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CRADA Final Report
for
CRADA Number ORNL94-0253

**The AMTEX™ Computer-Aided
Fabric Evaluation (CAFE) Project**

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Prepared by the
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THE AMTEX™ COMPUTER-AIDED FABRIC EVALUATION (CAFE) PROJECT

INTRODUCTION

The American textile industry has lost an estimated 400,000 jobs to offshore competitors since 1980. If trends continue unchanged, it is predicted they will lose an additional 600,000 jobs by the year 2002. These losses and the resulting economic threat to the U.S. textile industry can be attributed to the low operating costs of their offshore competitors' extensive use of cheap labor. In order to stem these rising losses and gain back lost market shares, the American textile industry has entered into a cooperative research and development agreement (CRADA) with the U.S. Department of Energy (DOE) in a program called the American Textile Partnership (AMTEX™). AMTEX™ is a working relationship aimed at leveraging technologies that currently exist at the DOE national laboratories for the benefit and development of a competitive market edge for the U.S. textile manufacturers. The application of these technologies to identified needs will result in new and emerging manufacturing innovations for the U.S. textile industry and its vendors.

Since the minimum U.S. labor rate is well above that of its offshore competitors, one of the competitive factors the U.S. industry hopes to gain is a higher quality fabric. To facilitate this, a Computer-Aided Fabric Evaluation (CAFE) System (automated fabric and color/patterns inspection process) has been developed by the CAFE National Laboratory Working Group to increase product quality, material throughput, and manufacturing efficiency. The CAFE Working Group is composed of researchers and scientists from Argonne National Laboratory, Oak Ridge National Laboratory (ORNL), Lockheed Martin Energy Systems (LMES) or Y-12, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Sandia National Laboratories. This interim report identifies those technologies developed by ORNL and LMES covering the period from April 1994 to September 1998 under CRADA94-0253.

The CAFE System is developed around a modular, open hardware and software architecture to ensure future growth. This approach provides the best cost structure due to increased competitive vendor support. The System is sensitive to the existing textile manufacturing infrastructure allowing the base-line subsystems to be used by any textile manufacturer, regardless of end process. A scale of economy has been applied to the System to ensure an appropriate return on investment for all industry partners.

STATEMENT OF THE OBJECTIVES

The need for increased fabric quality drove CAFE towards diverse yet complementary subsystems: The Greige Goods Inspection Subsystem for woven (knit) and the Color Print Pattern Goods (CPPG) Inspection Subsystem for inspecting color print materials. Included in the Greige Goods Inspection Subsystem is a machine diagnostic capability for diagnosing loom health. The functional requirements for each subsystem, with the exception of machine diagnostics, are detailed in an associated Functional Description and Requirements Document (FD/RD) developed under the Critical Path Elements Task. A summary of objectives for each subsystem is listed below.

Greige Goods Inspection Subsystem

1. Inspect greige cloth on-loom in real-time close to the point of fabric formation.
2. Detect defects in products with widths up to 4 meters (~150 in) wide with capabilities of expansion.
3. Detect and classify from 8 categories a predefined set of greige defects identified in the CAFE Economic Model. Categories cover both fill and warp directions.
4. Detail loom/machine operational problems.
5. Operate at loom speeds up to 1500 picks-per-minute.
6. Have a defect detection rate of 90% for major defects and 25%-50% for minor defects. Table 2 in the FD/RD for the Greige Goods Inspection Subsystem details the detection rates as a function of defect length.

7. Must be cost sensitive and meet the price point detailed in the CAFE Economic Model.
8. Measure and quantify certain fabric characteristics to include pick count, pick density, delta density, fabric velocity, and infer some defects. Measurement accuracy (detailed in the FD/RD for the Greige Goods Pick Measurement Device Subsystem) is pick count $\pm 0.15\%$ and pick density ± 0.10 picks/in.
9. Must provide adjustable alarms and users' interface that allows plant personnel to operate with minimal training.
10. System setup must be achievable either locally or remotely.

CPPG Inspection Subsystem

1. Inspect, detect, and classify CPPG defects on the print range and provide real-time evaluations to remediate problems. System shall detect at least 80% detection rate for top 6. Defect rates and false alarms are detailed in the FD/RD for Color Printed and Dyed Goods.
2. Provide side-to-side and end-to-end colorimetric measurements on the print range in real-time.
3. Operate at speeds up to 100 yards/min.
4. Detect defects in product widths to 4 meters.
5. Provide a user's interface that allows plant personnel to operate with minimal training.
6. Be cost sensitive and meet the price point detailed in the CAFE Economic Model.
7. System setup must be achievable either locally or remotely.
8. Must provide adjustable alarms.

BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The research conducted on this project will be of benefit to DOE by advancing technologies related to pattern recognition, computer vision, high-performance computing, advanced sensing capabilities, cognition, higher-level learning and concept formation, and context-dependent decision and control.

From the CPPG Inspection Subsystem, DOE can benefit in the area of robotic assembly or disassembly. Automation is currently applied to both processes with stringent requirements on accuracy. Computer vision techniques for segmenting and identifying objects can benefit from the segmentation approach used to identify components of a multicolor, complex printed pattern as required in CAFE.

