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The Relationship Between the Structural Geometry of a Textile Fabric and Its Physical Properties

Part III: Textile Geometry and Abrasion-Resistance*

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Abstract

This paper examines the relationship of structural geometry to the abrasion-resistance of textile fabrics. It is pointed out that the durability of a fabric can be significantly altered by modifying its structural design, without change in the fiber used in its manufacture. Earlier textile studies and heretofore unpublished Army test reports provide illustrations of the relationship between fabric geometry and durability. On the basis of this material, it is believed that lower rates of attrition can best be obtained by increasing the geometric area of contact between fabric and abradant. At the same time, fabric compliance and yarn mobility must be preserved at points of contact between the two rubbing surfaces. Thicker fabrics possessing minimum rates of attrition, consistent with other cloth requirements, will provide optimum durability for fatigue garments.

Abrasive Pressure and Textile Geometry

The nature of metallic wear and the mechanism of textile fabric abrasion are similar in that the rate of destruction of both materials increases with higher normal loads between abradant and test specimen. This similarity may arise from the same or different causes, depending upon the nature of the rubbing. When the abradant has a rough surface and is significantly harder than the metal or textile sample, increased rubbing pressures will cause the sharp protuberances of the abradant to penetrate more deeply into the test specimen, and in this manner the higher abrading load will increase the plowing damage. When the protuberances of the abradant are large and sharp, the abrasion mechanism takes on the aspects of surface cutting. On the other hand, when the rubbing surface is relatively smooth, wear may take place through the mechanism of successive local adhesions and adhesion ruptures between protuberances of the two rubbing surfaces. This type of damage, termed "direct frictional wear," is also dependent upon normal loads between rubbing surfaces. This dependence is due to the fact that higher intersurface loads demand larger areas of true contact between the two bodies, and thus lead to increased total damage. Briefly, in the former instance higher loads cause deeper damage over the same areas, while in the latter case they result in a greater area of damage of the same depth.

Both of these mechanisms have been discussed in Part II of this series (July, 1951, TEXTILE RESEARCH JOURNAL) and they can be observed in the service life of both metals and fabrics. In the case of machinery metals, the discussion of wear is usually limited to the adhesion mechanism, as studied by Bowden and Tabor [2]. In the case of textile materials, however, the range of rubbing surfaces encountered during the service life of the end item is such that both frictional and plowing or cutting (as well as snagging) damage must be considered. In Part II it was also pointed out that frictional adhesion at the cloth surface may result in secondary damage to the fabric which far exceeds the direct effects of frictional wear. This indirect damage is caused by transmittal of frictional forces along the length of the surface fibers, and is evidenced in tensile or bending fatigue of the fiber, or in its removal from the yarn structure

It is clear that one way of cutting down the wear between rubbing surfaces is to reduce the normal loads between them. However, when intersurface

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loads are fixed, the designer of durable materials must resort to other methods of reducing wear. In the case of metal, he will smooth and polish both rubbing surfaces and then add a lubricant (with proper bearing design) so as to support the load by means of hydrodynamic pressures rather than by metal-to-metal contact. The smoothing of the bearing surfaces is not intended to increase the area of contact between the surfaces and thus reduce local pressures, but is principally a precaution against gouging by rough spots on either surface. Actually, it has been shown that the true area of contact between two metal bodies (of given hardness), which may be of the order of one-thousandth the apparent or geometric area of contact, is dependent only upon the normal loads between the surfaces. This dependence arises from the fact that the contact points comprising the true area are generally deformed plastically. The bulk rigidity of the metal is so high that the local plastic deformation takes place and the intersurface load is supported by a constant flow pressure over a very small area *before* a large number of points can come into contact.

Burwell [3] pointed out that the bulk flexibility of visco-elastic materials permits numerous protuberances to come into contact before the load between surfaces is completely supported, and this is accompanied by a load reduction at each such contact point. As a result, the proportion of points undergoing plastic deformation will be considerably reduced. The geometric area of contact of individual fibers has been studied by Finch [12], and has been shown to depend upon the normal load at the point of contact, the principal curvatures of the fiber, the contour of the fiber cross section, and the fiber bulk modulus. With fabric structures, bulk modulus is a major factor influencing contact area under a given load. Actually, the apparent bulk modulus of the fabric as affected by the compressibility of its backing support during use must be taken into consideration. A low apparent bulk modulus, or high over-all flexibility, serves to bring as many yarn crowns in geometrical contact with the abrasive surface as is consistent with the fabric structure. The more numerous the crowns in contact and the more area per crown or per projecting yarn float, the less will be the local load at a fiber point. As local load is reduced, the true area of contact at each point is also reduced, and the abradant protuberance will descend into the yarn structure to a lesser degree. As a result, there will be less frictional wear at the local point of contact; less local frictional-resistance to develop axial components of fiber stress; reduced surface cutting of the fibers; and less fiber plucking, slippage, and tensile fatigue. It should be noted that high bulk flexibility of a textile fabric tends to amplify the *total* frictional-resistance observed when a foreign body is rubbed across the cloth because of the increase in total contact area, even though the frictional-resistance at each local point of contact may be reduced. The number of local contact points between fabric and abradant is affected by several geometric factors, each of which is discussed separately below.

Textile Structure and Local Pressures

Threads per Inch

When all other factors are held constant, the abrasion-resistance of warp-flush fabrics is improved by increasing the number of warp crowns per square inch of fabric, thus reducing the normal load per warp crown [27, 29, 30, 47, 49]. This same trend is observed in fabrics varying in weave and yarn diameters, as is indicated in the work of Tait [52] (summarized in Figures 1 and 2). Combat-course tests [41, 53, 59] have likewise shown the effect of warp threads per inch on the durability of a herringbone-twill cotton work garment. In Table I it is seen that a fabric with actual textures of 88 × 59 t.p.i. wore better than one with 77 × 59 t.p.i.; that 89 × 49 fabric wore better than 76 × 48; that 88 × 59 wore better than 89 × 49; that 77 × 59 wore better than 76 × 48. On the other hand, the 82 × 54 fabric wore more poorly than the 77 × 59, but better than the 76 × 48.

While several of the wear-score differences cited above lack precise statistical significance, there is sufficient evidence in the data of Table I and of Figures 1 and 2 to support the following general conclusions: In constructing twill or sateen fabrics with warp yarns exposed at the surface of wear: (1) increased warp textures (at constant pickage) will furnish greater durability; (2) increased filling textures (with a constant number of ends) result in increased fabric cohesion and greater fabric durability.

There are, of course, certain limitations to these conclusions which must be kept in mind in the design of more durable fabrics. If changes in warp crowns are to have an effect on cloth durability,

TABLE I. LABORATORY DATA, CAMP LEE SERIES*

	Group I—Nylon			*Group II—Weave*					*Group IV—Texture (nominal)*					*Group V—Yarn Count*				Standard
	0%N	23%N	50%N	HBT	HBT, M	Plain	Oxford	Sateen	84× 55	84× 45	78× 50	72× 55	72× 45	10× 8	10× 12	16× 8	16× 12	HBT
Fabric No.→	111	114	117	100	103	104	107	112	24	28	31	34	38	15	17	54	56	
Texture (threads/in., actual)																		
Warp	84.1	84.6	84.0	81.3	82.1	81.5	84.9	85.5	88.2	89.1	81.8	76.9	76.1	75.6	76.8	75.6	79.6	76
Filling	62.8	65.3	65.1	53.7	54.9	52.4	53.7	60.6	59.4	49.0	54.3	58.5	47.7	57.0	59.5	59.9	60.9	46
Weight (oz./sq.yd.)	10.2	10.6	10.0	9.9	10.1	9.2	9.7	10.5	10.5	9.7	9.8	10.2	8.7	12.2	10.4	9.8	8.5	8.9
Breaking load (lb.)																		
Strip, Warp	127	124	125	116	116	103	126	101	120	109	112	104	114	118	131	96	97	127
Filling	106	111	108	112	102	121	128	83	116	87	99	111	89	144	97	149	90	87
Grab, Warp	154	150	149	150	148	148	156	152	180	171	156	146	142	199	191	126	115	140
Filling	136	144	122	118	121	140	147	132	157	104	126	146	104	203	113	190	104	146
Elongation, Grab (%)																		
Warp	22.3	24.7	23.8	30.5	31.4	27.2	27.3	25.2	32.2	31.5	34.9	27.0	25.2	32.2	37.3	29.7	26.3	17.7
Filling	24.8	26.5	26.9	20.8	22.6	18.2	23.5	27.4	19.7	18.1	21.4	24.4	20.0	22.5	20.1	24.4	25.3	21.7
Tearing strength (lb.)																		
Tongue, Warp	10.7	10.9	9.3	6.4	6.0	4.5	7.4	10.4	6.3	7.7	6.6	5.9	7.8	7.1	7.6	4.2	4.8	3.8
Filling	7.7	8.1	10.7	4.8	4.9	4.1	5.2	8.4	4.8	5.5	5.6	6.2	5.8	7.1	4.3	7.6	5.2	4.9
Elmendorf, Warp	10.9	11.7	11.5	7.9	7.9	5.5	7.9	12.3	7.1	8.0	7.6	6.7	8.6	7.7	8.2	5.7	6.0	5.9
Filling	12.0	9.4	12.6	6.8	6.2	6.3	6.5	9.2	7.6	6.4	8.4	7.7	9.2	8.7	6.1	10.2	7.7	7.5
Bursting strength																		
Mullen (p.s.i.)	345	311	340	283	284	287	289	348	298	266	282	314	256	402	267	318	260	315
Ball (lb.)	249	264	271	219	175	213	199	237	227	177	263	226	208	302	177	210	219	178
Stiffness (0.001 lb.)																		
Warp	3.1	3.5	4.1	4.4	4.9	3.7	3.5	4.7	10.6	5.7	4.3	6.1	3.6	10.2	8.1	4.3	3.2	3.8
Filling	3.6	3.7	2.1	3.1	4.4	4.4	2.6	2.7	6.5	2.9	3.5	3.8	2.2	7.9	4.7	4.4	2.5	3.6
Thickness (0.001 in., 3.63 p.s.i.)	26.4	27.4	26.5	23.3	23.6	19.5	20.6	29.1	22.6	24.8	23.6	22.4	21.6	25.6	23.3	22.9	20.7	19.5
Camp Lee wear score 9th cycle, trousers	8.3	4.9	5.0	33.2	26.1	40.2	29.6	14.5	51.3	56.0	61.2	54.4	67.3	20.8	16.0	29.1	31.3	
Standard control HBT wear score	18.0			40.3					47.4					23.0				

