemented. The system design was predicated upon three ideas: 1.) It should conform to public standards, 2.) It should be modular for maximum flexibility, 3.) It should provide robust, accurate, and appropriate data collection. The system consists of a Motorola MVME 167 board running **VxWorks,** a real-time, POSIX compliant operating system. New data acquisition/display software was written in C, to allow simultaneous real-time monitoring of individual dye concentrations, and also exhaustion, **pH,** conductivity, and temperature.

Two models have been developed to represent the kinetic behavior of the batch dyeing process. The important considerations while developing the models were: the models need to be simple, to facilitate numerical calculation and simulation, yet should include all the major properties of the system; the model parameters should be easily identifiable for on-line identification and adaptive control. The first model is an adaptation of the **Langmuir** isotherm for the equilibrium distribution of dye between the solution and fabric, to explain the kinetic behavior. The dyeing process is assumed to be driven by two simultaneous processes of adsorption and desorption.
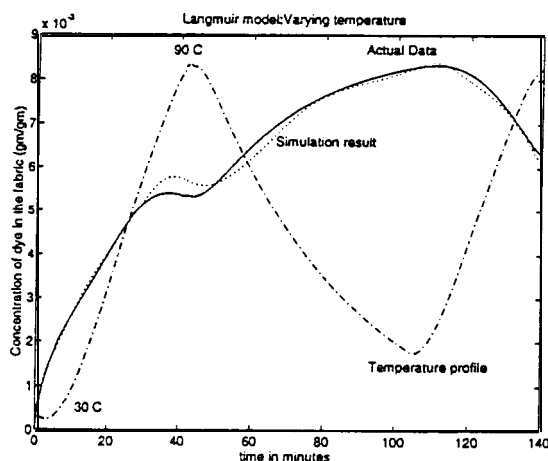
The **Figure** shows the simulation of a dyeing using the **Langmuir** model. Also shown for comparison are the **experimental** results, and the temperature profile during the process. The model parameters are the rate constants for the two processes, and the **Langmuir** saturation value. The rate constants are dependent on temperature, conductivity, and **pH,** among other factors. The parameters can be linearly separable, in spite of the model being non-linear, which enables application of the classical least squares method for identification of the parameters, making the model suitable for adaptive control. The second model is based on the assumption that batch dyeing is controlled by diffusion of dye from the solution to the fibers. The important model parameters are the aqueous **diffusion** constant D, which determines the rate of dyeing, and the distribution coefficient **K,** which determines the equilibrium **dyebath** exhaustion. The above models are valid for a solution of a single dye only. The models can predict the effect of

temperature change on the dyeing process. Future work includes extending the models to predict the effect of salt, and also to handle mixtures of two or three dyes.

Fuzzy-Logic Control:

A fuzzy logic controller, which is used to simulate the decision-making activities of an experienced dyer, has been developed to control dye concentration in batch dyeing processes. The control decisions of the dyer can be expressed linguistically as a set of heuristic decision rules, which are used to build rule-bases for the controller. Also, certain algorithms are used to convert the rules to quantitative control outputs.

Based on previous work, some enhanced fuzzy logic control schemes, which can develop control rules automatically with very limited process knowledge, ie the controller has learning ability, have been formed. Efforts to combine fuzzy logic and optimization to control complex multi-input-multi-output (MIMO) systems have been made. Computer simulations suggest that those schemes can control the exhaustions of dyes in a multiple component dyebath.

A temperature controller for a dyebath, consisting of a relay circuit, digital I/O, and a computer, has been developed. With this system, the adaptive fuzzy logic control schemes are being tested experimentally.

Comparisons between model-based control design, and rule-based control design have been made . Some promising results have been obtained. Issues of stability and robustness of fuzzy logic control have also been studied.

