GENETIC VARIATION IN FIBER QUALITY

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INTRODUCTION

Historical records suggest that cotton textile products have existed for over two and one-half millenia (Ramey, 1980). Improvement of cotton fiber quality to enhance its use as a textile fiber began as ancient peoples domesticated cotton, altering it from a wild, photoperiodic, short-staple, low yielding plant into one that produces more and longer lint and is adapted to extra-tropical latitudes (Fryxell, 1979). With the advent of nonsubjective fiber quality evaluations, knowledge of how fiber properties contribute to textile performance, and expressed needs by textile manufacturers for improved fiber quality, breeders began to emphasize fiber quality in their genetic improvement programs. Breeders are charged also with simultaneously improving lint yield and traits such as plant type and host-resistance to insects and pathogens. Applied breeders probably would generally not emphasize improvement of fiber quality ahead of lint yield in a list of priorities. The complexity of these issues is such, however, that this chapter will focus on the genetics of fiber quality for upland (*Gossypium hirsutum* L.) cotton. Consideration will be given also to the future as textile industry priorities for cotton fiber properties change to reflect the requirements of more efficient yarn spinning and fabric manufacturing technologies.

Before examining genetic variation for fiber quality, it is instructive to review the brief history of breeding cotton for improved fiber quality and how fiber properties became recognized

as important predictors of textile performance. From this brief history lesson, we learn the relationship between fiber quality and a healthy cotton industry.

Brief History of Efforts to Improve Cotton Fiber Quality

Cotton became an important crop in the United States in the mid-1700s (Ware, 1936). Quality of cotton fiber about this time was assessed by fiber length as longer-fibered types generally spun more efficiently and produced higher quality yarns on the spinning equipment of this era. Ware (1935) describes the names of U.S. grown cottons that were recognized by foreign buyers as representing different levels of fiber quality. So called "Benders" type cottons were grown along the bends of the Mississippi River and were recognized as having excellent fiber quality. The next lower level of fiber quality was associated with "Rivers" types produced along the Mississippi River tributaries. Finally, there were "Creeks" and "Uplands" with creeks denoting a lower level of quality than "Rivers" and the term "Upland" denoting short-staple types. Although there were few recorded organized breeding efforts at improving fiber quality around this time, there was some effort at selection for longer fibered cottons. Mass selection within existing varieties along with chance outcrosses directed these initial variety development efforts (Calhoun, Bowman, and May, 1994). Late maturity was associated with long-fibered cottons of the time and when the boll weevil (*Anthonomus grandis* Bohemen) invaded the U.S. Cotton Belt, these varieties were abandoned in favor of shorter staple, earlier maturing cultivars (Ware, 1936). As a breeder, this author wonders how many genes conferring fiber quality were lost, possibly forever, when the long-fibered types were discarded. It was not long before market demand decreased for fiber produced by the earlier maturing cottons as textile manufacturers recognized the lower fiber quality of these types. Subsequently, the United States Department of Agriculture

and some private breeders began to emphasize fiber quality in addition to earlier maturity of cultivars that could produce in the presence of the boll weevil (Ware, 1936).

Additional events occurred in the early 20th century that caused geneticists and breeders in the United States to consider fiber quality as important as yield, plant type, or disease resistance. The enactment of the U.S. Cotton Futures Act of 1914 set rules by which the quality of cotton would be determined (Brown, 1938). The use of these standards for the classing of cotton became mandatory in 1923 with passage of the U.S. Cotton Standards Act (Ramey, 1980). The terminology U.S. Cotton Standards was soon replaced with the terms Universal Cotton Standards to reflect the input from international textile groups (Brown, 1938). Cotton was classed based on staple length and grade, the latter consisting of color, preparation, and nonlint content (Lewis and Richmond, 1968). The preparation component of grade refers to a visual assessment of orientation of fiber in the sample (Hake et al., 1990). Cotton 'classers' assigned a grade to a bale of cotton based on visual comparison between a lint sample drawn from the bale and a standard comparison sample devised by the U.S. government through the Cotton Standards Act. Classers also could assign grades based on a mental image comparison with an official standard (Lewis and Richmond, 1968). Staple or fiber length was determined from parallelized fibers 'pulled' from the bale sample and called to the nearest 1/32 of an inch (Hake et al., 1990). Although still considered subjective measures of fiber quality, cotton classing was an improvement over assessing quality based on area of growth or species such as upland or Sea Island (Perkins, Ethridge, and Bragg, 1984). These subjective measures of fiber quality were all that were available until advances in mechanical fiber property measurement. The fact that all cotton sold was assigned a grade and staple, elevated the status of fiber quality as an important breeding objective.

Mechanization in the textile industry was another vehicle by which the fiber properties of a cotton variety became to be recognized as important as its yield potential. Yarn spinners banded together in the mid-1920s to demand cotton with longer staple due to its superior performance relative to that from short-staple varieties (Brown, 1938). International demand for U.S. cotton declined in the early 1930s as other countries made concerted efforts to improve the staple length of their cotton varieties (Ware, 1936). These factors also contributed to the emphasis of fiber quality in U.S. cotton breeding programs.

Early cotton breeding efforts at improving fiber quality were not just limited to the United States. International demand for cotton with improved fiber quality was spurred by development in the 19th or early 20th century of a mechanized spinning industry that replaced hand spinning. The then new spinning technology could not efficiently manufacture yarn with short-staple cottons that typically had staple lengths of less than 25 mm. Culture of cotton in Russia, Brazil, Peru, and Argentina was expanded due to shortages caused by the decline in United States production during its Civil War. This emphasis on cotton production was a stimulus for variety development and also varieties with improved fiber quality. A common theme among international breeding efforts was the introduction of American upland germplasm and almost complete abandonment of shorter staple Asiatic species (Ware, 1936).

Prior to the development of the United States cotton industry, India was the world leader in cotton production (Ware, 1936). India is likely the original place where cotton was used in textile products (Percival and Kohel, 1990). As in the United States, organized cotton breeding did not begin until the early 1900s. Publication of Mendel's work and the replacement of hand spinning methods with machine technology spurred efforts to improve the fiber quality of Indian cotton varieties. India had historically grown the diploid cotton species, *G. arboreum* L. and *G.*

herbaceum L., with staple length of around 13 mm or less rather than upland types. To improve the fiber quality of Indian cotton, upland and Sea Island (*G. barbadense*) cottons were introduced. Also organized selection for longer staple within *G. herbaceum* resulted in several cotton varieties with sufficient fiber quality to meet mill needs. Organized breeding efforts with the introduced upland types in the cotton producing provinces of India, such as the Punjab area, resulted in varieties with improved fiber quality.

Similar to the situation in India, Chinese cotton production initially relied on short-staple Asiatic cotton species (Ware, 1936). Not until a modern textile industry developed in the 1890s was there recognition that cotton with better fiber properties was needed. Initially this need was met by importing cotton from the United States and India. During the 1920s, breeding efforts were initiated at the University of Nanking. Seed of American cottons was provided by the United States Department of Agriculture with which breeding efforts commenced. In the early 1920s, these efforts produced the cultivar 'Million Dollar' with a level of fiber quality such that textile mills paid a premium for its fiber.

Russian efforts to improve cotton fiber quality coincided with development of a mechanized textile industry in the late 1800s. Introduction of American uplands replaced the short-staple Asiatic types, thereby improving the textile performance of the Russian cotton. Breeders and agronomists were hired, and emphasis was placed in part on improvement of fiber quality. Ultimately, from an initial germplasm base comprised primarily of the American uplands of the mid- to late-1800s era, Russian breeders developed their own locally adapted varieties (Ware, 1936).

Similar events in Brazil, Peru, Argentina, Korea, and Sudan led to efforts to breed cottons with improved fiber quality.

Modern research into cotton fiber quality

Improvement of cotton fiber quality accelerated after advances in several areas of science occurred in the early 1900s. First of all, the specific fiber properties that define quality had to be understood through studies relating raw fiber properties to textile performance (Moore, 1938). Concurrently, technological advances in instrumentation to accurately measure fiber properties such as length, strength, and fineness were made. The speed and accuracy of these instruments in measuring fiber properties allowed breeders to study the genetics of quality parameters. A brief synopsis of several key events is provided below.

Although the instrumentation was crude by modern standards, Balls (1928) was one of the first researchers to measure fiber physical properties to facilitate breeding cottons that would benefit the textile industry. In the United States, fiber technology research progressed in the late 1920s with the opening at Clemson College, Clemson, SC, of a fiber and spinning laboratory by the Bureau of Agricultural Economics in cooperation with the Bureau of Plant Industry. It was recognized at the time that more precise measurement of raw fiber properties than that provided by cotton classers would benefit yarn spinners and ultimately breeders in improving fiber quality (Willis, 1926). Soon after, a laboratory with similar function was created in Washington, DC, by the Department of Agriculture (Lewis and Richmond, 1968; Lee, 1984). At the same time, H.W. Barre, head of the Cotton Division, Bureau of Plant Industry, recognized the importance of synergy between cotton breeders and the developing fiber technology. He fostered cooperative ties with R.W. Webb, head of the fiber and spinning laboratory, in bringing fiber technology to cotton breeding. Under the leadership of Webb, investigations to determine the importance to spinning of fiber length, strength, fineness, and maturity were begun.

Fiber length was initially assessed by measuring the length of fiber samples from ginned lint or by combing fibers on seeds (Brown, 1938; Harrison, 1939). Fiber length uniformity was similarly measured in a painstaking process of manually collecting lint into classes representing 32nd's of an inch categories and then weighing to determine relative fiber length uniformity. An early instrument method of assessing fiber length uniformity was the Suter-Webb sorter (Brown, 1938) that remains in use today. While potentially useful to the cotton technologist, this method was too labor intensive to be applied to breeding for improved fiber length uniformity. Another device that allowed fiber length uniformity to be assessed with seedcotton was reported by McNamara and Stutts (1935). This instrument, while not requiring ginned lint, similarly operated by successively combing and removing by hand fibers of decreasing length. Apparently the labor required in the process kept this instrument from being used to any extent in efforts to reduce fiber length variability through breeding.