Many environmental restoration laboratories over the past years have developed autonomous robotic systems for the specific purpose of navigation, obstacle avoidance, and material handling. These intelligent systems are the result of integrating artificial intelligence with machine vision. These developed technologies will be applied to the CAFE detection and classification problem. DOE will benefit from this work. As the complexity of tasks to be performed by these inspection subsystems increases, so will the need for higher-level machine cognition and learning. These expanded capabilities promise to push the limits of current thinking in concept formation to formulations of context-dependent decision and control. These will provide added benefits to new manufacturing facilities and processes.

CAFE is also investigating the use of sensor technologies to interrogate and diagnose the health of particular machines. The energy research laboratories have developed capabilities such as these over the past years in support of numerous projects. Currently, these technologies are being enhanced to include single point diagnostics for process qualification and control. These capabilities directly support new initiatives in the area of anticipatory prognostics and health assessment. Instead of periodic maintenance calculated from statistics, anticipatory prognostics and health assessment (or performance-based maintenance) only requires machine intervention when needed based on machine condition, operation requirements, materials, etc. Sensor technologies married with advanced computational methods, such as those being developed by CAFE, will provide the anticipatory capabilities to optimize system performance from both time and material criticality which will enhance future manufacturing capabilities. These capabilities are also expected to impact energy conservation and machine efficiency.

TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

Technical Approach

The approach taken by the CAFE project team was to logically partition the technical requirements into short-term, near-term, and future activities based on their relative economic impact. The sequence in which each task was addressed depended upon its individual priority assignment established by the CAFE industry partners. Figure 1 is a logic flow diagram depicting this approach. For a more detailed description of the process, see Task II. Critical Path Elements.

Appendix A is the commercialization approach adopted by CAFE. It details the necessary steps to be taken to ensure that the CAFE sensor suites will be successfully commercialized. There were numerous go/no-go decision points in the development path. At each, the CAFE industry partners made strategic decisions as to which subsystem would go forward and which would not. The decisions were based on the operational and functional capabilities of each sensor as it related to each particular inspection subsystem. This approach ensured the technology growth and associated costs for any unit could be justified in terms of industry impact.

Figure 1. Logic flow diagram depicting critical elements and flow of information.

Task Descriptions

The initial work distribution for the national laboratories is shown in Figure 2. This represents the major lines of technical reporting and responsibility for the CAFE Project. This section provides a technical description of these tasks as they relate to ORNL and LMES.

Task I. Project Management

See Appendix B for details.

Task II. Critical Path Elements (FY94-FY96)

The first major development effort was the Critical Path Elements task. It involved completing several studies and surveys to determine what the research and development (R&D) requirements were for the CAFE Project. This effort included conducting a preliminary defect analysis study, developing a FD/RD, System Architectures Document, CAFE Economic Model, and State-of-the-Art Assessment. These documents identified the needs of the textile industry and what R&D was required to support a complete automated fabric, yarn, and color inspection system. This effort culminated in the development of the CAFE Assessment and Feasibility Document identifying the short-term, near-term, and future efforts for the National Laboratory Working Group.

The main responsibility for the Critical Path Elements task belonged to Lawrence Berkeley National Laboratory and ORNL. In FY94, the team developed: (1) a preliminary defect database for greige material, (2) the

Preliminary FD/RD for the Greige Goods Inspection Subsystem, (3) a planned approach for initiating the FD/RD for the CPPG and Knitting Subsystems, (4) a preliminary Economic Model, and (5) the initial Industry Survey and Study to detail the CAFE System's architecture requirements. In FY95, the team delivered the final FD/RD for the Greige Goods Inspection Subsystem, developed a defect database for color printed and knit material, developed a preliminary FD/RD for CPPG, delivered the final FD/RD for the CPPG and the preliminary FD/RD for the Knitting, and finished the CAFE System's Architecture Document and the Economic Model.

Figure 2. Work distribution by task and assigned responsibility.

Task III. Greige Goods Inspection Subsystem (FY94-FY98)

The focus of the Greige Goods Inspection Subsystem was the development of an economically viable greige inspection subsystem that could be positioned on the loom close to the point of fabric formation to provide real-time evaluations on defects and information on the characteristics of the cloth. Due to the requirement that the subsystem meet a calculated price, it was necessary to design two complementary sensor suites. The first a full-width inspection subsystem and the second a subsystem designed to measure cloth characteristics. Both have elements of hardware and defect segmentation algorithms.

Task IIIa. ORNL Greige Goods Full-width Inspection System

The laboratories involved on the task were Argonne National Laboratory, ORNL, LMES, and Sandia National Laboratories. In FY94 the team completed a greige defect analysis that defined the feature vector that would be used as the primary attribute for defects detected and the fabric characteristics needed to ensure operational compliance. The team also completed a sensor analysis and design correlating detection with fabric, sensor resolution, and particular defect categories. This work helped define the requirements and functional needs of the on-loom inspection subsystem. In FY95, the team completed the defect and sensor study and designed the

proof-of-concept inspection subsystem(s) that were Alpha Tested. This test began in March of 1995 and continued through the end of the fiscal year and tested each subsystem on-loom.

Hardware Description

The ORNL Greige Goods Full-width Inspection System was based on a 4096-element line scan camera that was synchronized to the moving fabric by means of an incremental encoder (see Figure 3). The system also included a source illumination for backlighting the fabric, a digital signal processing-based image acquisition and processing card, and a personal computer (PC). Figure 4 is a block diagram representation of the system. The only custom-made component was the camera-encoder interface used to extract the true forward movement of the fabric from the oscillatory motion induced by the loom. This enabled accurate image-line triggering for the camera.