Dimensionless Groups of Variables:

The use of dimensionless groups of variables can provide compact descriptions of kinetic and equilibrium systems, and reveal interactions between the effects of different individual parameters. The experimental behavior is often determined by specific products or ratios of individual parameters, and therefore a specific objective can often be achieved by altering more than one single parameter, or by changing a different parameter from the obvious one. The assumption of an "instantaneous surface equilibrium", between the dyebath concentration of dye and the concentration of dye in the fiber surface during dyeing, permits useful conclusions about dyeing kinetics as well as final dyebath exhaustions. With this in mind, a dimensionless equilibrium model has been developed to explain the sorption of polysufonated acid dyes by polyamide fibers. The model is based on an ion distribution function described by the Donnan equations, and on the assumption of an electrically neutral dyebath and fiber substrate. The model was used to analyze data for the equilibrium uptake of C.I. Acid Blue 45 by nylon 6. A good non-linear fit of the experimental data, based on the measured acidic and basic end group contents of the fibers, was obtained from the dimensionless model, as can be seen in the **Figure. The** dimensionless parameters were estimated while fitting the data to the dimensionless model. On
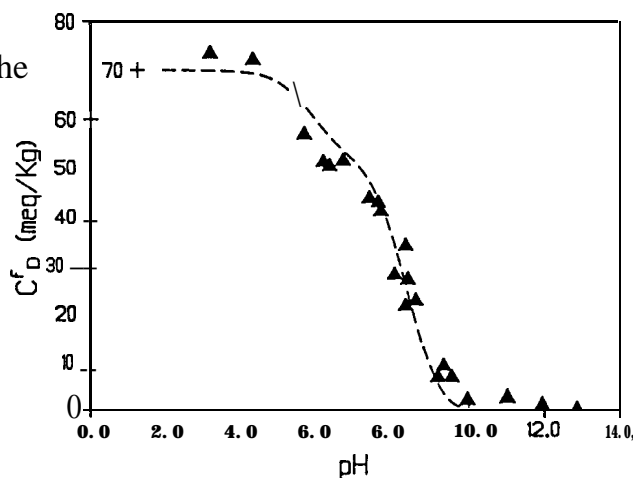
assigning values to some of the individual parameters, using estimates obtained from the literature, the unknown equilibrium dye distribution coefficient and the dissociation coefficient for the basic group were also estimated.

The above model, and the parameters estimated from it, will be used to control the uptake of acid dyes on nylon by controlling the **dyebath pH.** The model can predict an instantaneous surface equilibrium, using the data for dye concentration and hydrogen ion concentration in the bath. The model can therefore be used to estimate the **pH** of the bath needed to obtain a desired surface dye concentration on the fiber. The **pH** of the bath will be controlled by dosing acid or alkali into the bath. A pair of piston pumps will be used to dose these solutions into the **dyebath.** A program has been written to control the pumps through the computer, and so, based on the above model, the pumps can be used to control the **pH** of the **dyebath.**

Some dyeings have been done by controlling the **pH** of the **dyebath,** and thus controlling the uptake of the dye on the fabric. The starting **pH** of the **dyebath** is very alkaline to avoid a high strike on the fabric in the initial stages of dyeing, and thus to obtain a level dyeing. The acid is then dosed in the **dyebath** at regular intervals to increase the uptake of the dye by the substrate. The temperature of the dyeing is about 95°C throughout the dyeing period. High temperature is used to heat treat the different yarns, and to equalize the differences in their heat histories, and thus to reduce the problem of barre' dyeing caused due to yarn differences. Another good feature of this type of control is that, by lowering the **pH** of the bath, almost 100% exhaustion can be obtained, thus making it an environmentally friendly process.

Recent Progress in Real-Time **Adaptive** Control of Batch **Dyeing.:**

The Dye Applications Research Group (DARG) has developed novel monitoring and process control methods for batch dyeing, which feature accurate, adaptive, real-time estimation of kinetic dyeing parameters, e.g. rate constants for dye sorption. Since dyes interact in solution, prediction of optical and kinetic behavior of dye mixtures from data on individual dyes is uncertain. Each major dye class has subclasses which further categorize dyes by application properties such as: dyeing rate; affmity; temperature, salt and **pH** sensitivity; susceptibility to reduction; metal or **chelate** sensitivity; fixation efficiency; leveling ability; etc. This allows dyers to select combinations which perform well under specific limitations of equipment, water, controls available, time constraints, and the like. Most often, dye properties **are** ascertained by individual dye tests, and then dye behavior in mixtures is inferred from the data for individual dyes. Dye mixtures are of great practical concern to the dyer but, in fact, the behavior in dye mixtures cannot be inferred from experimental data for single dyes.

