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

TEXTILE SERIES - REPORT NO. 54

Mar. 1949

AN IMPROVED MULTIPURPOSE ABRASION TESTER AND ITS APPLICATION FOR THE EVALUATION OF THE WEAR RESISTANCE OF TEXTILES

By

R. G. STOLL

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FOREWORD

The improvement of the resistance to wear of military textiles came to be regarded by Quartermaster Research and Development personnel during the latter part of World War II as a matter of major importance. At that time it was apparent that the manufacturing facilities of the American textile industry were not adequate to meet the combined demands being made upon them by the military services and the civilian economy. It was apparent also that the rate of replacement of worn items was discouragingly high, and that one of the most important ways of meeting the supply needs of the Army would be to reduce them through extending the service life of military textile items.

Studies were accordingly commenced in the Textile Section of the Research and Development Branch to explore the basic factors of construction and finish which might contribute to producing fabrics of longer wear life.

While these studies were getting under way, the end of the war in Europe brought an opportunity to send technical investigators into Germany to make available to the military effort the experience of the Germans during the war and the record of what they had accomplished along technical lines. Our office accordingly organized technical teams to survey the available data in Germany which might have significance to our military technical needs.

One of the reports of these investigators dealt with the work of Mr. R. G. Stoll, who was during the war director of textile research and technical services of Sueddeutsche Zellwolle, A. G. Particularly interesting to this office was Mr. Stoll's work on serviceability testing of textiles and especially the testing devices which he developed to measure the resistance of fabrics to abrasion and flexing. Accordingly, arrangements were soon made to bring Mr. Stoll to this country. Since that time he has been engaged under Quartermaster Corps direction in the perfecting of his apparatus and in further exploration of his theories concerning the serviceability of textiles.

About two years ago his work on abrasion testing had been brought to a point where it was considered desirable to produce an experimental model of his improved multipurpose abrasion tester. Arrangements were made under our joint research and development program with the National Bureau of Standards to have that office supervise the production of the first Stoll-Quartermaster Wear Tester.

This instrument, which is described in detail in this report, has been in use experimentally for approximately a year, during which time a great deal has been learned as to its application to the study of textiles and their resistance to wear.

Perhaps the most significant point about this new instrument is that a high correlation has been found to exist between its results and data obtained in controlled field wear tests, particularly on the Combat Course at the Quartermaster Board, Camp Lee, Va. Data obtained thus far indicate that proper application of this instrument will contribute substantially to a solution of the difficult problem of predicting service wear on the basis of laboratory tests.

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

15 March 1949

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ABSTRACT

On the basis of a systematic consideration of the mechanics of fabric wear and abrasion, and extensive experimentation with various test methods and machines, an improved multipurpose abrasion tester has been developed under the research program of the Quartermaster Corps. This work was carried out jointly by the Quartermaster Textile Materials Engineering Laboratory and the Textile Section of the National Bureau of Standards. The apparatus is capable of quantitatively measuring resistance to flat, edge, and flex abrasion under carefully controlled conditions, producing macro- and micro-wear patterns which are the same as those obtained in actual wear. Materials tested in the machine are abraded to an endpoint which is quantitatively defined and independent of individual judgment. Deviation in test results due to the machine are insignificant compared to the deviation of the samples themselves. A correlation has been found to exist between accelerated combat wear data and results obtained on the new tester.

I. INTRODUCTION AND PROBLEM

During the past twelve years methods for evaluating the durability or wear resistance of fabrics have been the subject of numerous investigations.[2,9,16,24] These studies have served to clarify the hitherto rather confused terminology used in considering the durability and wear resistance of textiles, and have also laid the groundwork for further research by indicating the method to be followed in attacking the problem as a whole. The results of the previous investigations also demonstrate that the durability of textile materials is determined by a great number of destructive, disintegrating, and degrading physical and chemical actions to which they may be subject. These actions vary considerably according to the use of the material.[2,17,21,22] It is neither possible nor necessary to consider every wear factor which can be isolated for a specific use. Instead, attention need be given only to those actions found to be critical as a result of service tests and salvage studies.[10] Although qualitative classifications of the importance of the various wear factors of textiles for specific purposes have been presented,[21] our quantitative conceptions of the relative significance of these factors from the standpoint of over-all serviceability are still based largely on guesswork.

A. Composition of Wear

The results of more recent salvage analyses conducted by the Office of The Quartermaster General on large series of field uniforms[23] indicate that in normal wear the mechanical factors of actual destruction and gradual disintegration can be divided approximately as follows:

30 per cent plane abrasion
20 per cent edge and projection abrasion
20 per cent flexing and folding
20 per cent tear
10 per cent other mechanical actions

Similar relations have also been derived in other investigations for civilian garments in general.[14] It has also been found,* however, that the relative importance of the wear factors can be of a very different order due to specific intrinsic properties of the fiber material. For rayon and rayon-blended fabrics in comparison with cotton, for example, the resistance to plane abrasion in a wet condition and to flex abrasion in a dry state are the critical wear

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* Unpublished results of investigations performed by the author as part of a research program of the Sueddeutsche Zellwolle, A.G. Kelheim (South German Rayon Company, Inc.) on serviceability of rayon.

factors in many applications. In the case of resin-treated fabrics, edge abrasion in connection with flexing and folding becomes of the highest relative importance for many uses. The figures on the relative importance of the wear factors obtained by salvage analysis of service tests may also require correction, since it is impossible to obtain visually, even with the aid of a microscope, a quantitative analysis of all the factors which contribute to a given failure. In the formation of a hole apparently caused by plane abrasion, for example, other factors may also have been partially responsible, such as tearing or the unevenness of the fabric. Nevertheless, these qualitative and semiquantitative analyses and deductions indicate consistently that as far as mechanical disintegration of the fabric and yarn structure and gradual breaking up of the individual fiber are concerned, the following must be considered as major wear actions:

(a) Plane or flat abrasion.
(b) Abrasion on edges, folds, and projections.
(c) Abrasion by flexing and bending.

The relative resistance of comparable samples to these three wear actions can be of a different order. In general, therefore, it is impossible to test mechanical disintegration with one type of abrasion. Nor can an attempted combination of the three types of abrasion in one complex test action be recommended, since their relative importance is dependent upon the specific use for which a given fabric is intended and the raw material from which it is made. From the viewpoint of controlling the mechanics of the test actions it is also preferable to test the different abrasions separately rather than in combination.

B. Three Basic Cohesive Forces Determining Abrasion

The mechanical reactions of fabrics to all three abrasion actions are determined by the same three cohesive forces,[12] namely:

(a) The cohesion between the abrasive and the fiber.
(b) The cohesion between contiguous fibers.
(c) The cohesion between the structural parts of the fibers themselves.

It should be possible, therefore, theoretically at least, to predict the resistance of textiles to the various types of abrasion on the basis of the inherent and geometrical properties of the fiber material, the form factors of the yarn and fabric structures, and the frictional forces between the fiber or fabric and various abrasives. Some approaches in this respect have already been made.[1,8,10,25]

However, the mechanics of these actions and reactions are so complex and so incompletely understood that the study of these basic cohesion properties cannot replace the use of adequate instruments to measure the abrasion resistance of fabric samples on the basis of isolated test actions, such as plane abrasion, edge abrasion, and flex abrasion.

C. Abrasion Conditions

All three types of abrasion have a number of conditions in common which more or less significantly influence the degree of gradual destruction which takes place. Among these are the following:

(a) General conditions, such as dry abrasion, wet abrasion, or abrasion under other specific functional conditions.
(b) Nature of abradant.
(c) Pressure on the sample and tension of the sample.
(d) Direction and speed of the motion.
(e) Removal of lint and other debris.

Variation in these abrasion conditions can easily cause a larger deviation in the test response than is due to differences among the samples, thus invalidating the results of an entire test.

D. Abrasion Resistance

Another fundamental problem of equal importance for all types of abrasion is the definition and measurement of the abrasion resistance. The relative and absolute resistance of a fabric to a specific abrasion action is best expressed by the ratio of the quantity of abrasion action (represented by an energy or a relative value for that energy) to the quantity of abrasion. The quantity of abrasion should be measured in terms of the volume or weight of the material removed by attrition or as the area of the cross section which has been completely disintegrated by the test action. It may not be necessary that an isolated test action duplicate a specific wear action precisely,[10,13] but the former must produce a mechanical disintegration which is comparable to the actual wear pattern.[5,12]

On the basis of this systematic consideration of wear and abrasion factors and of a long practical experience with various commercial and experimental abrasion machines, an improved multipurpose abrasion tester has been developed jointly with the Textile Section of the National Bureau of Standards as part of the wear resistance project of the Quartermaster Textile Materials Engineering Laboratory. A model of this machine has been constructed by the American Instrument Company, Silver Spring, Md. The tester is capable of producing the three major types of mechanical wear in various modifications and under carefully controlled conditions. Many of the finer points in the constructional details of this instrument have been developed as a result of experimentation on previous models with hundreds of samples.[21,22] This experience has proved to be as important to the precision of the machine as consideration of the basic principles of the abrasion factors.

II. DESCRIPTION OF THE MACHINE

The machine consists of eight main parts:

- Framework.
- Driving mechanism.
- Abrasion head.
- Pneumatically controlled rotary sample clamp mechanism.
- Pneumatic tension control system.
- Special edge abrasion clamp.
- Flat abrasion table with tension and folding device.
- Electric devices for pressure control and endpoint stop.

The principle of the construction of the apparatus and the method of testing flat, edge, and flex abrasion are indicated in the schematic diagrams shown in Figures 1, 2, and 3. Two photocomposites of the apparatus and its different interchangeable parts are shown in Figures 4 and 5.

A. Framework.

All the main parts of the apparatus are assembled on a steel plate which is supported by five angle irons mounted on a heavy base plate. The framework is enclosed by removable panels and the front panel serves as control board with the electric devices mounted on the rear side.

B. Driving Mechanism

A 1/4 H.P. 115 Volt A.C. motor with a 1:10 speed reducer drives a crank disk by a pair of interchangeable spur gears and a clutch, and a sliding plate by a connecting rod. The plate is guided by dovetail sliding strips. The reciprocal motion of the sliding plate may be operated at 60, 120, 176, and 245 double strokes per minute. (A suitable speed for most tests has been found to be 120 strokes per minute.) The stroke length can be set at 1/2 inch, 3/4 inch, and 1-1/2 inches. The latter length has been determined as most