Fiber strength was measured first by hand breaking small tufts of fibers until spinners recognized that these breaking measurements often had little relationship with yarn strength (Brown, 1938). Early machine testers of fiber strength included the Dewey single fiber method (Dewey, 1913) and the Chandler bundle strength tester (Brown, 1938). While these instruments provided nonsubjective measurements of fiber strength and were in this manner an improvement over hand breaking tests, they still were slow and not readily available to cotton breeders.

By the mid- to late-1930s, fiber technology research had progressed with the development of instruments providing raw fiber properties useful to spinners, cotton technologists, and breeders. The fibrograph, an instrument that rapidly measures fiber length by photoelectric sensor, was developed (Hertel and Zervigon, 1936; Hertel, 1940). Fiber length uniformity could be calculated from fibrograph measurements without resorting to the tedious process of sorting

and weighing fibers into length groups. A more rapid measure of fiber strength was available with the Pressley tester (Pressley, 1942). The Arealometer was developed and provided estimates of fiber surface area measured at two air pressures from which fiber perimeter and wall thickness could be calculated (Hertel and Craven, 1951). Fiber measurements from the fibrograph, Pressley, and the Arealometer were shown to relate to yarn strength (Barker and Pope, 1948; Landstreet, 1954). The Stelometer (Hertel, 1953), an instrument that gives both fiber bundle strength and fiber elongation, provided another tool for breeders to evaluate their experimental cottons. The relative speed of measurement of these instruments accelerated breeding efforts at improving cotton fiber quality.

GENETIC VARIATION IN FIBER QUALITY

Genetic variation must exist for selection to be effective. Fortunately, sources of genetic variation for fiber quality exist within and among the cultivated species of cotton. Within upland cotton, genetic variability for fiber quality exists among cultivars (USDA, 1995), germplasm lines (Anonymous, 1974; Green, 1950), and in primitive germplasm converted to non-photoperiodic flowering habit (McCarty and Jenkins, 1992; McCarty et al., 1996). The range of fiber properties available in several germplasm collections is extensive (Green, 1950; Anonymous, 1974). Breeders have access to a wealth of germplasm from the United States National Cotton Germplasm Collection, maintained by the Department of Agriculture, Agricultural Research Service, College Station, TX, containing over 5100 seed samples of *Gossypium* spp. (Percival and Kohel, 1990). A general categorization of *Gossypium* spp. with respect to fiber type would be the relatively short length and coarse diploid Asiatic species, upland, with intermediate levels of length and fineness, followed by Egyptian, Pima, and Sea Island with generally fine, long, and strong fiber (Ramey, 1980). The primary gene pool or that most readily available to upland

breeders includes the tetraploid species *G. hirsutum* L. (upland) and *G. barbadense* L. (Pima, Egyptian, and Sea Island)(Stewart, 1988). We can include the Asiatic diploid species *G. herbaceum* and *G. arboreum* if more complicated crossing schemes are considered (Fryxell, 1984). We should note, however, that attempts at stable introgression of genes from a non-upland source into a *G. hirsutum* background are not without difficulty, which could limit the primary gene pool for upland improvement (Stephens, 1949; McKenzie, 1970). Although the genus *Gossypium* is comprised of a number of species (Stewart, 1988), those producing useable fiber would seem most appropriate for consideration as a germplasm source for a breeder interested in improving fiber quality. Because *G. hirsutum* is the most widely grown species of cotton, we will concentrate on this species.

An understanding of those fiber quality traits that contribute to textile performance is a prerequisite for setting priorities in a breeding program. This chapter will examine genetic control of the common fiber properties consisting of fiber length measures, strength, elongation, and fineness plus short fiber content and properties measured by the Advanced Fiber Information System (Behery, 1993). There exist other properties such as dust content (Deussen, 1992) that also define fiber quality, however, space limitations prevent their consideration in this chapter. Genetic vs. non-genetic influences, type of gene action, heritability, and where available, selection response are presented. To simplify tables, data (variances, mean squares) have been rounded from the authors' original values or expressed as ratios where appropriate. The final discussion is whether new yarn manufacturing systems will require breeders to emphasize different fiber properties than those known to benefit ring spinning systems.

Measures of Fiber Length

Since the development of mechanical spinning frames in the 1700s, fiber length has been recognized as a contributor to yarn strength and processing performance (Brown, 1938; Perkins, Ethridge, and Bragg, 1984). As we have seen, fiber length was the initial property used to assess cotton quality and its suitability for certain end-uses. Knowledge of fiber length is critical to manufacture a yarn of specific size on ring spinning systems (Rusca and Reaves, 1968). With respect to processing, certain measures of fiber length are used to set the distance between rolls in the drafting procedure during yarn manufacture (Ducket, 1974; Behery, 1993). As for yarn strength, the effect of fiber length on the maximum strength of yarns spun with optimum twist according to Landstreet (1954) is secondary. Holding other fiber properties constant, longer fiber requires less twist to produce maximum yarn strength. In contrast, relatively short-staple cotton has reduced holding surface compared with longer staples and requires increased twist to produce maximum yarn strength. Increasing twist beyond this optimum reduces fiber strength, which then causes loss in yarn strength. Longer fiber length is desirable for the production of fine yarns and low twist yarns such as knitting yarns (Landstreet, 1954). Longer fiber requires less twist in the roving process of cotton destined to be ring spun. The minimum twist insertion necessary to produce roving from sliver is desirable to control yarn manufacturing costs (Perkins, Ethridge, and Bragg, 1984).

Fiber length is measured by classers staple, reviewed earlier, and instrument estimates by the fibrograph, high volume instrument (HVI), or the new Advanced Fiber Information System (AFIS) (Behery, 1993). These measures include upper half mean (mean length of the longer 50% of the fiber by weight as tested by the HVI), 2.5% and 50% span lengths (respectively, distance spanned by the indicated percentage of the fibers in the beard tested on a fibrograph), and upper

quartile length (length at which 25% of the fiber by weight is longer when measured with Suter-Webb array)(Behery, 1993). That there is a strong genetic basis for fiber length despite various methods of measurement is evident from the data in Table 1. These data were derived from a broad array of studies conducted across the United States Cotton Belt that included breeding populations and cultivar evaluations. Whether assessed by classers staple, Suter-Webb array, or fibrograph (upper half mean or span length), where genetic differences exist, the magnitude of genetic variance generally is greater than that of non-genetic influences. In a few instances, genotype x location, year, or higher order interactions are noted, yet they are small in magnitude when compared with genetic variation. These findings indicate that extensive environmental replication is not necessary to evaluate and select breeding material on the basis of fiber length parameters. Note also that experimental error (see references E, F, J, and K - Table 1) was of similar or greater magnitude than genotypic variance in some studies. However, these non-genetic influences apparently are not related to effects of years or locations and ultimately should not preclude the identification of genotypes with desired fiber length. Most studies where genetic variation for measures of fiber length has been broken down into components report additive variance to be more important than non-additive types of genetic variance (Table 2). Meredith and Bridge (1972) report one instance where the expression of additive effects governing 2.5% and 50% span lengths varied over locations (data not shown). In their combined analysis over locations, dominance main effects were greater than additive main effects, but the additive x location and dominance x location interactions indicated that additive effects were more important than dominance effects in specific locations. Remaining studies that report additive and non-additive genetic variance or effects over environments support data in Table 1 that environmental influences on length parameters are not of a magnitude that should hinder breeding efforts.

Table 1. Genetic and environmental influences on various measures of fiber length.

Reference	Genotype	Genotype x Location	Genotype x Year	Genotype x Location x Year	Residual
A	350	-	5	-	-
B	9	2	<1	2	1
C	0.6	<.01	<.01	<.01	<.01
D	1	<.01	-	-	<.01
E	0.001	0!	0	<.001	0.001
F	5	0!	.06	1	5
G	16	<.1	<.1	0.4	0.8
H	61	8	<1	15	32
I	5	<1	<1	1	5
J	0.9	0.05	0.05	0.2	1
K	0.6	0.02	0.04	0!	0.9
L	315	4	-	-	<1
M	0.5	0.03	-	-	-
N	24	8	-	-	16

! Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

A. Classers staple length, 24 genotypes, four years, one location, analysis of variance F values. Neely (1940).

B. Upper half mean length, four cultivars, three locations, two years, mean squares. Hancock (1944).

C. Upper quartile length, 16 cultivars, seven locations, three years, mean squares. Pearson (1944).

(Table 1 continued)

D. Upper quartile length, 16 cultivars, nine locations, one year, mean squares. Pope and Ware (1945).

E. Upper half mean length, 95 $F_{2:4}$ or $F_{2:5}$ lines, two locations, two years, variance components. Miller et al. (1958).

F. Upper half mean length, 15 cultivars, nine locations, three years, variance components ($\times 10^{-4}$). Miller, Robinson, and Williams (1959).

G. Classers staple length, 16 cultivars, 11 locations, three years, variance components. Miller, Robinson, and Pope (1962).

H. Upper half mean length, four cultivars, 101 location x year combinations, variance components. Abouh-El-Fittouh, Rawlings, and Miller (1969).

I. 2.5% span length, eight cultivars, three locations, three years, variance components ($\times 10^{-4}$). Bridge, Meredith, and Chism (1969).

J. Upper half mean length, three cultivars, 28 locations, three years, ratio of indicated source to error variance. El-Sourady, Worley, and Stith (1969).