Two properties in which dyes in mixtures deviate from their individual properties are optical absorbance and dyeing kinetics parameters. Both deviations are thought to be at least in part due to dye-dye interactions in solution, and both affect the way dyers measure concentrations, determine dyeing properties, predict the outcome of dyeings, and control processes. Since both are related at least in part to the same phenomena in solution, we are investigating correlations between optical and kinetic deviations, and also the possibility of improving predictions of mixture dyeing behavior, by taking into account the optical deviations which reveal something about dye-dye interactions in solution.

For dynamic control, the DARG system predicts final exhaustion, based on the **dyebath** state at any given time, and then determines an optimized predicted process needed to reach the target. Predictions are based on the standard **Langmuir** kinetic model, characterized by the sorption and desorption rate constants (k_s and k_d respectively), a parameter (S) related to the "dye

sites", or dyeing capacity of the **fiber**, and the solution and fiber concentrations of dye at any time (c^s and c^f). The **Langmuir** kinetic equation,

$$dc^f/dt = [k_a \, c^s \; (S\text{-}c?] \; - [k_d \, c^f] \qquad\qquad \text{Eq 1: Langmuir}$$

must be supplemented by conservation equations which relate the two concentrations c^s and c_f through the liquor ratio, or bath ratio L.

   DARG process control strategies based on the above parametric model have been highly successful for real time control of processes involving individual dyes. The necessary control parameters are determined from ordinary production dyeings, and then used in predictive models of dye process behavior, including for example, temperature dependence of the above parameters for individual dyes. In this way, real-time adaptive control models can be developed without extensive test dyeings on production machinery.

   Optical absorptivity can easily be determined by measuring a series of dye concentrations, and modeled by Beer's Law.

$$A, = a, b \; c^s \qquad\qquad \text{Equation 2: Beer's Law}$$

where A, is the absorbance at a specified wavelength (l), a, is the absorptivity of the dye at that wavelength, b is the path length, and c^s is the solution concentration of the dye.

   Dyeings using individual dyes have been successfully controlled using parametric and non-parametric models. In the parametric methods, parameters in the control model are related to physically teal attributes of the dyeing system as mentioned previously, such as dyeing rate, affinity, salt, **pH** and temperature sensitivity. In the non parametric models, e.g. neural networks and fuzzy logic rule-based control schemes, the parameters are only related to the control system itself and have no inherent relationship to physically meaningful attributes of the dyeing system. Although both types are effective for control purposes, the parametric type is somewhat more useful in understanding dyeing processes.

   More recent work has focused on four items. The first item is closing the control loop (auto actuation) for temperature and other parameters, e.g. dosing of salt, dye and buffers. The second item is evaluating many-inputs-to-many-outputs control strategies (MIMO), using the multiple parameters previously mentioned. The third area is the continuation of developing an indirect **dyebath** monitoring system, using flow injection analysis, as previously described.
The fourth item is the estimation of optical and kinetic parameters for dyes in mixtures. Details of the estimation of dye concentrations in mixtures, a prerequisite to the real-time adaptive estimation of kinetic behavior of dyes in mixtures, were presented in last year's AATCC conference.

   It is well known that the kinetic behavior of dyes in a mixture is not always completely predictable from individual dye data.   Lemin showed that dyes in mixtures exhibit altered exhaustion characteristics, and in fact even qualitative predictions of dyeing rate are difficult to make in many cases. He showed that qualitative predictions as to which dye in a pair would have the shortest time of half dyeing ($t_{1/2}$) in mixtures, from data on individual dyes, were correct in only 60% of the cases. In addition, he also demonstrated that predictions of **thermodynamic** properties (distribution coefficient and standard affinity) were unsuccessful. Colour Index **(CI)** Direct Blue 1 and CI Direct Yellow 12 alone, at different temperatures, showed decreased standard affinity with increasing temperature, as would be expected. But in mixtures, the blue

showed increased standard **affinity** with increasing temperature in the mixture, contrary to its individual behavior, and to normal expectations.