* It will be noted that the wear score of the standard HBT control fabric varies from test run to test run on the combat course, as summarized in Table I. While caution was used in applying techniques of experimental design and statistical interpretation to insure the validity of data from single test runs, there were certain conditions which could not be controlled from run to run. For example, the men assigned as test subjects were changed between runs, and the over-all weather conditions also changed. Considerable time was spent in determining to what extent fabric ranking would vary from run to run. After a careful procedure was inaugurated for screening maverick test subjects prior to each run, it was found that the significant ranking of fabrics was unchanged from run to run, and this enabled the investigator to subsequently use the control results as a weighting factor to compare fabrics among groups (corresponding to runs) as well as within groups.

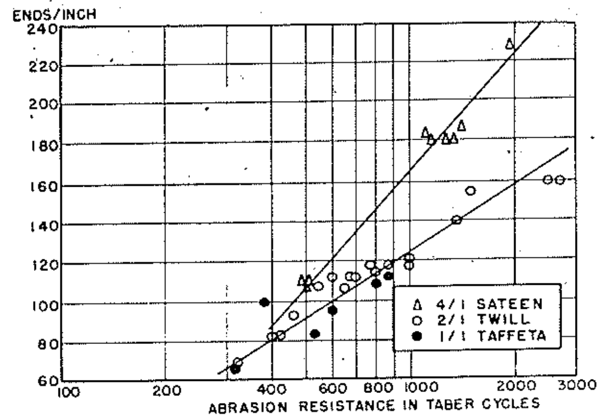

FIG. 1. *Effect of weave on the abrasion-resistance of rayon linings. Fabrics were made of 150-den., 40-filament yarn, warp and filling. Fabrics were viscose or viscose-acetate combinations. (Source, Tait* [52].)

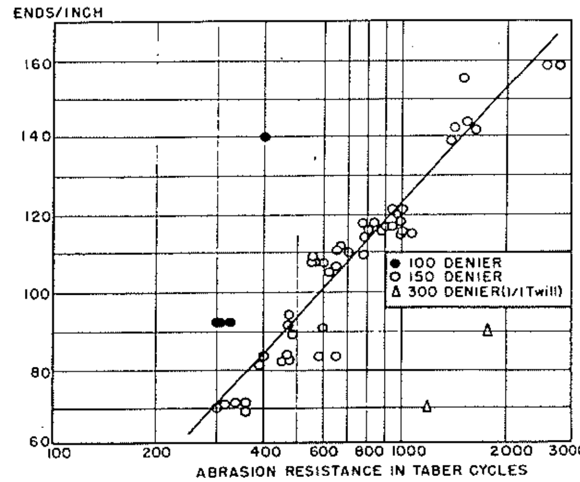

FIG. 2. *Effect of warp yarn count on the abrasion-resistance of viscose rayon linings. Fabrics were 2/1 twill, except one indicated as 1/1 twill. (Source, Tait [52].)*

the abraded surface must in all cases be the warp-flush side of the cloth. The greater number of warp crowns per square inch of fabric surface must not be obtained by increasing the warp texture to the point of jamming the warp threads and markedly reducing the flexibility of the fabric structure. Likewise, the filling texture should not be excessive nor the warp float so short that the warp crowns become rigid knuckles incapable of absorbing abrasive energy without early rupture of surface fibers.

Structural changes in textile fabrics often occur in use. The effect of laundering on fabric geometry is one of the most pronounced factors in this connection. Shrinkage serves to increase the number of threads per inch and thus to reduce the wear rate in subsequent rubbing [27]. It follows that laboratory abrasion tests should be conducted on the fabric in the state which it will maintain over the major portion of its service life.

The importance of cohesion as applied to fiber, yarn, and fabric structures has been stressed by investigators of fabric wear-resistance [33, 51]. Cohesion may be obtained in the yarn form by resorting to higher twists, or in the fabric form through use of closer weaves and higher textures. It has been considered desirable to use the latter means of securing cohesion because it permits use of lower yarn twist, which leads to yarn flattening, presentation of greater surface, and reduction of local loads [29].

The abrasion of textile fabrics is so complex a mechanism that the effect of local crown loads on durability is often masked by interactions with other factors. A large part of this complexity is eliminated when the cloth specimen is constructed of monofilament yarns. A single row of vinylidene monofilament crowns rubbed with emery paper shows (Figure 3) the effect of a reduction in crown pressure on depth of cut. Here the total load on the abradant was held constant and the number of crowns supporting the load was varied.

Although many elastic solids give evidence of a straight-line relationship between load and abrasion damage [15], the yarn crowns of Figure 3 do not. One reason for this is the change in crown-abradant contact area which occurs as the monofilament is worn down. The yarn crown in a plain weave resembles a torus, such as is pictured in Figure 4. If sections of this torus are sliced off perpendicular to the z-axis, the area of the exposed surface will vary in a nonlinear fashion. The relationship be-

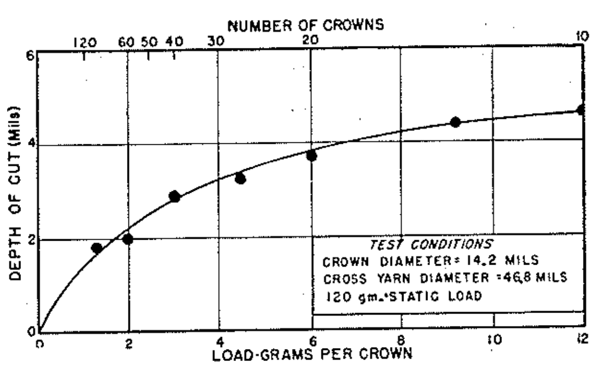

FIG. 3. *Abrasion-resistance of vinylidene monofilaments.*

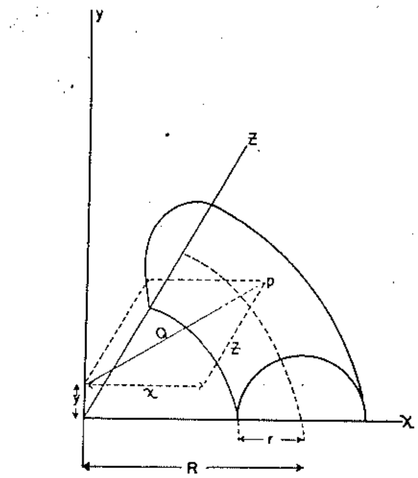

FIG. 4. *Three-dimensional view of torus section formed by crown.*

tween these sectional areas and the depth of cut and torus dimensions has been determined by mechanical integration and is pictured in Figures 5 and 6 for tori with varying inner and outer radii.

By using these curves, one can easily calculate the local bearing surfaces in a plain-weave textile fabric as its thickness is reduced in abrasion. This is, of course, the most elementary case, corresponding to the type of monofilament fabric used for seat covers in railway coaches. In ordinary spun fabrics, where the fibers are not retained in a matrix of starch or other coating material, the surface fibers spring up in a fuzz after abrasive rupture and the yarn structure is radically altered [1, 4]. In addition, the contact areas calculated for the torus do not take into account the effect of compressive changes in the form of the torus itself resulting from normal loads. It suffices to say that in textile materials the contact area will increase as a consequence of wear, but only in the case of monofilament materials can this increase be predicted. It may be expected that the wear rate under constant conditions of abrasion will fall off as the contact area between fabric and abradant increases. This effect is demonstrated in abrasion tests on vinylidene yarn (Figures 7 and 8).

Figure 7a shows the reduction in monofilament thickness at the point of abrasion as the number of rubs increases. These tests were conducted on the apparatus described by Stoll [51]. Several outer yarns of varying diameter were used, each being wrapped around an inner cross yarn (actually a steel wire) of 46.8 mils diameter and subjected to a load of 7.5 g. per outer yarn crown during abrasion with emery paper. The results of a similar test carried out with a reduced load and an increased cross-yarn diameter are shown in Figure 7b. Figures 7a and 7b illustrate the falling-off of the rate of abrasion as the depth of cut increases. This change in slope corresponds to the increase of geometric area of contact shown in Figures 5 and 6. The maximum torus sections plotted in Figures 5 and 6 are seen to occur at a point where approximately three-fourths of the crown yarn has been removed. Since yarn rupture takes place at or before this depth of cut, there is no tendency for the abrasion rate of monofilament crowns to increase in the final stages of the test.

