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Office of The Quartermaster General
Military Planning Division
Research and Development Branch

TEXTILE SERIES-REPORT NO. 55

A STUDY OF SOME FACTORS AFFECTING THE SHRINK-RESISTANCE OF WOOL

Submitted by
The Harris Research Laboratories
Washington, D.C.

Released for public information
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The Office of Technical Services
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FOREWORD

Previous Textile Series Reports, Numbers 46 and 53, have outlined the work done during the war by the Quartermaster Corps on the shrink-resistance of wool and the general objectives of the continuing Quartermaster research program in this field.

It has been the feeling of our office that because of the extremely important position of wool in Quartermaster clothing and the critical nature of the shrinkage problem in its utilization, it is a matter of basic priority that research on the behavior of wool with respect to shrinkage should be an integral part of the Quartermaster research program. Accordingly, at the end of the war, upon the recommendation of the National Research Council Committee on Quartermaster Problems, a basic study of shrink-resistance of wool was initiated under contract by the Harris Research Laboratories, Washington, D. C. In a sense, this work was a continuation of that done by the staff of this organization for the Quartermaster Corps during the war on the shrink-resistant treatment of socks. It was intended, however, that the new program would be concerned primarily with the fundamental characteristics of the behavior of wool with respect to the mechanism of shrink-resistance.

This report represents a preliminary statement of some of this work. In part, the material reported herein has been presented before scientific bodies and in technical journals under agreement with the research contractor, but this report for the first time makes the material available in a form suitable for general use by cooperating organizations working with the Quartermaster Corps on the solution of the problem of wool shrinkage.

Additional progress reports of this nature will be forthcoming covering the work conducted by the Harris Research Laboratory and our own Textile Finishing Research Laboratory in Philadelphia.

This report was prepared by various members of the staff of the Harris Research Laboratories including: Dr. Milton Harris, Director; Mr. Arnold Sookne, who is in charge of the shrinkage project; Mr. Herman Bogaty; Mr. Daniel Frischman and Mr. Robert E. Wright, Librarian of the Laboratory.

General supervision of the Quartermaster Corps project on shrink-resistance has been under the leadership of Mr. Louis I. Weiner, of the Quartermaster Textile Finishing Research Laboratory in Philadelphia. Mr. Gerald Winston and Mr. John Medernach of the Quartermaster Laboratories also assisted in the preparation of the tabular and graphical material.

S. J. KENNEDY
Research Director
for
Textiles, Clothing and Footwear

May 1949

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ABSTRACT

An instrument has been devised which yields reproducible values for the surface friction of wool fibers in either direction in air, water, or any desired medium. With this device, measurements have been made which show the distribution of frictional properties among fibers withdrawn from the same fabric, and which demonstrate the differences in frictional properties found among fibers of various types of wool.

In a study of the influence of the pH of the wash liquor on shrinkage in laundering, rate of shrinkage was found to be directly related to area shrinkage after two hours, and shrinkage was found to decrease with increasing pH.

Investigations of resin-treated fabrics have indicated that resins confer shrink-resistance by bonding the fibers to each other, rather than by modifying the surface frictional properties or the stress-strain characteristics.

In evaluating the effects of various chemical agents on felting, two useful tests for determining damage or modification to fiber properties are the "30% index" and the "alkali solubility" test. The former is the ratio of work required to stretch a treated fiber 30%, to the work required to stretch an untreated fiber 30%. The alkali solubility test measures the increase in alkali solubility in wool which has been subjected to a given treatment.

In order to determine quickly the effect of chemical treatments on the felting tendency, a method was devised for testing the shrinkage of wool in the form of top, so that the delay involved in having treated top spun into yarn and then woven or knitted into a fabric was avoided.

The results of a study of the complex reaction between wool and active chlorine have shown that: (1) with increasing times of chlorination, fiber modification increases and strength decreases; (2) with short times of chlorination, fiber modification is relatively unaffected by the pH of the solution for equivalent degrees of shrink-resistance; (3) felt-resistance is remarkably sensitive to chlorine concentration in acid chlorination, but chlorination under the latter conditions is less pH-sensitive than alkaline chlorination; and (4) for a given time and pH of chlorination, the shrink-resistance of fabric is approximately linearly related to the chlorine concentration.

Section A

THE MECHANISM OF FELTING SHRINKAGE

1. Introduction. The high regard in which wool has been held for many centuries as a material for human garments is based on a group of properties possessed by the fiber which make it eminently suitable for clothing. The unique balance of these properties -- strength, long-range elasticity, resilience, and ability to absorb moisture without feeling wet -- yields fabrics which resist wear, feel soft and comfortable on the body, insulate well against heat and cold, and resume their original shape after considerable distortion. It is obvious that such fabrics are of exceptional value in military apparel, for the soldier's clothing must have excellent shape-holding characteristics (both for appearance and comfort), must furnish protection from extremes of temperature without undue bulk, and must stand up under severe conditions of wear for long periods.

However, there is another characteristic of wool which reduces its usefulness in items which require frequent laundering, such as shirts, socks, and underwear. This characteristic is the tendency of wool to felt -- that is, for the fibers to become closely entangled and matted -- when agitated or rubbed together in the presence of moisture, as in laundering. Felting not only produces a stiff, "boardy" fabric, but also results in a progressive type of shrinkage, i.e., each time the garment is washed it shrinks further until it may become only a fraction of its original size.

This felting tendency has imposed stringent restrictions on the manner in which wool fabrics can be cleaned: they have had to be dry cleaned (although some felting may still result, since some dry cleaning solutions contain water), or washed by hand with great care and stretched or boarded to the correct shape and size afterward. In addition, felting will actually take place during wear in such items as wool socks and in areas such as the armpits of sweaters and shirts, since the rubbing and presence of perspiration furnish the necessary conditions.

2. Relation of surface friction to felting. Many hypotheses have been advanced in attempts to explain the phenomenon of felting in wool. A number of workers have developed evidence which points to the important role of the surface scale structure of the fiber. One suggestion, that the scales function as a series of interlocking barbs, has not been supported by observation. Another hypothesis relates the felting tendency to the mechanical properties of the fiber. More recently, most investigators have accepted the view that the relationship of the scales to the frictional properties is one of the major contributing factors in

a more satisfactory explanation of the felting phenomenon.

This latter view is based in part on the fact that the scales are arranged so that they overlap like shingles on a roof, with their outer ends projecting in the direction of the fiber tip. Thus, the fiber is rougher (i.e., the friction is greater) when rubbed from tip to root than from root to tip. Accordingly, when a wool fabric is subjected to mechanical action as in laundering, the fibers tend to migrate in the direction of least resistance, i.e., in the direction of their roots. However, since portions of the fibers are tied down more or less securely in the yarn or fabric, the tendency to migrate causes the fibers to wrap around each other and form an irreversibly entangled mass known as a felt.

Since a wool fiber is rougher when rubbed in one direction then in the other, each fiber will have two values (or "coefficients") of friction, depending upon the direction in which the friction is measured. The lower coefficient (usually referred to as μ_2) may be subtracted from the higher coefficient (μ_1) to yield a value known as the "friction difference," or the two coefficients may be added to obtain the "friction sum." These terms are useful for calculating the change in frictional properties which takes place upon treatment with various chemicals, as explained later in this report.

3. Measurement of surface friction. During the course of work on the present project at Harris Research Laboratories, it became evident that some means was needed for securing accurate and reproducible measurements of the surface friction of wool fibers, in order to explore effectively the fundamental aspects of the felting mechanism. Accordingly, the instrument shown in Figure 1 was devised.