K. 2.5% span length, 62 BC_2F_4 lines, two locations, two years, variance components. Murray and Verhalen (1969).

L. 2.5% span length, four cultivars, four environments (year x soil type combinations), mean squares. Meredith and Bridge (1973).

M. 2.5% span length, 89 early-generation families evaluated in three environments (year x location combinations), variance components. Scholl and Miller (1976).

(Table 1 continued)

N. 2.5% span length, 18 genotypes including advanced breeding lines and cultivars, seven locations, variance components expressed as percent of total variance. Meredith, Sasser, and Rayburn (1996).

Table 2. Additive and non-additive genetic and environmental influences on fiber length.

Reference	Additive	Additive x Loc	Additive x Yr	Additive x Loc x Yr	Non-additive	Non-additive x Loc	Non-additive x Yr	Non-additive x Loc x Yr	Residual
A	48	-	-	-	-	-	-	-	-
B	2	-	-	-	-	-	-	-	-
C	2	-	-	-	0	-	-	-	-
D	5	-	-	-	<1	-	-	-	-
E	670	3	10	0	10	0!	30	0!	1640
F	0.006	-	-	-	<.01	-	-	-	<.01
G	11	-	-	-	-	-	-	-	-
H	0.6	-	-	-	-	-	-	-	-
I	2	-	-	-	-	-	-	-	-
J	1	-	-	-	-	-	-	-	-
K	4	0.5	-	-	3	1	-	-	1
L	9	0.5	-	-	1	0.3	-	-	0.3
M	0.05	0.02	-	-	4	-	-	-	-

! Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

(Table 2 continued)

A. Upper half mean length. Ratio of general combining ability to specific combining ability mean squares calculated from data in Barnes and Staten (1961).

B. Upper half mean length. Ratio of general combining ability to specific combining ability mean squares calculated from data in Barnes and Staten (1961).

C. Upper half mean length. General and specific combining ability variances (x 10^{-3}). Miller and Marani (1963).

D. Upper half mean length. Additive and dominance genetic variances (x 10^{-4}). Ramey and Miller (1966).

E. Upper half mean length. Additive and dominance genetic variances rounded. Lee, Miller, and Rawlings (1967).

F. 2.5% span length. Additive and non-additive genetic and environmental variances. Al-Rawi and Kohel (1970).

G. 2.5% span length. Ratio of general and specific combining ability mean squares averaged from the F_2 and F_3 generation of diallel progenies. Meredith and Bridge (1973).

H, I. 2.5% span length. Ratio of additive to non-additive genetic variance within High-Plains and Acala germplasm, respectively. Quisenberry (1975).

J. 2.5% span length. Ratio of additive genetic variance to total genetic variance. Wilson and Wilson (1975).

K. 2.5% span length. General and specific combining ability mean squares. Green and Culp (1990).

L. 2.5% span length. General and specific combining ability mean squares. Tang et al. (1993).

(Table 2 continued)

M. 2.5% span length. Additive, additive x additive, and dominance genetic variances (x 10^{-3}). May and Green (1994).

Quisenberry (1975), and May and Green (1994) found non-additive genetic variance was larger than additive variance for fiber length (Table 2). Within the Pee Dee germplasm, the finding of low additive genetic variance could reflect its exhaustion from over 40 years of breeding for improved fiber properties.

Heterosis, whether expressed as deviations from the mid or extreme parent, is another means by which genetic control of fiber length can be inferred (Table 3). These data indicate that extreme parent heterosis for fiber length can occur in cotton, but generally the magnitude of the transgressive expression is small. Miller and Lee (1965) reached similar conclusions. Thus, despite a few examples of dominant gene action for fiber length, the majority of the data are consistent with mainly additive genetic control of fiber length. A sample of heritability estimates for fiber length measures from a divergent sample of cotton populations and various selection units suggests that selection for various length parameters should be effective (Table 4). Designed experiments to measure response of length parameters to selection report responses of a magnitude typical for a quantitatively inherited trait (Table 5).

There exists an upper limit to the need to increase length of medium staple (about 25-30 mm) cottons to enhance their spinning performance, particularly for open-end rotor spinning systems (Deussen, 1992). Consequently, the textile industry would benefit more by concentrating breeding efforts on other quality factors related to fiber length distribution, specifically on improving length uniformity and reducing short fiber content. By its nature, fibers in a sample of

Table 3. Heterosis for fiber length expressed as number of hybrids or average millimeters by which the hybrids exceeded midparent or parental values.

Reference	No. hybrids > longest parent	No. hybrids < shortest parent	Avg. hybrid deviation from midparent	Avg. hybrid deviation from extreme parent
A	2	0	-	-
B	2	1	-	-
C	-	-	+1.0	-
D	5	-	-	+0.9
E	5	-	-	+1.5
F	-	-	+0.3	-
G	-	-	+0.8	-
H	-	-	-	+1.5
I	1	-	-	+1.0

A. Twenty-two F_1 hybrids from crossing Acala 1517C or Acala 1517D with 11 other *G. hirsutum* cottons representing Acala, Mississippi Delta, and southeastern U.S. germplasm. Upper half mean (UHM). Barnes and Staten (1961).

B. Twenty-one F_1 hybrids from half-diallel among seven Acala germplasms. UHM length. Barnes and Staten (1961).

C. Twenty-two F_1 hybrids from crosses between two medium staple uplands and 11 long and extra-long staple uplands. UHM length. Harrell (1961).

D. Seven F_1 hybrids between seven uplands and one Acala. UHM length. Pate and Duncan (1961).

E. Ten F_1 hybrids among upland and wild upland. UHM length. White and Richmond (1963).

(Table 3 continued)

F,G. Four F_1 intra-specific hybrids, respectively, from crosses within *G. hirsutum* and *G. barbadense* cultivar groups. UHM length. Marani (1968a).

H. Nine inter-specific F_1 between *G. hirsutum* and *G. barbadense* cultivars. UHM length. Marani (1968b).

I. Three F_1 hybrids from upland crosses. 2.5% span length. Meredith, Bridge, and Chism (1970).

Table 4. Heritability estimates for fiber length measurements.

Reference		Reference	
A	0.79	I	0.56
B	0.88	J	1.0
C	0.39	K	0.91
D	0.49	L	0.67
E	0.10	M	0.48
F	0.31	N	0.77
G	0.85	O	0.54
H	0.55		

A. Upper half mean (UHM), F_3 line selection unit, broad-sense. Al-Jibouri, Miller, and Robinson (1958).

B. UHM, F_4 line selection unit, broad-sense. Miller et al. (1958).

C. UHM, F_2 plant selection unit, narrow-sense. Lewis (1957).

D. 2.5% span length, F_1 entry mean selection unit, narrow-sense. Verhalen and Murray (1967).

E. 2.5% span length, F_2 plant selection unit, narrow-sense. Murray and Verhalen (1969).

(Table 4 continued)

F. 2.5% span length, F_2 plant selection unit, narrow-sense. Murray and Verhalen (1969).

G. 2.5% span length, BC_2F_4 line selection unit, broad-sense. Murray and Verhalen (1969).

H. 2.5% span length, F_1 entry mean selection unit, narrow-sense. Verhalen and Murray (1969).

I. 2.5% span length, F_1 entry mean selection unit, narrow-sense. Al-Rawi and Kohel (1970).

J. 2.5% span length, F_1 entry mean selection unit, narrow-sense. Wilson and Wilson (1975).

K. 2.5% span length, F_3 progeny mean selection unit, broad-sense. Scholl and Miller (1976).

L. 2.5% span length, F_6 line mean selection unit, narrow-sense. Keim and Quisenberry (1983).

M. 2.5% span length, F_2 plant selection unit, narrow-sense. May and Green (1994).

N. 2.5% span length, F_2 population bulk selection unit, broad-sense. May and Green (1994).

O. 2.5% span length, F_3 line selection unit, broad-sense. May and Green (1994).

Table 5. Summary of selection experiments toward fiber length modification.

Reference	Response of fiber length measure (mm)	
A	+2.3	
B	+1.0	-0.8
C	+2.5	
D	+1.5	

A. Ten years of mass selection for increased upper half mean length with forced self-pollination within four originally open-pollinated cultivars. Mean response of three cultivars exhibiting response to selection. Simpson and Duncan (1953).

B. Single cycle of divergent mass selection for 2.5% span length. Murray and Verhalen (1969).

(Table 5 continued)

C. Three cycles of divergent selection for combination of 2.5% span length and micronaire. Mean difference between 2.5% span length groups presented. Quisenberry, Ray, and Jones (1975).

D. Single cycle of divergent mass selection within a cultivar. Average response from two methods of selection and two selection intensities. Verhalen, Baker, and McNew (1975).

cotton are not all of the same length, varying even on the same seed (Richmond and Fulton, 1936). High length uniformity and low short fiber content are desired by textile manufacturers as these traits are associated with reduced manufacturing waste, neps, and ends-down during yarn production along with improved yarn appearance and strength (Behery, 1993). Two measures of length uniformity are commonly defined. Length uniformity index (LUI) is the ratio of the mean length and the upper half mean length, while length uniformity ratio (UR) is the ratio of two span lengths, 50%/2.5% span length (Behery, 1993). Deussen (1992) indicates that for ring-spinning, fiber length uniformity is an important determinant of yarn quality and spinning performance.

Less attention has been paid to fiber length uniformity than to the genetics of fiber length as indicated by comparing the volume of data between Tables 1-5 and Table 6. Variation for fiber length uniformity exists and, in part, it is attributable to genetic variation (Table 6). Environmental influences on fiber length uniformity are present but are not of a magnitude to preclude separation of genetic differences (Meredith et al., 1991; Meredith, Sasser, and Rayburn, 1996). Genetic variance for fiber length uniformity seems to be mostly of the fixable types for a self-pollinated crop, and there exists reasonable heritability estimates. Hence, further improvement of fiber length uniformity seems possible and should receive additional attention in

Table 6. Pertinent data describing the genetic control of fiber length uniformity.