Figure 3. The Greige Goods Full-width Inspection Subsystem mounted on a loom.

Figure 4. Block diagram representation of the Greige Goods Full-width Inspection Subsystem.

Defect Detection Approach and Algorithm

In designing the defect segmentation algorithm for the inspection system, it was observed that the fabric images constituted ordered textures that were globally homogenous, i.e., statistics measured from different patches in the image are correlated. It was further noted that images containing defects were less homogenous than those defect free. Based on this observation, the segmentation algorithm was developed to localize defect events that disrupted the global homogeneity of the background texture. Figure 5 is a flowchart of the segmentation algorithm. As seen, a multi-step process is used to identify and characterize a defect. This multi-step process includes a wavelet transform, edge fusion coupled with signal conditioning, calculations on local roughness and global homogeneity, a comparison of homogeneity, and, if a defect is present, a blob analysis.

Results

The performance of the prototype system was evaluated in two stages using a production-grade loom. In the first stage, the loom was set up to produce sheeting fabric using filament and a plain weave. The pick and warp densities were 58 yarns/in. In the second stage, the same fabric construction was used with spun yarn. The prototype system was set up to cover a 20 in.-wide area of fabric with the understanding the system was scalable to full width. The loom was operated at a speed of 700 picks per minute. Seventeen defect types for filament and 26 for spun were presented to the system for detection. Defects included mispicks, reed marks, mixed filling, moiré, dirty yarn, misreed, and hanging end.

Figure 5. Flowchart of the presented defect segmentation scheme, indicating its algorithmic models.

The image acquisition subsystem consistently produced high-quality images of the fabric for both types. The image resolution in the pick and warp-direction was set at 100 pixels/in. for filament and 200 pixels/in. for spun. The higher resolution was necessary to compensate for the naturally occurring impurities present in the natural fiber material.

Based on analyzing more than 3700 images of both types of fabric, the overall detection rate was found to be 89% with a localization accuracy of 0.2 in. and a false detection rate of 2.5%. False alarms were computed as the total number of false detections divided by the total number of processed images. Note that the 89% detection rate is an average over all of the defects presented. In general, the system had a 50%-60% defect detection rate on defects that present subtle intensity transitions and a 100% defect detection rate on those with

more serious defects (cost) such as mispicks, end-outs, and slubs. This system scored the highest during the Alpha Test.

The work on this vision-based subsystem was suspended due to uncertainties on the cost of a final system. The project management team suggested that this system (and those prototypes developed at Argonne National Laboratory) be taken to Phase I Beta test level. This would provide an operationally compliant system that could be evaluated at a later date for its economic viability. The Industry Technical Advisory Committee's (ITAC) decision was to stop all work immediately.

Task IIb. ORNL Greige Goods Fabric Characterization Subsystem – Pick Measurement Device (PMD)

The PMD was developed to fill the void of a low-cost sensor/system that could accurately characterize fabric structure and provide process information such as web velocities and total yards made. The system, as currently configured, provides an encoding function, signal to a marking system, an operator's panel, control signals to a loom, alarm lights, and a network and laptop configuration capability—requirements established by the CAFE industry partners. Figure 6 shows the device mounted on an operational loom in Burlington's Johnson City Plant.

The device provides immediate fabric quality measurements—pick density, changes in pick density, and total picks thrown. The device has been tested on various looms for both plain weave and twill. The system has been operated continuously since July 1996 in three different plants. The PMD requires as little as 30 minutes for setup and configuration. Its current design includes remote setup and operations and independent data collection and analysis.

Figure 6. ORNL's PMD installed on an operational loom in Burlington's Johnson City Plant.

Hardware Description

The PMD uses a class 3a laser and a set of cylindrical lenses in a front-lit pitch-and-catch mode to image picks onto a linear array. The image on the array appears as sets of parallel lines, each representing one pick. The lenses are arrayed in such a fashion as to eliminate interference of the warp yarns. The device can also be operated in a backlit mode using a halogen (or equivalent) light source, but this configuration requires special operational considerations. The electronics and optical hardware are housed in a 72-inch-long black anodized tube (Figure 7) with an associated user's control panel. The tube has a chamfered edge housing a sapphire window that presents the cloth to the imaging optics. The system is composed of three major subsystems: the

laser and cylindrical lenses, PC-board housing the linear diode array and microprocessor, and the PC-board housing the in-line power supply and external input-output (I/O) control and external connections.

Figure 7. Electronic package and assembly for the PMD. Unit includes the operator panel for display and setup of system.

Defect Detection Approach and Algorithm

The laser-optic subsystem images a linear slice of the material captured as a digital signal by the microprocessor. Here the image is analyzed for structure, providing information on each pick as it is laid down. These data provide the operational information needed to characterize plant and operational efficiency. The data are further analyzed to determine if any anomalies have been found in the cloth. If so, these are analyzed to see if they should be characterized as defects. These defects include mispicks, heavy marks, light marks, and dimensional information (see Figure 8). The identification of a defect by itself cannot justify the cost of a PMD to the weaving industry. The device must also resolve the location of the defect and identify it by name. The PMD has these capabilities. This unique measurement capability includes acting as its own encoder. Additional analytic capabilities include being able to resolve 30% variations in filament diameters (diameters ranging from 2 or 3 mills to 8 mills), barré and moiré patterns, and process parameters associated with the running of the weaving machine.