Yarn Diameters

The association of greater wear life with increased thickness of a given material has been reported many times, and implies a direct relationship between the decrease in thickness and the number of

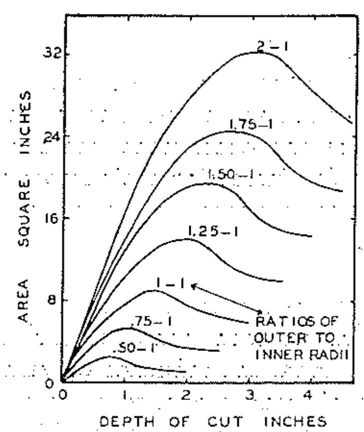

FIG. 5. *Area of torus sections (inner radius = 1 in.).*

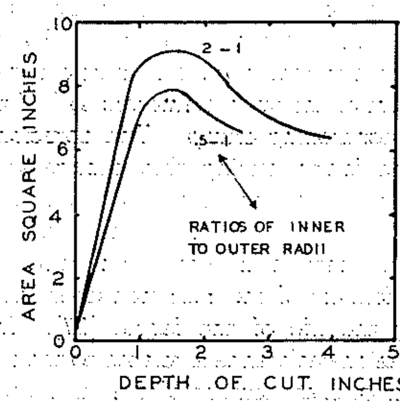

FIG. 6. *Area of torus sections (outer radius = 1 in.).*

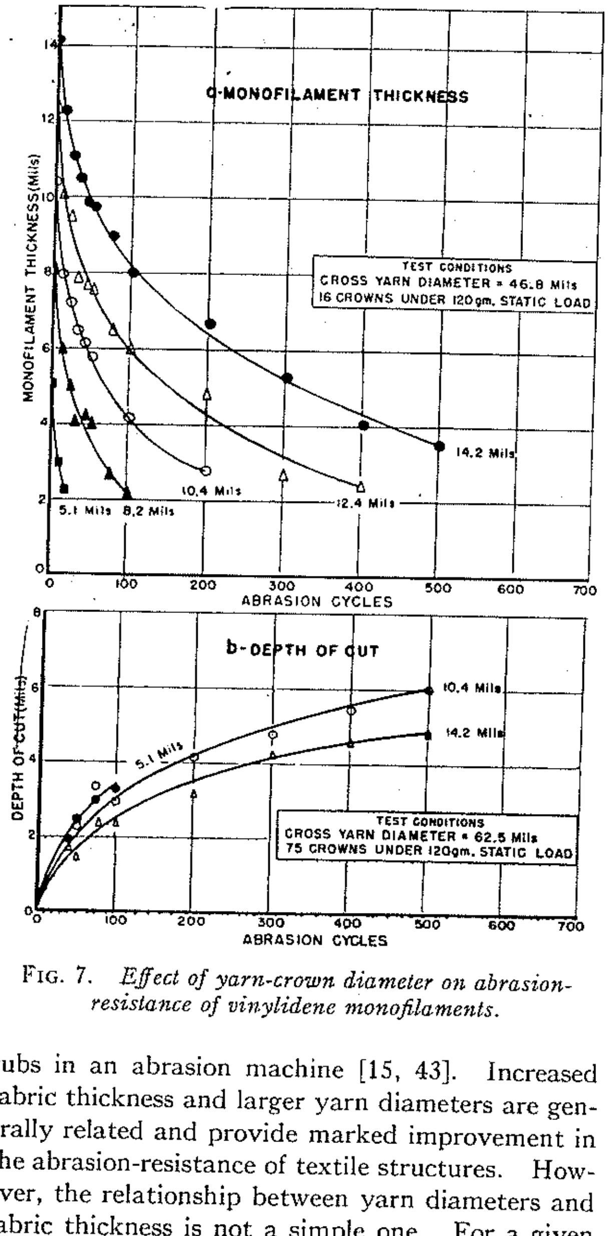

FIG. 7. *Effect of yarn-crown diameter on abrasion-resistance of vinylidene monofilaments.*

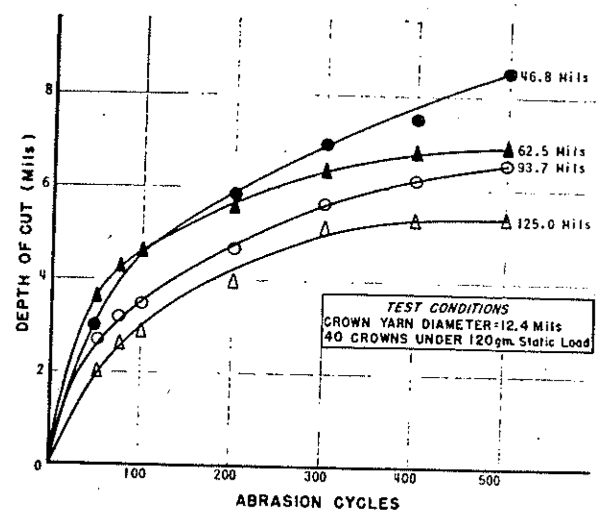

FIG. 8. *Effect of cross-yarn diameter on abrasion-resistance of vinylidene monofilaments.*

rubs in an abrasion machine [15, 43]. Increased fabric thickness and larger yarn diameters are generally related and provide marked improvement in the abrasion-resistance of textile structures. However, the relationship between yarn diameters and fabric thickness is not a simple one. For a given set of balanced yarns, fabric thickness can be varied from the sum of the yarn diameters to $\frac{3}{2}$ of the sum simply by controlling crimp. The abrasion-resistance of the fabric during this change will vary significantly, but by no means proportionately to the change in thickness, indicating that once the surface yarns have been severely abraded, the remaining thickness of the specimen does little more to prolong the life of the fabric [27]. In other words, abrasion-resistance is related to the thickness or diameter of that element of the textile structure which is exposed at the rubbing surface.

Both yarn [18, 56] and fabric abrasion studies [48, 52] have indicated the effect of the diameter of exposed yarns on the abrasion life of textile materials. Tait's detailed data, plotted in Figures 1 and 2, show significant increases in the abrasion life of lining fabrics as heavier yarns are used. Studies of cotton fatigue fabrics [1, 42, 60] have shown significantly longer combat-course life of cotton fabrics with lower warp yarn counts (*i.e.*, heavier warp yarns) since this set of yarns is subjected to the most severe wear in the herringbone-twill structure (see Table I). Corresponding results are reported in laboratory abrasion tests.

When the effect of yarn diameter was evaluated on vinylidene monofilaments, the data plotted in Figure 7a were obtained. The cycles corresponding to the end-point of other types of yarn abrasion tests are represented by the lowest recording on each of the curves for the varied-diameter monofils. These tests were conducted with a 120-g. load on 16 crowns, wound and abraded as indicated above [51]. In a second experiment, the abrasive load was reduced (by increasing the number of crowns) so as to increase the sensitivity of the abrasion test and permit study of the rates of wear on the monofilaments. Data of the second test are plotted in Figure 7b, and represent the depth of cut *vs.* abrasion cycles, rather than monofil thickness *vs.* abrasion cycles. Here the influence of yarn diameter on the rate of wear is clearly indicated, resulting from differences in sectional areas (Figure 5) and therefore in local pressures at points of contact.

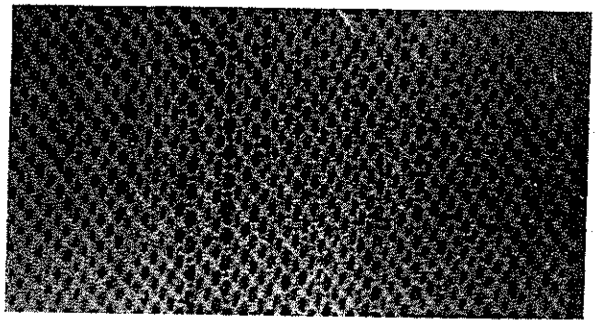

FIG. 9. *Surface contact of a cotton sateen under pressure (8.2 lbs. exerted with a hard backing against a sample 1.0 in. by 0.5 in.). Differences in compression due to uneven yarns are indicated.*

Other experiments were conducted using a constant (12.4 mils) diameter crown yarn and modifying the radius of curvature of the bent crown (corresponding to the radius of the cross yarn, or $R-r$ in Figure 4). Here, again, differences in sectional areas of contact may be expected from the yarn geometry. This is seen in Figure 6, in which areas of the torus sections are plotted against depth of cut for constant-radius crown yarns, but with varying cross-yarn radius. The results of the abrasion tests with varying cross-yarn diameters are plotted in Figure 8. Again the influence of sectional areas on rate of abrasion is demonstrated, this time on crown yarns of constant diameter.