Reference	Genotype	Genotype x Environment	Residual
A	20	2	
B	3	1	15
	GCA/SCA		
C	5		
D	0.5		
E	1.2		
F	Add.	Dom.	A x A
	1.6	0	0.4
G	F_2 plant	F_2 bulk	F_3 row
	0.4	0.6	0.2

A. ANOVA F values (rounded to nearest whole number) of length uniformity index (LUI) from evaluation of 19 cultivars and advanced breeding lines in two states in the USA. Meredith et al. (1991).

B. Percentage (rounded to whole numbers) of total variance of LUI accounted for by the indicated source of variation from the evaluation of 18 genotypes at seven locations in the upland Cotton Belt of the USA. Meredith, Sasser, and Rayburn (1996).

C. Ratio of GCA to SCA mean squares for LUI from a cross-classified mating design. Barnes and Staten (1961).

D. Average ratio of variances of additive to non-additive effects for LUI averaged over seven parents crossed in a half-diallel. Barnes and Staten (1961).

E. Ratio of GCA to SCA mean squares for length uniformity ratio (UR) derived from a five-parent half-diallel. Green and Culp (1990).

(Table 6 continued)

F. Additive, dominance, and additive x additive genetic variance (x 10^{-4}) for UR resolved from the F_2 and F_3 generations of a 4 x 4 design II mating. May and Green (1994).

G. Standard unit heritability (Frey and Horner, 1957) estimates for UR. May and Green (1994).

breeding programs. However, it is probably not realistic that all fiber length variation will be alleviated through breeding.

Short fiber content (SFC) is defined as the percentage of fibers by weight with length less than 12.7 mm (Behery, 1993). Sources of short fibers include those inherent to the genotype and its reaction to the environment, and those introduced by mechanical handling of the cotton. Breeders have relied mainly on indirect indicators of SFC, the LUI and UR, as direct measurements by Suter-Webb array are too slow. However, Behery (1993) and Meredith, Sasser, and Rayburn (1996) suggest that LUI and UR might not be acceptable measures of SFC. For more information on the limitations of estimating SFC from UR or LUI data see Bargeron (1990) and Woo and Suh (1994). A relatively new instrument, the AFIS provides a direct and relatively rapid measurement of SFC (Behery, 1993; Bragg and Shofner, 1993). The genetic control of SFC has not been extensively investigated because a suitably rapid measurement needed for breeding work was not available until the development of the AFIS. Behery (1993) suggests that the genotype causes short fibers only indirectly and that most are the result of fiber breakage related to fiber strength. Meredith, Sasser, and Rayburn (1996) report a correlation between fiber strength and AFIS SFC of only -0.02, suggesting that genetic factors other than those imparting fiber strength may be involved in causing SFC. Another reason why the correlation between fiber strength and SFC was low in this study could be related to how the cotton was processed. These

data were derived from the High Quality Regional Cotton Variety Test (USDA, 1995) where fiber samples are not ginned on commercial gins nor processed through one or more lint cleaners. Thus, as Meredith, Sasser, and Rayburn (1996) point out, this fiber may not be similar to that derived from commercial ginning with respect to the degree of stress and associated fiber breakage from commercial processing. As a result, the effect of fiber strength on SFC may not have been realized and may partially explain their low correlation. Genotypic differences in SFC have been reported (Williford, Meredith, and Griffin, 1984; Meredith, Sasser, and Rayburn, 1996), and the genotypic component of SFC as measured by AFIS is greater than the genotype x environment variation (Meredith, Sasser, and Rayburn, 1996). Now that a reliable and relatively quick method of assessing SFC from the AFIS is available, it should be possible to further investigate the genetic basis of SFC and the degree to which it has a separate genetic basis than that of fiber strength.

Measures of Fiber Strength

Fiber strength or tenacity is perhaps the most important fiber property other then length contributing to cotton's use as a textile fiber. Thus, its inheritance and efforts at improvement have been the subject of extensive study. Fiber strength translates almost directly into yarn strength (Landstreet, 1954; Meredith et al., 1991; Deussen, 1992) and is related to spinnability, defined as ends-down during yarn manufacture (Deussen, 1992). In woven and knit fabric manufacture, it affects production speed (Perkins, Ethridge, and Bragg, 1984) and is essential to maintenance of cotton's natural qualities after chemical processing of fabric (Rowland et al. 1976). Among the common fiber properties, fiber strength ranks first in order of precedence in rotor spinning systems (Deussen, 1992) and it contributes to fiber durability from mechanical stresses in the harvest, ginning, and yarn manufacturing processes (Perkins, Ethridge, and Bragg,

1984; Deussen, 1992). Fiber strength is more important to open-end spinning because of the different yarn structure of an open-end vs. ring spun yarn (Konishi, 1975). Although fiber strength can be measured on single fibers (Sasser, 1992), it is most commonly measured on a bundle of fibers by Pressley (Pressley, 1942), Stelometer (Hertel, 1953), or HVI instruments (Taylor, 1982).

Data in Table 7 indicate that fiber strength is very much a genetic property and that genotype x environment interactions are small relative to genetic influences. Similar to the data for fiber length, additive gene action predominates for fiber strength (Table 8) with usually small and not generally meaningful amounts of heterosis (Table 9). Additionally, heritability is generally high for selection units ranging from single plants to population bulks (Table 10). Recurrent and mass selection has resulted in positive gains in strength (Table 11). Other examples of strength improvement through plant selection have been documented by Singh et al. (1990, 1991). Estimates of gene number influencing fiber strength range from five (Self and Henderson, 1954) to as many as 14 (Tipton et al., 1964a), typical for a quantitatively inherited trait. We should note that studies reporting the number of loci influencing strength do not account for the possible bias of duplicate loci, as upland cotton is an allotetraploid (Endrizzi, Turcotte, and Kohel, 1984). Abdel-Nabi, Jones, and Tipton (1965) reported finding only a single transgressive segregate out of 1731 F_3 plants from a strong-fibered Acala x weak-fibered upland cross, suggesting that the parents differed for many genes affecting fiber strength. However, other data suggest fiber strength may not always segregate in a quantitative manner. Richmond (1951) indicated that recovery of high strength segregates from small backcross populations during introgression of

Table 7. Genetic and environmental influences on various measures of fiber strength.

Reference	Genotype	Genotype x Location	Genotype x Year	Genotype x Location x Year	Residual
A	2.3	<.1	<.1	<.1	<.1
B	1870	30			7
C	0.06	0[!]	<.01	0	0.09
D	29	0[i]	<.1	5	14
E	0.05	<.01	<.01	<.01	<.01
F	0.2	0[i]	0[i]	0.1	0.4
G	0.5	0[i]	0.1	0.3	1.0
H	0.2	<0.01	0.06	<0.01	1.7
I	58	<1			<1
J	44	0[i]			

[i] Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

A. Pressley strength, four cultivars, three locations, two years, mean squares. Hancock (1944).

B. Chandler strength, 16 cultivars, 10 locations, mean squares. Pope and Ware (1945).

C. Pressley strength, 92 $F_{2:4}$ or $F_{2:5}$ lines, two locations, two years, variance components. Miller et al. (1958).

D. Pressley strength, 15 cultivars, nine locations, three years, variance components. Miller, Robinson, and Williams (1959).

E. Stelometer strength, four cultivars, 101 location x year combinations, variance components. Abouh-El-Fittouh, Rawlings, and Miller (1969).

F. Stelometer strength, eight cultivars, three locations, three years, variance components. Bridge, Meredith, and Chism (1969).

(Table 7 continued)

G. Stelometer strength, three cultivars, 28 locations, three years, ratio of indicated source to error variance. El-Sourady, Worley, and Stith (1969).

H. Stelometer strength, 62 BC_2F_4 lines, two locations, two years, variance components. Murray and Verhalen (1969).

I. Stelometer strength, four cultivars, four environments (year x soil type combinations), mean squares. Meredith and Bridge (1973).

J. Stelometer strength, 89 early-generation families evaluated in three environments (year x location combinations), variance components. Scholl and Miller (1976).

strength from the triple hybrid (*G. thurberi x G. arboreum x G. hirsutum*) (Beasley, 1940) was evidence for only a few major genes controlling strength. Meredith (1977) came to a similar conclusion after several cycles of backcross breeding to improve fiber strength. Meredith (1992) reported the superior fiber strength of his cultivar MD51ne was conditioned by as few as two major genes, with the high strength being derived from the germplasm line FTA 263 (Culp and Harrell, 1980). The high fiber strength of FTA 263 results from a germplasm pool that includes Acala (AHA 6-1-4) and *G. barbadense* types but is primarily thought to derive from introgression from triple hybrid origin (Culp, 1992). Some indirect evidence also suggests that fiber strength can be conditioned by only a few major genes. May et al. (1994) released F_4 germplasm combining brown lint color and relatively high fiber strength. In that material, the highest fiber strength is associated with plants heterozygous for lint color, where lint color is expressed in an incompletely dominant manner to produce a light-brown phenotype in the F_1 Upon selfing of light-brown types, the progeny segregates into parental dark-brown and weak-fiber types, light-

Table 8. Additive and non-additive genetic and environmental influences on fiber strength.