We are currently evaluating a modified form of the **Langmuir** kinetic model, including non-ideality in terms of dye-dye interactions in solution

Eq 3: Modified **Nonideal Langmuir** Kinetics

$$dc^f_i/dt = [(k_a\, d_{i,j}\, c^s_i)(S - \Sigma c^f_i)] - [k_d\, c^f_i]$$

where $d_{i,j}$ is a **pairwise** dye-dye kinetic interaction parameter, and all of the other terms are as defined previously.

The exhaustion properties of a dye can be affected in many ways, e.g. by aggregation, which alters the dye's diffusion and sorption characteristics. There are also potentially important effects which occur at the fiber surface, or within the fiber. One of these is included in the modified version of the **Langmuir** kinetic equation 3, i.e. dyes in mixtures compete for the available dyeing capacity of a substrate. This is the origin of the term $(S - \Sigma c^f_i)$ as a replacement of $(S-c^f)$ in equation 1. Other potential effects, e.g. increased sodium ion concentration in the substrate due to other dyes, decreasing the equilibrium exhaustion of each dye, are not explicitly included.

Our general observations show that the equilibrium exhaustions of dyes in mixtures is seen to decrease, compared to individual behavior, as expected. The degree of exhaustion decrease varies with different dye mixtures. Because of these properties, mixtures of dyes which would appear to be compatible, based on individual dyeing properties, may not be suitable in mixtures, and dyes which appear not to be compatible from their individual dyeing properties may, in reality, form suitable mixtures. When the solution interactions do not appear to occur, a dyer can easily select specific dyes that will have compatible dye rates and equilibrium exhaust to achieve on-tone build and reproducible dyeings, based on individual dye data. When interactions occur, that process may be flawed.

Several fiber reactive dyes were selected for analysis (and several more are in work at this time). The example data below are given for Cibacron Blue TR-E, Yellow R-E and Red 2G-E, which were commercial samples supplied by Ciba and used without any additional purification. The DDMS data set in this case included only the initial exhaust phase of a two step dyeing fiber reactive procedure. Dyeings and optical measurements were done at a variety of concentrations for each dye individually and in mixtures.

Several trichromes are being investigated, and this one is presented as a typical example of current work To date, kinetic data have been collected and analyzed on several two and three dye combinations, and optical absorbance data have been collected and analyzed on all combinations.

In summary, dyeings of individual dyes can be well controlled by parametric algorithms based on the **Langmuir** kinetic model. The necessary parameters can be adaptively estimated from real-time data for individual dyes. It is possible to accurately estimate dye concentrations in mixtures, from real time **dyebath** data on mixtures, by taking **pairwise** interactions into account. It is possible to estimate kinetic parameters of dyes in mixtures, from real time **dyebath** data on mixtures, by taking **pairwise** interactions into account. Dyes in mixtures exhibit kinetic properties which are different from those observed in dyeings with individual dyes, but kinetic parameters for mixture dyeing behavior can be measured and quantified in real time using **direct dyebath** measurements in mixture dyeing.

Examples of interaction parameters for dye mixtures are given below.

Table I: Pair-wise Interaction Parameters
Optical Interaction ($e_{i,j}$)

Parameter Value in Mixture

Dye	w/Yellow	w/Red	w/Blue
Yellow	1.000	0.798	0.823
Red	0.977	1.000	n/a
Blue	0.856	n/a	1.000

Kinetic Interaction ($d_{i,j}$)

Parameter Value in Mixture

Dye	w/Yellow	w/Red	w/Blue
Yellow	1.00	0.75	0.61
Red	1.07	1.00	n/a
Blue	0.99	n/a	1.00

Package Dyeing:

An Ahiba Color-mat laboratory package dyeing machine has been installed, and used for fiber reactive dyeings on cotton. Initial programming problems have been overcome. Some progress has been made in overcoming the unlevelness of the initial dyeings, through progressive dosing of alkali, which has reduced streakiness in the dyeings. Several different dyeing procedures are being tested to determine which will produce the most level dyeings.