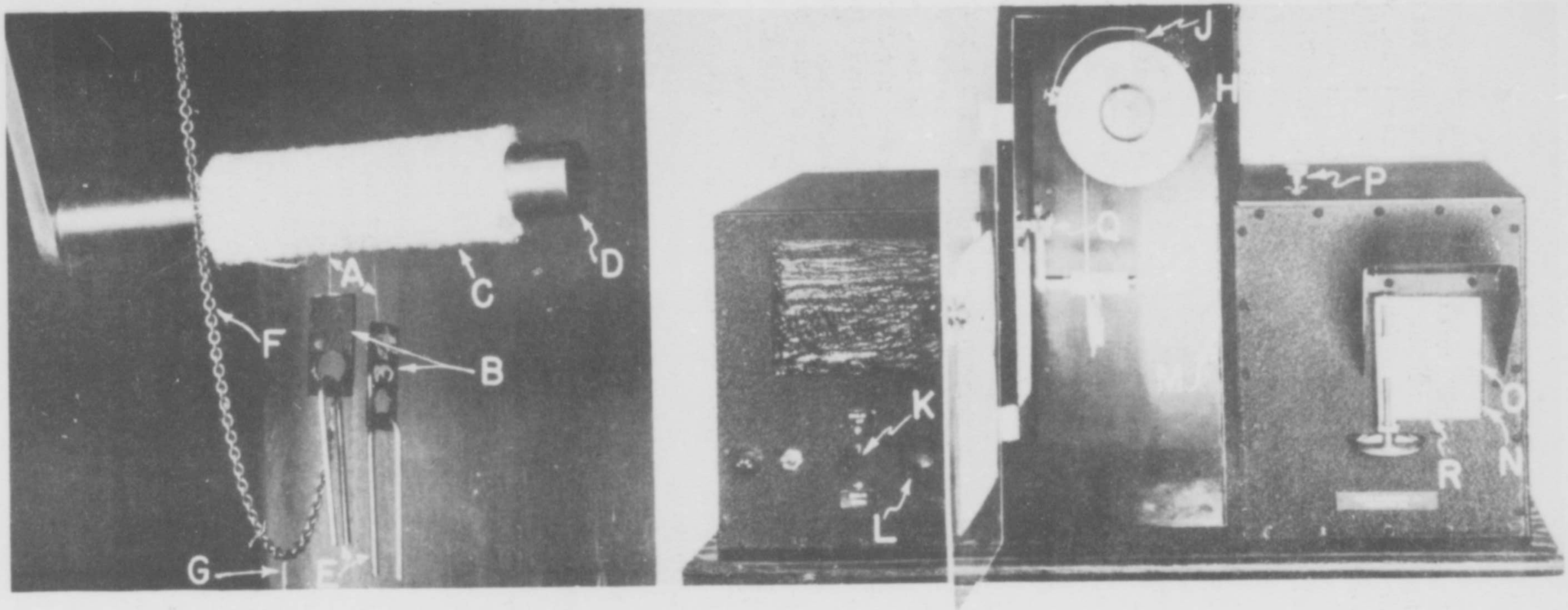
As shown in Figure 1 in the close up of the fiber and felt, the fiber (A) is attached with polystyrene cement to small Bakelite tabs (B) and hung over a dense wool felt (C) which has been wrapped around a rod (D). Small, known, constant weights (E), just sufficient to remove crimp from the fiber, are hung from the tabs. In operation an additional load is applied to one end of the fiber by means of a chainomatic device through chain (F) until the fiber just begins to slip. The coefficient of friction can then be calculated from the equation:

$$\mu = 0.733 \log_{10} (T/T_o),$$

where μ is the coefficient of friction, T_o is the constant weight on one end of the fiber, and T is the constant weight plus the weight of the chain at the other end of the fiber.

FIG. I

FIBER FRICTION METER



A

CLOSE UP OF FIBER & FELT

B

A = FIBER
B = BAKELITE TABS
C = DENSE WOOL FELT
D = ROD
E = KNOWN CONSTANT WEIGHTS
F = CHAIN
G = FINE PLATINUM WIRE

H = SCALE
J = ADJUSTABLE POINTER
K = ELECTRIC MOTOR SWITCH
L = KNOB
M = LENS
N = GROUND GLASS SCREEN
O = MOVABLE INDEX
P = LENS KNOB
Q = SLOTTED BAR
R = SHADOW IMAGE

The operating controls are shown in Figure 1B. Load is added through the chain by rotation of the drum carrying the scale (H), which measures the contribution of the chain to the total weight (T, in the equation above). An adjustable pointer (J) may be moved to zero on the scale, thus eliminating the necessity for adding or subtracting corrections to the zero point and making possible direct readings of the extent of movement of the chain, which may be converted into μ from prepared tables. In order to start each experiment with a constant tension on the fiber (which requires a constant length of chain), the chain is adjusted so that the fine platinum wire (G in Figure 1A) is suspended at the lowest point of the catenary. The chain is moved up or down by an electric motor controlled by switch (K); a knob (L) makes possible more rapid movement of the chain in either direction.

An optical system consisting of a light source, a lens (M), a set of mirrors, and a ground-glass screen (N) with a movable index (O) enables the operator to determine the exact moment when the fiber begins to slip. When the fiber is mounted on the felt, it is positioned so that the bottom of weight (E) is in line with the center of the ground-glass screen by means of vertical adjustments of the lens with knob (P) and adjustments of the fiber with a thumb screw and slotted bar (Q). The shadow image (R) of the end of weight (E) is focused on the ground-glass screen by moving the lens in its spiral mounting. The movable index on the screen is adjusted to lie at the end of the shadow image. When the fiber slips, the image of the weight will appear to move away from the index line on the screen. The optical system provides a magnification of about four times, so that a small movement of the fiber may be readily observed.

It is also possible with this device to measure the frictional properties of fibers while the fibers and the felt surface are immersed in water. This type of measurement is obviously of great value in relating surface friction to felting, since felting ordinarily takes place in the presence of moisture.

In tests made to determine the reproducibility of results obtained by this method, it was found that the mean of the coefficients of friction of a group of samples was highly reproducible from one set of tests to another, and that replacing the felt surface with a fresh one, although causing slight variations in individual measurements, did not affect the values for the friction difference. This latter result means that evaluation and comparison of chemical treatments on frictional properties are possible over a long period of time. In addition to determining the effects of various chemical agents on surface friction, this device has also been used in a number of valuable studies of other factors concerned with frictional properties, some of which are described below.

4. Distribution of surface friction values. Table I contains data illustrating the differences found in surface friction among fibers of various types of wool. That differences exist in frictional properties of fibers withdrawn from a single knit fabric is shown in Figure 2, where the points represent the actual data and the curves represent the normal distribution derived from the calculated averages (for 94 fibers) and standard deviations. These results are not surprising, in view of the variation in frictional properties among fibers from the same fleece found by other investigators.

Table I

FRICTIONAL PROPERTIES OF WOOLS OF VARIOUS ORIGINS

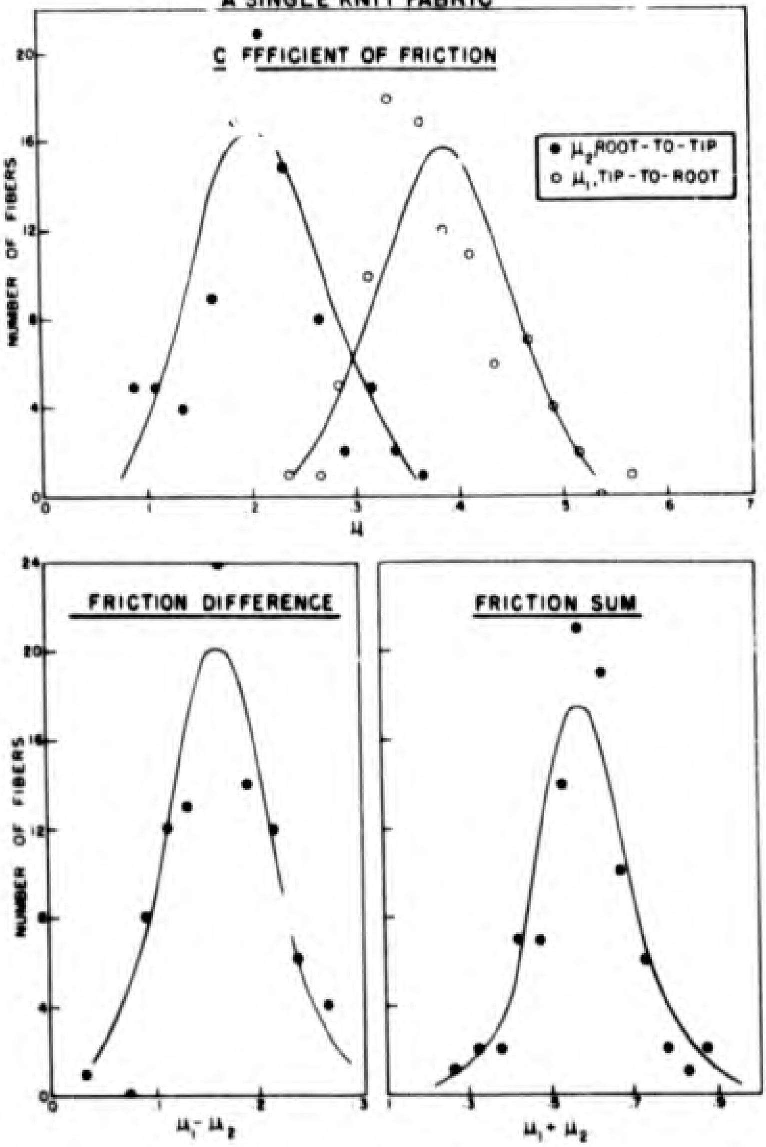
Type of Wool	μ_1	μ_2	$\mu_1 - \mu_2$	$\mu_1 + \mu_2$
Texas	0.51	0.18	0.33	0.69
Australian	.41	.11	.30	.52
Montevideo	.37	.15	.22	.52
Cape	.38	.16	.22	.54

(The above values were obtained in measurements in distilled water.)

5. Relation of fiber diameter to friction. In an attempt to determine whether differences in frictional properties were related to variations in fiber diameter, measurements were made of the diameters and coefficients of friction of 49 fibers withdrawn from a commercial fabric. Low correlation coefficients between friction and diameter values were obtained, and the best straight lines for the friction/diameter plots lacked significant slope. These results indicate that there is no significant correlation between fiber diameter and coefficient of friction in this case.

6. Wet vs. dry friction. In all cases, measurements of friction of wet fibers have given higher values than measurements made on the same fibers in the dry state. For example, a group of five wool fibers measured at 65% relative humidity against felt gave values of $\mu_1 = 0.35$ and $\mu_2 = 0.21$, whereas these same fibers measured in distilled water gave values of $\mu_1 = 0.42$ and $\mu_2 = 0.30$.