Reference	Additive	Additive x Loc	Additive x Yr	Additive x Loc x Yr	Non-additive	Non-additive x Loc	Non-additive x Yr	Non-additive x Loc x Yr	Residual
A	20	-	-	-	-	-	-	-	
B	4	-	-	-	3	-	-	-	
C	0.03	-	-	-	<0.01	-	-	-	
D	680	<10	<10	0[!]	0[!]	<10	<10	17	116
E	0.1	-	<0.01	-	-	-	-	-	<0.01
F	24	-	-	-	16	-	-	-	5
G	29	-	-	-	-	-	-	-	
H	4	-	-	-	-	-	-	-	
I	3	-	-	-	-	-	-	-	
J	0.73	-	-	-	-	-	-	-	
K	42	14	-	-	5	24	-	-	9
L	2900	141	-	-	200	90	-	-	70
M	0.05	-	-	-	2	-	-	-	

[!] Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

A. Stelometer strength. Ratio of general combining ability to specific combining ability mean squares calculated from data in Barnes and Staten (1961).

B. Stelometer strength. General and specific combining ability variances (x 10^{-3}). Miller and Marani (1963).

C. Stelometer strength. Additive and dominance genetic variances. Ramey and Miller (1966).

(Table 8 continued)

D. Stelometer strength. Additive and dominance genetic variances. Lee, Miller, and Rawlings (1967).

E. Stelometer strength. Mean squares of the additive component of genetic variation. Verhalen and Murray (1969).

F. Stelometer strength. Additive and non-additive genetic and environmental variances. Al-Rawi and Kohel (1970).

G. Stelometer strength. Ratio of general and specific combining ability mean squares averaged from the F_2 and F_3 generation of diallel progenies. Meredith and Bridge (1973).

H, I. Stelometer strength. Ratio of additive to non-additive genetic variance within High-Plains and Acala germplasm, respectively. Quisenberry (1975).

J. Stelometer strength. Ratio of additive genetic variance to total genetic variance. Wilson and Wilson (1975).

K. Stelometer strength. General and specific combining ability mean squares. Green and Culp (1990).

L. Stelometer strength. General and specific combining ability mean squares. Tang et al. (1993).

M. Stelometer strength. Additive and dominance genetic variances. May and Green (1994).

Table 9. Heterosis for fiber strength expressed as number of hybrids or average g/tex by which the hybrids exceeded parental or midparent values.

Reference	No. hybrids > strongest parent	No. hybrids < weakest parent	Avg. hybrid deviation from midparent	Avg. hybrid deviation from extreme parent
A	1	0		
B	4	7		
C	4			0.4
D			0.1	
E			0.9	
F			3.4	
G	0	0		0

A. Twenty-two F_1 hybrids from crossing Acala 1517C or Acala 1517D with 11 other *G. hirsutum* cottons representing Acala, Mississippi Delta, and southeastern U.S. germplasm. Stelometer strength. Barnes and Staten (1961).

B. Twenty-one F_1 hybrids from half-diallel among seven Acala germplasms. Stelometer strength. Barnes and Staten (1961).

C. Seven F_1 hybrids between seven uplands and one Acala. Stelometer strength. Pate and Duncan (1961).

D,E. Four F_1 intra-specific hybrids, respectively, from crosses within *G. hirsutum* and *G. barbadense* cultivar groups. Pressley strength converted to Stelometer units. Marani (1968a).

F. Nine inter-specific F_1 between *G. hirsutum* and *G. barbadense* cultivars. Pressley strength converted to Stelometer units. Marani (1968b).

(Table 9 continued)

G. Three F_1 hybrids from upland crosses. Stelometer strength. Meredith, Bridge, and Chism (1970).

Table 10. Heritability estimates for fiber strength.

Reference		Reference	
A	0.76	J	0.10
B	0.56	K	0.60
C	0.90	L	0.86
D	0.84	M	0.49
E	0.75	N	0.27
F	0.72	O	0.86
G	0.59	P	0.27
H	0.67	Q	0.64
I	0.56	R	0.15

A. Pressley strength, F_2 plant selection unit, narrow-sense. Self and Henderson (1954).

B. Pressley strength, F_2 plant selection unit, narrow-sense. Lewis (1957).

C. Stelometer strength, F_3 line selection unit, broad-sense. Al-Jibouri, Miller, and Robinson (1958).

D. Pressley strength, F_4 line selection unit, broad-sense, mean heritability for two populations calculated from data in Miller et al. (1958).

E. Pressley strength, F_2 plant selection unit, narrow-sense. Worley (1958).

F. Stelometer strength, F_2 plant selection unit, narrow-sense, mean heritability from two populations. Tipton et al. (1964a).

(Table 10 continued)

G. Stelometer strength, F_2 plant selection unit, narrow-sense. Abdel-Nabi, Jones, and Tipton (1965).

H. Stelometer strength, F_1 entry mean selection unit, narrow-sense. Verhalen and Murray (1967).

I. Stelometer strength, plot mean selection unit, broad-sense. Murray and Verhalen (1969).

J. Zero gage Stelometer strength, F_2 plant selection unit, narrow-sense, mean of the heritabilities given in two years. Murray and Verhalen (1969).

K. Stelometer strength, plot mean selection unit, narrow-sense, mean heritability from F_1 and F_2 data. Verhalen and Murray (1969).

L. Stelometer strength, plot mean selection unit, narrow-sense. Al-Rawi and Kohel (1970).

M. Stelometer strength, plot mean selection unit, narrow-sense. Baker and Verhalen (1973).

N. Stelometer strength, F_1 entry mean selection, narrow-sense. Wilson and Wilson (1975).

O. Stelometer strength, F_3 line selection unit, broad-sense. Scholl and Miller (1976).

P. Stelometer strength, F_2 plant selection unit, narrow-sense. May and Green (1994).

Q. Stelometer strength, F_2 population bulk selection unit, broad-sense. May and Green (1994).

R. Stelometer strength, F_3 line selection unit, broad-sense. May and Green (1994).

Table 11 Summary of selection experiments toward fiber strength modification.

Reference	Response of fiber strength measure (kN m kg^{-1})
A	24
B	31
C	60

(Table 11 continued)

A. Five cycles of recurrent selection from a Coker 100 strain/Acala 1517 strain population. Stelometer strength selected in last four cycles with Pressley strength selected in Cycle 1 Response calculated as difference between Cycle 5 and Cycle 0 (base population). Parents of base population isolated from Coker 100 and Acala 1517, respectively, by at least five generations of selfing. Miller (1965).

B. Single cycle of divergent mass selection for Stelometer strength in a Texas upland/Acala population. Response calculated as mean difference between high and low strength selected populations. Turner, Worley, and Ramey (1980).

C. Five cycles of divergent mass selection for Stelometer fiber strength accomplished with forced self-pollination. Base population was a composite F_2 derived from 45 F_1s created with a 10- parent half-diallel. Response calculated as mean difference between 5th cycle high and low strength selected populations. McCall, Verhalen, and McNew (1986).

brown and high-strength lint color heterozygotes, and normal white lint color and high strength types (May, unpublished data). Apparently, the lint color locus is tightly linked to genes conditioning fiber strength, again suggesting effects of a few major genes controlling fiber strength. The source of fiber strength from the normal white lint parent was the cultivar PD-3 (Culp et al., 1988), which similarly experienced triple hybrid introgression, albeit distant in its ancestry. Is it possible then that fiber strength derived from a triple hybrid background is conditioned by only a few major genes while that from an Acala background (other than Del Cerro which has triple hybrid in its pedigree) (Calhoun, Bowman, and May, 1994) is controlled by numerous loci?

Meredith (1992) studied the components of bundle fiber strength which include single fiber strength, number of fibers in the bundle, and fiber length. These data illustrate the nature of interaction of basic fiber properties. Significant contributors to bundle fiber strength were 50% span length and individual fiber strength. In a multiple regression model predicting bundle strength from 50% span length, individual fiber strength, and Arealometer perimeter, most of the sums of squares were accounted for by the three-factor interaction among these predictors. Ultimately, breeders might make more progress in improving bundle strength by selection for one or more of its components through multiple trait selection strategies such as index selection or independent culling. The decision to conduct direct vs. indirect selection for bundle strength by selection for correlated traits would have to consider magnitude of genetic variance and heritability among bundle strength and its components along with ease of measurement.

Overall, the improvement of strength would seem a relatively straightforward breeding

However, the challenge to the breeder is to develop a product that meets the needs of both the textile industry and the producer. The antagonistic relationship between yield and fiber strength has made their simultaneous improvement difficult (Culp, Harrell, and Kerr, 1979; Culp, 1992).

An unresolved issue in breeding cottons with higher fiber strength is which instrument, the Stelometer, Pressley, or HVI, should be used to select progenies. Each measures fiber bundle strength by different methods (Taylor, 1982; Taylor et al., 1995), which has led to reports that the various instruments may not evaluate the same genetic properties controlling fiber strength. The HVI instrument does not weigh the fiber sample to determine mass, rather mass is indirectly estimated (Taylor and Godbey, 1992). In contrast, the operator of Pressley and Stelometer instruments measures the mass of fiber bundles of determined length (Taylor, 1982). Another

variable between the methods is that fiber crimp is eliminated during operator sample preparation for Stelometer and Pressley but not HVI (Taylor, 1982). Taylor and Godbey (1992) indicate that high- and low-micronaire cottons are particularly subject to HVI strength measurement errors. Also, when measured with HVI, certain cottons exhibit unusually high bundle strength that is not reflected in higher yarn strength (Brown and Taylor, 1988). Where fiber strength measurements from Stelometer and HVI have been compared, only moderate (0.4-0.6) correlations have been found (Green and Culp, 1988). Generally, these findings suggest that each instrument may evaluate different components of bundle fiber strength, reflecting idiosyncracies of each instrument and perhaps sample preparation. Cooper, Oakley, and Dobbs (1988) and Green and Culp (1988) found that the HVI instrument was not able to separate small strength differences between experimental cottons. Such small differences in strength frequently represent the size of genetic gains that breeders have achieved over time. May (unpub. data) has found standard-unit heritability of HVI strength in two populations to be lower than that of Stelometer strength. In contrast, Latimer, Wallace, and Calhoun (1996) found that heritability of HVI strength was similar to that determined with the Pressley instrument. Overall, their study showed that HVI fiber testing was sufficient for breeders to use in selecting for high fiber quality. There is no argument that the HVI technology has had a positive impact on the U.S. cotton industry (Chewning, 1992). The majority of the data, however, suggests that Stelometer and perhaps Pressley are more useful to breeders as measurement tools to select for improved fiber strength.