Fig. 1 - DIAGRAM OF A TESTER SHOWING FLAT ABRASION ATTACHMENT

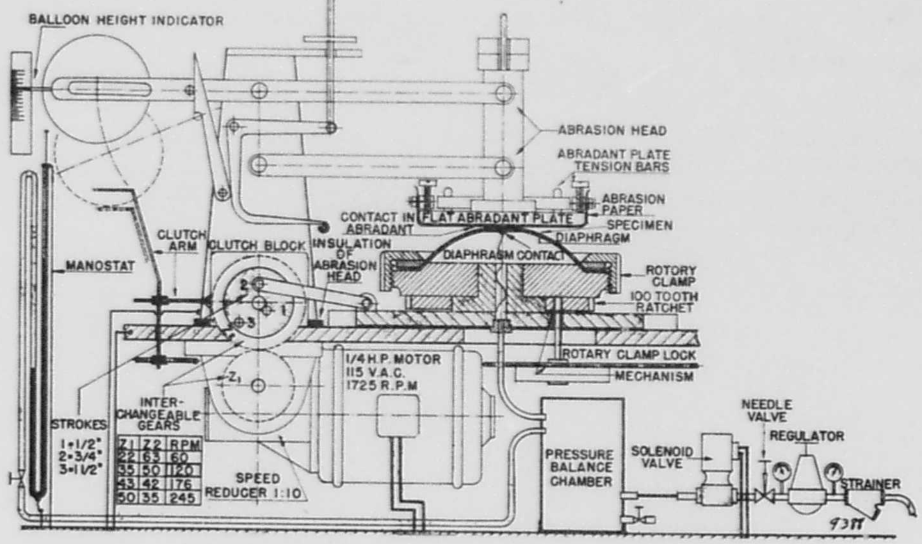


Fig. 2 - DIAGRAM OF EDGE-ABRASION ATTACHMENT

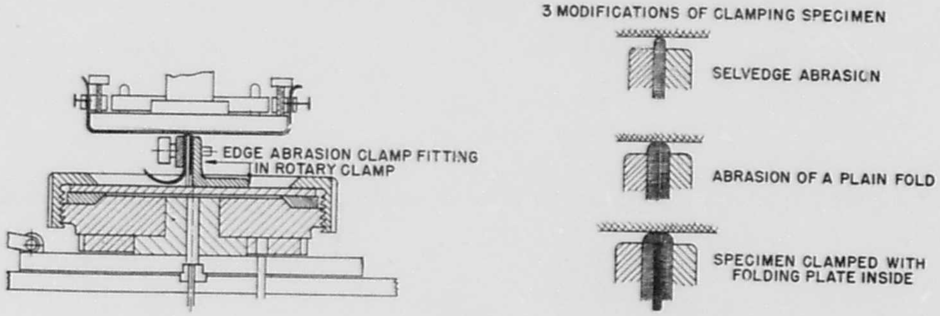


Fig. 3 - DIAGRAM OF FLEX ABRASION ATTACHMENT

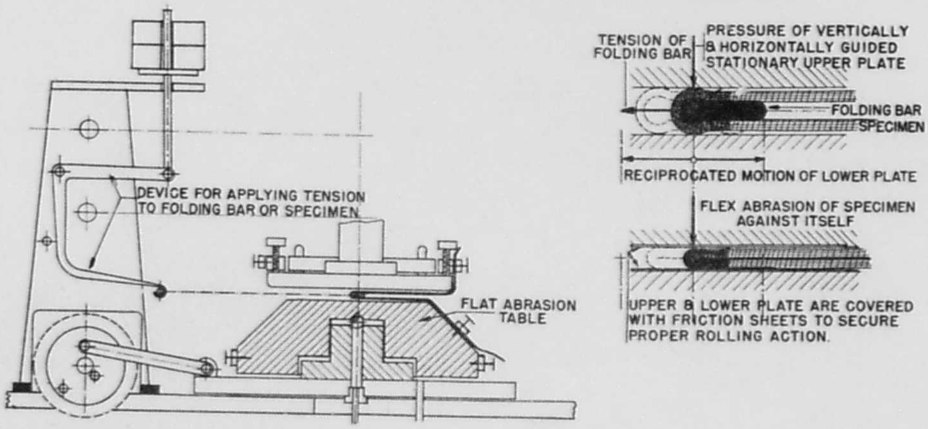


FIG. 4 - FRONT VIEW OF TESTER SHOWING FLAT ABRADED FABRIC IN PNEUMATICALLY CONTROLLED ROTARY SAMPLE CLAMP

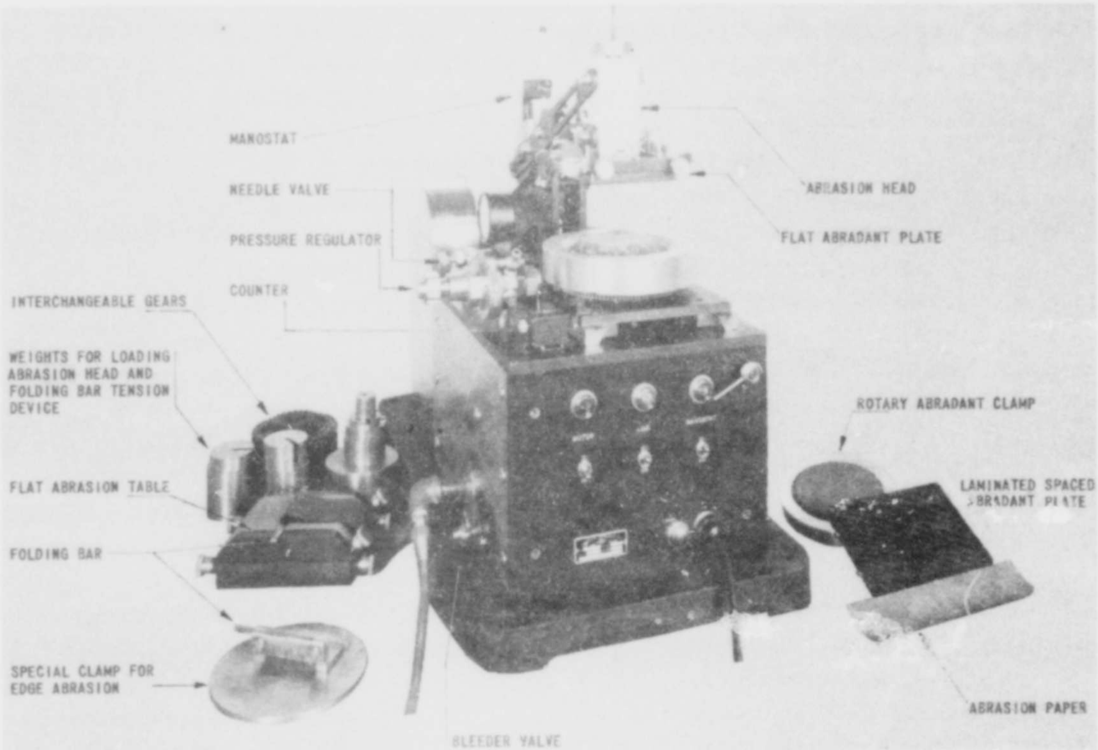
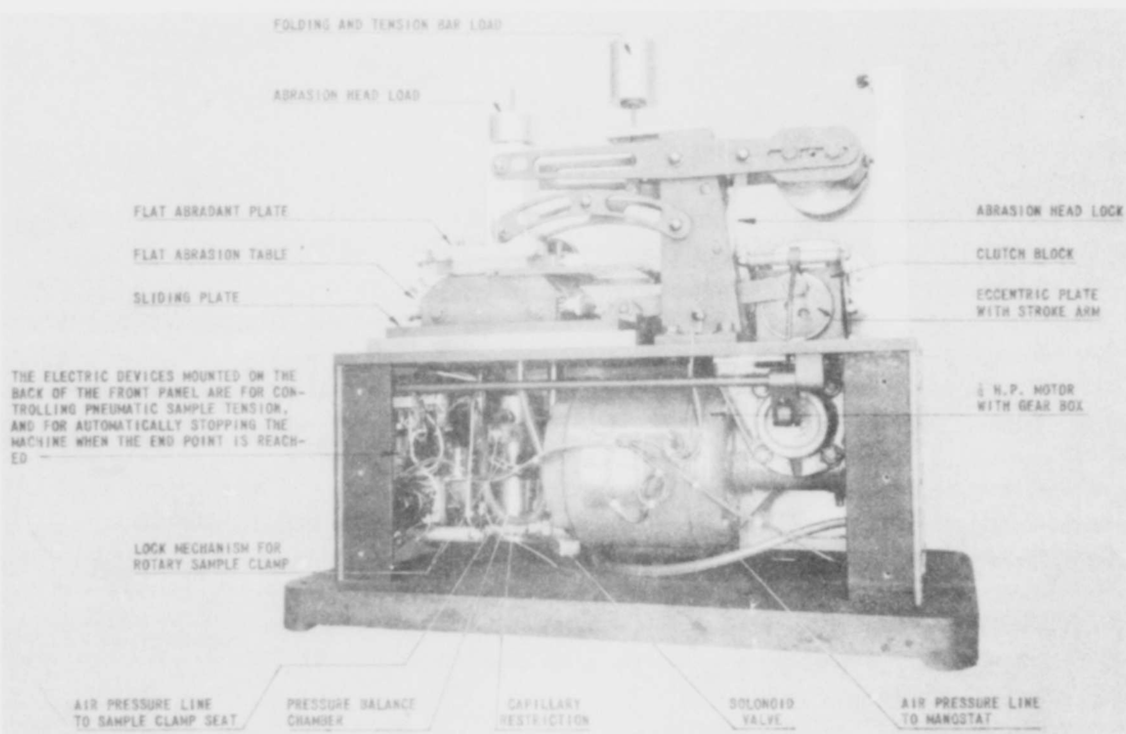


FIG. 5 SIDE VIEW OF TESTER (PANEL REMOVED) SHOWING FLEX ABRASION WITH FOLDING AND TENSION BAR



suitable for flat and edge abrasion, while the 3/4 inch is most practical for flex abrasion. The mechanical clutch provides a means for immediately stopping a test at any time without shutting off the motor. The clutch is disengaged either by operating a handle on the front panel or by lifting the abradant plate. The number of double strokes of the sliding plate is indicated by a counter which records the quantity of abrasion action, since in all applications of the instrument this action will always be proportional to the number of strokes.

C. Abrasion Head

A bracket, electrically insulated against the upper base plate, supports a structural lever assembly in ball bearings. This double-lever parallelogram guides the abradant plate in an exact horizontal position and permits its vertical movement under a load which can be precisely balanced. The abrasion head is insulated against the other parts of the machine so that upon complete abrasion or rupture of the specimen the machine is stopped immediately by contact. The following three different types of abradant plates fit into the abrasion head post and can be easily interchanged:

(a) A flat abradant plate which is normally used in all three types of tests. This plate is provided with adjustable clamps on each side for holding the abrasion material (abrasion sheets or strips of fabric) in a stretched position. A contact pin is inserted on the lower side of the plate on the length axis at the turning point of the rotary clamp (see D below). This pin extends through a hole of the same diameter which is made in the abradant at this point. The pin is adjustable to the thickness of the abradant.

(b) A laminated spaced abradant plate similar to the clock-spring abradant used on the Schiefer testing machine.[15]

(c) A rotary abradant clamp which can be rotated manually. This clamp, particularly suitable for fabric-on-fabric abrasion, also permits changing the position of that portion of the abradant which is in contact with the specimen.

D Pneumatically Controlled Rotary Sample Clamp Mechanism

The body of the clamp consists of a round plate and a 100-tooth ratchet gear mounted on a flange attached to the reciprocating plate. At the end of each double stroke the clamp is turned slightly a distance equal to one, two, or three teeth of the ratchet gear by an adjustable pawl mechanism assembled on the sliding plate. The specimen is mounted on top of the round plate over a rubber diaphragm by means of a retaining ring and a tightening collar. Two different rings are provided with the clamp which permit testing over a clamped area of 50 or 100 square centimeters as desired. When installing or removing the specimen, the rotary clamp can be locked by a special safety device which is coupled with the clutch of the driving mechanism and which simultaneously releases the pawl from the ratchet gear. If it is desired to abrade the specimen in one selective direction only, the pawl can be released by means of a button on the front panel. The diaphragm is inflated by a controlled air pressure which is introduced through a flange by a flexible hose connected to the sliding plate. A contact pin is mounted in the center of the diaphragm to provide an automatic endpoint stop for flat-abrasion tests using the pneumatically controlled rotary sample clamp. A thin spring wire, sliding in the orifice of the flange, makes contact with the grounded parts of the machine when the specimen is completely abraded.

E. Pneumatic Tension Control System

A constant air-pressure control which can be regulated from zero to six pounds per square inch as required in the tests is accomplished by a system which is adaptable to the various pressure supplies available in most laboratories. It consists of a supply line, strainer, constant-pressure regulator (diaphragm type), needle valve, and a solenoid valve connected with a pressure-balance chamber by a capillary restriction. Flexible hoses connect the chamber with the rotary clamp and a manostat which controls the pressure in the balance chamber by opening and closing the solenoid valve. A bleeder valve is also connected to the chamber for releasing the pressure during changing of the specimen. Proper preregulation by the constant pressure valve makes it possible to keep the pressure under the specimen at ± 1 mm. mercury, securing a very uniform abrasion pressure and sample tension.