FIG. 2
DIFFERENCES IN FRICTIONAL PROPERTIES OF FIBERS FROM A SINGLE KNIT FABRIC



7. Relation of friction to felting, and the effects of chemical agents. In order to determine the effects of shrink-resistant treatments on surface friction and to relate frictional properties to actual felting shrinkage of wool during laundering, a number of tests were made in which the coefficients of friction of wool fibers were measured both before and after the wool had been subjected to various chemical shrink-resistant treatments; laundering tests to determine area shrink-

age of treated and untreated samples were also made. The frictional measurements showed that the fibers became "rougher," that is, their over-all friction increased, but even more important was the fact that the active chemical agent reduced the friction difference by raising the lower (with-scale) coefficient. This is shown in Table II, where values of μ_1 and μ_2, measured in the wet state, are given for untreated fibers and for fibers subjected to increasing concentrations of a chlorination treatment. The reduction in area shrinkage accompanying the decrease in the friction difference is also well illustrated in this table.

TABLE II

EFFECT OF CHLORINE CONCENTRATION ON AREA SHRINKAGE AND FRICTIONAL PROPERTIES

Treatment, % Chlorine	Area Shrinkage,%*	Coefficient of Friction		Friction Difference
		$\mu 1$	$\mu 2$	$\mu 1 - \mu 2$
Untreated	69	0.39	0.19	0.20
5	28	.39	.22	.17
7	12	.44	.36	.08
10	6	.47	.44	.03

* Two hour machine laundering, soap, 150°F.

A convenient way of expressing this change in frictional properties is by two derived quantities, the "friction difference index" and the "friction sum index," defined by the following equations:

$$\text{Friction Difference Index (\%)} = \frac{\mu 1_T - \mu 2_T}{\mu 1_U - \mu 2_U} \times 100, \text{ and}$$

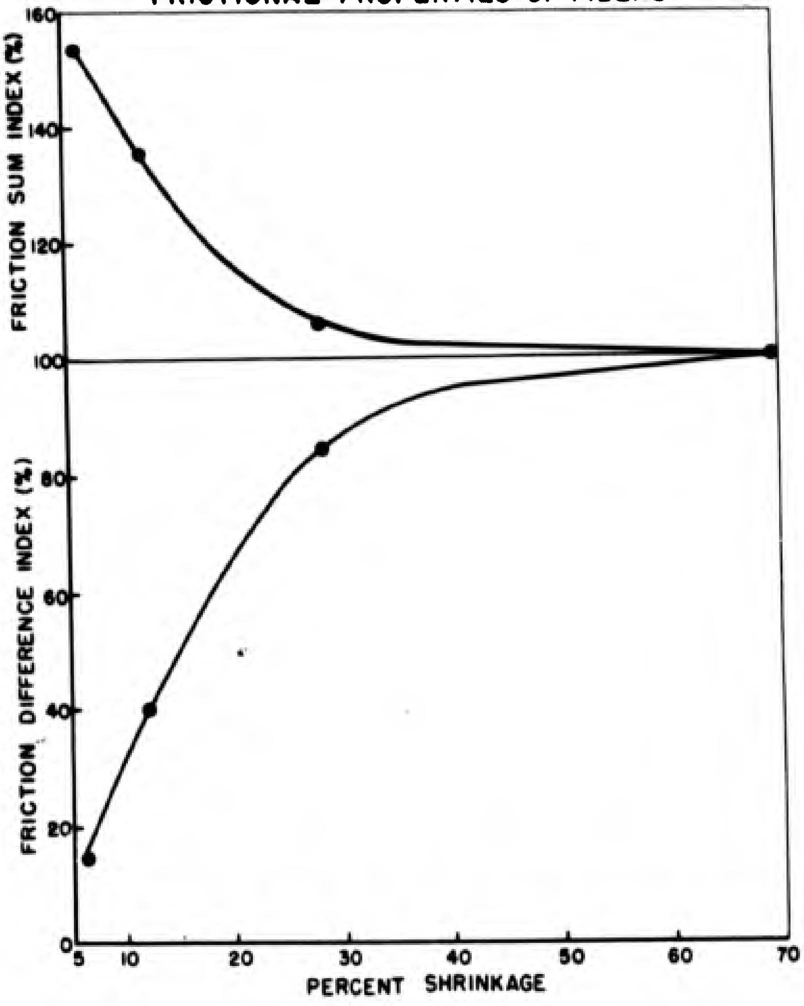
$$\text{Friction Sum Index (\%)} = \frac{\mu 1_T + \mu 2_T}{\mu 1_U + \mu 2_U} \times 100,$$

where T and U identify treated and untreated fibers, respectively.

Figure 3, which illustrates the use of these two quantities calculated from the data given in Table II, shows that shrinkage decreases markedly with decreasing friction difference index, and with increasing friction sum index. However, shrinkage is relatively insensitive to changes in the latter quantity over a substantial range.

FIG. 3

RELATIONSHIP BETWEEN FABRIC SHRINKAGE AND FRICTIONAL PROPERTIES OF FIBERS

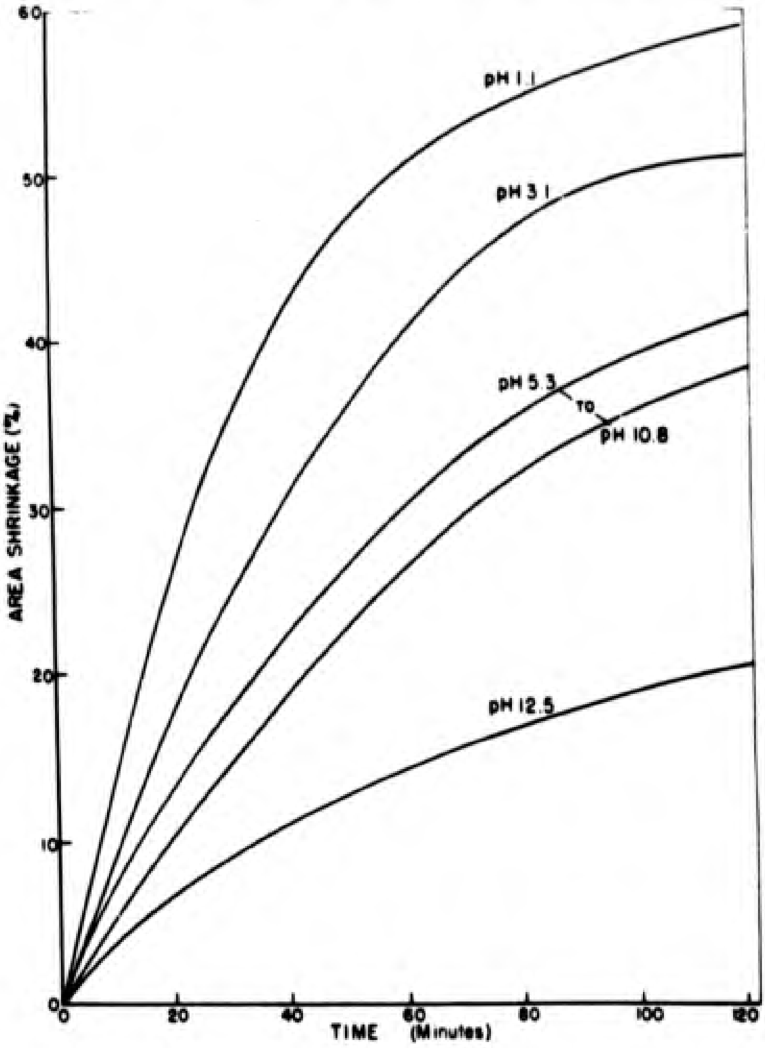


8. Effect of pH on frictional properties and felting. Further confirmation of the relationship between surface friction and felting shrinkage was obtained during an investigation into the influence of

the pH of the wash liquor on shrinkage. In this study swatches of knit fabrics were tumbled for two hours in 6-liter jars containing test solutions adjusted to different pH's but brought to equal ionic strength. The samples were removed from the jars and measured for shrinkage at intervals during the test period; provision was made for maintaining constant pH in the various test solutions. The area shrinkages as a function of time in the different solutions are shown in Figure 4. It is apparent that shrinkage decreases with increasing pH, although there is little difference in the range pH 5 to 10.8.

