There is a perception that U.S. upland cotton has high levels of nep, which add extra costs to the cotton industry. More than 90% of neps in a finished fabric have immature fibers. Immature fiber does not have enough cellulose to retain the dye, causing undyed spots, known as white specks, in finished fabrics. This work compared the fiber longitudinal measurements with white speck data of 16 different cottons, and studied the possibility of establishing a predictive equation for white speck contents from bale fiber samples. The main advantages of using the longitudinal FIAS test are that it can more readily detect dead and immature fibers and takes much less time in preparing sample slides than the cross-sectional FIAS test.

Key words convolution, cotton maturity, cross-sections, image analysis, translucence, white specks
rial dies, the fiber collapses and twists about its own axis. If this process is interrupted by plant stress (e.g., drought, insect attack, flooding, hail, etc.), the seed may abort and the fiber will stop maturing. Immature fibers can also be associated with healthy seeds, and will remain through gin processing and be present in the bale. It is desirable to find a means to predict the level of white speck defects from measurement data of bale fibers. In this study, we utilized Fiber Image Analysis System (FIAS) to perform the fiber longitudinal and cross-sectional tests on 16 cottons, and a customized system for fabric appearance assessment to measure white speck data of the corresponding dyed fabrics. The two sets of data have been compared to explore the possibility of establishing a predictive equation for white speck contents from bale fiber samples.

**Methods**

**Fiber Measurements**

Cotton fibers were tested by FIAS, which is a customized microscopic image analysis system for automatic measurements of fiber geometric attributes. The basic FIAS functions include fiber cross-sectional analysis and longitudinal analysis, resulting in maturity, fineness, and other geometric data.

Cross-sectional analysis of cotton fibers provides direct, accurate measurements on fiber fineness and maturity, which are often regarded as the reference for validating or calibrating other indirect measurements of these important
cotton properties [3, 4]. Figure 3 displays the cross-sections and corresponding dyed fabrics of two different cottons. Cotton A was bred to mature earlier than Cotton B. From Figure 3, it is clear that Cotton B had a higher level of flat, immature fibers, and its finished fabric also exhibited a higher level of white specks than Cotton A. Hence, it is possible to use fiber cross-sectional data to predict severity levels of white speck for a finished fabric.

Cross-section analysis constitutes two critical steps: fiber cross-sectioning and image analysis. The USDA Southern Regional Research Center (SRRC) developed an effective, but time-consuming cross-sectioning method [2, 5, 6]. As demonstrated in Figure 4, this method consisted of blending fibers (Figures 4-1 and 4-2), combing fiber bundles (Figure 4-3), embedding the bundle tube in a methacrylate matrix (Figures 4-4 and 4-5), which was then polymerized into a solid cylinder that was sliced into thin sections (1-μm thick) with an ultra microtome (Figures 4-6, 4-7, and 4-8). The thin sections were then mounted onto microscope slides which were placed on a transmission microscope equipped with a CCD camera and frame grabber. Along with this cross-sectioning method, FIAS was chosen to analyze cotton cross-sectional images for a multiple-year project conducted by the SRRC, Texas Tech University, and Cotton Incorporated, which aimed to build a reference database for cotton maturity [7]. Currently, the
cross-section analysis with FIAS can yield such cross-sectional data as total fiber area, wall area, lumen area, fiber perimeter, lumen perimeter, equivalent diameter, wall thickness, maturity (theta value $\theta$), and calculated micronaire [3]. Ten slides were normally analyzed for each cotton sample, yielding approximately 500 cross-section measurements per sample.

Despite its importance, the cross-sectional method of using image analysis has not been broadly applied to cotton quality evaluations because of the tedious procedures in both preparing cotton samples and processing cross-section images [2–4]. In addition, it is not robust when evaluating extremely immature cottons because the cross-sectioning can easily shred the thin walls of dead fibers, and some immature fibers may be folded together too (Figure 5). Therefore, visual editing tools are necessary to remove wrongly traced fibers. However, omitting the data of immature fibers from the sample can seriously distort the testing results.