F. Special Edge Abrasion Clamp

A special edge-abrasion clamp can be mounted in the rotary clamp instead of the rubber diaphragm. Warpwise, fillingwise, or bias strips, clamped as indicated in Figure 2, can be exposed either to a unidirectional reciprocating abrasion or to a multidirectional action by the reciprocating and simultaneous rotation of the rotary clamp. In selvedge and plain fold abrasion, the machine is automatically stopped when the endpoint is reached by an electric contact between the contact pin in the abradant plate and the edge-abradant clamp. When the folding plate is used, this plate forms the contact with the pin in the abradant plate when the edge of the specimen is rubbed off. This device is also suitable for the testing of yarns or monofilaments which can be wound under a certain tension around a flat plate with a round edge or a pin fitting to the edge-abrasion clamp.

G. Flat Abrasion Table with Tension and Folding Device

This table is chiefly provided for flex abrasion testing, as schematically illustrated in Figure 3. It can also be used, however, for the plane abrasion of fabric strips whereby the specimen can be stretched with a known force by a weight-lever mechanism.

The plane-parallel adjustment of abrasion table and abradant, which is very important for uniform test action, is accomplished here by a steel ball inserted between the flat abrasion table and the mounting flange. On the sides of the table are adjusting plates which can be used for rigid plane-parallel mounting.

Flex abrasion of the specimen can be accomplished either by use of a folding and tension bar or by flexing the folded sample against itself. In the first case the folding bar, which can have either sharp or rounded edges, is subjected to a controlled tensile load by the weight-lever system located in the bracket of the abrasion head. This device is also designed to make a contact to stop the machine when the endpoint is reached. In the second type of test, in which the folded sample is abraded against itself, the upper and lower plates are covered with a friction sheet (this may be a regular abrasion paper) so that the folded specimen receives the proper rolling action from the reciprocating motion of the abrasion table. In all tests with the flat abrasion table, the plane-parallel guided abrasion head subjects the specimen to a controlled pressure.

H. Electric Devices

The electric devices mounted on the rear of the front panel serve to control the pneumatic specimen tension and to stop the machine automatically at the endpoint of a test. If the set pressure in the manostat is exceeded, the mercury contacts an adjustable platinum wire actuating a relay which closes the solenoid valve in the pressure line. The balloon height of the inflated specimen, which is a function of the elongation of the sample, can also be used to control the pressure. Thus the elongation under which the fabric is tested can be controlled and can be selected from a wide range. In this case the indicator installed on the lever mechanism of the abradant head makes contact to actuate the relay and the solenoid valve. Contact between the insulated abradant plate and the sample clamp mechanism or another part of the machine stops the motor by a manual reset relay which is actuated by a midget relay.

III. CONTROL OF THE ABRASION CONDITIONS

The foregoing description of the apparatus has also indicated in general how it can be used for measuring resistance to flat, edge, and flex abrasion. It is now intended to discuss the abrasion conditions mentioned in part I-C. and to show how they are controlled in the various applications of the tester. Some results on the relative importance of these abrasion factors will indicate what has to be considered in the performance and evaluation of abrasion tests.

A. General Abrasion Conditions

It is obvious that the general conditions of temperature and humidity under which abrasion tests are conducted are of considerable significance. Normally, the standard conditions for testing textiles (70 F. ± 10 F. and 65 ± 2 per cent relative humidity) should be maintained unless special functional requirements (e.g. use in extremely low temperatures) are indicated.

Where the fabric is to be used in the presence of water or other liquid, it should be tested in a wet condition. Particular note should be taken of the possibilities afforded by this apparatus for the performance of both flat- and flex-abrasion tests on materials in a wet condition. Such tests, which are most important for all fibers with low wet strengths, are difficult to carry out on most abrasion machines. In flat abrasion the specimen is clamped on the rotary head, then immersed in water or any other liquid. As the diaphragm is inflated, the central portion of the fabric surface is raised above the level of the liquid, a ring of the liquid being formed around the circumference. Thus, although the area of abrasion is not directly immersed during the test, it is kept wet by the wicking capacity of the fabric, further aided by a slight tendency of the liquid to splash onto the raised portion of the specimen by virtue of the test motion. The adhesive forces between the water and the fabric and abradant are another contributing factor to maintaining the fabric in a wet state during the test. In flex-abrasion experiments with the folding bar the specimen strips are first immersed, then tested as in the dry state.

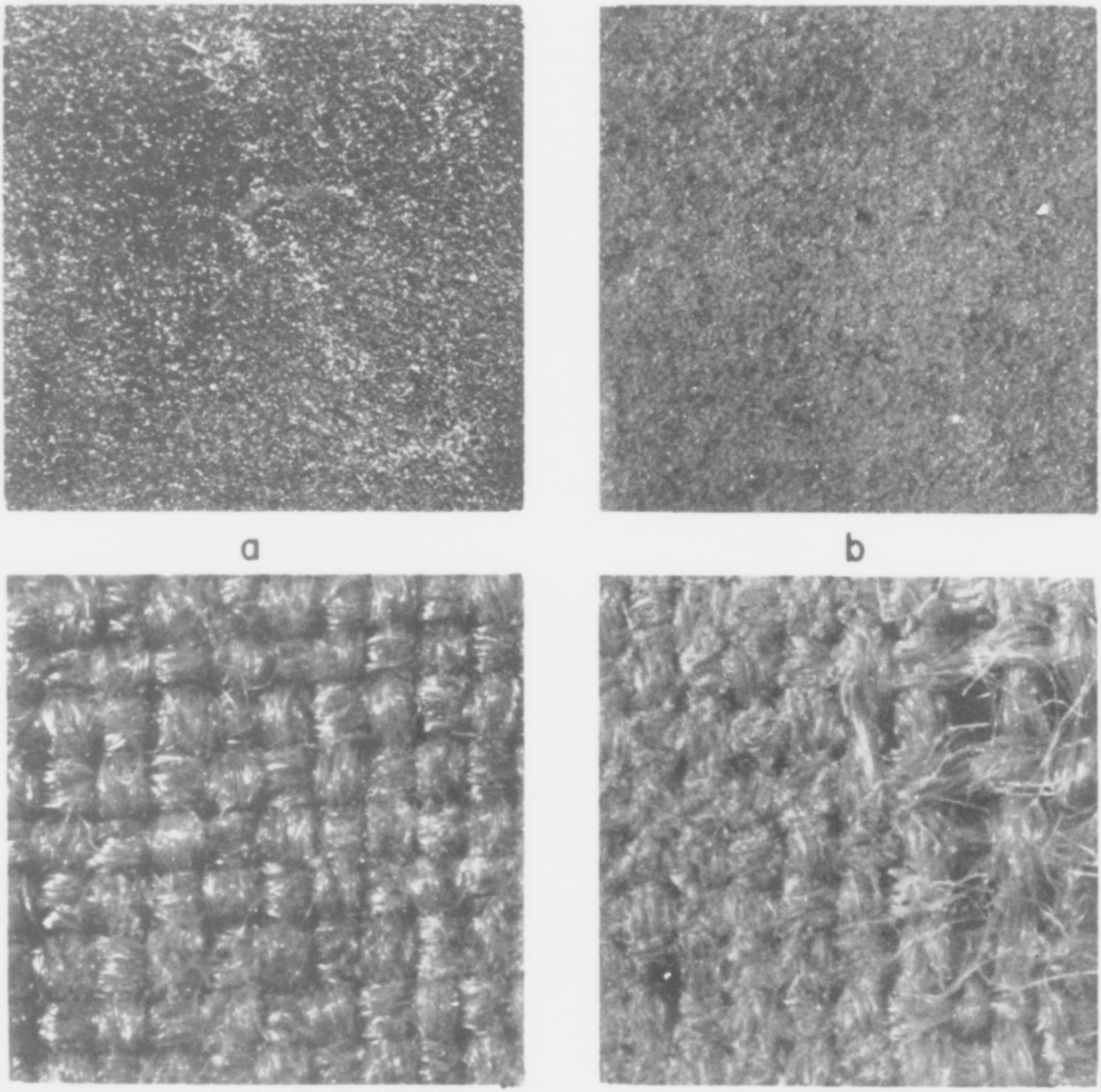
B. Nature of the Abradant

The nature of the abradant determines largely the character and degree of attrition, and is thus a major factor in the performance of any kind of abrasion tests. In the simulation of most service abrasion actions, the abradant must drag the fibers apart by friction rather than by a cutting action. For this reason, the mineral abrasives, which have a strong tendency towards cutting, have been objected to.[3,13,24] However, emery is still the most used abradant in the testing of fabrics, largely because other materials, such as fabrics, metal screening, files, etc., are either impractical or disadvantageous in some other respects.[19]

It is logical that the grain size of an abradant should have a significant influence upon the wear pattern obtained in abrasion testing. When the dimensions of the emery grain are smaller than the thickness of the individual fibers it can be expected that instead of producing a snagging and cutting action, the abradant would have the effect of gradually breaking up the inherent cohesion of the fiber material. That the latter condition exists for abradants of the fineness of Emery 0 or similar papers is indicated by Figure 6. It has been found[5,12] that in actual wear innumerable small portions of the individual fiber are torn away. Cotton fibers, for example, break up into spicules about two or three microns wide and up to 40 or 50 microns in length. Rayons also show a splintering of the fiber as a result of actual wear and particularly in laundering. Similar patterns can be produced by the use of fine abrasion papers on the instrument described in this report, as is demonstrated in the photomicrographs shown in Figures 7 to 10 inclusive. In Figure 7 is shown the disintegration of the wool fibers which occurred upon abrasion of the specimen shown in Figure 6. Figures 8, 9, and 10 illustrate how the mechanical effect of laundering on cotton and rayon fibers can be reproduced by conducting a wet-abrasion test on the fabrics using a water-resistant abrasion paper, such as silicon carbide No. 600.

Previous experimental studies[11] on abrasion papers have also indicated that the finest papers available are satisfactory as far as the character of attrition is concerned. However, some of these papers are subject to a high deviation within themselves, and may also change considerably during the course of a test. Previous experiments have indicated[11,19] that paper of sufficient uniformity can be secured so that deviation from abradant to abradant is not a serious consideration. With respect to the change of abradant with use, the calibration curve shown in Figure 11 has been established with this apparatus for Emery 0 paper used on two different

FIGURE 6
SURFACE APPEARANCE OF ABRADANT & SAMPLE



a = EMERY 0 ABRASION PAPER (UNUSED)
b = " " " " (AFTER 500 CYCLES)
c = TROPICAL WORSTED SAMPLE (UNABRADED)
d = " " " (AFTER 500 CYCLES)

Scale ├──┤ = 1 mm.

PHOTOMICROGRAPHS OF FIBER DEBRIS PRODUCED BY FLAT ABRASION OF VARIOUS MATERIALS

TROPICAL WORSTED

DRY ABRASION WITH EMERY 0 ABRASION PAPER

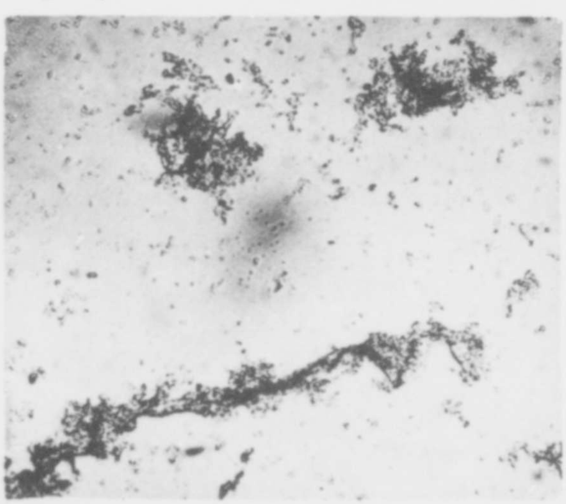
FIGURE 7

COTTON

WET ABRASION WITH WATER RESISTANT ABRASION PAPER

FIGURE 8

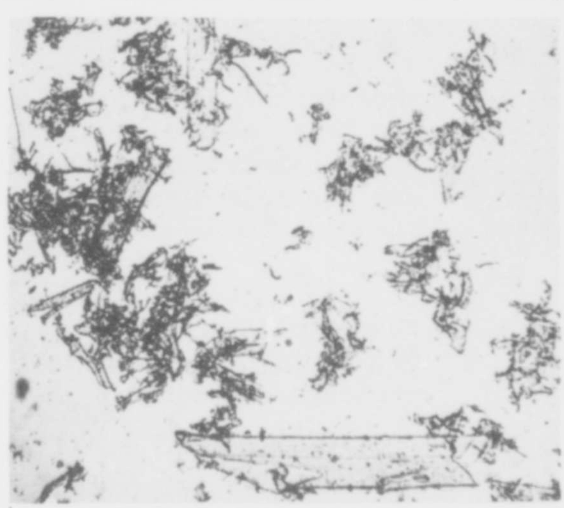
STANDARD VISCOSE RAYON (3 den.)