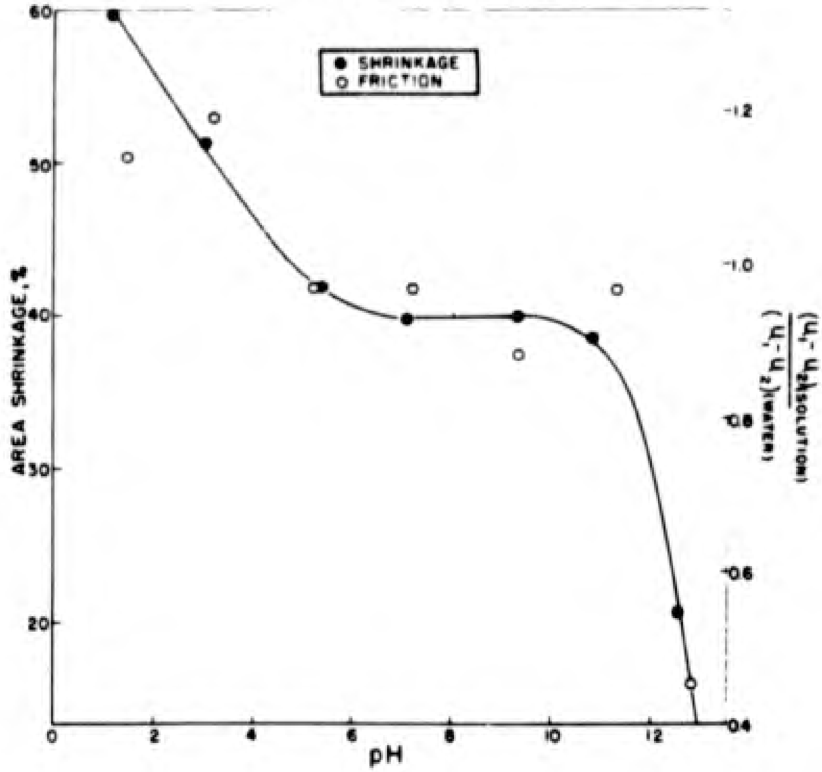
FIG.4

AREA SHRINKAGE OF SWEATER FABRIC AT DIFFERENT pH's



Of particular interest are the curves shown in Figure 5, where extent of shrinkage after two hours tumbling is plotted against pH, and where changes in friction difference of fibers measured in the same solutions used for the shrinkage tests are also plotted against pH. Both curves have the same general shape.

FIG.5
THE EFFECT OF pH ON THE SHRINKAGE OF KNIT SWEATERS AND ON THE FRICTIONAL PROPERTIES OF FIBERS



9. <u>Relation of fabric structure to felting</u>. In addition to the knowledge gained concerning the relationship of surface frictional properties to felting shrinkage, some insight has also been obtained into the influence on felting of another factor -- fabric construction.

It is quite reasonable to expect that felting shrinkage, which results from the preferential migration of fibers, should be affected by yarn and fabric construction. Thus, a sample of mildly-chlorinated wool top may be made to felt readily, because the movement of the fibers is not restrained by twist, weave, or knit. In contrast, a tight worsted fabric made from the top will show a high degree of resistance to felting.

In view of the nature of felting, it might almost be stated a priori that felting would decrease with increased twist, ply, and fineness of yarn, and tightness of weave or knit, since all of these factors would tend to inhibit fiber migration. Indeed, the influence of these factors is well recognized by some knitters and other members of the industry, but the quantitative contribution of each factor to felt-resistance remains largely unknown.

An important study of some quantitative aspects of this problem has been made by W. A. Dutton of the British Wool Industries Research Association. In this work it was shown that loosely knitted wool fabrics, even when made of shrink-resistant yarns, show considerably less dimensional stability than tightly knitted fabrics that were otherwise identical. A comparable study of the effect of knit and other factors on the dimensional stability of cotton knit fabrics is in progress at the Quartermaster Textile Finishing Research Laboratory.

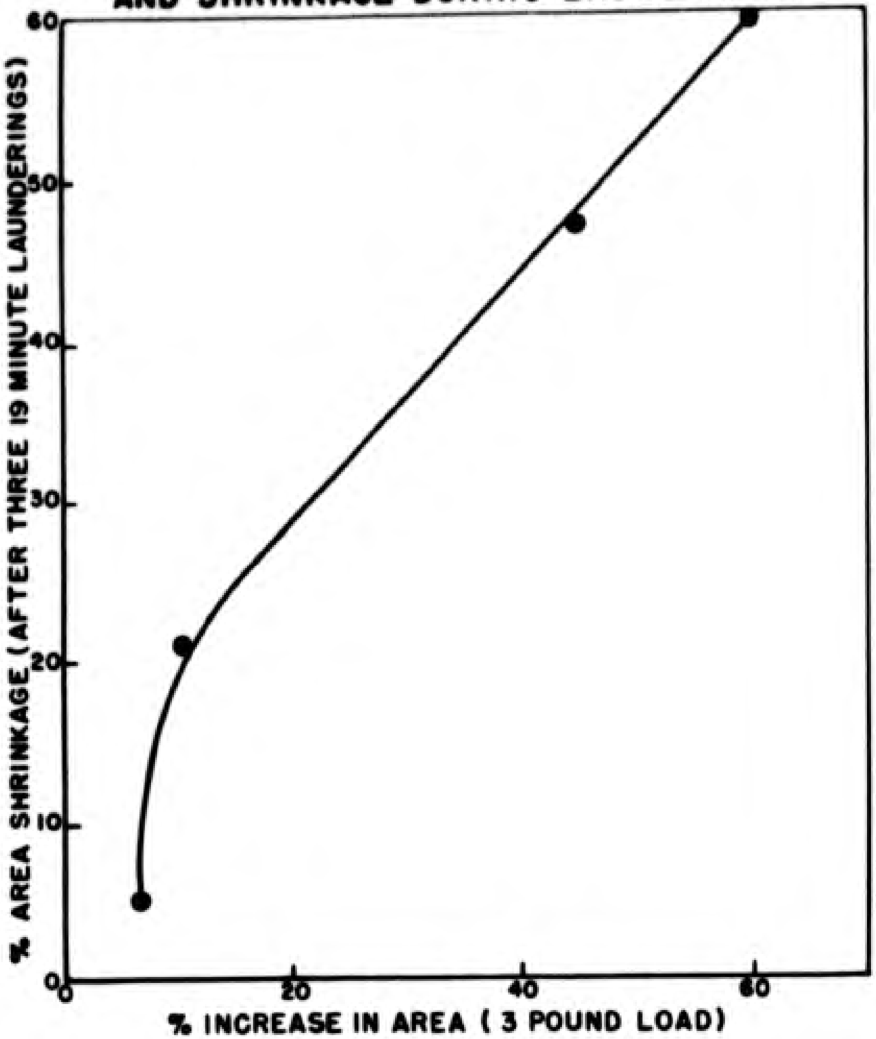
In view of the obvious importance of fabric geometry to felt-resistance, it is believed that a systematic study of this subject should be made, and plans for such a program are outlined at the end of this section. In the course of working with chlorinated and unchlorinated woolens of various constructions, however, a number of preliminary observations concerning the effect of fabric geometry on felt resistance have been made, and these results are presented below as a matter of general interest.

In a study of untreated fabrics conducted at Harris Research Laboratories, it was found that a factor which is closely related to shrinkage during laundering is the ability of the fabric to be deformed. This property was measured by applying a radial load of three pounds to a sample of the fabric and measuring the resulting increase in fabric area. In Figure 6 the total shrinkage caused by three 19-minute Army mobile launderings is plotted against the area increase under a three-pound load. The results are interpreted to mean that in tight, firm (and hence not easily deformed) fabrics, the individual fibers and yarns are well bound in position and are prevented from migrating (and felting) during laundering. It is apparent, however, that the property of deformability must be broken down into twist, ply, weave or knit, etc., for a thorough analysis of the problem.

Examples of the effect of construction on shrinkage have also been observed in a series of tests on Army high neck sweaters which had been made to the same specifications by different manufacturers. The felting shrinkage in five 19-minute Army launderings, together with approximate construction data, are shown in Table III. The results indicate the improvement in shrinkage control arising from increased tightness of knit and from the use of plied yarns. Thus, felting shrinkage on

FIG. 6

RELATIONSHIP BETWEEN FABRIC DEFORMABILITY AND SHRINKAGE DURING LAUNDERING



the collars decreases from 19 to 0 percent (samples C, K, and E) upon increasing the count from 24 x 18 to 24 x 24. Decreasing the ply of the yarns from 2 to 1 (samples D and S) results in increased feltability. In the case of the waistband ribbing, increasing the ply and tightness of knit (samples S, E, and K) results in improved launderability. Sample C, despite the lower count, shows good shrinkage resistance, possibly because of the type of knit -- 2 x 2 rib -- compared to the 1 x 1 rib construction of the remainder of the group.

TABLE III

SHRINKAGE OF ARMY SWEATERS AFTER FIVE 19-MINUTE LAUNDERINGS

Sample Designation	Dimension	Construction[a]	Felting Shrinkage, %
C	Collar (courses)	24 x 18, 2 ply	19
K	Collar (courses)	25 x 21, 2 ply	5
E	Collar (courses)	28 x 24, 2 ply	0
D[b]	Collar (courses)	32 x 32, 1 ply	6
S	Collar (courses)	28 x 26, 1 ply	10
S	Bottom ribbing (courses)	14 x 14, 2 ply	26
E	Bottom ribbing (courses)	16 x 15, 4 ply	10
K	Bottom ribbing (courses)	18 x 15, 4 ply	-3
C	Bottom ribbing (courses)	13 x 14, 4 ply[c]	-3
S	Body length (wales)	10 x 10, 2 ply	37
E	Body length (wales)	12 x 11, 2 ply	31
K	Body length (wales)	11 x 13, 4 ply	29

[a] = Collar and bottom ribbing are 1 x 1 rib knit except ribbing on sample C[c] which is 2 x 2 rib; body is half cardigan construction.