Fiber Elongation

Fiber elongation is a property of fiber that is measured during the determination of bundle strength (Hertel, 1953). The contribution of fiber elongation to spinning and textile performance occurs in several ways. Backe (1996) studied the effect of variation in fiber elongation on yarn

and textile manufacturing. In this study, bales representing three levels of fiber elongation were grouped while other fiber properties were held relatively constant between the elongation levels. Generally, increased elongation was associated with improved yarn quality of the open-end spun yarn as measured by evenness, strength, and reduced hairiness among other properties and ability to withstand the demands of weaving. When the genetic association between elongation and yarn strength is examined, a different relationship is evident. Meredith et al. (1991) reported moderate negative phenotypic correlations between elongation and yarn strength of ring and open-end spun yarns of various counts from a study of advanced breeding lines and cultivars. Though phenotypic correlations, the associations were deemed largely genetic as non-genetic influences (interactions with environments and experimental error) were small. Green and Culp (1990) similarly found a low negative genetic correlation between elongation determined by Stelometer and skein strength of a 27 tex ring-spun yarn.

As elongation is a property normally measured by Stelometer and reported along with strength and length parameters, its genetic parameters have been extensively studied. It is doubtful, however, that fiber elongation has ever been a selection criteria receiving much emphasis during breeding line or cultivar development, but as spinning and textile manufacturing technologies change, it may become a more important property. Similar to what we saw with measures of fiber length and strength where genetic differences exist, interactions of genotypes with locations and years are of minor importance and should not, in general, hinder the identification of superior types (Table 12). With a few exceptions (references H and L, Table 13), the expression of elongation is most influenced by additive genetic variance. In the two studies reporting the magnitude of dominance genetic variance greater than additive variance

Table 12. Genetic and environmental influences on fiber elongation.

Reference	Genotype	Genotype x Location	Genotype x Year	Genotype x Location x Year	Residual
A	0.7	<.1	<.1	0.1	0.2
B	1.0	<.1	<.1	<.1	0.2
C	6	0.3	0.2	2	1
D	15		<1		<1
E	0.2		<.01		

A. Four cultivars, 101 location x year combinations, variance components. Abouh-El-Fittouh, Rawlings, and Miller (1969).

B. Eight cultivars, three locations, three years, variance components. Bridge, Meredith, and Chism (1969).

C. Three cultivars, 28 locations, three years, ratio of indicated source to error variance. El-Sourady, Worley, and Stith (1969).

D. Four cultivars, four environments (year x soil type combinations), mean squares, genotype x year interaction is genotype x environment interaction. Meredith and Bridge (1973).

E. Eighty-nine early-generation families evaluated in three environments (year x location combinations), variance components, genotype x year interaction is the genotype x environment interaction. Scholl and Miller (1976).

Table 13 Additive and non-additive genetic and environmental influences on various measures of fiber elongation.

Reference	Additive	Additive x Loc	Additive x Yr	Additive x Loc x Yr	Non-additive	Non-additive x Loc	Non-additive x Yr	Non-additive x Loc x Yr	Residual
A	22	-	-	-	-	-	-	-	
B	1.5	-	-	-	-	-	-	-	
C	0.2	-	-	-	<.01	-	-	-	
D	950	15	23	9	2	35	0[!]	7	600
E	3	-	-	-	2	-	-	-	0.5
F	41	-	-	-	-	-	-	-	
G	2.4	-	-	-	-	-	-	-	
H	0.1	-	-	-	-	-	-	-	
I	0.9	-	-	-	-	-	-	-	
J	5	0.5	-	-	0.5	0.3	-	-	0.3
K	7	0.2	-	-	0.5	0.3	-	-	0.3
L	0.02	-	-	-	0.8	-	-	-	

[!] Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

A. Ratio of general combining ability to specific combining ability mean squares calculated from data in Barnes and Staten (1961).

B. Ratio of general combining ability to specific combining ability mean squares from a diallel among seven Acala germplasms calculated from data in Barnes and Staten (1961).

C. Additive and dominance genetic variances. Ramey and Miller (1966).

D. Additive and dominance genetic variances. Lee, Miller, and Rawlings (1967).

(Table 13 continued)

E. Additive and non-additive genetic and environmental variances. Al-Rawi and Kohel (1970).

F. Ratio of general and specific combining ability mean squares averaged from the F_2 and F_3 generation of diallel progenies. Meredith and Bridge (1973).

G, H. Ratio of additive to non-additive genetic variance within High-Plains and Acala germplasm respectively. Quisenberry (1975).

I. Ratio of additive genetic variance to total genetic variance. Wilson and Wilson (1975).

J. General and specific combining ability mean squares. Green and Culp (1990).

K. General and specific combining ability mean squares. Tang et al. (1993).

L. Additive and dominance genetic variances. May and Green (1994).

(Quisenberry, 1975; May and Green, 1994), the additive genetic variance could simply have been exhausted in the germplasm studied. Heritability estimates for fiber elongation indicate that pedigree selection, or early-generation testing schemes, should be effective breeding tools (Table 14). Tipton et al. (1964b) found four to five loci affected elongation in two single-cross cotton populations.

Measures of Fineness/Maturity

Fiber fineness determines the spin limit defined by Faerber and Deussen (1994) as the finest yarn count that can be spun with an acceptable level of yarn quality and ends down. Deussen (1992) indicates that fineness contributes to yarn strength and spinnability measured as number of ends down, particularly for open-end spinning systems. Increased levels of fiber fineness promote fiber-to-fiber cooperation in the yarn permitting less yarn twist, which translates

Table 14. Heritability estimates for fiber elongation.

Reference		Reference	
A	0.90	F	0.80
B	0.36	G	0.36
C	0.80	H	0.77
D	0.77	I	0.21
E	0.43		

A. F_2 plant selection unit, narrow-sense. Tipton et al. (1964b).

B. F_2 plant selection unit, narrow-sense. Tipton et al. (1964b).

C. F_2 plant selection unit, narrow-sense. Abdel-Nabi, Jones, and Tipton (1965).

D. Plot mean selection unit, narrow-sense. Al-Rawi and Kohel (1970).

E. F_1 entry mean selection unit, narrow-sense. Wilson and Wilson (1975).

F. F_3 line selection unit, broad-sense. Scholl and Miller (1976).

G. F_2 plant selection unit, narrow-sense. May and Green (1994).

H. F_2 population bulk selection unit, broad-sense. May and Green (1994).

I. F_3 line selection unit, broad-sense. May and Green (1994).

into a gain in productivity for the yarn manufacturer. Instrument measures of fineness/maturity include the Micronaire (Johnson, 1952), Shirley fineness and maturity tester (American Society for Testing and Materials, 1993), Arealometer (Hertel and Craven, 1951), and the relatively new AFIS fineness and maturity module (Bradow et al., 1996).

Micronaire reading (MIC) is one of several properties textile mills use to make bale lay-downs prior to yarn manufacture (Hake et al., 1990). High (>5.0) MIC fiber, usually indicating coarse fiber, does not spin efficiently into fine count yarns, while low (<3.5) MIC cotton that is

immature can cause neps and dye defects (Hake et al., 1990). MIC reading is used in combination with other fiber properties such as strength and the span lengths to make a certain size yarn and to promote consistency of performance of a set of cotton bales in the yarn manufacturing process (Perkins, Ethridge, and Bragg, 1984). Unfortunately, as MIC reading is a measure of resistance to airflow of a constant weight of fibers at one air pressure (Johnson, 1952), maturity and fineness can be confounded. With knowledge of fiber maturity, the degree to which the fiber lumen has filled in (Basra and Malik, 1984), MIC reading can be interpreted as a measure of fineness. Also, if fiber perimeter is known, MIC reading can indicate relative maturity (American Society for Testing and Materials, 1993). Without knowledge of fiber maturity or perimeter, low MIC cotton, for example, could result from immature fiber or genetically fine (e.g, small perimeter) fiber. Given this information, a question is how to interpret the genetic control of MIC. Meredith (1994) indicates that maturity and fineness account for 90% of the variation in MIC reading with the remainder being experimental error. Genetic variation for MIC is due to nearly equal effects of maturity and perimeter (Meredith, 1991). Consequently, if we wish to investigate the genetic control of MIC, perhaps we should concentrate on the separate genetic control of fineness and maturity.

Despite these reservations, data in Table 15 indicate that breeders have relied extensively on MIC reading as a measure of fiber fineness. MIC reading is normally provided with length, strength, and elongation measurements for a nominal fee and likely explains the prevalence of MIC reading as a measure of fineness. Extensive use of the Arealometer and Shirley Fineness-Maturity Tester in genetic studies has not occurred but may reflect additional measurement costs over that of the common fiber properties. Of the 17 studies of fiber fineness/maturity summarized

Table 15. Genetic and environmental influences on various measures of fiber fineness.