It should be emphasized that the larger diameters of the abrasion-bearing yarns must be accompanied by yarn uniformity if increased wear life is desired. Nonuniform heavy yarns actually serve as focal points in fabric degradation because of the high pressure concentrations which occur at their crowns. The irregular compression pattern resulting from nonuniform yarns is clearly indicated in Figure 9,

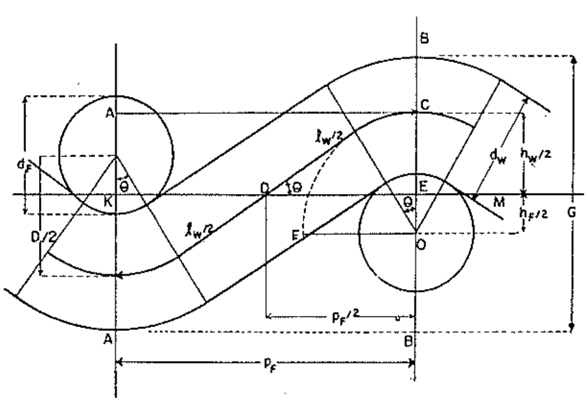

FIG. 10. *Crimp diagram.*

which pictures the contact area of a cotton sateen pressed against a piece of ground glass under a load of 16.4 lbs. per sq. in. [24]. Several heavy filling yarns (shown in the vertical direction) protrude above the nominal surface of the fabric and are therefore subject to higher pressures than the other yarns. These occasionally heavier picks also cause the lighter warp yarns (horizontal) crossing them to rise to the surface and be subject to abrasive damage.

Crimp Distribution

Crimp distribution determines the relative vertical displacement of each set of yarns above and below the plane of the fabric. As defined in studies of cloth geometry [32, 34], true crimp, c, is the ratio of the differences between the axis length of a yarn, l, and its horizontal projection, p, to the horizontal projection (Figure 10). Crimp is usually determined by measuring the difference between yarn length in the fabric and its length when unravelled from the cloth and straightened. Crimp values obtained in this manner apply to the unit cell of a plain weave, but must be multiplied by a weave factor, M, when other cloth structures are considered. M is determined from the weave pattern—for example, for warp yarns $\frac{1}{M_w}$ is the ratio of warp crossovers per repeat to the number of filling threads per repeat. M can easily be computed—*e.g.*, in the case of twill constructions one up to the right: a $\frac{5}{5}$ fabric has M equal to $\frac{10}{2}$, or 5; a $\frac{3}{2}$ fabric has M equal to $\frac{5}{2}$, or 2.5; a $\frac{4}{2}\frac{1}{2}$ fabric has M equal to $\frac{9}{4}$, or 2.25.

The sum of the vertical displacement of the crimped path of each yarn system, h, and its diameter, d, will determine which yarns will project at the rubbing surface of the fabric and therefore will be subjected to maximum damage in abrasion [23, 28]. An expression relating yarn displacement, h, to true crimp, c, and yarn spacings, p,

$$h_w = 4p_f\sqrt{c_w}/3,$$

has been found to apply over a wide range of fabric structures [32, 34]. Thus, if the fabric (made of twisted yarns) is designed with a value of $(h_w + d_w) - (h_f + d_f)$ greater than d_w, one may expect the warp to suffer complete abrasive destruction, without damage occurring to the filling.

More recently, a surface coefficient, K_n [11], has been proposed to establish the protruding yarn system based on the fabric geometry. Here $K_n = 0.667 n_w \sqrt{N_w} / n_f \sqrt{N_f}$, where n_w and n_f are the fabric densities in warp and filling directions, respectively, and N_w and N_f are the corresponding warp and filling yarn numbers. Thus, if K_n is less than 1.0, the warp threads protrude at the surface of the fabric; if K_n equals 1.0, the crowns of both yarns lie in the plane of the fabric surface.

In studies of plain weaves possessing high warp and low filling crimp, the curve showing warp strength *vs.* abrasion cycles demonstrates a steep negative slope, indicative of a high rate of damage, while the filling-strength curve is quite flat until the warp is almost worn away [6, 22, 26]. In similar studies [21] dealing with twill, sateen, and herringbone-twill weaves, negligible wear damage is noted in yarns which are buried below the rubbing surface, and, conversely, maximum abrasion takes place on the surface yarns. Evidence of the extent to which damage can occur to one set of yarns while the other remains relatively untouched is presented in a photomicrograph of a horizontal section of an Army poplin material (Figure 11). This photograph demonstrates the extent of abrasive warp damage which may occur before the filling yarns are reached. The usefulness of such longitudinal sections in studying fabric geometry as related to abrasion-resistance has been amply demonstrated [23, 35].

With the importance of crimp distribution established, it is conceivable that the abrasion characteristics of a fabric can be altered by any factor which will modify the crimp balance. Comparisons of fabrics in the loom state with high warp crimp *vs.* fabrics in the finished state, in which the warp crimp has been significantly reduced, have shown significant differences in abrasion performance. Laundering of the finished fabrics and subsequent shrinkage similarly modify crimp distributions, and therefore the abrasion mechanism of the fabric changes [26, 27]; but here the effect of the increased number of threads per inch must also be considered. Finally, slight modifications in fabric construction or weaving conditions—*e.g.*, reed width and warp tensions—may significantly alter the surface of a fabric and its abrasion performance [5]. In effecting crimp changes through control of "in-loom" construction or weaving and finishing conditions, one must have full cognizance of the geometric limitations resulting from yarn jamming [32, 34] and the physical limitations imposed by inherent yarn properties, particularly stiffness. Abrasion experiments have illustrated the importance of this requirement. In one case [27], fabrics were constructed with high filling and low warp crimp, resulting in great damage to the filling in wear and little damage to the warp. In slightly modified constructions, the warp texture was increased, resulting in greater filling crimp. The experimental series was extended until the jamming point was reached, beyond which warp-texture increases simply reduced filling crimp. Just before the jamming point, protection to the warp yarns was noted to be the highest. The protection of the filling yarns, on the other hand, was not at a minimum at this point, because their twisted structure tended to rupture long before the final fiber was worn away. In another instance [6], increased warp tensions in weaving were not sufficient to overcome the jamming which occurred in the constructions selected for study, and weaving conditions were not found to significantly affect wear-resistance. In still another case, it was found advantageous to reduce filling texture so as to enhance warp crimp, thus protecting the loosely twisted filling from surface abrasion [23].

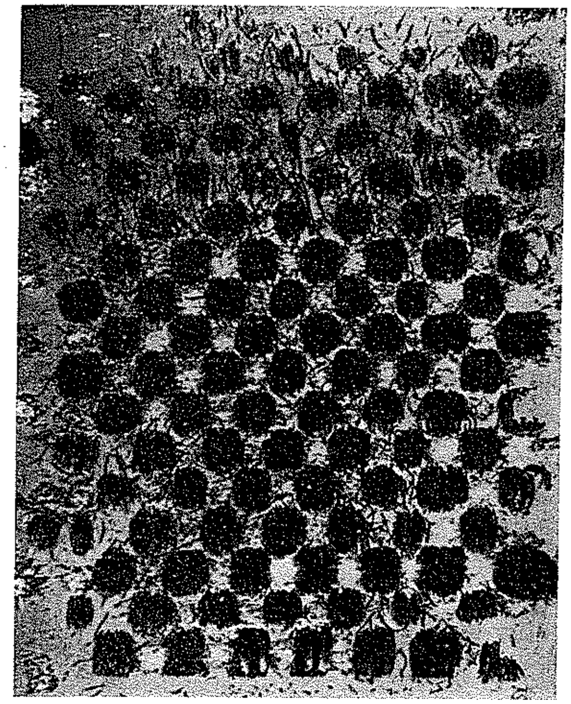

FIG. 11. *Horizontal section of Army poplin.*

In few instances will tension during an abrasion test or during the wear life of a fabric be sufficient to alter the crimp balance in the material [6]. However, wherever the stresses are of sufficient order to reduce crimp in either direction, modified abrasion results may be expected. This is particularly true in novelty and fancy fabrics where long floats at irregular intervals cause a maldistribution of tensile stresses, or where ribs occur, or where intermittent heavy yarns in warp and filling cross one another and create projecting crowns [36]. Thus, it may be expected that a fabric which does not possess over-all dimensional stability will give trouble in laundering, pressing, and subsequent wear.

It is interesting to note that where bursting strengths are used as a measurement of wear damage, crimp distribution affects both abrasion damage and its measurement. In one case reported [8] of a low-warp, high-filling-crimp sateen, bursting strength was found to be a measure of damage in only one system of threads, the low-crimp warp. Thus, when wear took place on the side where the warp was protected by the highly crimped filling, little loss in bursting strength was observed, and vice versa.

Weave as It Influences Projection

In a balanced-yarn, plain-weave fabric constructed with high warp covers (for definition, see [32]), anywhere from $K = 20$ to $K = 30$, the warp threads will bend about the filling threads and little opportunity will be afforded for filling crimp to occur. Even when extra-width reeds are used and the material is subjected to high tensions in the loom or in subsequent finishing procedures, the jammed condition [34] is reached before any measure of crimp redistribution takes place, and the warp remains projected on the surface of the fabric. This is particularly true in tightly woven poplin [55] constructions (Figure 11) where the filling yarns are heavier than the warp yarns, resulting in greater resistance to bending of the former. In such cases, the warp thread projects significantly on both face and back of the fabric, as is pictured in the ideal crimp diagram of Figure 10.

Where twills or sateens are considered, it is evident that many of the assumptions of the simplified cloth geometry no longer apply. The longer the float, the less the restraint on the yarn system. Here yarns are no longer restricted to alternating from one side of the fabric to the other, but bend sideways and allow for the closer packing characteristic of twills and sateens. In particularly long floats, such as are found in the Army five-harness sateen [54], the torus-cylinder form of alternating yarns is modified and a general arclike form is assumed This, when combined with the tendency of adjacent yarns to override one another (see Figure 12), results in higher projection of the yarn system containing the greater number of floats on each side of the fabric, despite the distribution of crimp. This tendency is used to good advantage in protecting from surface abrasion the system of yarns which bears the major stresses during service. In Army utility garments, Kaswell has observed that the longitudinal yarns, normally the warp, bear the major stresses during combat or fatigue activity of the wearer [20]. Damage to the warp is further affected by the relative direction of the yarn twist and of the twill [49], the more pronounced twills suffering earlier loss in strength.