The longitudinal analysis is another main function of FIAS [8], which has recently had more improvement in its automation and precision [9]. The new FIAS function targets high-speed and high-volume measurements of fiber maturity using fiber snippets. The system mainly consists of a zoomable microscope, a high-resolution digital camera (up to 3M pixels), a motorized stage, and a pneumatic fiber snippet cutter/spreader [9]. We normally set the zooming power between $4 \times$ and $5 \times$, which yields approximately 1 $\mu$m/pixel image resolution. The motorized stage automatically transports the sample slide horizontally and vertically, so that up to 1,000 frames of images can be captured and analyzed sequentially in one run. The pneumatic fiber cutter and spreader tremendously reduces the time and complexity of sample preparation for longitudinal measurements, which is literally a matter of seconds as compared to a full day for cross-section preparation. The sample does not need to be combed. It only needs to be briefly drawn before being placed underneath the blades for making snippets. As shown in Figure 6, the blades can cut fibers at multiple locations along their long axes so that the maturity variability within a fiber can be included as well. The fiber snippets are then sprayed on two slides which are sandwiched together and labeled (Figure 7).

The basic principle of measuring maturity in the longitudinal view is based on variability in ribbon width (fiber convolution) and intensity (fiber translucency). The former reflects the convolution of fiber, while the latter indicates the translucency of fiber, i.e. wall thickness [2, 9]. Fibers are scanned at a five-pixel interval along the axes (Figure 8). If a fiber has extremely thin walls, its main body is highly transmissive (translucent), and becomes voids in the fiber after image segmentation. These voids are marked by the system as ‘dead’ scans. The ratio of the dead scans to the total scans is called the dead scan ratio (DS). For each scanned slide, the software calculates the following:

Fiber: the number of fiber snippets analyzed.
Scan: the number of scans for all of the fiber snippets analyzed.
**Figure 7** Fiber preparation for FIAS. Fiber snippets were cut by the fiber cutter/spreader and sprayed on two slides which were then sandwiched together.

**Figure 8** FIAS longitudinal image analysis of fibers. Transverse scans indicate immature fibers.

\[ D_{\text{mean}}: \] the mean fiber width (ribbon width) of the scanned segments. \( D_{\text{mean}} \) reflects the fineness of fiber.

\[ D_{\text{sd}}: \] the standard deviation of fiber width. \( D_{\text{sd}} \) reflects the convolution of fiber. The more twists a fiber has, the higher the \( D_{\text{sd}} \) is.

\[ G_{\text{mean}}: \] the mean intensity of the scanned segments. \( G_{\text{mean}} \) indicates the wall thickness of fiber.

\[ G_{\text{sd}}: \] the standard deviation of the intensity of the scanned segments.

**Bright:** the brightness of the fibers relative to the background, that is, Bright = \( G_{\text{mean}} \)/the grayscale of the entire image. Bright takes the difference in overall illumination among different images into account, which gives more stable measurements than \( G_{\text{mean}} \).
Fine: the modified fiber fineness by including the influence of $G_{\text{mean}}$. $D_{\text{mean}}$ is the width of a fiber projected in the image plane, and it does not contain thickness information in the perpendicular direction. $G_{\text{mean}}$ is related to fiber thickness. An empirical formula, $\text{Fine} = D_{\text{mean}} \exp (-0.1 G_{\text{mean}})$, is established to perform the modification. When the $G_{\text{mean}}$ of a snippet is zero, the fiber image is black, indicating it is a mature fiber whose cross-section is more likely to be circular. Therefore, its Fine is equal to $D_{\text{mean}}$, which can be regarded as the diameter. When $G_{\text{mean}}$ is not zero, Fine is modified by a negative exponent factor to be smaller than $D_{\text{mean}}$, which can be regarded as an equivalent fiber diameter.