Reference	Genotype	Genotype x Location	Genotype x Year	Genotype x Location x Year	Residual
A	0.4	<.1	<.1	<.1	<.1
B	1388	<10	13	<10	<10
C	14	<.1			<.1
D	540	30	100	80	990
E	0.06	<.01	<.01	<.01	0.05
F	0.02	<.01	<.01	0.03	0.03
G	0.02	0[1]	0[1]	0.02	0.03
H	0.8	0.3	<.01	0.4	1.0
I	0.5	0[1]	0.4	1	6
J	5		1		
K	40	9			9

[1] Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

A. Arealometer specific surface area, four cultivars, three locations, two years, mean squares. Hancock (1944).

B. Mass per unit length, 16 cultivars, seven locations, three years, mean squares. Pearson (1944).

C. Mass per unit length, 16 cultivars, nine locations, one year, mean squares. Pope and Ware (1945).

D. Arealometer specific surface area, 95 breeding lines, two locations, two years, variance components. Miller et al. (1958).

(Table continued)

E. Micronaire reading, cultivars, nine locations, three years, variance components. Miller Robinson. and Williams (: 59)

Micronaire reading, four cultivars, year location combinations, variance components Abouh-El-Fittouh, Rawlings, and Miller 969)

F Micronaire reading, eight cultivars, three locations, three years, variance components. Bridge, Meredith, and Chism 969

H. Arealometer specific surface area, three cultivars, 28 locations, three years, ratio of indicated source of variation to error variance. El-Sourady, Worley land Stith. 1969)

I. Micronaire reading, 62 BC_2F_4, two locations, two years, variance components (x 0^{-2}). Murray and Verhalen 969).

Shirley Fineness-Maturity Tester cultivars and advanced breeding lines, two locations, one year, ANOVA values. Meredith et al. 99

K. Advanced Fiber Information System area, genotypes including advanced breeding lines and cultivars, locations, variance components expressed as percent of total variance. Meredith, Sasser, and Rayburn 996).

in Tables and about half indicate that non-genetic influences are greater than genetic differences Of the studies where genetic differences were smaller than non-genetic variation, three involved MIC and thus do not know the influence of immature fiber on MIC reading Meredith, Sasser, and Rayburn 996) notes that AFIS fiber area and diameter measure large genetic opposed to non-genetic influences. The AFIS measurements are not necessarily confounded with fiber maturity (because this estimate provided) and would appear to provide

Table 16. Genetic and environmental influences on fiber maturity and related properties.

Reference	Genotype	Genotype x Location	Genotype x Year	Genotype x Location x Year	Residual
A	630	20	40	20	10
B	9	7	-	-	14
C	11	7	-	-	12
D	8	-	2	-	-
E	14	2	-	-	27
F	61	11	-	-	14

A. Percent thin-walled fibers, 16 cultivars, seven locations, three years, mean squares. Pearson (1944).

B. Arealometer maturity, 18 genotypes including advanced breeding lines and cultivars, seven locations, variance components expressed as percent of total variance. Meredith, Sasser, and Rayburn (1996).

C. Advanced Fiber Information System maturity, 18 genotypes including advanced breeding lines and cultivars, seven locations, variance components expressed as percent of total variance. Meredith, Sasser, and Rayburn (1996).

D. Arealometer perimeter, 19 cultivars and advanced breeding lines, two locations, one year, ANOVA F values. Meredith et al. (1991).

E. Arealometer perimeter, 18 genotypes including advanced breeding lines and cultivars, seven locations, variance components expressed as percent of total variance. Meredith, Sasser, and Rayburn (1996).

(Table 16 continued)

F. Advanced Fiber Information System diameter, 18 genotypes including advanced breeding lines and cultivars, seven locations, variance components expressed as percent of total variance. Meredith, Sasser, and Rayburn (1996).

breeders with a new tool to modify fiber fineness. MIC reading and Arealometer specific surface area are mostly influenced by additive genetic variance though some studies report non-additive variance (Table 17). Reasonably high heritability estimates for MIC reading (Table 18) and fiber shape parameters (Table 19) suggest they can be modified through selection. Characterization of sources of variation for fiber fineness in *G. hirsutum* is needed if this trait is to be emphasized in breeding programs.

Wax Content

Another property of cotton fiber contributing to its ability to be spun into yarn is wax content (Perkins, Ethridge, and Bragg, 1984). Taylor (1996) reported that addition of wax content to models containing HVI fiber strength data improved prediction of fabric tear strength among bale cotton samples. Additionally, this study reported a rapid method of wax measurement using near infrared reflectance as opposed to time consuming wet chemistry (American Society for Testing and Materials, 1982). Perkins, Ethridge, and Bragg (1984) do not indicate what levels of wax are considered high or low, but they suggest that extreme values are detrimental to spinnability. Little genetic information exists about wax content in cotton. Conrad and Neely (1943) reported the inheritance of wax content in green lint, high wax x normal white lint, low wax crosses. The data indicated a pleiotropic effect of the green lint gene or tight

Table 17. Additive and non-additive genetic and environmental influences on various measures of fiber fineness.

Reference	Additive	Additive x Loc	Additive x Yr	Additive x Loc x Yr	Non-additive	Non-additive x Loc	Non-additive x Yr	Non-additive x Loc x Yr	Residual
A	2.5	-	-	-	-	-	-	-	-
B	0.64	-	-	-	-	-	-	-	-
C	370	-	-	-	20	-	-	-	-
D	700	60	10	100	30	0!	40	0!	400
E	0.09	-	-	-	0.1	-	-	-	0.2
F	60	-	-	-	20	-	-	-	20
G	0.3	0.2	-	-	<.1	0.2	-	-	-
H	12	-	-	-	-	-	-	-	-
I	0	-	-	-	-	-	-	-	-
J	0.06	-	-	-	-	-	-	-	-
K	0.96	-	-	-	-	-	-	-	-
L	1	0.4	-	-	0.2	0.3	-	-	0.3
M	1.5	0.1	-	-	0.1	<.1	-	-	<.1
N	<.1	-	-	-	.1	-	-	-	-

! Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

A. Micronaire reading, ratio of general combining ability to specific combining ability mean squares calculated from data in Barnes and Staten (1961).

B. Micronaire reading, ratio of variance due to additive vs. non-additive effects averaged over parents from a half-diallel among seven Acala germplasms. Barnes and Staten (1961).

Table 18. Heritability estimates for Micronaire reading.

Reference		Reference	
A	0.61	F	0.26
B	0.40	G	0.87
C	0.23	H	0.49
D	0.08	I	0.82
E	0.53	J	0.53

A. F_2 plant selection unit, broad-sense. Bilbro (1961).

B. F_1 entry mean selection unit, narrow-sense. Verhalen and Murray (1967).

C. F_2 plant selection unit, narrow-sense. Murray and Verhalen (1969).

D. Plot mean selection unit, narrow-sense. Al-Rawi and Kohel (1970).

E. Plot mean selection unit, narrow-sense. Baker and Verhalen (1973).

F. F_1 entry mean selection unit, narrow-sense. Wilson and Wilson (1975).

G. F_3 line selection unit, broad-sense. Scholl and Miller (1976).

H. F_2 plant selection unit, narrow-sense. May and Green (1994).

I. F_2 population bulk selection unit, broad-sense. May and Green (1994).

J. F_3 line selection unit, broad-sense. May and Green (1994).

Table 19. Heritability estimates for fiber fineness related traits.

Reference		Reference	
A	0.51	E	0.58
B	0.43	F	0.68
C	0.55	G	0.72
D	0.07	H	0.61

(Table 17 continued)

C. Arealometer specific surface area, additive and dominance genetic variances. Ramey and Miller (1966).

D. Micronaire reading, additive and dominance genetic variances. Lee, Miller, and Rawlings (1967).

E. Micronaire reading, additive and non-additive genetic and environmental variances. Al-Rawi and Kohel (1970).

F. Micronaire reading, general and specific combining ability mean squares. Thomson (1971).

G. Micronaire reading, generation means analysis of six crosses evaluated at three locations, data for one cross presented. Meredith and Bridge (1972).

H. Micronaire reading, ratio of general and specific combining ability mean squares averaged from the F_2 and F_3 generation of diallel progenies. Meredith and Bridge (1973).

I, J. Micronaire reading, ratio of additive to non-additive genetic variance within High-Plains and Acala germplasm. Quisenberry (1975).

K. Micronaire reading, ratio of additive genetic variance to total genetic variance. Wilson and Wilson (1975).

L. Micronaire reading, general and specific combining ability mean squares. Green and Culp (1990).

M. Micronaire reading, general and specific combining ability mean squares. Tang et al. (1993).

N. Micronaire reading, additive x additive and dominance genetic variances, additive variance was not detected. May and Green (1994).

(Table 19 continued)

A. Fiber perimeter, F_2 plant selection unit, narrow-sense. Bishr (1954).

B. Fiber cell wall thickness, F_2 plant selection unit, narrow-sense. Bishr (1954).

C. Arealometer fiber specific area, F_2 plant selection unit, narrow-sense. Lewis (1957).

D. Arealometer perimeter, F_2 plant selection unit, narrow-sense. Lewis (1957).

E. Arealometer D value (measure of fiber shape), F_2 plant selection unit, narrow-sense. Lewis (1957).

F. Arealometer fiber specific area, F_3 line selection unit, broad-sense. Al-Jibouri, Miller, and Johnson (1958).

G, H. Arealometer fiber specific area, F_4 line selection unit, broad-sense, heritability from two populations calculated from data in Miller et al. (1958).

linkage with the gene or genes affecting wax content. Further genetic study of the relationship of wax content and textile performance seems warranted.