Combat-course tests have shown that the filling-flush sateen [21] offers more protection [38] to warp threads during harsh abrasive wear than does the structure of the herringbone twill. In the case of herringbone twill and sateen arranged so that the filling floats are exposed, filling damage is three to six times that of the warp in the herringbone twill and fifteen to twenty times that of the warp in the sateen. In short, the sateen showed the least warp damage of all the fabrics tested [40]. When cross sections of the fabrics in question are observed (Figure 12), the additional protection afforded the warp by the longer filling float of the sateen becomes evident.

Laboratory tests [21] conducted on sateen, herringbone twill, and uniform twill with reciprocating and rotating type abrasion machines have consistently shown the sateen structure to furnish maximum warp protection when the filling floats are subjected to rubbing. No reversal in this tendency was noted as a result of change in abrasion direction. Conversely, maximum damage occurred to the filling floats of the sateen weave. This is demonstrated in the surface photomicrograph of Army sateen shown in Figure 13. When warp floats are exposed on the rubbing surface, it is seen that the longer floats suffer greater damage [49, 52, 57]—*e.g.*, in the tests on 4/1 sateens, 2/1 twills, and 1/1 taffetas (Figure 1).

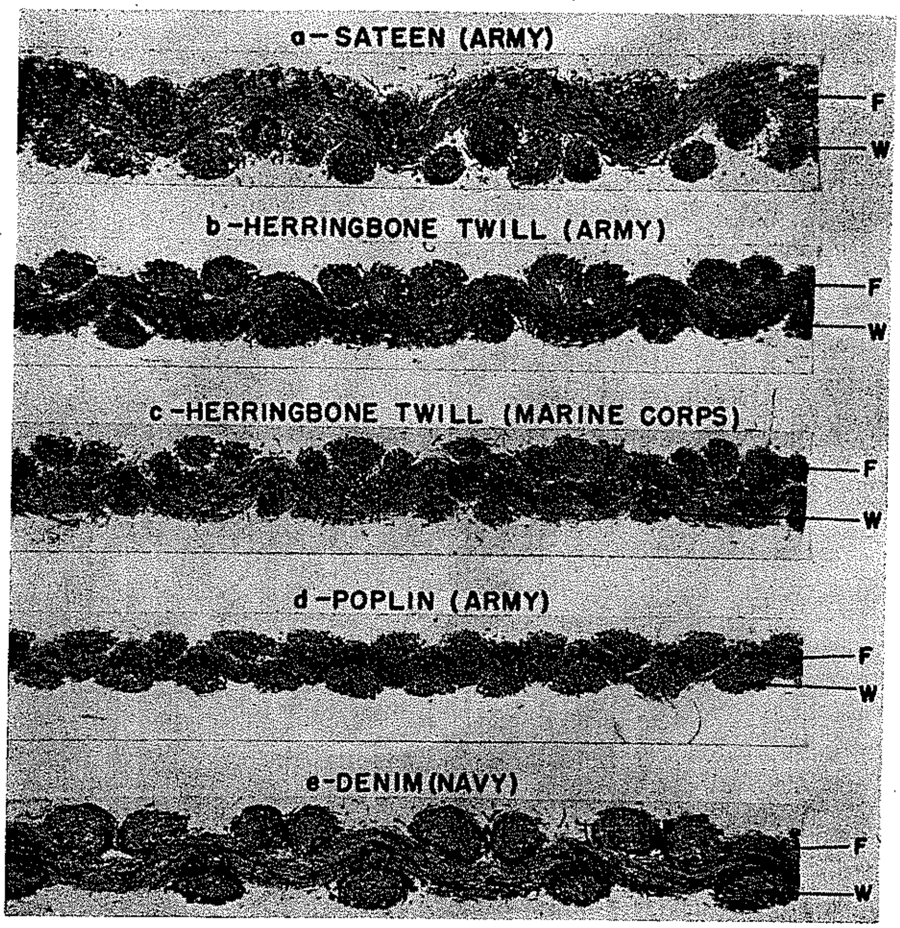

FIG. 12. *Cross-sectional views of various cotton fabrics used by the armed services.*

It has thus been shown to be characteristic of the five-harness sateen that the warp yarns project on one surface and the filling yarns on the other. In tightly woven, high-warp-cover plain or denim (twill) weaves, the warp yarn projects on both face and back and is subject to immediate damage, regardless of the surface abraded. In the herring bone twills, the warp yarns project on the face but are almost flush with the filling floats at the back. The wave height of an alternating yarn is generally related to the relative float lengths of the yarn, for it is evident that the longest float will balloon out

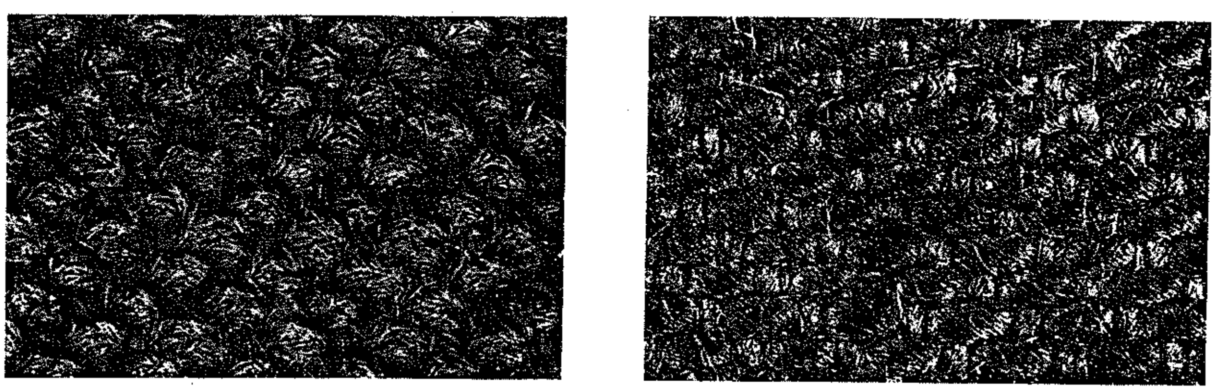

FIG. 13. *Abrasion damage to sateen worn filling flush.* Left—*Abraded.* Right—*Unabraded.*

the most. Measurements of float length in selected experiments [20] are presented in Table II. Here it is shown that the back of the sateen construction has the longest filling float and the highest ratio of filling to warp floats. The warp yarns are to be protected in use, and therefore protrusion of the filling yarn at the outer surface of the fabric is desired.

Comparison between the several fatigue fabrics of the various services has further demonstrated the influence of weave and float length on yarn projection and relative protection of the two systems from surface abrasion. Two herringbone twills were evaluated—one with a float of two cross yarns, the other with a float of three. The other fabrics were a five-harness sateen and a 2/1 denim construction. Details on these fabrics are furnished in Table IV. From Table III it is seen that all of the twills lose significantly in warp breaking strength after reciprocating warpwise rubbing (face up). However, when the fabrics are reversed, the sateen, with the maximum filling float length, is the only material which demonstrates almost complete warp protection under the conditions of abrasion used. This is borne out in Figure 12, where the role of float length and weave in determining yarn displacement is evident.

It has been shown [51] that flex abrasion most nearly correlates with combat-course results on the fabrics described in Table I, for here the abrasion is directed along the warp and the sample reaches the end-point when the warp strength is reduced below the level of the tensile load applied during the test. The flex-abrasion results of Table III (for the back of the fabrics) demonstrates the amount of protection afforded the stress-bearing warp yarns by the filling.

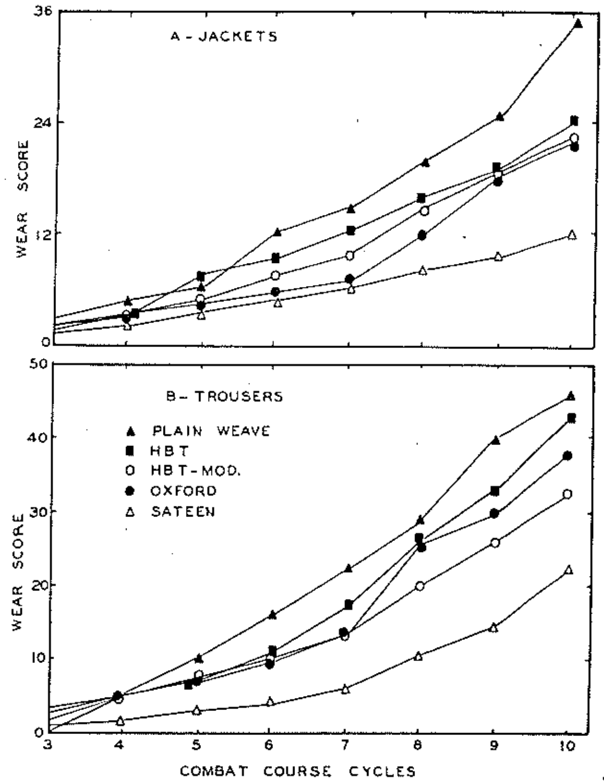

Fig. 14. *Effect of weave variations on combat-course wear scores.*

TABLE II. Float Lengths of Selected Army Fabrics

		Warp (mm.)	Filling (mm.)
Twill	Face	0.95	—*
	Back	0.26	0.53
Sateen	Face	0.74	—*
	Back	0.26	0.74
Herringbone twill	Face	0.90	0.26
	Back	0.53	0.58

* Not discernible in photomicrograph.