WET ABRASION WITH WATER RESISTANT ABRASION PAPER NO. 500

FIGURE 9

HIGHLY ORIENTED VISCOSE RAYON (3 den.)



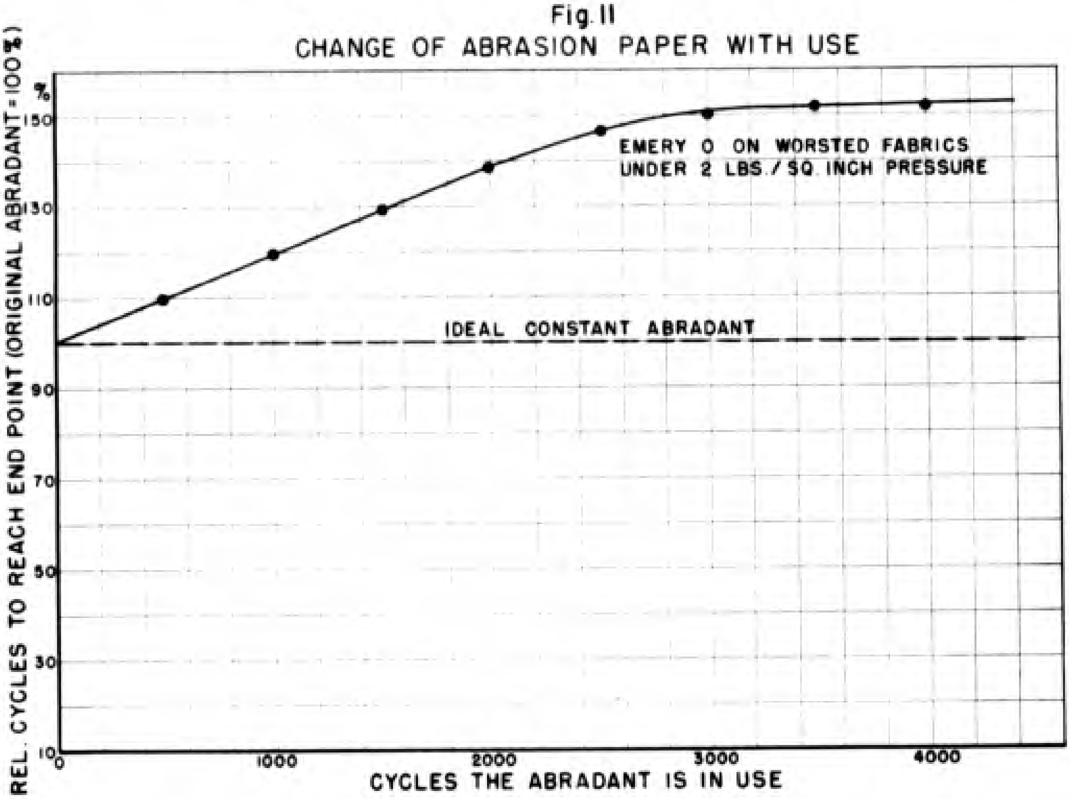
WET ABRASION WITH WATER RESISTANT ABRASION PAPER NO. 500

FIGURE 10

types of worsted fabrics (flannel and tropical worsted). This curve indicates the correction which must be applied to convert the results obtained to those which would be secured with an ideal constant abradant. In practical testing, however, such a correction has been found unnecessary because comparable materials produce a similar change of the abradant during testing, provided the abradant is changed after the evaluation of each specimen or at equal intervals.

Fig. II

CHANGE OF ABRASION PAPER WITH USE



For flat- and edge-abrasion testing with this instrument the abrasion papers Emery 0 and water-resistant silicon carbide No. 600 have shown satisfactory qualities and can be recommended. The construction of the flat-abrasion plate makes it possible to use a single abrasion sheet for several tests by slightly shifting the abrasion area after each test.

Use of constant abradants, such as files[19] or laminated spaced plates similar to the Schiefer abradant,[15] have not proved to be too suitable for this apparatus because of the high pressure and tension required to complete a test in a practical length of time. The variation between different abradants of this type is also larger than the variables of a good abrasion paper.

In flex-abrasion testing with the folding bar the bar serves not only as a means for maintaining the specimen in a folded condition and under tension, but also as an abradant, hence its surface and edges must be kept constant. In the evaluation of a test series consisting of more than 100,000 cycles performed with the same hardened steel bar, it was found that during this period the abrading characteristics of the bar (edge effect) did not change. (Note that in Table III, Page 33, there is no significant difference between the means of the vertical columns, which represent the sequence of test performance.)

However, the production of different bars with the same characteristics introduces the same problems which have been mentioned above. Calibration of the bars may help to overcome these difficulties and may permit calculation of directly comparable values obtained in different apparatuses.

C. Abrasion Pressure and Sample Tension

In mechanics of solid materials the degree of abrasion is normally defined as the ratio of the quantity of abraded material to the quantity and pressure of the abrasion action.(7) The straight-line relationship which exists between these factors for most solid materials could also be found for a number of homogeneous textile fabrics.(19) With respect to textiles, however, it is rather difficult to determine the direct proportionality between the degree of abrasion and the normal pressure because in testing as well as in actual wear, any change in abrasion pressure produces a simultaneous alteration in some other factors which also influence the degree of abrasion. But there can be no doubt that the normal pressure effective in the area of contact has an important influence on the degree of abrasion. Control of pressure conditions to obtain uniform abrasion entails not only regulation of the over-all load of the abradant on the sample, but also maintenance during the test of a uniformity of the normal pressure effective upon every location within the area of abrasion. Such control is extremely difficult due to the nature of textile fabrics, and this feature has not been accorded sufficient consideration in the construction of most abrasion instruments.

The new machine, with its combination of precisely guided abradant of controlled pressure and pneumatic sample clamping system, produces a uniform contact between fabric and abradant by the flattening of the balloon-shaped inflated sample. Due to the flexibility of most textile materials and the highly elastic extensibility of the diaphragm, it can be assumed for the forms used in the apparatus that the following relationship exists between the area of abrasion (A), the load of the abradant (L), and the air pressure under the diaphragm (p):

$$A = \frac{L \text{ (lbs.)}}{p \text{ (lbs./sq.in.)}} \qquad (1)$$

This equilibrium between abradant load and pneumatic pressure secures a uniform normal pressure in every location of the flattened contact (abrasion) area, even if the sample is not of uniform thickness. The specific abrasion pressure (p) is equal to the air pressure, and independent of the abradant load (L). The latter, however, controls the area of abrasion. Since the air pressure under the diaphragm can be kept constant with an accuracy of $\pm$ 1 mm. of mercury, and regulated from 0 to 6 pounds per square inch, the abrasion pressure is controlled within a range which is approximately the same as that encountered in actual wear.

The influence of sample tension on mechanical disintegration by abrasion, folding, and flexing has been established for fibers, yarns, and fabrics.(19,22) It has been found that the relation between resistance to abrasion or folding and sample tension is in principle a hyperbolic function with the general formula:

$$n = c \cdot p^{a} , \qquad (2)$$

where n is the resistance to abrasion, p the exterior tension applied to the sample, c a material constant chiefly dependent upon the inherent properties of the fiber and the total volume or weight per unit area of the sample, and a a form factor largely determined by the geometrical form of the fabric and yarn.

The relation between sample tension and resistance to flat abrasion is shown in Figures 12 and 13, in which are plotted

FIG. 12 - RELATION BETWEEN SAMPLE TENSION & RESISTANCE TO DRY & WET ABRASION

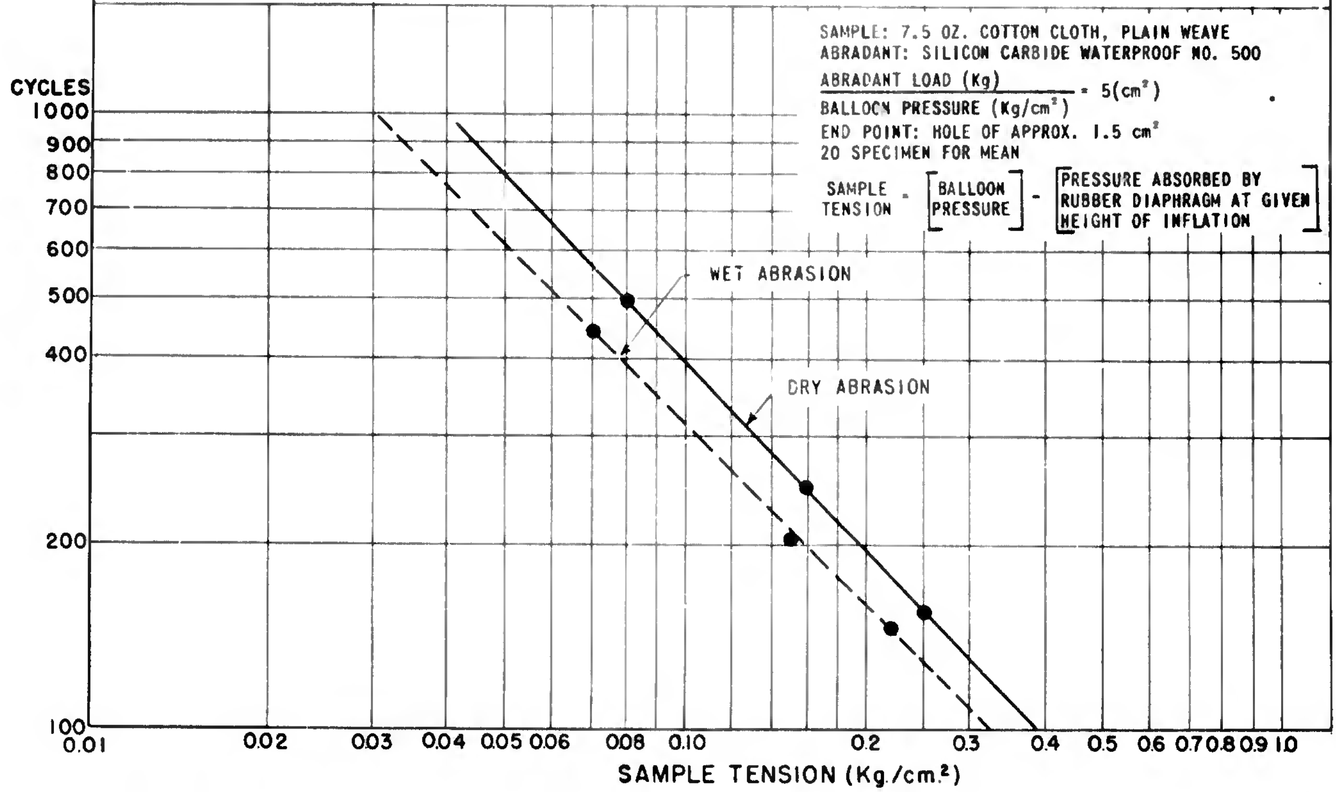
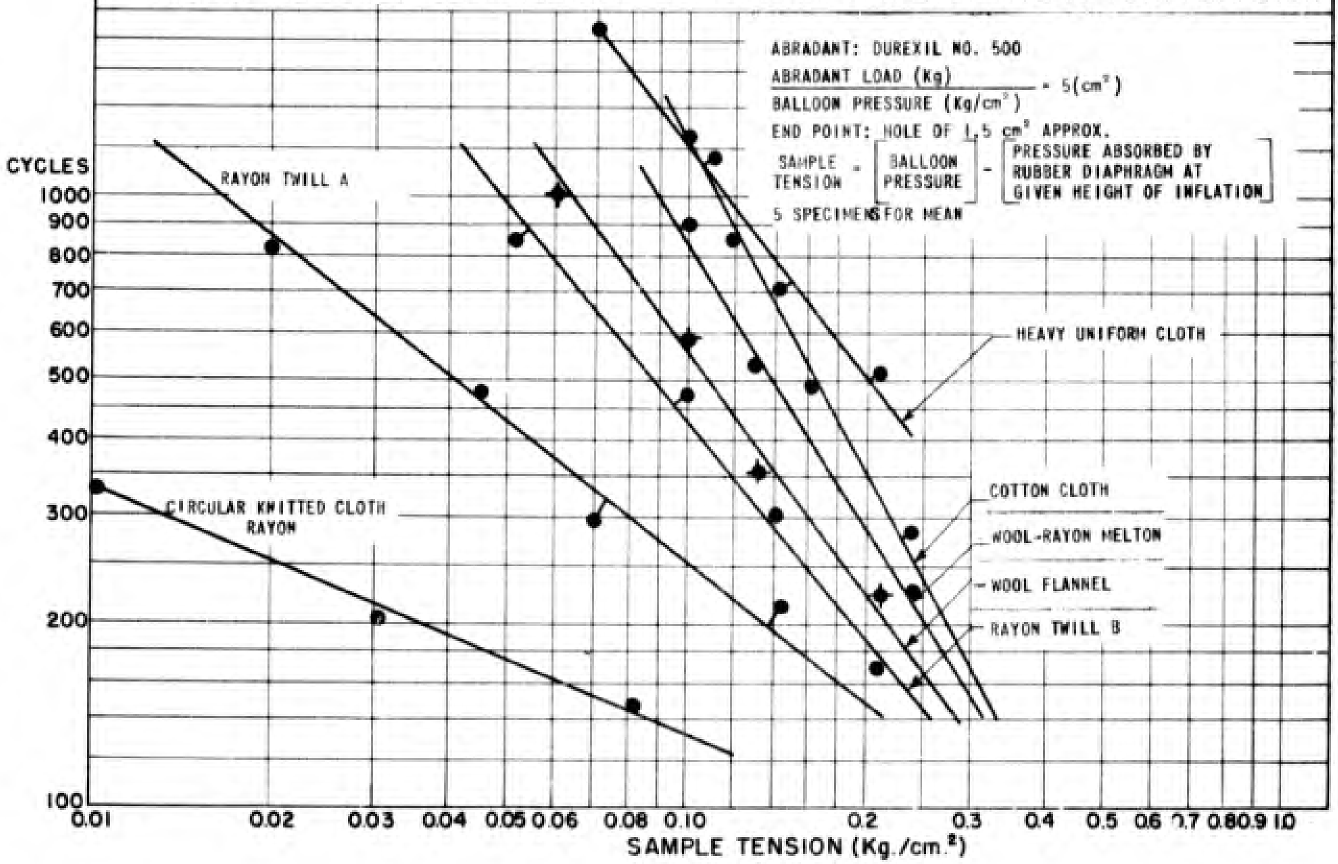