The device also uses its internal processing capabilities to provide additional quality information to the user and production staff. With the proper settings available through the user's panel or network connection, plant and production information can be selectively addressed for display and control. The device can be set to sound an alarm when an absolute value is attained or certain parameters change, providing the capability to run the device as a closed-loop controller or as an alarm module driving audio or visual drivers.

Using the device, loom operators can measure pick density and variability, map defects, and identify and correct for fabric anomalies as the fabric is woven, without stopping the loom. This information is crucial in determining material quality, maximizing plant profits, reducing the number of "seconds" (off-quality cloth sold at a reduced price), and eliminating shipments of excess material.

Results

The linear diode PMD has achieved cost-effective measures of pick density (± 0.1 pick variation), pick counts ($<1\%$ variation), fabric length, and fabric velocity. This is a significant technical innovation that avoids the cost and complexity of conventional imaging processes. A version of the PMD has been operationally tested in three different plants over the past year and a half. These facilities have provided different types of looms (air jet, water jet, and rapier) and end products based on different material blends such as cotton, cotton blends, and polyester. Based on the performance of this system, a prototype commercial unit has been built and undergone successful compliance testing at LMES and an operational weaving plant in the U.S. These tests confirmed the capability of the device to meet the ± 0.1 pick variation on pick density measurements and $.05\%$ variation on

total pick counts. The device was installed at the Glen Raven plant in Burnsville, North Carolina, and then moved to the Institute of Technology (ITT) in Charlottesville, Virginia, for final functional testing.

The device has been patented and is being licensed to ITT, who with the help of a selected vendor, will manufacture, market, and sell the device to the textile industry. It is believed the device will find widespread use in the textile industry and will help make textile manufacturers more competitive in both the U.S. and world markets.

Figure 8. Prototype defect detection interface for the PMD highlighting variations in density as measured by the PMD. The high and low limits identify process control points. Major excursions are due to varying in fabric structure. A result of light and heavy marks and pattern variations.

Task IV. ORNL's Imaging Tristimulus Colorimeter (ITC) Subsystem (CPPG Inspection Subsystem (continuing))

The CPPG subsystem is being developed to provide finishing plants a full-width printed pattern inspection system along with a colorimetry capability to measure color variations side-to-side and full length. The full-width inspection system is camera based and is being developed by Sandia with support from ORNL and LMES. In FY95, ORNL and LMES provided technical support in the design and deployment of a lighting system. During this time, a preliminary theoretical study was conducted to determine the feasibility of designing a camera-based photospectrometer to provide accurate color measurements. In FY98, ORNL developed a proof-of-concept system that was tested in a laboratory against known standards. The test was successful, leading to FY99 funding to build a prototype system. The design of the prototype tristimulus imaging colorimetry is the main activity for ORNL this fiscal year. Plans include testing on the ORNL Web Test Bed.

Hardware Description

A benchtop prototype was configured to implement the concept of an imaging tristimulus colorimeter. This system was designed to test and validate the projection on convex sets (POCS) algorithm that serves as the workhorse for the system. The main components of the system are a monochrome, charge coupled device (CCD) electronic camera, a color filter wheel, illumination, and personal computer. Figure 9 shows a schematic of the system.

The camera is a standard RS-170 format, CCD without automatic gain. The imaged data from the camera was digitized using a Matrox Pulsar (peripheral component interconnect) PCI-based card. The analog-to-digital converter on the Pulsar used a black level clamp based on the "back porch" section of the RS-170 signal to

ensure consistent and repeatable data acquisition. An eight slot Integrated Scientific color filter wheel was used to generate a three component color image. Commercially available colored glass filters in combination with neutral density filters were used to obtain a relatively even response for all three-component color images. Illumination was provided by the two MacBeth Sol-Source lamps positioned at an angle of 45 degrees to the surface of the object. The benchtop system used a PC2000 Ocean Optics photospectrometer. The host PC is a Windows NT 4.0, Pentium system with Microsoft Developers Studio for software development.

The testing of the system was accomplished in several phases with the initial work performed on the MacBeth ColorChecker™ chart and subsequent analysis on actual textile samples. The MacBeth chart consists of 18 colors and 6 neutral tiles that cover the visible spectrum. A HunterLab UltraScan™ XE spectrophotometer was used as a baseline to measure the true tristimulus values of the individual tiles.

Defect Detection Approach and Algorithm

The focus of this research is the development of a color measurement device that can quantitatively access color variations in printed textile materials during the on-line manufacturing process. The approach is to match Commission Internationale de l'Eclairage (CIE) human tristimulus response and values through mapping, to specify color. The accurate measurement of the color surfaces using human tristimulus models is a difficult task. The reasons for this are many with the primary issues being the highly nonlinear conversion between color spaces, accurate spectral characterization of the illumination and sensor, and the uniform perceptual based metrics.

Figure 9. Schematic of the ITC Subsystem.

A set, theoretic approach based on the method of projection onto convex sets is taken to solve the nonlinear optimization problem of transforming the measured component colors to the predicted tristimulus responses. This differs from classical estimation in that the solution is not based on minimizing/maximizing a cost function but rather finding a solution which satisfies all the prescribed constraints.