TABLE III. Laboratory Abrasion Tests on Cotton Fatigue Fabrics

Fabric	Float length (in.) Warp*	Float length (in.) Filling†	Wyzenbeek abrasion‡ (% loss in warp strength) Face	Wyzenbeek abrasion‡ Back	Flex abrasion** (cycles when abraded) Face	Flex abrasion** Back
Sateen (No. 111)	.0635	.0476	—	0	—	2029
Herringbone twill 2/1	.0434	.0263	12	6	646	1315
Herringbone twill 3/1	.0600	.0288	19	9	595	1255
Denim	.0426	.0286	23	—	1784	—

* On warp-flush side (computed).
† On filling-flush side (computed).
‡ Wyzenbeek Precision Wear Test Meter, 2-lb. load, 2 lbs. tension, abraded warpwise, 250 cycles.
** Stoll-Quartermaster Abrasion Tester, warpwise flex abrasion with folding bar, 4 lbs. pressure, 4 lbs. tension, 1-in. wide warp strips, end-point cycles to rupture.

TABLE IV. PHYSICAL PROPERTIES OF STANDARD SERVICE FABRICS

	Army		Marine Corps	Navy
Construction	Sateen	Standard HBT	HBT	Denim
Weave	5-harness	HBT 2/1 12 ends right 12 ends left	HBT 3/1 16 ends right 16 ends left	2/1 twill
Weight (oz./sq.yd.)				
Experimental	10.2	8.9	9.4	10.0
Theoretical			9.3	9.9
Texture				
Ends/in.	84	76	104	70
Picks/in.	63	46	50	47
Yarn number, singles cotton				
Warp	13	13	17	8.5
Filling	10	8	8.2	13.2
Cover factor, K_w	23.0	21	25.0	24.0
K_f	20.0	16	17.0	13.0
Yarn crimp (%)				
Warp	12.3	11.8	12.6	27.6
Filling	14.6	11.3	10.2	10.2
Physical Properties				
Breaking strength (lb.)				
Warp	154	140	130	160
Filling	136	146	134	70
Tearing strength (lb.)				
Elmendorf, Warp	10.9	5.9	8.2	10.0
Elmendorf, Filling	12.0	7.5	9.4	4.5
Tongue, Warp	10.7	3.8	6.2	—*
Tongue, Filling	7.7	4.9	7.4	3.0
Thickness (0.001 in.)	26.4	19.5	20.4	25.8
Stiffness (0.001 lb.)				
Warp	3.1	3.8	3.7	13.0
Filling	3.6	3.6	4.2	5.4
Air permeability (ft.^{3}/min./ft.^{2})	9.8	21.4	14.9	18.0
Wear score, revised (Camp Lee)	8.0	23.0		

Warp yarn in the left twill—Z twist
Warp yarn in the right twill—S twist

* Did not tear in warp. Tore across the filling.

The most striking example of this warp-protection mechanism is seen in the results of combat-course tests plotted in Figure 14 and summarized in Table I. The plain-weave fabric possessing tight warp crowns and with a filling float length of one crossover has the poorest (highest wear score) resistance, while the sateen with a filling float length of four cross-overs has the best. Intermediate wear scores are evidenced in the herringbone twills and the Oxford fabric, which have the filling float passing over two cross yarns. As Kaswell pointed out [21], the important part of this geometric consideration is the protection of the tensile stress-bearing yarns, which in the case of combat-course wear are the warp yarns. Other considerations, such as that of yarn mobility, are present, but these are discussed later (p. 649).

Finally, it should be stressed that irregularities in the weave pattern should be avoided to prevent one portion of the repeat from projecting above the

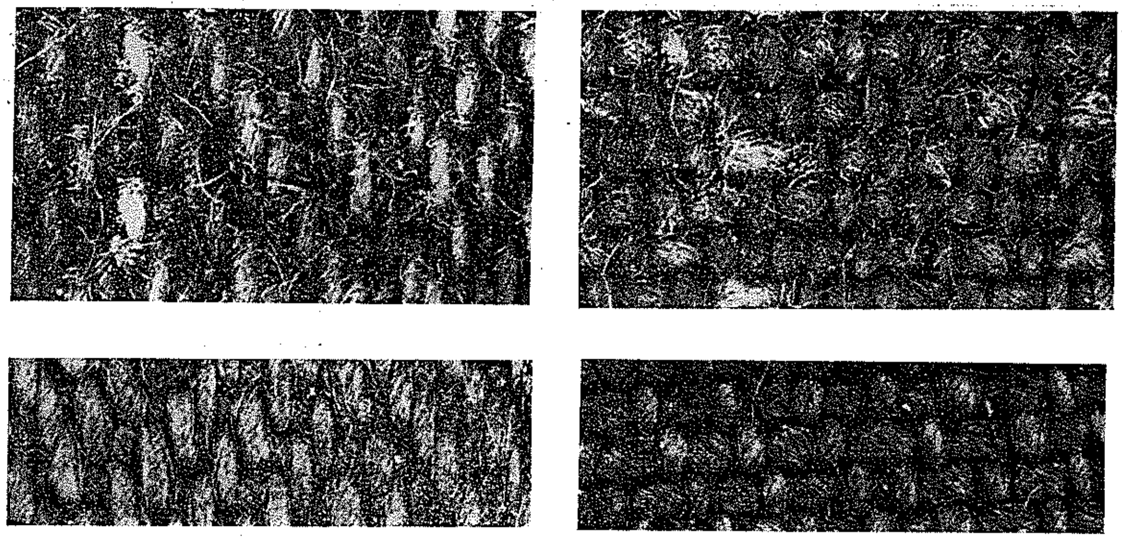

FIG. 15. *Abrasion of projecting floats of herringbone twill.* Top—*Abraded samples, face (left) and back (right).* Bottom—*Unabraded samples, face (left) and back (right).*

other and receiving the brunt of the wear. An example of this is seen in the herringbone-twill fabric, in which at one point in the repeat the length of the filling float is reduced by 50%. This throws the warp thread crossing the filling at this point out of the plane of the fabric surface and subjects it to excess wear at an early stage, as is evident in Figure 15 (left). At another point in the herringbone twill, where a filling float is increased by 50%, causing it to arch out of the plane of the back surface of the fabric, maximum wear is again noted (Figure 15, right).

Twist as It Influences Contact Area

The importance of cohesion of fiber, yarn, and fabric has been stressed by many investigators of the wear phenomenon [32, 51]. It has been shown that the surface wear of fabrics can consist of fiber damage, with either partial or complete rupture of the individual hairs, or a plucking of the fiber from the yarn structure [6, 57]. For good wear, the tearing-out action can be reduced by a firm binding of the fibers [28]. This binding may be accomplished by increasing yarn solidarity, with higher twists, or by use of tighter weaves. When twist multiples are increased from 1.5 to 2.3 in the yarns of linen fabrics, an increase of 15% in abrasion-resistance has been reported [27], and it was thought that the harder, more highly twisted yarns had less contact with the abrasive surface and so suffered less damage at the surface fibers. Based on results of more recent yarn tests, it would appear that lower twists afford poor fiber binding while high twists stiffen the yarn to a point where there is very little contact between yarn and abrasive. This, in turn, results in high local abrasive pressures and early breakdown of the yarn structure. However, when materials are laundered to a greater extent than abraded, the poor fiber binding of low-twist yarns plays a major role in causing early breakdown. Here, higher yarn twists are more durable [14]. In the experiments with viscose materials [18], an optimum twist is recorded beyond which increases in the number of turns per inch result in lower abrasion-resistance. The curves of abrasion-resistance *vs.* twist follow the pattern of the well-known, tenacity-twist curves [37]. It is seen, therefore, that the compressional characteristics of a yarn and its cohesiveness play dual roles in determining abrasion-resistance as its twist is altered. It follows that different abrasion behavior may be expected in fabrics of varying yarn twists, depending upon the normal loads between the rubbing surfaces.