Much time has been spent working on the Schwieter winder, which is used to make yarn packages for the Color-mat. The problem was that the dye tubes and packages for the Colormat are too small to be properly wound on this winder. The package was not in contact with the drive drum of the winder. This caused severe overthrows on the package ends, and prevented the yarn from unwinding off the package. The winder has since been modified by a Schwieter representative, and it is now working well.

Currently, preparations are being made to monitor the dyeings in the Colormat by connecting it to the FL4 system. These preparations include modifying the Colormat lid so that the dyebath can be circulated back into the machine after analysis, and obtaining a suitable pump to circulate the bath through the FIA loop.

Publications:

W. Jasper, E. Kovacs, and G. A. Berkstresser,IV, "Using Neural Networks to Predict Dye Concentrations in Multiple-Dye Mixtures", Textile Research Journal, (to appear September 1993).

J. Lu and G. Lee "A Self-Learning Fuzzy Logic Controller with On-line Scaling Factor Tuning", International Conference on Computer Applications, Long Beach CA (to appear March 1994).

G. A. Berkstresser IV, K. R. Beck, B. Smith, R. McGregor, and W. Jasper, "Novel Approaches for the Real-Time Prediction of Dye Concentrations in Three Dye Mixtures", Book of Papers, American Association of Textile Chemists and Colorists International Conference and Exhibition, Montreal, Quebec (to appear October 1993).

M. R. Lefeber, K. R. Beck, B. Smith, R. McGregor, and W. Hunter, "Flow Injection Analysis of Dyebaths", Book of Papers, American Association of Textile Chemists and Colorists International Conference and Exhibition, Atlanta, GA, October 1992.

M. R. Lefeber, K. R. Beck, B. Smith, R. McGregor, and W. Hunter, "Flow Injection Analysis of Dyebaths", Textile Chemist and Colorist (accepted for publication).

R. McGregor and M. Arora, "Dimensionless Groups for the Sorption of Dye and other Ions by Polymers. III. Polysulfonated Acid Dyes and Polyamides", Submitted to Journal of Applied Polymer Science.

B. Smith and J. Lu, "Improving Computer Control of Batch Dyeing Operations", American Dyestuff Reporter (accepted for publication).

E. T. Kovacs, "Utilization of Backpropagation Neural Networks to Interpret Spectral Data in Textiles: Two Applications", IMSEI Masters Thesis, NCSU, June 1993.

M. R. Lefeber, "Flow Injection Analysis of Dyebaths", TECS Masters Thesis, NCSU, July 1993.

Presentations:

G. A. Berkstresser IV, K.R. Beck, C.B. Smith, W.J. Jasper, and R. McGregor, "On-Line Continuous Determination Of Individual Dye Concentrations From Spectra Of Dye Mixtures In Solution: Deviations From Beer's Law, American Chemical Society North Carolina Sectional Meeting, Raleigh NC, April 1993.

K. R. Beck, M. Arora, G. A. Berkstresser, IV, W. Jasper, G. Lee, M. R. Lefeber, J. Lu, R. McGregor, and B. Smith, "Real-Time Data Acquisition, Theoretical Modeling, and Adaptive Control of Batch Dyeing Process", Institute for Textile Technology Technical Advisory Committee Meeting Invited Paper, April 1993.

K. R. Beck, M. Arora, G. A. Berkstresser, IV, W. Jasper, G. Koksal, M. R. Lefeber, J. Lu, R. McGregor, B. Smith, and W. Smith, "Real-Time Data Acquisition, Theoretical Modeling, and Adaptive Control of Batch Dyeing Processs", First Annual National Textile Center Forum Plenary Session, Auburn, AL, February 1993.

M. R. Lefeber, K. R. Beck, B. Smith, R. McGregor, and W. Hunter, 'Flow Injection Analysis of Dyebaths", American Association of Textile Chemists and Colorists International Conference and Exhibition, Atlanta, GA, October 1992.