FIG. 13 - RELATION BETWEEN SAMPLE TENSION & RESISTANCE TO FLAT ABRASION



test results obtained on this machine for a number of fabrics. These figures demonstrate the importance of precise control of sample tension throughout an entire test, and also show that resistance to abrasion under varying degrees of severity can only be indicated by tests conducted under different tensions. The sample tension shown in these figures is the pneumatic tension effective upon the specimen, which has been determined as the difference between the air pressure under the diaphragm (test pressure) and that portion of the pressure which is absorbed by the diaphragm at a given height of inflation (read from a calibrated curve for the rubber diaphragm).

The pneumatic tension causes two distinguishable reactions in the specimen, each of which can be considered as a separate abrasion factor: (a) linear tensile stress effective in the direction of the threads, and (b) compression stress perpendicular to the plane of the specimen. The former is a hyperbolic function of the effective pressure p, the radius r of the clamped area, and the inflation h_1 of the specimen (balloon height). The functions (3) and (4) below, which have been derived for the bursting-strength test(16,18) can be applied here for the evaluation of the linear tensile stresses which are effective during a flat-abrasion test with the pneumatically controlled sample clamp.

Linear tension in the direction of the threads $$K = p \cdot \frac{r^2 + h_1^2}{4h_1} \text{ (lbs/sq.in.)} \quad (3)$$

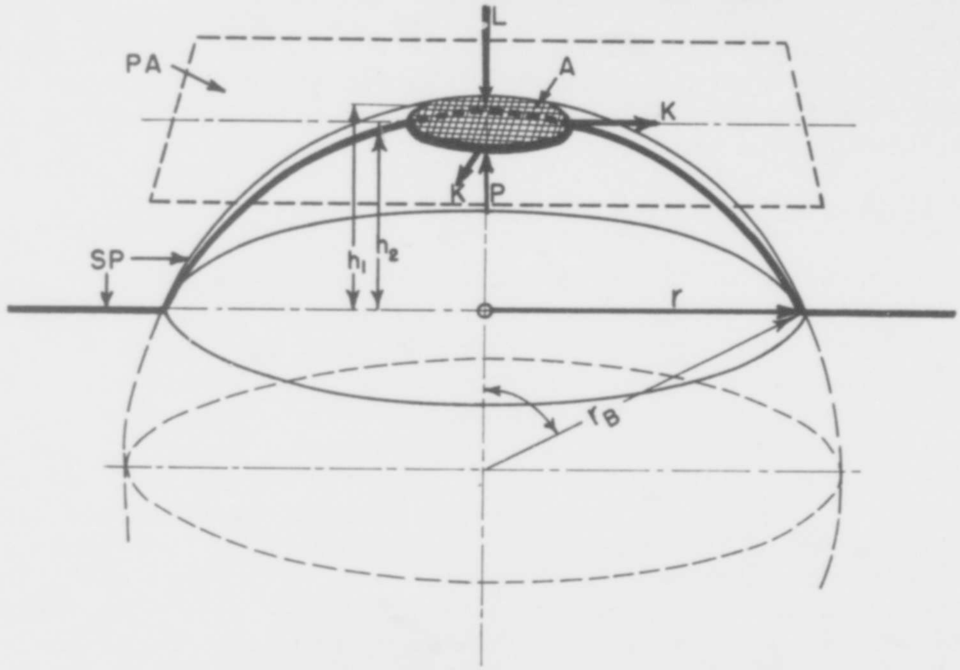
Linear elongation of the specimen $$\delta = \left[\frac{(r^2 + h_1^2)\,\pi\,\alpha}{r \cdot h_1 \cdot 360} - 1 \right] 100\ (\%) \quad (4)$$

$$\text{where } \tan \frac{\delta}{2} = \frac{h_1}{r}$$

A schematic diagram of the inflated specimen shown in Figure 14 illustrates the conditions expressed in equations (1), (3), and (4).

FIG. 14

DISTRIBUTION OF ABRASION PRESSURE AND FABRIC TENSION OF INFLATED SPECIMEN



SP	=	Specimen
PA	=	Plane of the Surface of Abradant
r	=	Radius of the Clamped Area
h_1	=	Deflection of the Unflattened Specimen
h_2	=	Deflection of the Flattened Specimen
r_B	=	Radius of Assumed Spherical Balloon
P	=	Air Pressure Inside the Balloon
L	=	Load of Abradant
A	=	Area of Contact (Abrasion)
K	=	Tensile Stress in Directions of Thread (lbs. per 1 inch Width)

The compression component mentioned under (b) above is the normal pressure under which the abrasion is performed and is equal to the test pressure, as has been discussed earlier [equation (1)]. This component, in reciprocal action with the frictional properties of specimen against abradant, determines the frictional forces and the energy of friction which is imposed upon the specimen during test. Further discussion of these actions and reactions and interpretations of the experimentally determined equation (2) must be reserved for a later study on the subject. They have been mentioned here only to indicate the influence of abrasion pressure and sample tension and to demonstrate how these two major abrasion factors can be controlled.

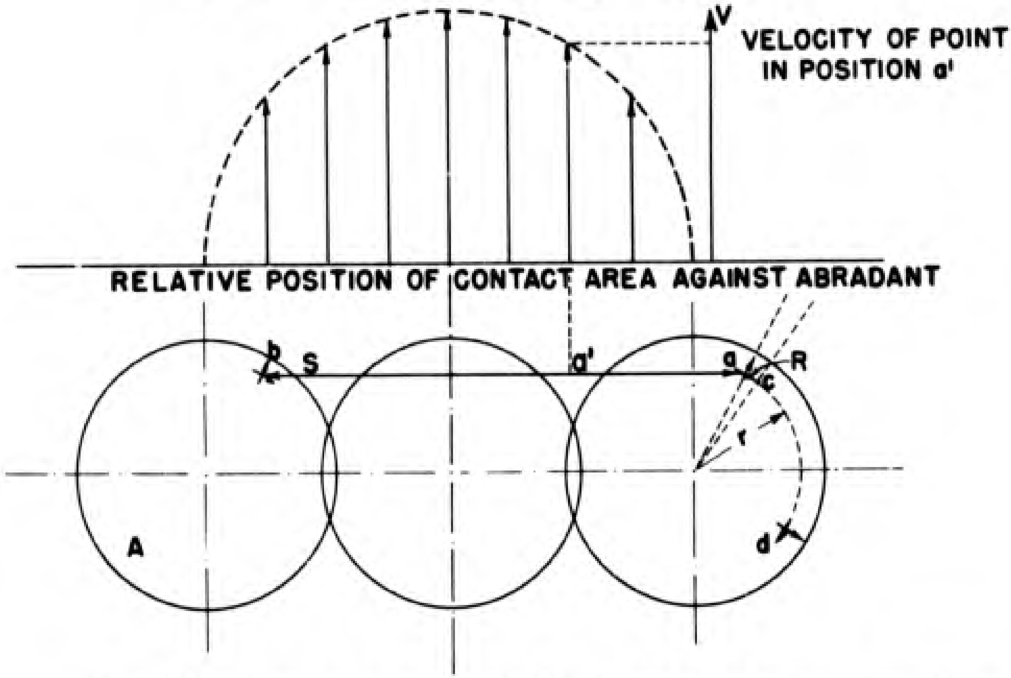
In flex-abrasion testing, pressure and tension control and uniform distribution of the stresses with the abrasion area are also secured with high accuracy, as has already been demonstrated in the description of the machine.

D. Character of the Abrasion Motion

The character of the motion between the sample and the abradant is another factor influencing the resistance to abrasion. Schiefer states[15] that uniform abrasion is dependent upon satisfaction of these two considerations; "(a) The instantaneous relative velocity between the abradant and the specimen is constant in magnitude and direction for every point of the abraded area,. . . . . . and (b) the instantaneous relative velocity between the abradant and the specimen at any point of this area is constant in magnitude but changes in direction relative to the specimen from instant to instant in a continuous and uniform manner." This first condition is ensured in all three applications of the new apparatus. The second can be practically accomplished by the rotation of the specimen in flat- and edge-abrasion tests. Figure 15 illustrates that displacement and instantaneous velocity between specimen and abradant are constant at any point of contact and that through rotation of the rotary sample clamp the direction of the abrasion related to every point of the contact area changes from cycle to cycle in a continuous and uniform manner.

If the specimen tension is two-dimensional as in the flat-abrasion test with this apparatus it has been determined that the influence of the relative direction of motion between abradant and specimen is not as significant as has been theoretically assumed. Table II (page 32), for example, demonstrates among other things that under a 4-pounds-per-square-inch pressure the sateen #111, abraded filling face up, reached the endpoint at 731.8 cycles when abraded from every direction, at 729.2 cycles when abraded parallel to the warp yarns, and at 747.3 when abraded parallel to the filling yarns. These results indicate that in a state of tension equilibrium in warp and filling directions the production of a hole by attrition is largely determined by the intrinsic resistance of the fiber material to the specific abradant and by the thickness of the layers which must be rubbed through. Under such conditions the direction of the action is of minor influence.