In considering end-points, twist is a significant factor in determining the loss in yarn strength which may be expected for a given depth of cut at the crown of the yarn float. Yarn twist brings different fibers to the surface in any float length. The number of different fibers at any surface will depend upon the float length, the turns per inch, and the fiber and yarn diameters [37, 45]. In many instances, all of the fibers lying a given depth (abraded

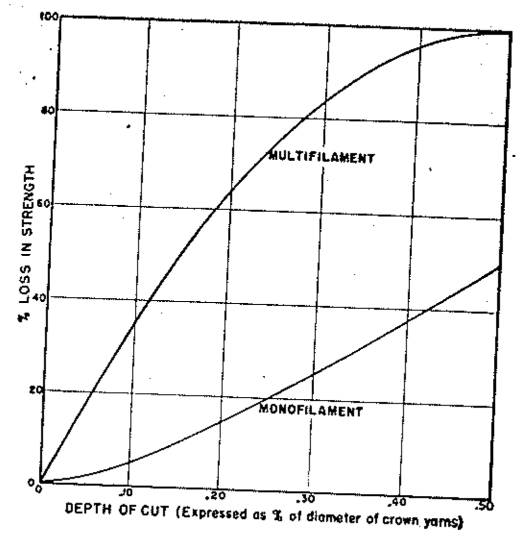

FIG. 16. *Relationship between depth of cut and % loss in strength of multifilaments and monofilaments.*

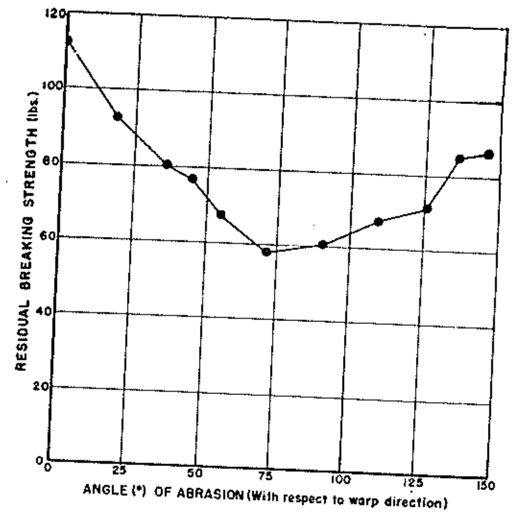

FIG. 17. *Effect of direction of rubbing on the abrasion-resistance of Army poplin.*

depth of crown) from the yarn surface rise to the surface at each float or at adjacent floats, thus degrading yarn strength by an amount proportional to their cross-sectional area. Platt [37] pointed out that when this loss is compared to the loss of strength at the same depth of cut in a monofil yarn, the relationship plotted in Figure 16 is seen. It is further noted that the strength loss of the monofilament is, in fact, directly proportional to the volume of yarn removed and therefore to the loss in weight during abrasion. In fabric-abrasion tests, these same relationships have been observed between loss in weight of the specimen and loss in strength [6].

Combat-course evaluations of the wear-resistance of fabrics differing only in yarn twist have been limited to tests of 2/1 twill weaves. Three of these fabrics had different twist multiples in the warp—namely, 4.25, 4.75, and 5.25—while the filling twist multiples were kept constant at 3.75. The other fabrics had warp twist multiples of 4.75 and filling twist factors of 3.25, 3.75, and 4.25, respectively. The combat-course tests showed a very slight, though consistent, improvement in fabric wear (in both test series) as the twist multiples of either warp or filling yarns were increased in the range indicated. All of the twills tested had the twill line running up to the right, with the exception of one left-hand twill. There was no difference noted between the wear score of the left-hand twill and a comparable fabric in a right-hand twill.

Direction of Abrasion

Major differences exist in the abrasion performance of textile fabrics when the direction of rubbing is altered with respect to warp and filling coordinates [27, 46]. The advisability of analyzing field wear to establish the predominant direction of wear and stress has been noted in early abrasion studies [6, 23]. In experiments where fabrics have been rubbed in warp and filling direction, a ratio as high as 2:1 has been observed in the number of strokes required to form a hole [8]. Generally, the yarns which project on the rubbing surface of the fabric will suffer the greatest damage when abrasion takes place in a direction perpendicular to their float lengths [17, 21, 28, 47]—*e.g.*, Figure 17. Where it is evident that abrasion and tensile stresses occur in one direction, it is desirable to increase the perpendicular set of yarns as to frequency and diameter and bring them to the surface to absorb the wear [20]. Under these conditions, unfortunately, the cross yarns absorb maximum damage during a period of rubbing. Maximum resistance is achieved when the non-stress-bearing yarns are presented at the rubbing surface with their floats running in the direction of rubbing [28]. Since the direction of service wear and stress is often the same, the maximum abrasion life of the fabric is not often realized. Wherever possible, however, the design of the garment or lay of the fabric in the pattern should be altered so as to eliminate perpendicular rubbing of the surface yarns during the wear of the item.

This is more easily accomplished in the manufacture of fatigue garments for Army use than of dress uniforms or civilian clothing. One feature that can be modified quite easily is the exposure of face or back of the material to the rubbing element, depending upon which side exposes the nonstressed yarns. Fabric reversal of this nature is resorted to in a number of Army garments.

Mention has been made of the two types of breakdown which occur in fabric wear [28]: the loss in internal cohesion of the fiber and the loss in structural cohesion between fibers. The relative occurrence of these two phenomena depend to a great extent upon the structural compactness of yarn and fabric, and upon the direction of abrasion with respect to surface yarns. Abrasion directed along the yarn in tight, sharp-knuckled fabrics often results in a great many sheared fibers. Abrasion directed across these same yarns tends to snag the fibers, leaving a hairy surface after a few rubs. Studies conducted in the Quartermaster laboratories on weaves of different float lengths demonstrated varying degrees of damage on warp and filling yarns, depending upon the nature of yarn projection, the float length, and the direction of abrasion. Abrasion, in this case, was of short duration so as to permit microscopic evaluation of the initial stages of surface wear before the destruction progressed to a point where it was impossible to distinguish between the types of mechanical breakdown and to assign damage to specific yarn systems. To extend the usefulness of this technique, it is, of course, necessary to study surface disturbance on fabrics whose structures have been brought to equilibrium in laundering. Another technique used to good advantage in studying surface structure of Army fabrics is the three-dimensional photography or vectograph process.

Compliancy

Relationship to Compressional Properties

The influence of backing materials in abrasion testing is well known, although little is reported in the literature since most investigators arbitrarily standardize the type of backing used in a given test. The various degrees of backing softness on a man's body have an effect on the relative wear of different portions of his garment. This factor is believed to play an important role in the variation in wear scores recorded in combat-course tests of Army clothing, although another factor which must be considered at the same time is the wearing habit of the individual—that is, what portions of his body he brings into contact with the different abrasive elements during traversal of the course. Soft backing, extra padding thickness, or napping of the fabrics in test add to the compressive give, and thereby to the ability to escape damage at the abrading surface [13, 19, 25, 49].

Finally, it is concluded that the compressive behavior of the surface structure itself bears on its wear performance, and it may be expected that a low compressive modulus and high rate of recovery will enhance abrasion-resistance, reducing the normal pressures at local protuberances.

Relationship to Fabric Tightness

Reduction in the extent of fiber plucking during wear, by closer weave or high twist, should not be effected at the expense of local rigidity at the fabric surface. There is sufficient evidence to demonstrate that tightly woven, knuckled fabrics possess low wear-resistance [21, 40, 58]. This is caused by the inability of the surface fiber to translate and avoid the path of the abradant particle. As a result, stresses are set up in the fiber which may exceed the multidirectional shear or tensile strength at the localized point of contact, or the axial tensile tenacity in the case of macrosnagging [49]. In general, the mobility required to alleviate surface stresses on individual fibers can be achieved by flattening the yarn structure in compression, as indicated above, or by rotation of the yarn, or by yarn translation within the fabric structure.

The use of lubricants has often been proposed as a means of increasing yarn mobility and thus of extending the wear life of textiles. It has been the experience of the Quartermaster laboratories that small percentages of lubricants may be beneficial to the abrasion life of cotton fabric as measured in the laboratory, but this is not always borne out in service. In one of three field tests in which the Quartermaster Corps participated, improvement of the treated fabric was noted to be due, in part, to the reduced laundering resulting from the stain-resisting character of the lubricant. In the other tests where uniform laundering procedure was followed, little difference existed between treated and untreated materials after extended periods of use. Lubricants have been found to be extremely useful in reducing the amount of thread damage occurring during the sewing operation. It has, in fact, been possible to sew with a high degree of seam efficiency fabrics which in the unlubricated state were badly perforated in the manufacture of shirts and were torn as easily as paper. Textile lubricants are generally looked upon as enhancing fiber and yarn movement within the fabric. They contribute in varying degrees to increased sewability, more seam slippage, higher laboratory abrasion-resistance, and, on occasion, improved wear life in service.

For the case of macrosnagging, the amount of yarn rotation depends upon yarn twist and fiber tensile modulus, for these factors determine the torsional rigidity of the yarn. If the yarn rotates enough to permit the surface fiber to slip from under the abrasive asperity, little immediate damage will occur, although long-time cumulative effects may be present, such as removal of secondary creep and bending fatigue. However, if the surface torque developed during yarn rotation is of such a magnitude as to cause fiber rupture, damage will be evident after the initial passes of the abradant surface over all parts of the fabric. To avoid excessive torques, one may use a fiber of lower tensile modulus or a yarn of lower twist. Finally, the use of longer floats (assuming the same torsional rigidity of the yarn system) reduces the magnitude of stress at the surface fiber.

In repeated impacts of the abradant, it is important that the fiber and yarn return to their original positions before approach of the second particle. If struck while in the rotated position, the higher twist of the yarn will effect a higher torsional rigidity and will therefore cause an increase in the force at the newly exposed surface fiber before the necessary rotation for clearance of the abradant particle can take place.

It follows that the ability of the yarn to recover its original position before the approach of subsequent abradant particles significantly affects its wear-resistance. This recoverability is related to: the inherent immediate elastic properties [16] of the fibers; the twist of the yarn; the distribution of sharp particles on the surface of the abrasive; the relative velocity between abradant and specimen (extent of rest periods); the path of the abradant across the specimen [7, 44].

In field tests the material is often allowed to recover after abrasive treatments, and thus heat of friction is disposed of and primary creep is recovered so that yarn and fiber assume a position near to their original state. In laboratory tests, however, there is no allowance for the time factor and for relaxation between cycles [10, 50], and materials which cannot recover in time for repeated abrasive runs tend to have low abrasion-resistance. Under modified conditions of abrasion, it is likely that rankings may be easily reversed because the influence of yarn compliance is weighted differently.