The tristimulus response of the human eye to a solid-colored object is a function of three physical attributes: the spectral content of the object, the spectral content of the light illuminating the object, and the spectral response of the viewer. The spectral response of the viewer is defined by the tristimulus response curves determined by the CIE. Therefore the tristimulus values are given by the following equation

$$\{d_1, d_2, d_3\} = \{x_1(\lambda), x_2(\lambda), x_3(\lambda)\} E(\lambda) \rho(\lambda) d\lambda \text{ or } d = XE\rho, \quad (1)$$

where $E(\lambda)$ is the spectral response of the illumination, $\rho(\lambda)$ is the spectral reflectance of the object, and $\{x_1(\lambda), x_2(\lambda), x_3(\lambda)\}$ are the human tristimulus response curves.

A colorimeter instrument has a spectral response that is different from the CIE-defined human spectral response and the resulting measured tristimulus values are given by

$$\{c_1, c_2, c_3\} = \{r_1(\lambda), r_2(\lambda), r_3(\lambda)\} E(\lambda) \rho(\lambda) d\lambda \text{ or } c = RE\rho, \quad (2)$$

where $\{r_1(\lambda), r_2(\lambda), r_3(\lambda)\}$ represents the spectral responses of the three component color channels of the colorimeter. The primary objective of the nonlinear optimization is to derive a mapping that converts the vector c to d .

Results (FY98)

The tristimulus imaging colorimeter demonstrated a favorable comparison between an on-line imaging colorimeter and an off-line spectrophotometer. Target goals for the system were a DECMC accuracy of +/- 0.1 and a repeatability of +/- 0.05. An initial test of the benchtop system yielded an accuracy of +/- 0.26 and a repeatability of +/- 0.1.

The follow-on development activities for FY99 will focus on incremental improvements in several aspects of the ITC. The first will be to identify and purchase a new camera that has improved stability and spectral response. In addition to this, a new illumination source will be evaluated and the PC-based spectrometer will be integrated into the system. Finally, two possible improvements in the POCS algorithm will be investigated to improve performance.

Task V. Machine Diagnostics (FY96-FY98)

During the course of developing the Greige Goods Inspection Subsystem, it became obvious the need existed for a diagnostic capability for looms. As a result of this, ORNL and LMES developed such a concept. The system is based on a single, diagnostic point capable of determining loom health in terms of a bad clutch, motor, sley drive, and a particular set of gears. The sensor technologies include acoustic and acceleration.

The basic attribute of Machine Diagnostics is a single number representing a measure of machine health. It provides a single point of reference for a loom operator or plant technician to make decisions about maintenance and repair. This attribute (Beta function) is a function of power, frequency, and time. Figure 10 shows this calculated value for a new machine, a quiet (rebuilt) machine, and a machine with a noisy clutch and bad sley drive. These data were collected during a field experiment at a select site. As seen, there is an order of magnitude difference between the calculated values, providing the necessary sensitivity to discriminate between machine operational states.

Following the initial data collection, a series of operational tests were performed. The intent was to see how effective the approach was at diagnosing problems in a plant environment. Figure 11 shows the results from one such test. Here, five looms were selected at random to conduct a diagnostic study on. Based on the calculated Beta value, only one machine (No. 109) was identified as having a problem. Further investigation using the Beta value diagnosed the problem as a bad sley drive. Based on the finding, the machine was pulled out of service and an overhaul performed. During this service, the sley drive was found to be in need of repair, which came as a surprise to the plant and loom operator. The consensus from the test was that the machine diagnostics methodology and approach did provide a diagnostic capability that could support plant operations and that it had the sensitivity and selectivity to identify those major machine problems that contribute to off-quality cloth.

Figure 10. A plot of the Beta values for a new machine, a quiet (rebuilt) machine, a machine with a noisy clutch, and a machine with a bad sley drive. These data were collected during a field test at a select site.

108 & 109 -50/50 Poly-Cotton, 505 RPM, 74 Fics/In
 237, 255, 256 -50/50 Poly-Cotton, 505 RPM, 56 Fics/In

Figure 11. Diagnostics performed on five randomly selected looms identifies a bad sley drive on unit no. 109.

Following these tests, the Machine Diagnostics system was deployed to a plant for long-term testing. During these studies, two additional operational elements were characterized: machine setup and machine startup. As shown in Figure 12, the Beta value has the capability to provide a quantitative measure for both of them. Machine startup is important because it identifies transitional points in the fabric that will be different from the steady state structure. Machine setup is significant because it can identify an operational state where the economics of the process are reduced because the machine specifications have not been met.

Currently, the Machine Diagnostics approach is being applied to the Enriched Uranium Operations at LMES (Y-12 plant). This development effort continues in FY99.

Figure 12. The Beta value has the capability to provide a quantitative measure for both machine startup and setup. Each has a significant impact on the operational economy of the process.