Fig. 15 - MOTION BETWEEN SAMPLE AND ABRADANT IN FLAT ABRASION TESTING



A... Circular area of contact (abrasion) between specimen and abradant.
a... Location of a given point on the abraded surface of the specimen at the beginning of a stroke.
b... Same as a at the end of a single stroke.
c... Same as a at the end of a double stroke.
d... Same as a after 25 double strokes.
r... Distance of this point from center of contact area.
S... Magnitude and direction of the longitudinal reciprocating displacement.
R... Magnitude and direction of the rotational displacement is:

$R = \frac{2\pi r}{100}$, where $0 \leq r \leq \sqrt{\frac{L}{p \cdot \pi}}$ and L = abradant load, p = pneumatic pressure

Under normal operating conditions of the machine the ratio between the maximum rotational displacement (R_{max}) and the longitudinal reciprocating displacement (S) is less than .013.

v... Velocity of the reciprocating motion at given positions is:

$v = m.\omega(\sin\alpha + (\lambda/2)\sin 2\alpha)$ where $m = \frac{S}{2}$ = crank radius

$v_{max} = m.\omega\sqrt{1+\lambda 2}$

$\bar{v}_{mean} = 0.637\ m.\omega$

ω = angular velocity of the crank
α = crank angle
λ = ratio between length of stroke arm and crank radius

If the distribution of the tension, however, is not uniform or if the fabric consists of layers which are under different tensions, then the direction becomes a major factor of the resistance. Such conditions exist frequently in practical wear and they are the major cause for the superiority of certain constructions for specific purposes. Later in the report this will be discussed again, confirmed by accelerated combat-service test results and reproduced by flex abrasion with this apparatus. It has been mentioned in this connection to demonstrate that the simulation of service action sometimes calls for unidirectional abrasion, and therefore a tester should be capable of reproducing this type of action as well as multidirectional abrasion of constant magnitude in each point of the abrasion area. These conditions are satisfied in the wear tester in such a manner that theoretical as well as practical requirements are met.

E. Removal of Lint and Other Debris

The last factor considered in the design of this machine is that of removal of lint or debris during conduct of the test. In flat-abrasion testing most of the abraded fiber debris is removed from the contact area by virtue of the balloon shape in which the fabric is held, so that the test action cannot be seriously affected by this residue. It was found in a quantitative test that manual removal of the lint during the abrasion can have a slight effect upon the relative precision and the average number of cycles required to reach the endpoint. In one test series, for example, the coefficient of variation of cycles for each endpoint has been decreased from 10.3 per cent to 8.1 per cent by removing the loose matted fibers at definite intervals, but comparative tests have also indicated that this does not significantly change the results obtained. Thus it is possible to perform experiments on this apparatus without interruption from the start of the test until the machine is automatically stopped as the endpoint is reached.

In edge-abrasion tests with the special clamp described earlier in this report the removal of debris is no problem since the rubbed-off fibers can cause practically no disturbance in the area of abrasion due to the shape of the specimen and the character of the motion.

In flex-abrasion testing with the folding bar it was found that most of the lint is removed from the area of flexing and abrasion. To a certain extent, pieces of fiber debris mat together between the specimen and the bar on the narrow front side of the folding bar. However, this condition does not change either the diameter of the bending action or the effect of the edge of the bar, hence it has no significant influence upon the number of cycles required to rupture the specimen.

IV. MACRO- AND MICRO-WEAR PATTERNS AND THEIR CONNECTION WITH THE NEW WEAR TESTER

It has already been mentioned in this report that an abrasion machine need not necessarily reproduce service wear actions in their entire complexity. But there is no doubt that the wear patterns produced by laboratory abrasion must be comparable to those obtained in corresponding service wear. In the comparison and interpretation of wear patterns certain principles should be observed which hitherto have not been given sufficient consideration.

A distinction should be made between a macro-wear and a micro-wear pattern. The macro-wear pattern is identical with the surface appearance of damages caused by plane abrasion, projection abrasion, flex abrasion, or abrasion of folded or stitched edges. These can generally be classified into wear areas and holes in wear. The type of pattern is largely determined by the surface character of the abrasive and the size of the contact area, by the motion between abrasive and sample, and by the geometric form of the weave and yarn structure. The micro-wear pattern can be described as the type of break-up of the individual fibers which is effected by the reciprocal action of all three cohesive forces (see Part I-B and Part III-B). It is possible that the same macro-wear pattern is formed by an action which cuts the fibers or produces a combined snagging, tearing, and unraveling effect upon the yarns as is formed by gradual attrition. Since the latter is, in most instances of practical wear, the most important type of mechanical disintegration, it is necessary that in abrasion tests not only the macro-wear pattern, but the micro-wear pattern as well, correlate with those obtained in service wear. The importance of the micro-wear pattern, not only from a testing viewpoint, but also for the engineering of wear-resistant fibers and fabrics, becomes more intelligible when we consider that wear resistance must have an inverse relationship to the fragment size of the rubbed-off fibers.(25) (The influence of the abradant upon the fragment size has already been discussed in Part III-B.) But besides the abrasive, which in actual wear changes continuously and in a very wide range, other factors, such as the geometrical form of the weave, yarns, and fibers and the inherent cohesion of the fiber material itself, also determine the size of debris which is formed. This phenomenon, for example, is the major cause for the superior durability of a coarser denier in staple rayon fabrics of the same construction and with same inherent properties of the fiber material.[20] In fabrics made of fine-denier fibers the cohesion between abrasive and fiber frequently produces a rupture of the entire fiber cross section, while when coarser fibers are used, only a portion of them is torn out and the average size of the fiber fragments is smaller. These actions and reactions as indicated by the micro-wear pattern can be summarized in terms of mechanics as follows: The amount of work required to abrade a fabric is proportional to the surface area of the fiber fragments. It is recognized, however, that only a relatively small amount of the energy expended in abrasive action (frictional work) is actually effective in mechanically disintegrating the fibers; most of it is absorbed by a visco-elastic deformation of the fiber, or by a displacement of the fiber within the yarn or fabric structure.

Micro-wear patterns produced by dry and wet flat abrasion on the new apparatus have already been discussed in connection with the effect of abradants and are shown in Figures 7 to 10 inclusive. The micro-wear pattern shown in Figure 16 is typical for a cotton fabric subjected to flex abrasion with the folding bar. The similarity of these patterns to those obtained by actual wear, as described in previous papers[5,12] and also in this report, is evident.

FIG.16 - PHOTOMICROGRAPH OF FIBER DEBRIS PRODUCED BY FLEX ABRASION OF COTTON SATEEN.

Area of abrasion and endpoint are two factors in abrasion testing which must also be considered together with the macro-wear pattern. The concentration of abrasion action within a small area does not influence the simulation of service wear as long as sample tension and abrasion pressure are comparable to those effective in service. These conditions exist for all three types of abrasion produced on this apparatus.

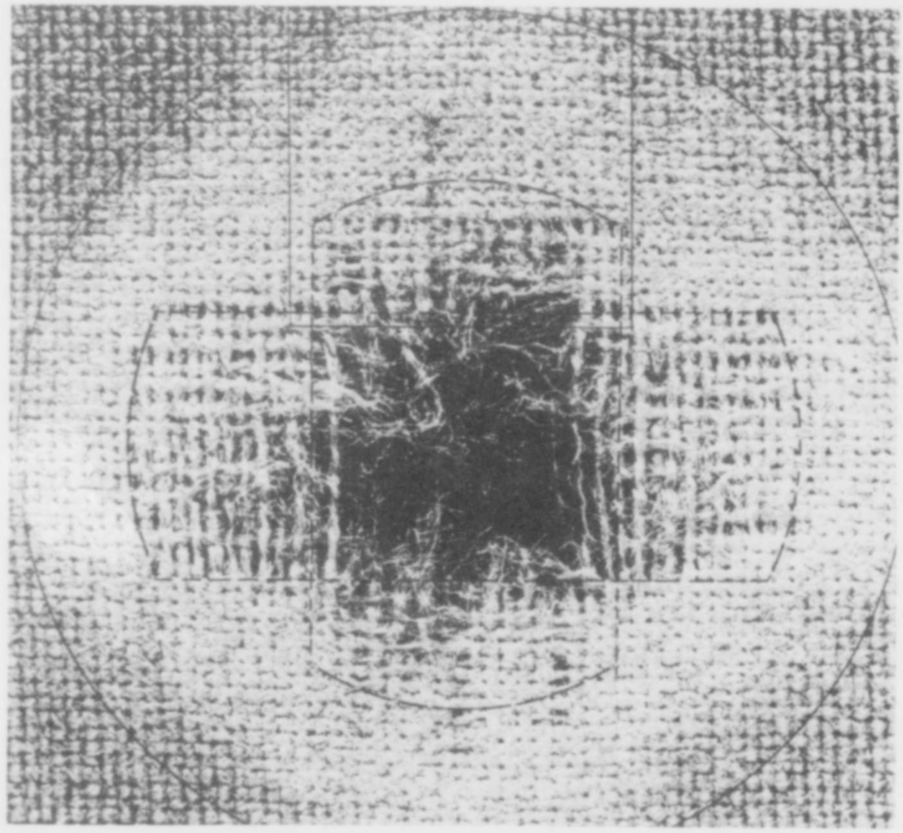


FIGURE 17
DRY ABRADED SPECIMEN OF TROPICAL WORSTED AT END POINT.
CROSS SHAPED AREA OF ABRASION IS DUE TO THE DIVISION OF THE RADIAL TENSION BETWEEN THE WARP AND FILLING THREADS

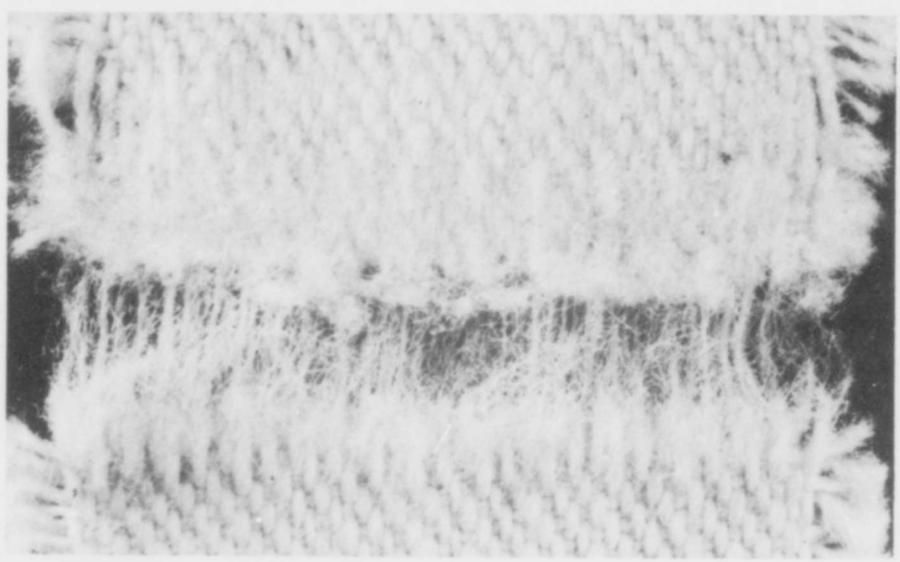


FIGURE 18
FLEX ABRADED SPECIMEN OF COTTON SATEEN SHORTLY BEFORE RUPTURE

A relatively small abrasion area, however, ensures much more accuracy in the attempt to evaluate visually the progress of abrasion(3) and to obtain a controlled endpoint which corresponds to a hole in wear. These conditions are met both in flat abrasion with the pneumatically controlled rotary clamp and in flex abrasion with the folding bar. Figure 17 is a macrophotograph of a flat-abraded specimen of tropical worsted at endpoint, and Figure 18, a sample of a cotton sateen exposed to flex abrasion. The picture of the latter was taken shortly before the endpoint was reached by rupture. Both are typical of the macro-wear patterns and endpoints obtained on the apparatus and are similar to known(10,23) macro-wear patterns of fabrics after service usage.

Knit goods have long presented a difficult problem with respect to the development of an abrasion test which results in a uniform wear pattern capable of quantitative evaluation. Figure 19 illustrates that this condition can be met with the new instrument even for a loose knitted construction.