[b] = Shrink-resistant sample; all other are untreated.

Similar improved behavior in laundering is shown in the body of the sweaters through the use of tighter constructions and plied yarns.

Measurements have also been conducted to illustrate the importance of knitting stiffness in chlorinated fabrics. Army high neck sweaters were made from top which had been given moderate and very mild shrink-resistant treatments, and from untreated top for comparison. These sweaters, which were made entirely of yarn of identical construction, contained portions knitted in different ways. The body was knitted relatively loosely, the ribbing at the bottom was more tightly knit, and the neck portion had a still tighter construction. These sweaters were relaxed (they showed quite similar relaxation behavior) and then were given four very severe launderings. The shrinkage data are shown in Table IV. These results suggest that those portions of the sweaters which are relatively tight structures are inherently more resistant to change in dimensions. It seems possible that in addition to the use of shrink-resistant wool in knitted fabrics, minor modifications in construction would be beneficial to dimensional stability.

TABLE IV

FELTING SHRINKAGE OF SWEATERS AFTER SEVERE LAUNDERING

Dimension	Construction (courses or wales per inch)	% Shrinkage during launderings of Sweaters made from top treated:		
		Moderately	Very Mildly	Untreated
Body length	15 courses	10	19	21
Neck width	24 courses	0	7	7
Width underarm	13 wales	-4	13	19
Width at ribbing	18 wales	-3	3	-1

In order to investigate more thoroughly the relationships between type of wool, fabric construction, and dimensional stability, a series of experiments is now under way at Harris Research Laboratories in which wool top has been subjected to mild, "optimum," and severe degrees of shrink-resistant treatment. The top has been spun into yarn of different counts on both the Bradford and French systems, and with varying amounts of twist. Portions of each sample of yarn will be knitted into fabrics employing several types of stitch and using normal, tight, and slack constructions. Both relaxation shrinkage and felting shrinkage in these fabrics will be evaluated and related to degree of shrink-resistant treatment and to yarn and fabric construction. It is expected that data provided by these tests will indicate the best degree of shrink-resistant treatment for different types of Army fabrics and may lead to improved constructions from the point of view of dimensional stability. Results of this study will be reported at a later date.

10. Mode of action of resins. In the course of some exploratory studies of treatments which had been found to modify the felting characteristics of wool, information was obtained which is believed to throw some light on the mode of action of resins in inhibiting felting. Measurements of air permeability and tensile strength were made on fabrics which had been treated with either a latex type resin (R-1) or one of two curing type resins (R-2 and R-3). As indicated in Table V, the tensile strengths of the resin-treated samples showed only minor differences from those of the untreated samples, but the air permeability sometimes showed a significant drop in the treated samples.

TABLE V

TENSILE STRENGTHS AND AIR PERMEABILITIES OF RESIN TREATED FABRICS

Treatment	Air Permeability	Breaking Load	
		Warp	Filling
	ft./min.	lbs.	lbs.
R-1	51	36	34
R-2	46	38	36
R-3	47	37	34
None	56	38	36

The fact that the air permeability of resin-treated fabrics is decreased indicates that at least some of the resin is deposited between the fibers or in the interstices of the fabric. Since no change in the stress-strain properties of the individual fibers was found (which result is contrary to what would be expected if the resin were within the fiber), and since a study of the surface frictional properties indicated no change of the kind found when active chemical agents are used, such as chlorine or caustic soda, it would appear that the resin which is effective in producing shrink-resistance works by bonding the fibers to each other.

The difference in the behavior of the curing and latex type resins on wool is indicated by the following experiments: Two-inch lengths of yarns from resin-treated fabrics were supported by a clamp at one end and at the other end were fastened to the center of a brass rod two inches long and 1/8 inch in diameter. The rod was rotated through a definite angle, released, and its period of vibration determined. The rigidity of the yarns was then calculated from these data with the results shown in Table VI. The increase in the rigidity of the yarn treated with the curing type resins (R-2 and R-3) is in agreement with an assumption that the resin binds the fibers together and that the bond is inelastic; the latex type (R-1) is rubber-like, probably more elastic than wool, and does not cause any restriction to rotation.

TABLE VI

RIGIDITY OF RESIN TREATED YARNS

Treatment	Rigidity (dyne-cm.^{2})
R-1	31
R-2	54
R-3	99
None	34

Section B

TEST METHODS

1. Fiber dimensions and mechanical properties. In the course of any investigation into the felting mechanism of wool, a number of methods must be employed to measure factors related to the phenomenon. For example, at some stage of the work measurements must usually be made of such properties as fiber diameter, strength, and elasticity. Satisfactory apparatus and techniques for securing these data are now fairly well standardized and have been described repeatedly in the literature (including Textile Series - Report No. 46), so they need not be discussed here.

2. Frictional properties. With the realization of the relationship between surface friction and felting, means had to be devised for obtaining accurate and reproducible values for this factor. The apparatus developed by Harris Research Laboratories for this purpose has been described and illustrated above.

3. Determination of fiber damage. As the investigation progressed into the evaluation of the effects of various chemical agents on felting, determinations had to be made of the extent to which other fiber properties were modified or damaged. Two of the most useful tests for fiber damage are the "30% index" and the "alkali solubility" tests. Although these tests were described in the earlier report, their importance in investigations of the felting problem would justify a brief re-statement at this point.

a. The 30% index is the ratio of the work required to stretch a treated fiber to the work required to stretch an untreated fiber, and is so designated because the fibers are stretched, while wet, to 30% over their original length. The lower the 30% index, the greater the degree of damage or modification of the fiber. Although this measurement does not indicate what chemical action has taken place, it affords a very sensitive method of detecting modification in the fibers.

b. Alkali solubility is defined as the percent loss in weight of one gram of wool which has been kept in 100 ml. of N/10 sodium hydroxide for one hour at 65° C., and then rinsed and dried. The greater the increase in alkali solubility of the treated wool over that of the untreated wool, the greater has been the degree of damage or modification. Since treatments with oxidizing agents increase the susceptibility of wool to attack by alkalies, as shown by the work of Harris and Smith, this test has been very useful in detecting chemical damage of this type.

4. Measurement of shrinkage. Since the most serious felting shrinkage results from the laundering of wool fabrics, the evaluation of the effects of chemical agents on the felting tendency must necessarily be based in large part on the performance of treated samples in laundering tests. Although it is obviously desirable to measure shrinkage of the sample under conditions identical with or bearing a known relation to those which will be met in actual use, the choice of testing conditions presents a number of problems. For example, in the course of this project evidence has been obtained that the results of laundering tests for resistance to felting shrinkage may be affected by the following variables: Time of wash cycle, number of successive launderings, volume and temperature of the wash liquor, pH of the wash liquor, nature and concentration of the detergent (and amount of resulting suds), fiber content and piece size of the ballast (blank samples to make up the load), size of load, method of drying, and whether measurements are made on wet or dry samples. It is apparent that "actual use" conditions which may involve so many variables can only be approximated in practicable test procedures. For this reason the several procedures which have been used during this investigation have been chosen because they were believed to be at least as severe as any to which the materials might be subjected in normal use, while at the same time not so strenuous as to lose all relationship to performance in actual use.

a. Fabric shrinkage tests. The earliest laundering procedures employed for fabrics in this project were extremely severe 1- and 2-hour cycles which had been used in the work resulting in the Controlled Chlorination Method. These were eventually replaced by successive launderings according to the Army 19-minute mobile laundering procedure, which was considered to be a more appropriate test. Although 10 successive launderings by this method were first used, the series was later reduced to five after investigations had shown that this number of successive launderings produced reliable and valid results. In addition, an accelerated test method for evaluating shrink-resistant wool has been developed for 10-1/2 oz. wool shirting at the Quartermaster Textile Finishing Research Laboratory; this method is fully described in Textile Series - Report No. 53.

b. Top shrinkage tests. During the course of studies on the effect of the reaction between wool and active chlorine on the felting tendency, it was considered advantageous to investigate the effects of the reaction on wool in the form of top. ("Top" is a manufacturing stage prior to the spinning of worsted yarn, in which the fibers lie approximately parallel in a continuous loose roving.) In order to evaluate the felting shrinkage of treated top by standard laundering procedures, it was necessary to wait for a considerable length of time while the top was spun into yarn and then knitted or woven into a fabric. This procedure was so unsatisfactory that a study was initiated to devise a method for determining felting shrinkage in the top itself.

Such a top shrinkage test was ultimately developed and has proved to be of great value because of its simplicity and speed in yielding reliable data, and because of the good correlation found between top shrinkage results and results of laundering tests ultimately made on the fabric into which the top is manufactured.

Briefly, the top shrinkage test involves placing a 12-inch length of top in a cheese-cloth sack of similar dimensions, sewing the top to the sack at points one inch from each end, wetting the sample in a buffer solution at pH 6, and measuring the distance between the sewed points. The sample is then tumbled for 10 minutes at room temperature in a six-liter jar containing one liter of a buffer solution at pH 6, and the distance between the sewed points is again measured on the wet sample. (The tumbling apparatus used is similar to that employed for the Dynamic Absorption Test described in Federal Specification CCC-T-191a, Supplement, October 8, 1945.)