DS: dead scan ratio, i.e. $\text{DS} = \frac{\text{dead scans}}{\text{total scans}}$. When the dead scan ratio of a fiber exceeds a preset threshold (0.2 was experimentally chosen in this study), the fiber is considered to be a dead fiber, for which the Bright is arbitrarily set to one to label an extreme. It is these dead fibers that are more likely to be entangled to be neps and to become the dye defects known as white specks in finished fabrics. $\text{DS}$ is used only for detecting dead fibers and maximizing the Bright value of the dead fibers.

The number of the scanned fibers per slide varies from 1,000–5,000, depending on the density of fiber snippets spread on the slide. Five slides were made and analyzed by FIAS for each cotton. These outputs provide measurements that can be correlated to both maturity and fineness data of the cross-section analysis for the same set of fibers [9], as well as the white speck data of their finished fabrics.

**Fabric White Speck Measurements**

White speck measurements of dyed fabrics can be obtained from another image analysis system dedicated for performing automatic ratings of fabric appearance [10]. The system is called ‘Autorate’, and its set-up and image processing techniques have been reported in previous publications [10, 11]. Four $127 \times 127 \text{mm}^2$ swatches were imaged for each fabric sample. The brightness setting was adjusted to 120 (on a 0–255 scale) when capturing images using Autorate. The brightness and contrast levels in the Autorate setting are adjustable by the user to find optimal results for specific samples. The user can also set the minimum size for white specks to eliminate small anomalies. The Autorate analysis program can highlight the detected white specks for visual verifications (Figure 9), and result in white speck count, size and area percent of white specks (% White). The percent white speck area (% White) is the most rational indicator of fiber neps existing in the fabrics.

**Material**

In order to compare maturity measurements from bale fiber samples to the level of white specks on dyed fabrics, we chose 16 different cottons from the U.S. Cotton Variety Textile Processing Trials, which were grown in Georgia, Mississippi and Texas during the 2001 season. Eight bales of cotton were collected and blended for each variety and location for a total of 128 bales. Blended bales were processed using the regular mill processing protocol equipment at SRRC. Both fillings (weft) and warps were ring spun yarns. Filling yarns were 29.5 tex with 130 T.M.$\alpha$m – metric twist factor (turns per meter/square root of yarn count) or 4.3 T.M.$\alpha$e (–turns per inch/square root of cotton count), and warp yarns 19.7 tex with a $127^2$ T.M.$\alpha$m (4.2 T.M.$\alpha$e). The fabrics were a five-harness, filling-face sateen weave.
The fabric was finished with a 0.1% Prechem 70, 0.3% T.S.PP. boil-off, a caustic scour of 1.1% Prechem SN, 1.1% Mayquest 80, 0.1% Prechem 70 and 0.7% sodium hydroxide (caustic soda), followed by the same boil-off procedure. The fabric was then bleached (0.1% Prechem 70, 0.5% Mayquest BLE and 3.0% peroxide (Albone 35)), followed by an acid sour (0.1% acetic acid) and dyed with 2.0% Cibacron Navy F-G Blue, 0.5% Calgon, 8.0% sodium chloride, 0.8% Na\textsubscript{2}CO\textsubscript{3} (soda ash), and 0.5% Triton Tx\textsubscript{100}. This dye has a high propensity for highlighting white specks in finished fabrics.

Brief visual examinations revealed the dyed fabrics of these variety cottons contained a wide range of white specks [10]. Figure 10 displays fabrics with the highest (#1) and lowest (#16) levels of white specks. The rest of the fabric samples were found to have middle levels of white speck. The raw fibers corresponding to these 16 fabrics were tested on FIAS for cross-section and longitudinal measurements, and the white specks of the fabrics were measured by Autorate.