INVENTIONS (MADE OR REPORTED)

Title	Invention Disclosure No.	Author(s)	Status
Loom Control Based on Pick Mass and Dynamics	ERID 0347	Glenn O. Allgood (LMER), Dale A. Treece (LMER), Blake W. Van Hoy (LMES)	Elected
Yarn Bulk Sensor	ESID 1570	Michael Duncan (LMES), Douglas Smith (LMES)	Under Review
Vision-Based, On-Loom Fabric Inspection System	ESID 1788	Hamed Sari-Sarraf (LMER), Jim S. Goddard (LMER), Earl W. Walker (LMES)	Patent Filed
Structure and Yarn Sensor for Fabric	ESID 1790	David K. Mee (LMES), Glenn O. Allgood (LMER), Larry R. Mooney (LMES), Michael G. Duncan (LMES), John C. Turner (LMER)	US Patent 5,825,501
Knitting Needle Position Monitor	ESID 1818	Steven A. Wallace (LMES)	Not Filed
A Method and System for Performing Imaging Tristimulus Colorimetry	TBD	Kenneth W. Tobin (LMER), Marc L. Simpson (LMER), Martin A. Hunt (LMER), Jim S. Goddard (LMER)	Working

COMMERCIALIZATION POSSIBILITIES

This section provides an overview of the commercialization activities associated with the PMD (Greige Goods Inspection Subsystem) and the Imaging Tristimulus Colorimetry Subsystem (CPPG Inspection Subsystem). These activities are continuing through FY99.

PMD and Greige Goods Inspection Subsystem

1. The laboratory project management team met with the CPPG team, vendor affiliate, and industry partners to finalize the Beta Test Plan. The meeting detailed the methodology and approach to be employed during the test to gauge the system's capability to meet the measures of performance (MOPs) and functionality documented in the Color Print Inspection's FD/RD. A similar meeting was held for the Greige and Knit Subsystems documenting the test procedure used. The PMD has passed its FD/RD compliance test.

Time: November/December 1998.

Deliverable: Color test plan, test results from PMD.

2. ITT and the vendor affiliate, Appalachian Electronic Instruments (AEI), completed the Beta Test for the new Greige Goods Inspection Subsystem on plain weave to ensure technical functionality. During this time, AEI modified the system according to needs and consulted with the laboratory team on an as needed basis.
3. ITT/AEI analyzed the results from the compliance tests in (2). These findings were used to map technology attributes and capabilities onto market segments that will benefit from the insertion of such technology. This became the greige weave market plan for AEI to follow. AEI will approach the industry partners with these findings to secure trial system orders. The laboratory team was consulted on an as needed basis.

Deliverable: Secured orders for trial systems.

4. Implement greige weave market plan and business expansion to accommodate the build and delivery of the greige goods inspection trial units. Build and deliver trial units to industry partners.

Time: 2-4 months from (3).

Deliverable: Trial units to industry partners (estimated number of units: 2-3).

5. Provide technical field support for trial units. Upgrade system performance as needed. During this time AEI will continue developing their market strategy and internal growth plan as they prepare to service the industry partner market. It is expected that at the end of the trial unit testing period, AEI will receive solid business orders for multiple systems.

Time: 4-6 months from delivery of trial systems.

Deliverable: Secure orders for multiple field units.

6. AEI will go into a production mode to fabricate, build, and deliver greige goods inspection field units to CAFE industry partners. During this time, AEI will begin developing a U.S. market strategy and begin planning for the introduction of this technology into the U.S. Based on current figures, there are approximately 70,000 shuttle looms in the U.S. Assuming the breakdown is 20% for CAFE partners and 80% for the remaining U.S. market and a conservative entry of 2%-5% for each, the expected numbers of greige goods inspection subsystems to be sold by AEI to the CAFE partners and U.S. market over a five year period are (280-700) and (1120-2800), respectively. AEI will also approach the loom manufacturers to secure a working relationship with them as original equipment manufacturers (OEMs) for the next generation machines.

7. AEI will continue testing of the PMD to determine suitability of the technology. These tests will encompass styles, yarns, and machine types and will establish market boundaries. AEI will modify the PMD as needed to support industry needs. During this time AEI will consult with the laboratory team as needed.

Current efforts.

8. ITT/AEI will analyze the results from the compliance tests in (7). These findings will map technology attributes and capabilities onto market segments that will benefit from the insertion of such technology. This will become the PMD market plan for AEI to follow. AEI will approach the industry partners with these findings to secure trial system orders. The laboratory team will be consulted on an as needed basis.

Time: 1 month from end of (7).

Deliverable: Secure orders for trial systems.

9. Implement PMD market plan and business expansion to accommodate the build and delivery of the PMD trial units. This effort should dovetail with those of (4).

Time: 4 months from (8).

Deliverable: Trial units to industry partners (estimated number of trial units: 3-6).

10. Provide technical field support for trial units. Upgrade system performance as needed. During this time AEI will continue developing their market strategy and internal growth plan as they prepare to service the industry partner market. It is expected that at the end of the trial unit testing period, AEI will receive solid business orders for multiple systems.

Time: 4-6 months from delivery of trial systems.

Deliverable: Secure orders for multiple field units.

11. AEI will go into a production mode to fabricate, build, and deliver PMD field units to CAFE industry partners. During this time, AEI will begin developing a U.S. market strategy and begin planning for the introduction of this technology into the U.S. Based on current figures, there are approximately 70,000 shuttleless looms in the U.S. Assuming the break down is 20% for CAFE partners and 80% for the remaining U.S. market and a conservative entry of 5%-8% for each, the expected numbers of PMDs to be sold by AEI to the CAFE partners and the U.S. market over a five year period are (700-1120) and (2800-4480), respectively. AEI will also approach the loom manufacturers to secure a working relationship with them as OEMs for the next generation machines.

Time: 4-6 months.

Deliverable: Field units to CAFE industry partners (estimated number of units: 8-12).