Genetic Associations Among Fiber Quality Traits

Thus far in discussing genetic variation for fiber properties, we have addressed each property except MIC reading as being an independent entity. We know that the fiber properties are not independent and that genetic correlations exist among them. The significance of genetic correlations to breeders is that selection for correlated traits results in their simultaneous modification. Fiber strength and length tend to be positively correlated (Table 20) as are length and measures of fineness. The variation in direction of the genetic correlations between length and fineness in Table 20 reflects different scale measurements. Low MIC reading and high fiber specific surface area in the absence of immature fiber indicate finer fiber and thus explain variation

Table 20. Summary of genetic correlations between fiber quality traits.

	Length			Strength	
Reference	Strength	Fineness	Elongation	Fineness	Elongation
A	0.10	0.05	-	-0.02	-
B	-0.23	0.66	-	-0.25	-
C	0.25	0.70	-	0.06	-
D	0.33	0.16	-	-0.31	-
E	-	-	-	-	-0.57
F	-	-	-	-	-0.39
G	-	-	-	-	-0.84
H	0.36	0.12	0.15	0.14	-0.51
I	0.41	-0.42	0.07	-0.21	0.03
J	-	-	-	-0.11	-
K	0.36	-0.48	-0.17	-0.15	-0.16

A. Ninety-two F_3 progenies, upper half mean length, Stelometer strength, and Arealometer specific surface area. Al-Jibouri, Miller, and Robinson (1958).

B, C, D. Ninety-five, 92, and 81 lines of separate populations evaluated in F_4 and F_5, upper half mean length, Pressley strength, Arealometer specific surface area. Miller et al. (1958).

E, F. Two populations, phenotypic correlations, Stelometer strength/elongation. Tipton et al. (1964b).

G. Sixty-nine F_3 lines, Stelometer strength/elongation. Abdel-Nabi, Jones, and Tipton (1965).

H. Ninety-six F_3 lines, upper half mean length, Stelometer strength/elongation, and micronaire reading. Miller and Rawlings (1967).

I. Ninety-six F_3 lines, 2.5% span length, Stelometer strength/elongation, and micronaire reading. Meredith and Bridge (1971).

(Table 20 continued)

J. Forty-five F_1 populations, Pressley strength, micronaire reading. Thomson (1971).

K. Eighty-nine early-generation families, 2.5% span length, Stelometer strength/elongation, and micronaire reading. Scholl and Miller (1976).

in sign of the correlation between length and fineness as longer fiber tends to have smaller perimeter. The positive association between fiber strength, length, and fineness would generally be considered advantageous, in that greater fineness, length, and strength are a desirable combination. Genes imparting fiber length and elongation appear to function independently as their genetic correlations are low (Table 20). The strongest genetic correlations existed between Stelometer strength and elongation with the assumption that increased strength would occur at the expense of elongation. This association would hinder efforts to improve strength and elongation to benefit textile performance. Genetic correlations arise from pleiotropy, linkage, or can be non-genetic, reflecting physiological relationships. Given that the major components of fiber bundle strength include 50% span length, fineness, and single fiber strength (Meredith, 1992), one wonders which component of bundle strength accounts for genetic gain in bundle strength. If the gain in bundle strength resulted from longer and consequently generally finer fiber as opposed to single fiber strength, then the association with length and strength might not be genetic. More fibers in the fiber bundle tested for strength might account for the increased strength. Data from the National Cotton Variety Tests (USDA, 1995) show that the strongest fiber also has the smallest perimeter. Were there a reasonably rapid method of measuring single fiber strength available to breeders, this might be an untapped source of genetic variation for the improvement of fiber strength.

Yarn Strength

Yarn strength is a critical factor in efficient manufacturing of knit and woven fabrics (Faerber, 1995), and its improvement is necessary to maintain cotton's dominance as a textile fiber. Further demand by the textile industry for stronger yarns derives from rising consumer preference for wrinkle resistant 100% cotton fabrics achieved by chemical treatment. Associated with the wrinkle resistant treatment is a 30-50% reduction in strength of the treated product (Faerber, 1995). Data in Table 21 show strength of 12-42 tex ring and open-end spun yarn is strongly determined by genetics and has high heritability. These data reflect the contribution of individual fiber properties such as bundle strength and length, which we saw had reasonable heritability. Extensive replication of experiments over locations and years to select for improved yarn strength does not seem warranted as interactions with locations and years are small. Genetic gain in yarn strength requires knowledge of which fiber properties that when selected will result in better yarn strength as this trait is too expensive to select for directly except in late generations of breeding.

Because of global competition, yarn and textile producers have been forced to adopt more efficient manufacturing technology (Deussen, 1992; Faerber, 1995). This technology requires stronger fiber to operate competitively in a global economy. Additionally, the open-end yarn spinning systems being adopted in the name of efficiency and at the expense of older ring spinning may require fiber with different profiles of length, strength, and fineness (Deussen, 1992). Breeders, therefore, are faced with meeting the fiber quality needs of both ring and open-end spinning. Since there is quite a lag time between initiation of breeding efforts and cultivar release, knowledge of the genetic association between fiber properties and yarns produced by the two

Table 21. Genetic and environmental influences on yarn strength.

Reference	Genotype	Genotype x Location	Genotype x Year	Genotype x Location x Year	Residual
A	240	1	<1	10	20
B	0.5	<.1	0!	0.3	1
C	3200	30	-	-	3
D	59	3	-	-	-
E	34	2	-	-	-
F	36	1	-	-	-
G	32	1	-	-	-
H	8	-	-	-	-
I	90	23	<20	<20	<20
J	0.74	-	-	-	-
K	50	7	-	-	12

! Analysis of variance estimate of the indicated variance was negative, thus most reasonable estimate is zero.

A. Twenty-seven tex, ring spun yarn, four cultivars, 101 location x year combinations, variance components. Abouh-El-Fittouh, Rawlings, and Miller (1969).

B. Twenty-seven tex, ring spun yarn, three cultivars, 28 locations, three years, ratio of indicated source to error variance. El-Sourady, Worley, and Stith (1969).

C. Twenty-seven tex, ring spun yarn, four cultivars, four environments (year x soil type combinations), mean squares. Meredith and Bridge (1973).

D. Twenty-seven tex, rotor spun yarn, 19 cultivars and advanced breeding lines, two locations, one year, ANOVA F values. Meredith et al. (1991).

(Table 21 continued)

E. Forty-two tex, rotor spun yarn, 19 cultivars and advanced breeding lines, two locations, one year, ANOVA F values. Meredith et al. (1991).

F. Twelve tex, ring spun yarn, 19 cultivars and advanced breeding lines, two locations, one year, ANOVA F values. Meredith et al. (1991).

G. Thirty tex, ring spun yarn, 19 cultivars and advanced breeding lines, two locations, one year, ANOVA F values. Meredith et al. (1991).

H. Twenty-seven tex, ring spun yarn, ratio between general and specific combining ability mean squares. Green and Culp (1990).

I, J. Twenty-seven tex, ring spun yarn, 25 advanced breeding lines, two production systems, two years, and heritability with F_5 line selection unit. May and Bridges (1995).

K. Twenty-seven tex, ring spun yarn, 18 genotypes including advanced breeding lines and cultivars, seven locations, variance components expressed as percent of total variance. Meredith, Sasser, and Rayburn (1996).

spinning systems would be helpful. Also, breeders do not select for yarn strength in early generations because it is too expensive to measure on large populations. Breeders select fiber properties such as length and strength with the aim of improving yarn strength. Yarn manufacturers indicate that breeders should rank the fiber properties strength, fineness, and length in decreasing priority for rotor spinning in contrast to length, strength, and fineness for ring spinning (Deussen, 1992). Meredith et al. (1991) and Meredith and Price (1996) provide the only data available comparing the genetic association of the common fiber properties with various count yarns produced on ring and rotor spinning systems. These data do not disagree with

Deussen (1992) based on simple correlations between Stelometer strength, length (2.5% span length or AFIS mean length), fineness (Shirley fineness maturity test or AFIS diameter) and yarn strengths of ring and open-end spun 12-42 tex yarns. These studies, however, do not necessarily show that breeders should attempt divergent selection strategies to meet the fiber profile needs of the two spinning systems. We do not know if the same holds for finer yarns and higher rotor speeds. If breeders make progress for higher bundle strength through finer fiber and single fiber strength, then the resulting fiber should benefit both yarn manufacturing systems. Again, breeders are faced with developing a germplasm that can produce economically sufficient amounts of lint yet meet textile processing requirements. Culp, Harrell, and Kerr (1979) have shown that although difficult, it is possible to simultaneously improve lint yield and ring spun yarn strength. Meredith and Price (1996) show an antagonistic correlation between lint yield and rotor spun yarn strength that suggests similar difficulty, though not impossibility, in achieving this goal.

CONCLUSION

The challenge facing breeders is to produce a cultivar that meets the needs of a textile industry in the midst of technological advancement and also produces enough lint for growers to make a profit. The common fiber properties such as length and strength tend to be moderately to highly heritable for various selection units with additive genetic variance playing a major role in their expression. Thus, their continued improvement is expected. New tools will facilitate breeding for fiber quality traits such as wax content, short fiber content, and fineness. The AFIS provides breeders with a direct measure of short fiber content and separate measures of fiber fineness and maturity. Progress in reducing short fiber content and achieving greater fiber fineness and length uniformity should be possible. Although yarn manufacturers are demanding fiber with greater strength and fineness for open-end spinning and better textile performance, the

data so far indicate that breeders do not necessarily need to alter their fiber quality objectives to meet the needs of different yarn spinning systems. Biotechnology will provide genes conferring specific fiber properties (John, 1992), and possibly molecular markers will allow direct selection for the genotype thereby providing a more efficient means of selecting for fiber properties. The incentive to genetically improve fiber quality must come from a realization that the long-term health of the cotton industry depends on it. A cotton marketing system that recognizes quality and adequately compensates growers for its delivery would be beneficial, but should not be a pre-requisite to move ahead with efforts to improve fiber quality.

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