**Results and Discussion**

Table 1 displays the fiber measurement data and the white speck contents of the 16 selected cottons. $\theta$ is the theta value of cotton cross-sections, which represents the maturity measurements of cotton. First, we analyzed the correlations of the longitudinal data with the cross-section data, and found there was no significant correlation between the two sets of data. This may be due to the difference in the sample preparations of the two testing methods. As pointed out previously, fiber bundles for the preparation of cross-section samples needed to be combed to straighten the fibers. Combing unavoidably dislodges fibers, typically dead or immature fibers which are more likely to form neps, skewing the data in relation to the level of white specks in the finished fabrics. Another reason for the low correlation is that the edges of dead fibers are more difficult to be detected completely in the cross-sectional image analysis, and therefore many dead fibers are miscounted in the measurements. Perhaps for the same reasons, the $\theta$ data of the cross-section analysis did not show a high correlation with the white speck measurements ($R^2 = 0.515$).

We then analyzed the correlations of the longitudinal measurements with the white speck count. In the longitudinal test, five slides were made for each cotton sample, and the data of all fibers on the five slides were summed. The correlations of different longitudinal measurements with % White varied dramatically. In the correlation rank with % White, Bright was the strongest ($R^2 = 0.832$) and Fine was the next strongest ($R^2 = 0.623$). The confidence interval for the Bright mean of all the samples (0.4708) was $\pm 0.0036$ at the significance level of 0.05. The better correlation with Bright was due to the fact that dead fibers were detected with DS and reflected in the Bright data. Bright is associated with fiber maturity and Fine indicates fiber fineness. However, only these two parameters showed reasonably high correlations. Bright and Fine can be regarded as normalized $G_{\text{mean}}$ (fiber brightness or translucency) and $D_{\text{mean}}$ (fiber width), both of which did not have good correlation with % White. The modifications of $G_{\text{mean}}$ and $D_{\text{mean}}$ seemed to be effective. We also noticed that three parameters, Bright, Fine, and $D_{\text{mean}}$ were negatively correlated with % White, which means that less mature and finer fibers increase the chance of forming neps in the textile processing, and in turn, white specks in the dyed fabrics. If both parameters were used to perform the linear regression, the correlation could be further improved to $R^2 = 0.864$, and a % White predication equation is given as follows:

![Figure 10](https://example.com/figure10.png)
However, we did not observe a high correlation between % White and \( D_{sd} \) from this data set. \( D_{sd} \) measures the variability of fiber widths, and should reflect the degree of fiber convolution, i.e. maturity. From many captured images (see Figure 11 for an example), we observed that dead fibers were just like flat ribbons that did not have twisted edges. Therefore, dead fibers may not yield high \( D_{sd} \) which compromises its correlation with % White. How to utilize the data of dead fibers is a worthwhile topic for further study.

**Conclusions**

This study was based on a subset of cotton samples with distinctly different fiber properties and nep levels. We explored the possibility of establishing predictive models for white speck contents of finished fabrics from the property measurements of the raw fibers, and identified the most promising factors for predicting white speck contents. The longitudinal measurements had better correlations with % White than the cross-sectional measurements. Dead fibers could be detected with a DS threshold, and the relevant
measurements, such as Bright, were modified to reflect dead fiber presence. When parameters Bright and Fine were used in the linear regression, the correlation coefficient ($R^2$) of the predicted % White and the measured % White was 0.864. Another advantage of the longitudinal FIAS test is that its sample preparation is considerably faster (a matter of seconds) than the cross-section fiber preparation, making it more useful for routine tests.

Acknowledgements

The research was partially supported by the National Research Initiative Competitive Grants Program of the United States Agriculture Department (Grant 2003-35504-12855), and Cotton Incorporated. We would like to thank Dr. Devron Thibodeaux, USDA Cotton Research Lab at Clemson, SC, for the cross-section data of the 16 cottons used in the study, and Ms. Mia Schexnayder for operating FIAS to collect the longitudinal data of the cottons.

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