The fact that top shrinkage results correlate well with shrinkage values on fabric from the same top, as mentioned above, is illustrated by the data in Table VII. The values in this table were obtained on sweaters and socks made from portions of top which had been treated with varying concentrations of chlorine. It should be noted that the values for top shrinkage are consistently much higher than the corresponding fabric shrinkage value. This is characteristic of the relationship between top shrinkage and fabric shrinkage, although the actual proportion between the values will vary, depending primarily upon the structure of the fabric.

Table VII also contains evidence of the effect of the type of drying on felting shrinkage. It can be seen that the socks which were tumble dried between launderings gave higher shrinkage values than those which were air dried. This indicates that the mechanical action in the tumble drying contributes to felting.

TABLE VII

RELATIONSHIP OF TOP SHRINKAGE TO FABRIC SHRINKAGE IN SOCKS AND SWEATERS LAUNDERED BY ARMY 19-MINUTE TESTS

Top Sample[a]	Top Shrinkage,%	Shrinkage in laundering after	
		1 test,%	10 tests,%
		Socks - Air Dried	
A	17	-3.8	-2.5
B	19	-0.5	-0.4
C	23	0	1.4
D	30	2.2	5.5
E	47	0.6	12.6
		Socks - Tumble Dried	
A	17	-0.5	1.2
B	19	-0.4	2.6
C	23	1.0	3.8
D	30	0.2	8.0
E	47	1.1	14.1
		Sweaters[b] - Air Dried	
A	17	-4	-2
B	19	0	-2
C	23	2	7
D	30	0	8
E	47	3	23

a = Samples A through D were subjected to decreasing chlorine concentrations, in that order; sample E was the untreated control.

b = Values are averages for shrinkage in neck, width, length and sleeve.

Section C

INVESTIGATION OF THE VARIABLES INVOLVED IN THE REACTION BETWEEN WOOL AND ACTIVE CHLORINE

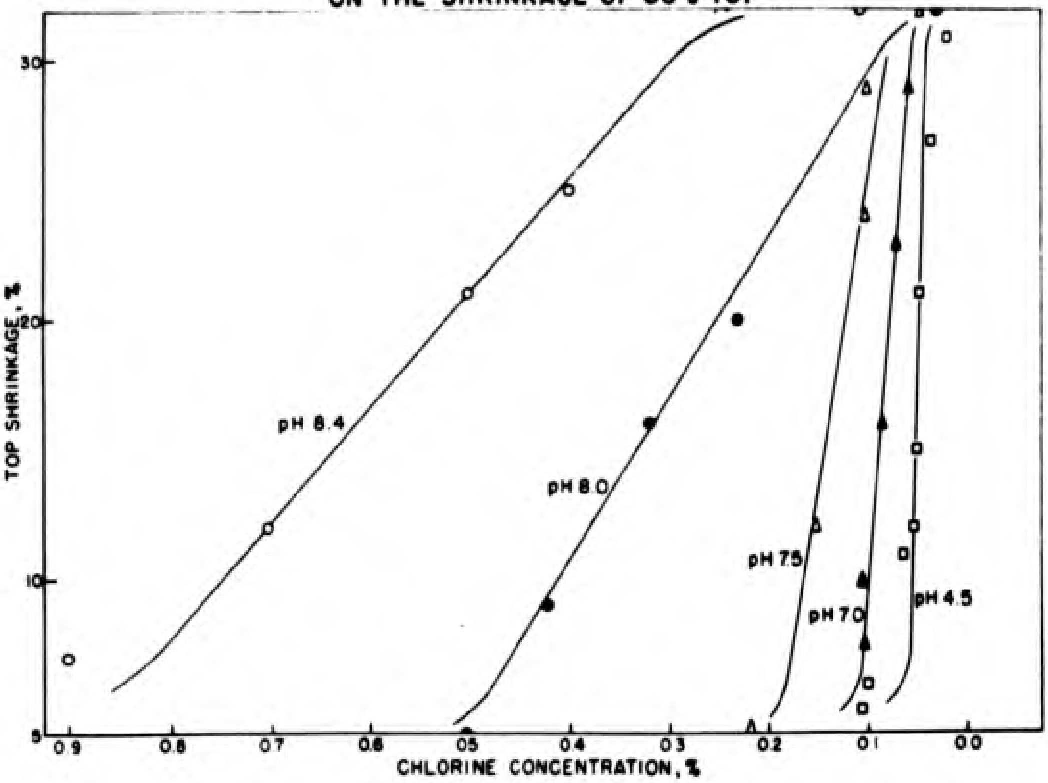
The results obtained in earlier work in this laboratory, as well as a survey of the literature, showed that the reaction between wool and active chlorine is extremely complex and varies markedly with the experimental conditions. Since no adequate investigation had been made of the effects of the several variables, it was decided to initiate a study of this type in order to elucidate the details of the reaction. The primary purpose of the work was to study the fundamentals of the reaction, and particularly the effect of pH, time, chlorine concentration, etc., on its course. Since the alkali solubility test has been shown to be a useful index of oxidative modification of wool, this measure was widely used to follow the effects of the reactions. A point of particular interest which has been studied concerns the effect of blending varying proportions of chlorinated and untreated fibers on the shrink-resistance of the blend.

Concomitantly with the observations of fundamental significance mentioned above, measurements were made of the strength, color, resilience and other properties of the wool of industrial significance, because of their general interest.

1. Effects of varying chlorine concentration, pH, temperature and time. It was anticipated that control of these four factors would be of primary importance in achieving surface modification of wool without also causing damage to the cortex or interior portion of the fiber. Accordingly, a large number of experiments were performed in which wool in the form of top and knitted and woven fabric was subjected to the action of available chlorine at different pH values, temperatures, concentrations of chlorine, and for varying times. The resistance to felting, alkali solubility, and other properties of the chlorinated samples were then examined. Examples of the results are presented below. In general, the data confirm the belief that the rate and extent of the reaction change markedly with change in experimental conditions, and indicate that precise control of these conditions is required if the reaction is to be reproducible.

a. Effects of chlorine concentration and pH on resistance to felting. Typical data relating the felt-resistance of top to pH and chlorine concentration of the reaction are presented in Figure 7. These results reveal the very marked sensitivity of the reaction to chlorine concentration in the acid region. Thus, within the pH range 4.5 to 7.0,

FIG. 7
EFFECT OF TREATMENT AT VARIOUS CHLORINE CONCENTRATIONS & pH VALUES ON THE SHRINKAGE OF 60's TOP

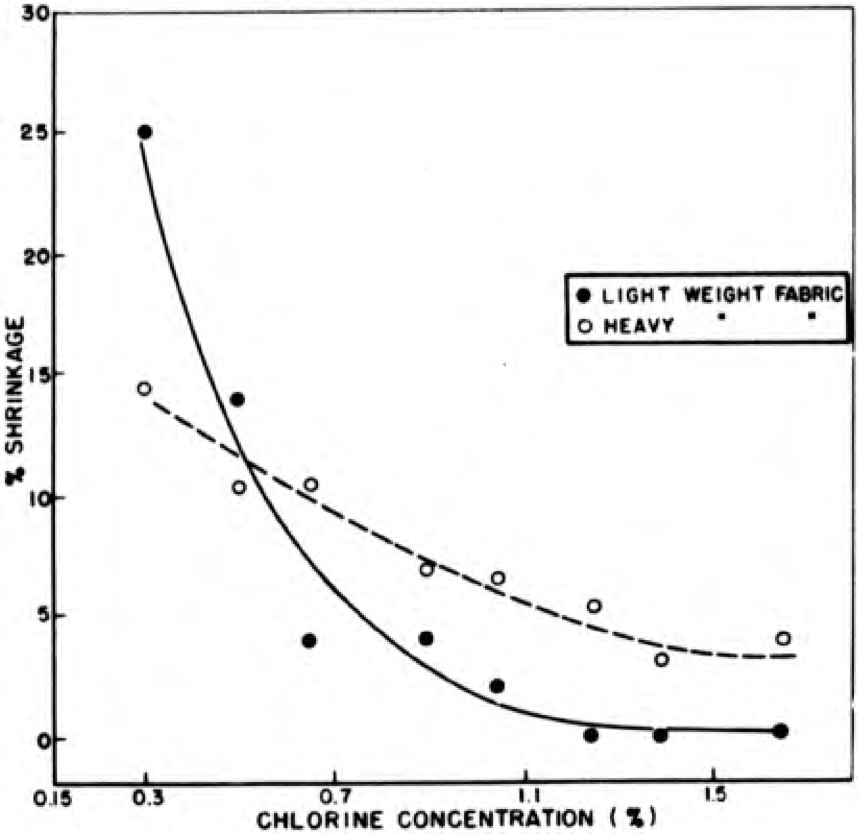


a change of chlorine concentration of as little as 0.05% produces the maximum change in top shrinkage value obtainable with this wool. In marked contrast are the results at pH 8.0 and 8.4, where the change in feltability is less sensitive to concentration by a factor of about ten. Conversely, the data indicate that the top shrinkage values are exceedingly sensitive to pH in the alkaline region, but are appreciably less pH-sensitive at pH 4.5.