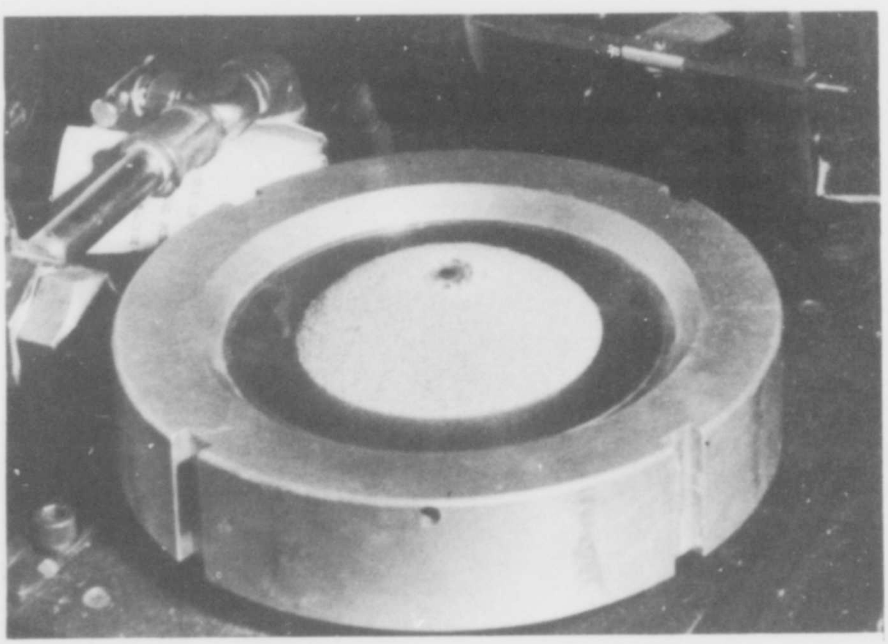


FIGURE 19
FLAT ABRADED KNITTED FABRIC AT END POINT

V. ACCURACY AND APPLICABILITY OF THE MACHINE

The accuracy of the new machine as of any other abrasion and wear tester, is determined by the following conditions:

(a) Establishment of an endpoint which is independent of individual judgment and can be quantitatively defined.

(b) Obtaining of test results whose deviation due to the machine is insignificant as compared to the deviation within the sample itself.

(c) Capability of measuring the quantity of abrasion action and the quantity of abraded material.

(d) Correlation of the results with corresponding reactions from service wear.

Conditions (a), (b) and (c) determine the precision of the tester and are the prerequisites for correlation between wear data and laboratory test results. The correlation (d) depends on the ability of the laboratory tests to reproduce the specific reactions to which a fabric is subject in wear, and on the employment of a quality index or ranking system which is based upon a properly weighted combination of the separately measured reactions.

A. Precision of the Machine

The first of these conditions stated above is met in flex abrasion with the folding bar by rupture of the specimen strip which has a given cross-sectional area. In edge abrasion the endpoint is reached when that portion of the specimen which is above the clamp is completely worn away. The quantity of this abrasion is determined by the type of clamping (Figure 2, Page 5), the unit weight, and the width of the specimen.

The second requirement is also sufficiently satisfied in flex and edge abrasion. Here variation in the number of cycles required to reach the endpoint is in the same range as that determined for the breaking strength of similar fabrics[6] or other fabric uniformity measurements. It can therefore be assumed that the variations shown, for example, in Table III, Page 33, are largely the result of the deviation within the sample itself.

The quantity of abrasion action for flex and edge abrasion is proportional to the number of cycles. The quantity of destruction is determined by the disintegrated cross section of the specimen. This can be expressed either on a weight basis (for example, in the grex system) or in terms of the cross section of the solid material. The ratio of these two quantities defines the specific abrasion resistance of the sample as it has been already mentioned in Part I-D. Thus the third requirement is met in flex and edge abrasion with the new apparatus.

In flat abrasion the endpoint is reached when electrical contact is made between the diaphragm and the abradant plate. This is the case when all the fibers in the center of the abrasion area are worn off (Figures 4, 17 and 19). Due to the precise control of the contact between abradant and specimen the holes produced are highly uniform in shape and size, as can be seen in Figure 20. In comparative testing the size of the hole can serve as a parameter for the quantity of abrasion. The number of cycles required to reach the endpoint is a measure of the quantity of

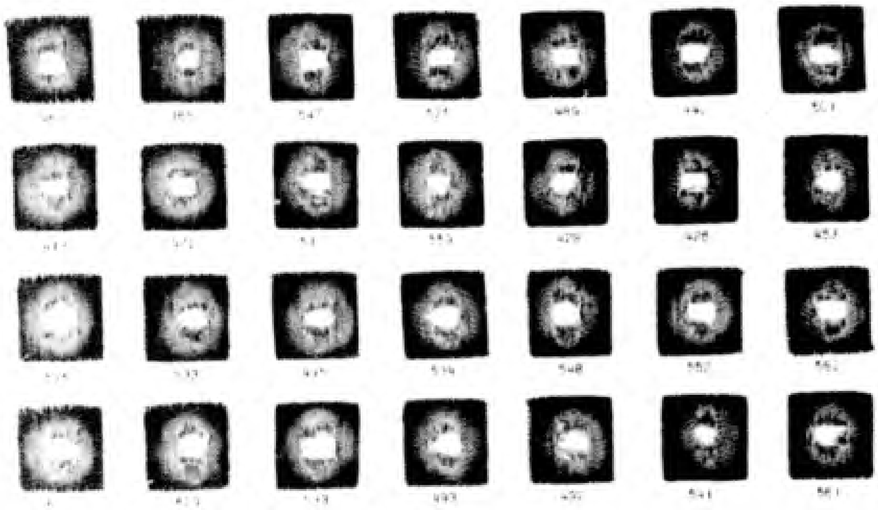


FIGURE 20

UNIFORMITY OF END POINT OBTAINED IN FLAT ABRASION

abrasion action. But the quantity of abrasion can also be determined in terms of weight of the abraded material. Instead of weighing the specimen before and after abrasion, the following method has been found to be more accurate:

From each abraded specimen two one-square-inch cutouts are made with a die, one from the abraded portion and the other from an unabraded part of the same specimen. The mean of these small abraded and unabraded samples and their standard deviation are then calculated. The difference of the two means represents the weight of the abraded material and comparison of the standard deviations gives an indication of the variations due to the machine and due to the unevenness of the fabric. Table I demonstrates such an evaluation, where each series consisted of 28 abraded specimens. (The cutouts of the abraded portion of series 1 are shown in Figure 20.)

TABLE I

Deviation of Flat-Abrasion Results

			Series 1	Series 2
Average cycles to endpoint			500.6	435.2
Coefficient of Variation of Cycles (%)			10.3	8.1
Weight of 1 sq. inch	(grams)	$\bar{X}_1$	0.1902	0.1898
Unabraded Section		σ_1	0.0031	0.0031
Weight of 1 sq. inch	(grams)	$\bar{X}_2$	0.1677	0.1724
Abraded Section		σ_2	0.0037	0.0034
Weight of Abraded Material		$(\bar{X}_1 - \bar{X}_2)$	0.0225	0.0174
Standard error of difference		$\sqrt{\left(\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}\right)}$	0.0009	0.0009

The coefficient of variation of the cycles required to reach the endpoint in flat-abrasion tests (see Tables I and II) lies within the same range as that discussed above in connection with flex-abrasion tests. But an even better indication of the precision of the machine is the insignificance of the difference in the deviation of the unabraded and abraded samples as shown in Table I. If this difference were high, it would indicate that much of the variation noted in the abraded samples was attributable to the machine.

Thus the three considerations mentioned above are also met in flat-abrasion testing with the new machine. The resistance to flat abrasion can be expressed as the ratio of the quantity of abrasion action (average cycles to endpoint) to the quantity (weight) of abraded material. It is remarkable that this can be obtained independent of other test methods, such as tensile or bursting strength, or thickness measurements, but by the production of a defined degree of damage which is similar to an actual hole in wear.

In some fundamental studies it may be desired to determine the quantity of abrasion action in terms of the frictional work expended during a test. The design of the apparatus makes it possible for an electric strain gage to be mounted in one of the bearings of the abrasion head. This can be used for continuous recording of the frictional force between sample and abradant. For an approximate evaluation, however, it is also possible to determine the coefficient of kinetic friction between sample and abradant in a separate test by means of a friction meter,(4) since it has been found that in repeated actions the coefficient soon reaches a constant value. The product of this value and the load of the abradant determines the frictional force effective during the test. The frictional work is obtained by multiplying this value by the distance of the reciprocating abrasion action and the number of cycles. Examples of such an evaluation are shown in Table II for various fabrics tested under different conditions.

B. Correlation with Service Wear and Determination of a Laboratory Wear Index

An extensive presentation and interpretation of results concerning correlation with wear tests must be reserved for another paper. However, the data shown in Tables II to V inclusive and Figure 21 will give a preliminary indication of the extent to which this tester may help to solve the much discussed and frequently misunderstood problem of predicting wear resistance on the basis of laboratory data. The fabrics concerned were evaluated on a broad basis on the Quartermaster Board Combat Course at Camp Lee, Virginia, in addition to being subjected to flat and flex abrasion by the new apparatus. In the combat-course tests there was a wide variability in the wear scores of garments made from the same fabric, which tended to obscure the existence of significant differences among the materials. However, a careful statistical evaluation revealed that the eight fabrics can be significantly ranked in the order of greatest resistance to wear as follows:

1. No. 114 - Sateen, 10.6 ounce, with 25 per cent nylon in the filling; and No. 117 - Sateen, 10.1 ounce, with 50 per cent nylon in the filling.

2. Nos. 111 and 112 - Sateen, 10.2 ounce and 10.5 ounce, respectively, 100 per cent cotton.

3. No. 103 - HBT Modified, 10.1 ounce; No. 107 - Oxford, 9.7 ounce; and No. 100 - HBT, 9.9 ounce (the latter somewhat poorer than Nos. 103 and 107). All 100 per cent cotton.

4. No. 104 - Plain Weave, 9.2 ounce, 100 per cent cotton.

Since yarn count and twist were the same for these experimental fabrics (all of the cotton constructions were made of approximately the same yarns), the difference in wear resistance can be attributed to two major factors, namely (1) the use of nylon-blended filling yarns, ensuring an inherently higher resistance, and (2) the geometrical form of the weave. The slight differences in weight among the fabrics are a minor factor in accounting for the differences in wear resistance, as is apparent when the laboratory data are related on a unit-weight basis.

Table II presents the data obtained by flat-abrasion tests, in which variations were made in the surface of the sample abraded, the abrasion direction, and the diaphragm pressure. As has been noted previously, this table demonstrates the quantitative method for evaluating flat-abrasion resistance, and also indicates the accuracy obtainable in this application of the tester.

Table III shows the individual data obtained in flex-abrasion tests of warp strips with the folding bar in contact with the fabric face. These figures demonstrate the consistency of results and also indicate the constancy of the folding bar as has been discussed earlier in this report. Flex-abrasion tests were also performed in the directions of the warp, filling, and bias both on the face and back of the fabric, and the results obtained are shown graphically in Figure 21.