12. During the test and build of the systems, AEI will investigate the possibilities of other market segments that include loom controllers for OEM applications. Secure orders for test and evaluation units.

Time: 6-9 months.

Deliverable: Secure order for trial unit(s).

CPPG Inspection Subsystem and Imaging Colorimetry Subsystem

1. The CAFE print inspection technology consists of two separate, but complementary, operational components. One is the Full-width Pattern Inspection Subsystem. The other is the Colorimetric Measurement Subsystem. Development efforts for the defect detection subsystem have preceded those for the colorimetric subsystem. Since both are still in the developmental and evaluation stages, a commercialization plan set forth at this time is simply a projection and cannot encompass specific dates and exact system cost estimates.

2. Hunter Associates Laboratory (HunterLab), located in Reston, Virginia, is the CAFE research affiliate that is responsible for the commercialization of the two systems. They have an extensive background and solid reputation in the area of color measurement and monitoring for both textile and nontextile applications. Since HunterLab is well versed in colorimetric science, it is anticipated that they will have the internal capabilities of advancing the novel POCS algorithm approach being evaluated in FY99. Their current plans are to utilize revenue from the sale of defect detection units to complete the development of the Imaging Tristimulus Colorimetry Subsystem. This subsystem represents tremendous value for the print industry in that the majority of past CAFE print partners cited shade variation from end-to-end and from run-to-run as being one of their top four causes for off-quality. As the FY99 efforts take us beyond the conceptual phase and closer to determining a reasonable cost estimate for the colorimetry subsystem, HunterLab will begin to assess full market potential of the subsystem within and outside of the CAFE consortium.
3. With the configuration of the print defect detection system being relatively close to that of a commercial system, HunterLab has been able to perform an initial cost analysis on the system. After traveling to several of the CAFE partners' plants to discuss system expectations and to gauge market potential, HunterLab developed an updated system cost projection and has entered into discussions with the Beta site partner, Pillowtex/Fieldcrest Cannon, regarding the purchase of a trial unit at its earliest available commercial delivery date. This is contingent upon successful completion of two efforts during the FY99 work year: full Beta testing of a multichannel system and transition to a manufacturing hardened system design (i.e., graphical user's interface, host computer configuration, lighting enclosures, etc.). The first of these efforts requires the continued developmental efforts of the laboratory researchers and support of plant personnel and HunterLab and is covered in the FY99 CAFE Project Plan. The second effort will be the responsibility of HunterLab and their sublicensed partner company SheLyn Incorporated out of Greensboro, North Carolina. They will be working closely with Pillowtex/Fieldcrest Cannon staff to ensure the system is user friendly and can be incorporated into the plant's standard operating procedures. Assuming successful testing in the currently projected timeframe, HunterLab anticipates having this system available for Pillowtex/Fieldcrest Cannon early in the 2000 calendar year. Installation and operation of the system will lead to further improvements of the system and subsequent sales volume within and outside of the CAFE consortium over the next several years.

CONCLUSIONS

Based on the Greige Goods and CPPG FD/RD's and the Economic Model, the subsystems developed by ORNL and LMES meet the established industry requirements. These requirements are in terms of the following.

- Functional capabilities to detect anomalies and classify them as defects based on a probability of detection. These defects were identified in the cost model.
- Operational requirements established in the initial plant study that identified environmental constraints present in weaving plants. Included in this are the power budget requirements, mounting restrictions, user restrictions, spin-up times, etc.
- Utility in terms of display, control, defect map, user's interface, database requirements, communication standards, and system protocols.
- The Imaging Tristimulus Colorimetry Subsystem has met the functional requirements established by the CAFE industry partners. The prototype is being developed under the multilaboratory CRADA.
- The machine diagnostic package has the capability to diagnose system problems as they relate to operations, setup, and defects.
- The Economic Model was instrumental in defining those MOPs critical to the success of the CRADA. This model continues to be used.

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APPENDIX B

Project Management

Project Management Approach

The particular approach being taken in the development of CAFE is described below. The significance of this scheme is that the process logically built upon itself and mandates a series of checks and balances so that the textile industry could review progress and, when necessary, redirect efforts.

Baseline CAFE Feature Descriptors. In order to define the composition of the CAFE System, it was necessary to describe in detail the operating profile of the complete process, which included on-line and off-line inspection needs for woven and knit materials. This descriptor provided the base-case system identifier from which anomalies and defects were categorized. In the development of this, an operational description of the CAFE System was developed, complete with defined sets of observable and controllable parameters. This required defining the CAFE System's operating profiles and developing data structures as a metaphor for the system's operating signatures. In this, the normal operating modes of an inspection system were defined which required extensive amounts of data collected for constructing the feature descriptors.

Design and Development of the CAFE System. With the CAFE feature descriptors, the laboratories developed a FD/RD for each of the CAFE inspection systems. This functional description was based on the inspection system's operational requirements and detail physical measurements that were made (set of observable parameters). From the physical measurement description came the sensor suite definitions. Once the sensor suites were properly defined, an investigation was made to determine the applicability of off-the-shelf technologies to meet operational requirements. With the proper definition in hand (functional and operational) an economic and infrastructure assessment was made to determine if the suite/subsystem, as it is defined, met the cost and operational objectives set forth in the Economic Model and System Architectures Documents.