Analogous data describing the effect of chlorine concentration on the felting resistance of a heavy and a light fabric treated at constant pH in the alkaline region are presented in Figure 8. These results confirm the sensitivity of shrink-resistance to concentration of available chlorine, and show that for these conditions a two-fold change in time produces approximately the same effect as an increase in chlorine concentration of 0.1%.

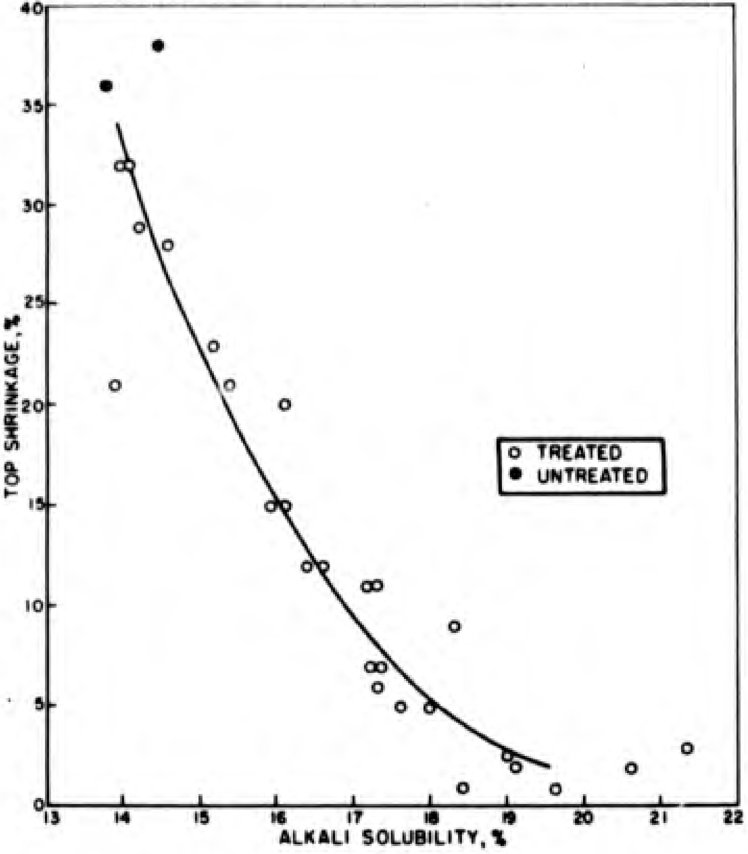
FIG. 8

EFFECT OF CHLORINE CONCENTRATION ON WARP SHRINKAGE OF DIFFERENT WEIGHT FABRICS IN FIVE-19 MINUTE LAUNDERINGS



b. Effect of conditions of treatment on fiber modification. It has long been known that chlorination of wool produces oxidative modification of the fiber, and it is of interest to examine the degree of modification as a function of the conditions of reaction. Data relating to this point for a variety of short-time alkaline chlorinations are presented in Figure 9. These results for top portray the alkali solubility (which is taken as a measure of oxidative modification) as a function of the top shrinkage value (or felt-resistance). The results of these measurements indicate that, to a first approximation and for short-time chlorinations in the alkaline range, there is a fixed amount of fiber modification which corresponds to a given degree of felt-resistance, regardless of the conditions of chlorination. Corresponding data for top chlorinated in the acid region at pH values as low as 4.5 have been obtained which are in complete agreement with the preceding data.

FIG. 9
RELATIONSHIP OF TOP SHRINKAGE TO ALKALI SOLUBILITY FOR A VARIETY OF SHORT-TIME TREATMENTS



c. <u>The effect of variation of time of chlorination</u> of fabric in the alkaline region is shown in Table VIII. These results indicate that the reactions conducted at longer times have a tendency to lower the strength of the wool, presumably because of attack of the cortex; this result is confirmed by the data presented in Table IX. The graphs in Figure 10 show some of the inter-relationships between time of chlorination, percent of available chlorine, and shrink-resistance of wool fabric. As might be expected, the shrinkage resistance is increased by longer times of reaction or increasing concentrations of chlorine, the latter relationship being approximately linear.

TABLE VIII

PROPERTIES OF FLANNEL FABRIC CHLORINATED FOR VARYING TIMES

Sample No.	Treating Conditions		Area Shrinkage[a]	Warp Breaking Strength Change[b]	Change in Yellowness Index[c]	Alkali Solubility	
	Time	Initial Chlorine Concentration				Value	Change[d]
		%	%	%	%	%	%
1	30 min.	0.18	14	+3.7	Y 24	13.2	3.1
2	30 min.	.23	9	-2.3	Y 56	14.4	4.3
3	30 min.	.27	6	-2.2	Y 66	14.4	4.3
4	30 min.	.46	-1	-4.6	Y 92	--	--
5	30 min.	.62	-1	-8.3	Y 98	--	--
6	3 min.	0.18	12	+5.0	Y 4.6	13.8	3.7
7	3 min.	.23	6	+5.8	Y 14	12.7	2.6
8	3 min.	.28	3	+1.2	Y 46	13.8	3.7
9	3 min.	.42	-1	+6.2	Y 52	--	--
10	3 min.	.81	-1	-1.7	Y 93	--	--
11	3 min.	1.0	-1	-14.6	Y 96	--	--
12	1 min.	0.62	0	+4.6	Y 39	--	--
13	1 min.	.87	-1	+4.6	Y 62	--	--
14	1 min.	1.2	-1	+5.9	Y 86	--	--
15	13 sec.	1.0	3	+2.2	W 13	--	--
16	13 sec.	1.4	0	+1.2	W 2.7	--	--
17	13 sec.	1.8	-1	+9.6	W 15	--	--
18	6 sec.	1.1	1	+2.9	W 12	12.5	2.4
19	6 sec.	1.4	-1	+2.5	W 25	12.9	2.8
20	6 sec.	1.7	-1	+8.8	W 4.6	14.8	4.7
21	6 sec.	3.0	-1	+20.0	W 3.3	--	--
22	3 sec.	1.5	8	+12.5	W 14	--	--
23	3 sec.	1.8	1	+10.0	W 4.0	--	--
24	3 sec.	2.1	-1	+10.0	W 13	--	--
25	3 sec.	2.4	0	+11.7	W 13	--	--
26	Untreated control		50	0	0	10.1	--

a = In five 19-minute launderings.
b = Plus sign indicates strength increase, negative sign indicates strength loss.
c = As measured with the Hunter Reflectometer; Y indicates fabric is yellower than untreated, W indicates whiter.
d = Absolute

TABLE IX

EFFECT OF TIME OF CHLORINATION ON STRENGTH AND AREA SHRINKAGE OF LIGHTWEIGHT FLANNEL

Treating Time	Initial Chlorine Concentration	Area Shrinkage During Five 19-min. Launderings	Breaking Strength Change
	%	%	%
6 sec.	2.0	0	+1
13 sec.	1.75	-1	+2
20 sec.	1.65	-1	-2
27 sec.	1.4	-2	+0.5
3 min.	0.18	14	-9
30 min.	0.18	20	-6.5

d. The effect of temperature of short-time chlorination of top in the alkaline region is shown in Table X. Approximately 1% decrease in top shrinkage results from an increase in temperature of 1°C. This result has been found to prevail rather generally in a variety of laboratory experiments within the range 15 to 30° C. Corresponding results for fabric are shown in Table XI, which also suggests that fiber modification increases slightly as the temperature is raised to 35° C.

TABLE X

VARIATION IN TOP SHRINKAGE WITH TEMPERATURE OF TREATING BATH

Temperature	Top Shrinkage	
	60's	64's
°C	%	%
15°	24	20
25°	12	10
30°	6	4

FIG. 10

SHRINKAGE DURING LAUNDERING (2 HOUR TEST) AS A FUNCTION OF THE CONCENTRATION OF AVAILABLE CHLORINE AT VARIOUS TIMES OF TREATMENT