Fabric compliance depends upon the threads per inch and the type of weave. Geometric studies have shown that the number of picks which may be woven in a fabric is limited by the number of warp ends per inch, assuming fixed yarn sizes. The limiting construction of picks for a given sley, or vice versa, is known as the jammed condition [32, 34]. The quantitative expression of tightness as the ratio of actual picks (or ends) per inch to the maximum number per inch for a given cover factor, K, in the opposite direction is quite useful in fabric development. It will be recalled that cover factor is the ratio of threads per inch to the square root of the yarn count (cotton system). For plain weaves [32]:

$$K_w = \frac{28}{(1+\beta)\sin\theta_f}$$

$$K_f = \frac{28}{(1+\beta)\sin\theta_w}$$

$$1 = \cos\theta_w + \cos\theta_f$$

for the jammed condition, where $\beta = \sqrt{N_w/N_f}$ and θ is the angle of inclination of the yarn system at the central plane of the fabric, as seen in Figure 10. If two of the five unknown quantities in the above three equations are selected arbitrarily, the remaining three quantities can be determined easily. For example, if the ratio of yarn diameters and the warp cover factor are known, one can solve to find the limiting pickage of the jammed structure and the inclinations of the yarns systems.

In considering weaves other than the plain weave, one must correct for differences in the intersections between yarns. This can be done by adjusting the measured cover factors for each weave and using the values which have been corrected in the above expressions. The formulas for cover-factor adjustment are as follows:

$$K_w' = \frac{1}{\dfrac{M_f}{K_w} - \dfrac{(M_f - 1)f_w}{28}};$$

$$K_f' = \frac{1}{\dfrac{M_w}{K_f} - \dfrac{(M_w - 1)f}{28}},$$

where K is the measured cover factor and K' the corrected cover factor, M is the weave factor, and f is the relative degree of flattening of the yarns, expressed as a ratio of major axis of flattened yarn to diameter of round yarn of the same count. While the original cover factor is related to the tightness of yarn in a given direction, exclusive of the effect of cross yarns, the modified cover factors are related to combined tightness, taking both sets of yarns into account. Within the practical ranges of weave factors and measured cover factors, M_f and K_w can be increased together without affecting K_w'. For example, if the maximum desirable tightness, K_w', is 15 and the flattening factor, f, is 1.4, then for a weave factor of $M = 5$ the actual warp cover factor is $K_w = 18.7$; for $M = 2.5$, as in the case of a five-harness sateen, $K_w = 17.7$; for $M = 1$, as in the case of a plain weave, $K_w = 15$.

The cover factor of the threads which protrude at the surface is the primary factor in determining the geometric area of contact of the fabric with the abradant, while the modified cover or tightness factor reflects the extent of mobility afforded the protruding yarns by the fabric geometry. It follows that fabrics with high values of M can pack considerably more yarn per unit area without increasing fabric tightness, thus avoiding reduction in abrasion-resistance through loss of mobility. Meanwhile, the increased bearing surface of the higher-textured fabrics results in reduced abrasive pressure per crown or float and less abrasive damage. Conversely, when textures are kept constant, the M values of a given structure determine yarn mobility and therefore are a measure of the ability of the yarns to redistribute stress concentrations in abrasion and also in tearing or snagging. In Table I and Figure 14 the sateen fabric with the weave factor of 2.5 in both warp and filling shows the maximum (of group II) abrasion-resistance and tear-resistance, together with the lowest tensile (strip) strength. The plain-weave fabric with M_w, $M_f = 1$, 1, respectively, shows the poorest abrasion- and tear-resistance, while the herringbone-twill and Oxford fabrics with weave factors M_w, $M_f = 1.5$, 1.5 and 1, 2, respectively, show intermediate values of tear- and abrasion-resistance. This ranking has been attributed to the protective protrusion of the longer filling floats, but it is highly probable that yarn mobility plays a significant role in determining the relative abrasion life of the fabrics whose warp yarns protrude at the rubbing surface—in this case, the plain, Oxford, and herringbone twills. Obviously, there is a limit in float length at which increased snagging of the protruding yarn vitiates the advantages of longer floats. In addition, the conditions of abrasion may be such that the yarn mobility may be inoperative—for example, as a result of fine abrasives moving at a high speed over the surface of the fabric. An instance of this is seen in the poor showing of the sateen construction in laboratory tests under conditions where compliance and recoverability are reduced in importance. Results of this sort [52] appear at first glance to be anomalous, and such anomalies continue to appear in any abrasion-testing program. It is therefore incumbent upon the individual investigator to see that the conditions of abrasion testing [5] are related to service conditions and that laboratory testing is confirmed, wherever possible, by service trials [8].

An important approach to the problem of reproducing service conditions is the study of worn garments from varied groups of consumers. Here is found valuable evidence of the nature of actual wear and clues as to the type of laboratory tests that are best suited to predict the type of service performance for particular usage. Here, too, is observed weak spots in fabric structure, finish, manufacturing technique, seam and stitch construction, thread quality, and garment design. Such surveys [4, 39] conducted during and after the war serve as the basis for improvement of Army fabrics and garments.

Development of improved laboratory abrasion equipment has been a successful part of this program [43, 51], and although there is confidence in the results obtained with these instruments, further work in their evaluation is still necessary. The variables indicated above emphasize the need for extreme caution in attempting to predict the performance of new fibers, fabric constructions, or finishes under conditions of service which have not been thoroughly studied for presently available textile materials.

Conclusions

The geometric area of contact between cloth and abradant surfaces determines the magnitude of local pressures occurring under a given abrasive load. Local pressures, in turn, influence first the depth of local penetration into the fabric structure by the abradant asperity, and then the true area of contact between cloth and abradant. The local penetration controls the magnitude of cutting and snagging damage, while the true area of contact determines the amount of frictional damage which takes place in the form of fiber slippage and/or fatigue. In short, the geometric area of contact between cloth and abradant determines the rate of fabric attrition during rubbing. This area can be increased in the normal course of designing a textile fabric, the simplest method being the use of higher cover factors and equal crown heights in warp and filling. Increased cover factors may be achieved through higher textures or coarser yarns. Crown heights can be equalized by adequate control of crimp. In addition, the use of lower twists is an alternative method of increasing contact between individual yarn crowns and the abradant. Finally, the total abrasion-resistance or wear life of cloth is related to the thickness or diameter of that element of the textile structure which is exposed at the rubbing surface.

The above modification of fabric structures can be carried out only within limited ranges, else their beneficial effects are offset by secondary factors. For example, if fabric textures are increased excessively, yarn mobility will be severely reduced and rigid knuckles will form which are incapable of absorbing abrasive energy without early failure of surface fibers. Use of overly large-diameter yarns in one direction and small-diameter yarns in the perpendicular direction will result in the lighter set bending freely while the heavier, stiffer set remains uncrimped. This condition will lead to an actual reduction in the geometric area of contact and to early damage to the exposed, lighter yarns. Yarn cohesiveness may be so reduced by use of low twist that excessive damage may soon occur through the snagging and slippage of loosely bound surface fibers.

In many cases, fabrics are subjected to both abrasive and tensile stresses during their use. In designing more durable cloth to meet the requirements of the above conditions, it is recommended that strong yarns be used in the direction of applied stresses and that these yarns be buried below the exposed surface. Protection of the stress-bearing yarns may be effected by the control of crimp in the design and manufacture of the cloth. Geometric relationships in plain-weave fabrics have been developed to the point where the relative protrusion of one system of yarns above the other can readily be designed and implemented in the course of fabric weaving and finishing. Twills and sateens do not meet the simplified assumptions of the plain-weave geometry; however, a first approximation in the design of short-symmetric-float weaves may be made by applying correction factors to the geometric relationships of the simpler structure. These methods break down in the case of the long-nonsymmetric-float weaves where cover factors are roughly balanced. This is explained by the fact that the long component of the nonsymmetric float will balloon out on one side of the fabric while its short component is buried on the other side. Of the two methods of burying the stress-bearing yarns —through crimp control and through the use of the long nonsymmetric float—the latter is preferable in the design of wear-resistant fabrics. It is simply not practical in the full-scale production required by Army procurements to attempt to set crimp specifications for the finished cloth.

Maximum damage in wear of a fabric will occur when the direction of rubbing is perpendicular to the exposed floats. It is therefore desirable to orient the fabric in the design of clothing, so that exposed floats are parallel to the predominant direction of rubbing. Unfortunately, this is not possible where abrasion and tensile-stress directions coincide, as in the case of Army fatigue garments.

Fabric durability is enhanced by increasing the compressive compliance at the rubbing surface. This may be done by modification of the structure of the cloth itself or by use of soft backing materials. Local yarn compliance is also important to promote stress distribution at points of contact, and it must be retained within limits when high cover factors are utilized to increase the bearing surface. Where high cover factors are required for purposes of water- or wind-resistance, it is desirable to utilize structures with higher weave factors (*i.e.*, with fewer intersections per unit area) in order to avoid jamming and knuckling of yarn crowns.

The above conclusions are admittedly qualitative and cannot be used to design a fabric from scratch to meet a specific end-use or to predict its wear life. Their value lies in their application to end-use problems where limited experience and quantitative information are already available. Here they serve to explain the reasons for low durability-weight ratios and point the way to significant improvements in wear-resistance consistent with other structural requirements. This report provides a background of quantitative data for selected fabrics and uses as reported previously in the literature and more recently developed in military studies. It is hoped that the reasoning presented here can be used as effectively in future civilian research as it has in past military programs.

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