Baseline Defect Feature Descriptors. Once the baseline CAFE feature descriptors were developed it became necessary to develop the off-operational mode descriptors that coincide with the forming of defects in the yarn or fabric, whether it be in greige, color printed, or knit. This required developing procedures by which off-performance operations in the systems were instituted and recorded. The data was correlated with defects that were formed in the fabric. In each instance, the off-performance characterization required partitioning the operational parameter set, making perturbations in these select parameters, and establishing causal effects on defects that occur in the fabric. The data structure that developed from this analysis formed the baseline defect feature descriptor for each of the CAFE Systems.

Classification Algorithms. Once the machine and defect descriptors were developed, they were integrated into a cohesive, seamless data structure for inclusion into the CAFE inspection system. This provided the mechanism by which the inspection system was able to discern operating excursions, make qualitative judgements about these changes, and then issue commands and set flags to either bring the system back into process control before defects occur or flag and electronically map defects that have occurred. To facilitate this required the application of advanced computational methods for diagnostics (wavelets, neural nets, etc.) and model verification and applying data fusion techniques to reduce data bandwidths and to support the development of higher cognitive processes for system recognition.

CAFE System Development and Design. Once a particular system's baseline machine and defect descriptors were formalized and the cost structure analyzed and accepted, that system went into the formal design and development phase. This task involved designing the system's enclosure, establishing the system's architecture definition, detailing power requirements, establishing isolation requirements and any operational constraints, establishing interface requirements, establishing operational performance parameters such as MTTR/MTBF, establishing data base requirements and data bandwidths, and detailing the human-machine interface.

CAFE Subsystem Integration. Once the system's definitions were established, its design impact from the perspective of the overall inspection system was investigated in relationship to the existing manufacturing infrastructure. This analysis included the hardware and software impact on a textile manufacturer, its operational requirements (power requirements, footprints, operating constraints), and its sociological, economic, and operational impact on the industry as a whole. Conducting this analysis ensured that all textile manufacturers can use any system regardless of end process.

Alpha Test and Evaluation of CAFE Proof-of-Principle. This represented the industry's first test and evaluation of the CAFE System. The effort required conducting the test, assessing operational performance, grading functional and operational effectiveness, providing effective measures of performance, documenting the results, writing the final test report, and reporting to the AMTEX™ Industry Board and to DOE their final assessment. Each system being developed goes through the Alpha testing phase to ensure compliance with the overall stated goals of the Project. This was the first in a series of checks and balances for any CAFE System.

Manufacturer's Test and Evaluation of CAFE Prototype Systems (Beta). This represents the industry's second test and evaluation of a particular CAFE System. This task requires conducting an operational test at a predefined manufacturing test site, assessing operational performance, grading functional and operational effectiveness, providing effective measures of performance, documenting the results, writing the final test report, and reporting to the AMTEX™ Industry Board and to DOE the final assessment. The period covered by this task extends for six months.

CAFE Assessment and Feasibility. During the evolution of the CAFE System it is important that a series of checks and balances be enforced to ensure compliance with the overall stated goals of the AMTEX™ CRADA. These goals include the operational and functional requirements of the system, the system's cost structure, and its overall stated impact on the textile industry itself. In order to facilitate these goals, monthly and quarterly reviews, assessment and feasibility reviews, will be held to allow the industry participants to review progress to date, make suggestions, and if needed, to redirect the efforts of the CAFE Project.

Industry Project Manager Description

The main responsibility of the Industry Project Manager is to ensure compliance of the overall goals set forth by the CAFE industry partners in relationship to each technical task. In this capacity the managers will serve as the link between the strategic goals (expectations) set forth by the textile industry and the technical requirements of the CAFE System. Their duties will include oversight, both strategic and technical, of each major task area and the coordination of all subtasks identified underneath it. In the capacity of strategic oversight, the laboratories will report directly to these positions. In the technical case, both industry and laboratory teams will share responsibilities. All industry subtask leaders will report to these positions.

The Industry Task Managers hold the same level of technical responsibility as the Laboratory Principal Investigators. As such, in instances where the Industry Project Manager has the lead responsibility for the task the laboratories will report directly to them. In the reverse, the Industry Manager will report to the Laboratory Principal Investigator on issues related to the technical task. In all cases, the industry and laboratory task teams form the synergism for completion of all tasks.

The Industry Project Manager will also serve as the technical liaison between the CAFE industry partners and the laboratory working group by serving as a member on the Industry Evaluation and Oversight Committee. In this capacity each will be responsible for developing test plans, defining measures of performance for each subsystem, and serving on the official evaluation committee during all tests phases of the CAFE System. This responsibility will require development of formal documentation and the reporting of test results for each system directly to the CAFE industry partners, ITAC, and to DOE.

Industry Task Leader Description

The Industry Task Leader has the technical responsibility for assigned subtasks under a major task heading and is responsible for compliance and oversight of the industry's work as it relates to the overall goal of the project. The Task Leader will report directly to the Industry Project Manager on all technical and management issues and will serve as the technical liaison between the textile industry and national laboratory on technical issues related to a particular effort. In this capacity the Task Leader will work directly with his laboratory counterparts, serving as a full-time team member. On tasks where the industry has the lead responsibility, the laboratories will report directly to them. When a laboratory has the lead responsibility, the Industry Task Leader will support them.

DISTRIBUTION

Internal

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- 7. J. M. Jansen Jr.
- 8. A. J. Luffman
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