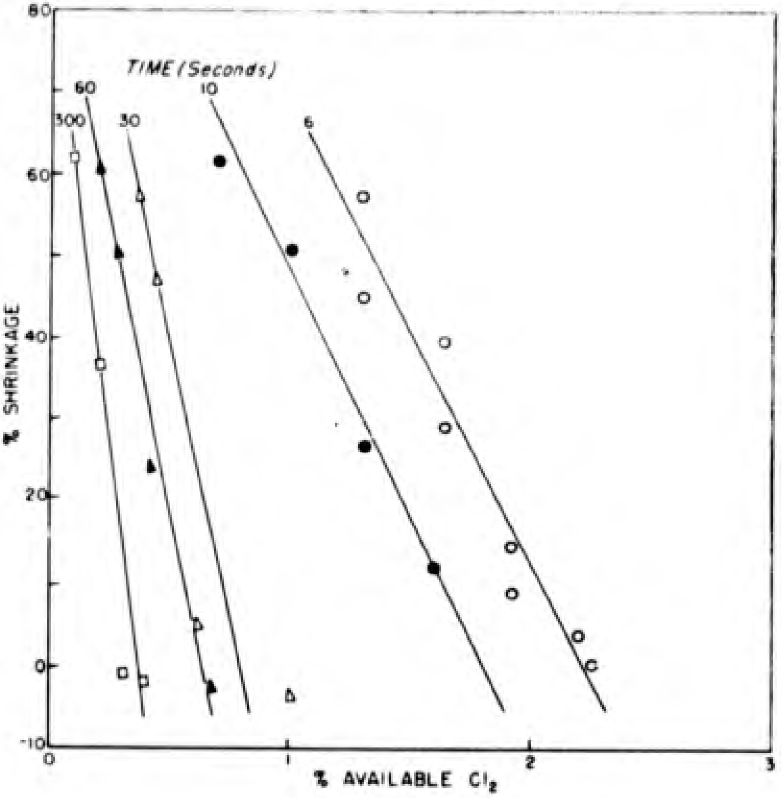


TABLE XI

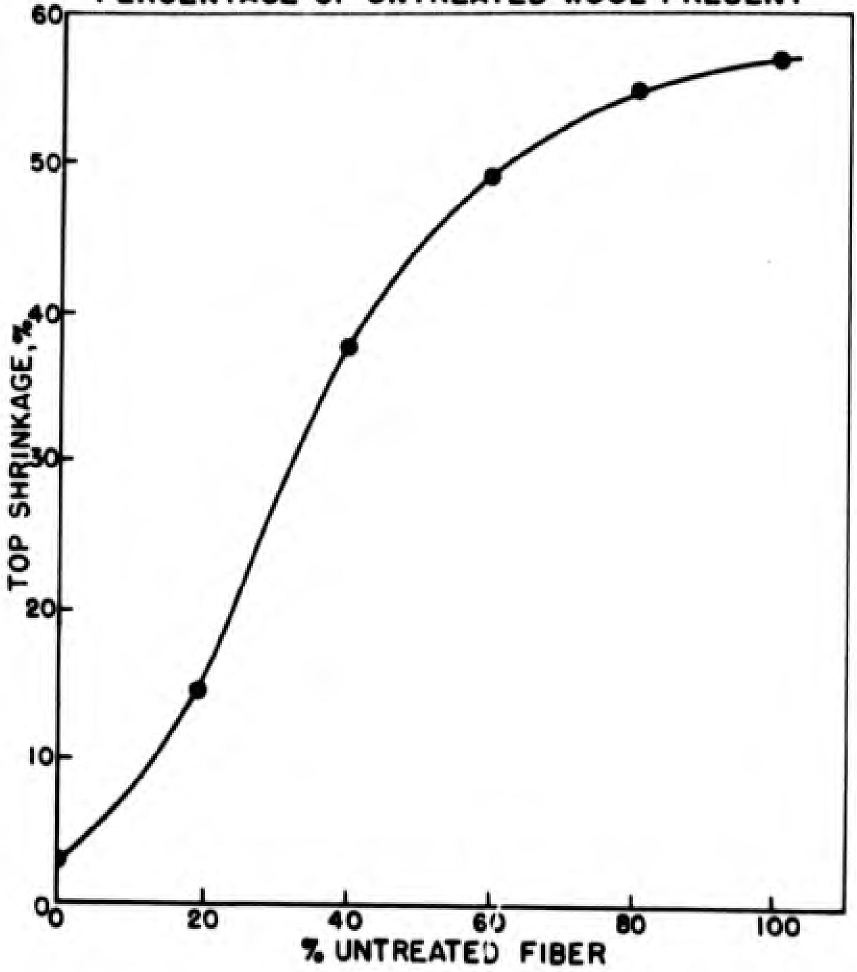
SHRINKAGE AND ALKALI SOLUBILITIES OF FABRICS TREATED AT THREE DIFFERENT TEMPERATURES

Temp. of Treatment	15°C.		25°C.		35°C.	
	*Shrinkage,%	Alk. Sol.,%	*Shrinkage,%	Alk. Sol.,%	*Shrinkage,%	Alk. Sol.,%
Flannel, Lightweight	42	12	33	12.5	8.6	15.5
Blanket	2.7	9.5	1.1	10	1.5	11

*Shrinkage data obtained on fabrics by the 2-hour laundering test.

FIG. 11

THE SHRINKAGE OF TOP AS A FUNCTION OF THE PERCENTAGE OF UNTREATED WOOL PRESENT



Section D

MISCELLANEOUS EFFECTS OF ACTIVE CHLORINE ON THE PROPERTIES OF WOOL

It has long been recognized that the reaction with active chlorine may produce fundamental modifications in the physical and chemical properties of wool which make it a less desirable textile fiber. Some of these effects, such as loss in weight during the reaction, increased solubility in alkali, decreased elasticity of form, etc., have been discussed in some detail in Textile Series - Report No. 46. It is reasonable to expect, however, that if the reaction of wool and chlorine could be limited primarily to the cuticle of the fiber, these secondary effects could be minimized. With this in mind, samples of wool were treated with solutions of active chlorine in the alkaline region for short periods of time, and the effects of the treatment on the fiber properties were measured.

1. Effects on weight and regain. The results shown in Table XII indicate that short-time alkaline chlorination of fabric produces a very small increase in weight, both when the fabric is conditioned at 65% relative humidity and in the bone-dry condition. Most of the weight increase at 65% relative humidity is caused by an increase in regain. Since the very small gain in weight in the dry condition is not paralleled by an increase in ash content, it is perhaps attributable to the slight oxidation accompanying the chlorination. Thus, the raising of some of the cystine groups to a higher state of oxidation at the surface of the fiber would account for a small gain in weight.

Results of a comparable experiment conducted on top are presented in Table XIII. In this experiment all of the changes in weight were very small, and of the order of magnitude of the experimental error. The very slight difference between the results on fabric and on top may perhaps result from the small loss of fiber inherent in the handling of wool in the top form.

2. Effects on strength, hand, thickness, compressional resilience, and compressibility. Among the most important attributes of wool fabrics in such applications as wearing apparel and blankets are the mechanical properties of strength, resilience, compressibility, thickness, etc. In addition to their effects on insulative, shape-holding, and wear-resistant qualities, many of these mechanical properties contribute to the hand of the material. Although no completely satisfactory objective method of measuring hand has been developed, the hand of different fabric samples can ordinarily be compared subjectively by experienced persons with a high degree of reproducibility of judgements. However, many of

TABLE XII

THE CHANGE IN WEIGHT, REGAIN AND ASH CONTENTS OF WOOL FABRICS TREATED BY SHORT-TIME CHLORINATION

Treatment*	Regain	Gain in Weight at 65% R.H.	Gain in Weight on a Bone Dry Basis	Ash Content on a Bone Dry Basis
	%	%	%	%
		White Worsted Fabric		
none	13.4	---	---	0.43
1	15.0	2.0	0.50	0.20
2	14.7	2.0	0.84	0.42
3	15.7	2.1	0.0	0.06
		O.D. Flannel		
none	12.2	---	---	0.80
1	14.9	3.2	0.75	0.65
2	14.8	3.1	0.72	0.84
3	15.5	2.9	0.03	0.74

* Treatment 1 = Buffered hypochlorite solution containing wetting agent, bisulfite antichlor, and rinse.

Treatment 2 = Wetting agent solution, bisulfite antichlor, and rinse.

Treatment 3 = Wetting agent solution and rinse.

TABLE XIII

CHANGE IN WEIGHT OF WOOL DURING CHLORINATION

Initial Weight of conditioned wool top, grams	2255
Moisture content, %	15.0
Petroleum ether extract (grease), %	2.0
91% isopropanol extract (soap), %	1.4
Initial weight of clean, dry top, grams	1839
Weight of conditioned top after chlorination, grams	2218
Moisture content, %	14.5
Petroleum ether extract (grease), %	1.1
91% isopropanol extract (soap), %	1.0
Weight of clean, dry, treated top, grams	1850
Increase in weight due to treatment, %	0.60
Estimated free bisulfite in treated wool, %	0.36
Estimated total bisulfite in treated wool, %	0.70
Change in weight of wool due to treatment	
Correcting for free bisulfite, % increase	0.22
Correcting for total bisulfite, % decrease	0.11

the mechanical properties can be measured individually by objective methods.

Table XIV shows typical values obtained in tests of the strength, thickness, compressional resilience, and compressibility of Army blankets which had been subjected to a short-time chlorination, compared with untreated but otherwise identical blankets. No differences in hand were observed between the treated and untreated blankets. The small difference in mechanical properties between the un-napped treated and untreated samples may be attributed to the mechanical handling of the fabrics during the reaction; when the chlorinated and untreated samples are subjected to the napping operation, differences between the two sets almost disappear.

TABLE XIV

THE MECHANICAL PROPERTIES OF ARMY BLANKETING SUBJECTED TO SHORT TIME CHLORINATION

Condition	Breaking Strength Warp	Breaking Strength Filling	Thickness at 0.1 $\frac{lb}{in^2}$	Compressional Resilience	Compressibility
	lbs.	lbs.	inches	%	$(Inches)^2/lbs.$
			Un-napped Blanketing		
Untreated	44	50	0.084	39	0.13
Treated	47	50	0.094	36	0.17
			Napped Blanketing		
Untreated	40	28	0.170	23	0.26
Treated	44	28	0.176	28	0.26