TABLE II

Flat-Abrasion Data Showing Accuracy of Machine and Influence of Test Conditions

Sample	Test Conditions			Cycles to Reach End Point			Weights of 1 Sq. Inch Areas Cut Out From Each Specimen (Grams)						Weight of Abraded Material (2)	Cycles / Weight	Coefficient of Friction (3)		Frictional Work / Abraded Material (4) mkg/g	
	Position of the Sample (1)	Abrasion Direction	Diaphragm Pressure				Unabraded			Abraded								
				$\bar{X}$	σ	V(%)	$\bar{X}_U$	σ_U	V_U(%)	$\bar{X}_A$	σ_A	V_A(%)	(Grams)	$(\frac{C}{G})$	μ_{ST} Static	μ_D Dynamic	(μ_{ST})	(μ_D)
Sateen (#111)	Face	Multidirectional	2 lbs/sq.in.	3122.1	431.0	13.8	.2352	.0082	3.5	.1821	.0056	3.0	.0531 ± .0031	5.88×10^4				
			4 lbs/sq.in.	731.8	82.8	11.3	.2294	.0075	3.3	.1879	.0083	4.4	.0415 ± .0035	1.76×10^4	.77	.76	470	462
			$5\frac{1}{2}$ lbs/sq.in.	388.7	34.6	8.9	.2338	.0057	2.5	.1927	.0073	3.8	.0411 ± .0029	0.95×10^4				
	Back	Multidirectional	4 lbs/sq.in.	708.6	77.0	10.9	.2333	.0037	1.6	.1896	.0046	2.4	.0530 ± .0019	1.34×10^4				
	Face	Parallel to warp	4 lbs/sq.in.	729.2	55.1	7.6	.2363	.0061	2.6	.1911	.0048	2.5	.0452 ± .0024	1.61×10^4				
		Parallel to filling	4 lbs/sq.in.	747.3	96.9	13.0	.2400	.0047	2.0	.1926	.0049	2.5	.0474 ± .0021	1.57×10^4				
Sateen (#117)	Face	Multidirectional	4 lbs/sq.in.	787.8	79.8	10.1	.2283	.0047	2.1	.1885	.0037	2.0	.0398 ± .0019	1.98×10^4	.70	.64	479	438
	Back	Multidirectional	4 lbs/sq.in.	947.1	82.0	8.7	.2237	.0056	2.5	.1762	.0035	2.0	.0475 ± .0021	1.99×10^4				
HBT (#100)	Face	Multidirectional	4 lbs/sq.in.	826.7	113.8	13.8	.2276	.0029	1.3	.1845	.0038	2.1	.0431 ± .0015	1.91×10^4	.68	.63	448	414
HBT-K (#103)	Face	Multidirectional	4 lbs/sq.in.	618.3	54.0	8.7	.2244	.0059	2.6	.1859	.0050	2.7	.0385 ± .0023	1.61×10^4	.78	.75	432	416
Plain (#104)	Face	Multidirectional	4 lbs/sq.in.	656.7	59.8	9.1	.2077	.0042	2.0	.1679	.0033	1.9	.0398 ± .0017	1.65×10^4	.73	.70	416	398
Oxford (#107)	Face	Multidirectional	4 lbs/sq.in.	574.8	55.2	9.6	.2193	.0069	3.1	.1787	.0045	2.5	.0406 ± .0026	1.42×10^4	.78	.77	386	381
Sateen (#114)	Face	Multidirectional	4 lbs/sq.in.	711.6	46.4	6.5	.2349	.0015	0.6	.1972	.0030	1.5	.0377 ± .0011	1.89×10^4	.76	.70	495	456

(1) "Position of the Sample" refers to the surface of the fabric which is in contact with the abradant. ("Face" is the surface worn outside. In these sateens, the filling yarns were flush on the outside surface.)

(2) Standard Error of Weight of Abraded Material $= \sqrt{\frac{\sigma_U^2 + \sigma_A^2}{n}}$

(3) Coefficient of Friction determined by Dreby Friction Meter

(4) $\frac{\text{Frictional Work}}{\text{Abraded Material}} = \frac{\text{Cycles x stroke length x 2 x abradant load x coefficient of friction}}{\text{Weight of abraded material}}$

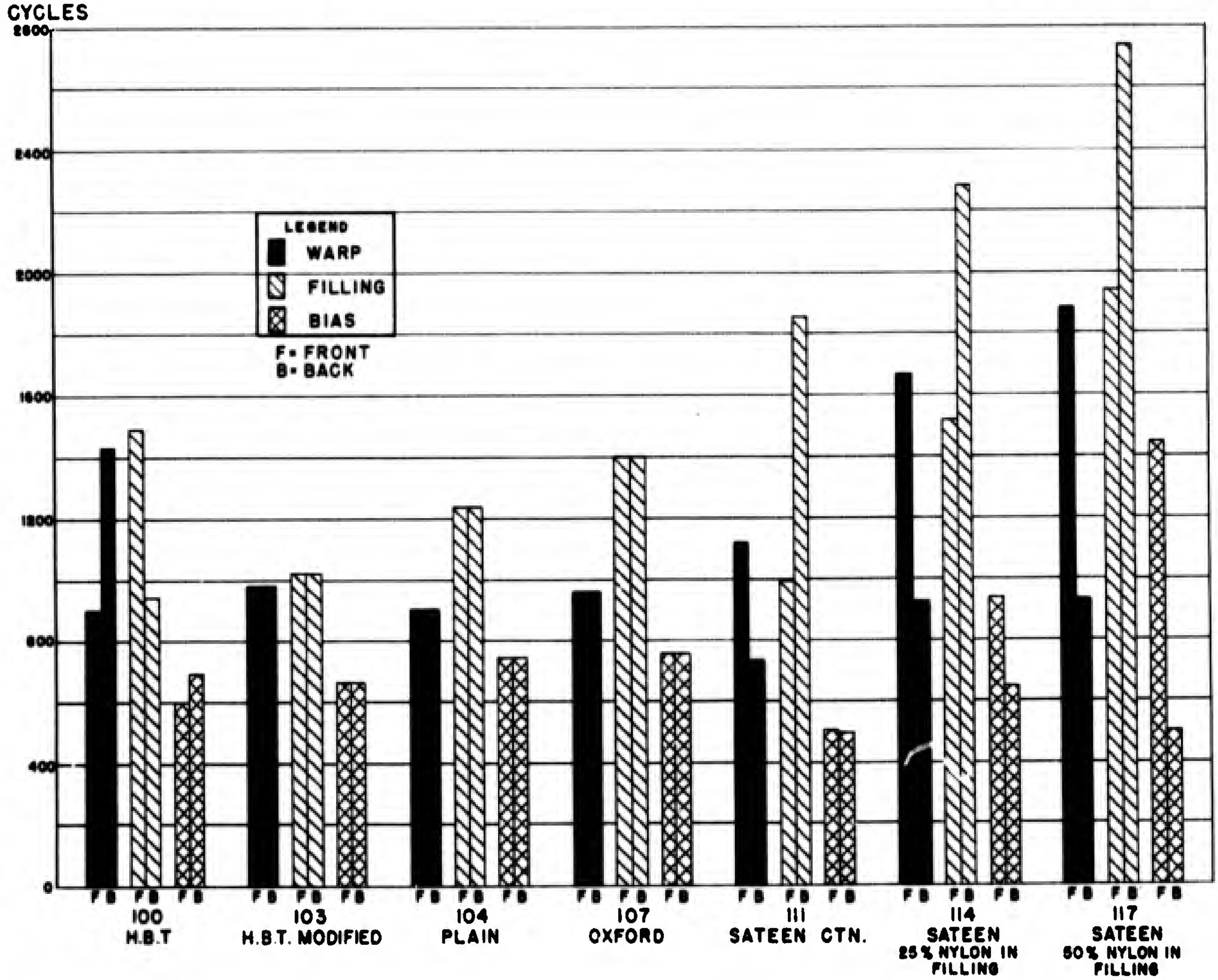
TABLE III

Flex Abrasion Data Showing Relative Precision of Machine

SAMPLE NO.	WEAVE	ENDS/INCH	Number of cycles (double strokes) to rupture												
			Specimen												
			1	2	3	4	5	6	7	8	9	10	$\bar{X}$	σ	V(%)
100	HBT	81.3	862	967	924	742	889	937	949	905	995	872	904	70.7	7.8
103	HBT - MOD.	82.1	997	909	944	984	1050	889	966	948	965	1147	980	73.9	7.5
104	PLAIN	81.5	758	945	735	849	894	1035	796	968	1020	1066	907	118.9	13.1
107	OXFORD	84.9	1124	922	756	899	1100	1120	760	978	950	1015	962	134.3	14.0
111	SATEEN-C	84.1	936	1212	1006	1022	1234	1204	1216	1342	969	990	1113	142.5	12.8
112	SATEEN-C	85.5	1010	1040	1022	1232	1199	1071	1200	1347	1277	1370	1177	134.2	11.4
114	SATEEN-25N	84.6	1626	1758	1796	1727	1569	1317	1612	1787	1657	1730	1658	142.6	8.6
117	SATEEN-50N	84.0	1922	2088	1930	1727	2135	1799	1663	1687	1883	1957	1879	160.8	8.6
		Σ	9235	9841	9113	9182	10070	9372	9162	9962	9716	10147	9580		
		σ	447	447	460	385	415	288	345	351	363	388			

Test Conditions: Folding Bar (1/16 by 3/8 in. hardened tool steel).
4 lbs. pressure load on abrasion head.
4 lbs. tensile load on folding bar.
3/4 inch stroke length.
120 double strokes per minute.
Specimen: Warpwise strips, 1 inch wide.
Sequence of test performance: Specimen #1 of each sample tested in order shown in table, followed by specimen #2 of each sample in same order, etc.

Fig.21-RESISTANCE TO FLEX-ABRASION OF FABRICS TESTED IN DIFFERENT DIRECTIONS



The development of a quality index on the basis of a weighted consideration of the various laboratory wear components involves the conversion of absolute into relative values. An accurate and simple method of accomplishing this is to express the absolute data as a percentage of the average value of each property included in the series. The weighted combination itself must be based upon the selection of test actions corresponding to those predominant in the combat course and on the application of the wear composition deducted by salvage studies. In accordance with the results of previous investigations(10,23) and the general composition of wear presented in Part I-A of this report, the following two formulae have been used in the calculation of quality indices:

TABLE IV

Relative Flat- and Flex-Abrasion Data and
Weighted Laboratory Quality Indices Compared to Combat-Course Ranking

FABRIC	FLAT ABRASION (Multidirectional) *Face of Fabric in Contact With Abradant					FLEX ABRASION (Unidirectional) Folding Bar in Contact With Face of Fabric				Back of Fabric				Over-All	OVER-ALL ABRASION	TEAR RESISTANCE	LABORATORY QUALITY INDEX		COMBAT-COURSE RANKING
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s
100	118	109	108	98	97	76	116	77	90	150	57	108	105	97.5	103	81	81.7	85.5	4
103	88	92	94	98	99	82	79	85	82	102	62	104	89	85.5	90	78	84.2	85.3	3
104	93	94	87	94	87	76	96	95	89	95	76	117	96	92.5	90	65	74.9	79.3	5
107	82	81	79	90	87	80	109	96	95	100	86	118	101	98	88.5	80	81.4	85.0	3
111	105	102	102	109	111	93	77	66	79	76	114	80	90	84.5	93	127	106.8	101.7	2
112						98	54	77	76	83	98	91	91	83.5		119		101.9	2
114	102	108	115	108	114	138	118	120	125	96	139	103	113	119	117	117	126.9	125.2	1
117	112	114	115	103	105	157	151	184	164	98	168	79	115	139.5	127	133	129.4	138.3	1
Ave.	100	100	100	100	100	100	100	100		100	100	100		100.0		100			

*Face is that surface of the fabric which is worn outside.

a Cycles to reach endpoint
b Cycles per unit abraded weight
c Cycles per unit abraded area
d Frictional work per unit abraded weight
e Frictional work per unit abraded area

f and j Cycles to rupture (warp direction)
g and k Cycles to rupture (filling direction)
h and l Cycles to rupture (45° bias)
i Average of f, g and h
m Average of j, k and l

n Average of i and m
o Average of n and c
p Average of warp and filling tear (Elmendorf tearing strength test)

Formula I: (Column q in Table IV)	.50 flex abrasion, warpwise, face of fabric in contact with folding bar.
	.20 flat abrasion, multidirectional (cycles per unit abraded area).
	.30 tear resistance (average warp and filling).
Formula II: (Column r in Table IV)	.40 flex abrasion, warpwise .20 flex abrasion, over-all .20 flat abrasion, multidirectional .20 tear resistance

The relative laboratory data obtained as a result of these evaluations are shown in Table IV together with the quality indices (based on the two formulae as indicated above) and the combat-course rankings. The relative data of the individual properties and indices, compared with the combat-course results by Spearman's Rank Correlation Coefficient,* are shown in Table V.

On the basis of these results the following observations may be made:

A weighted combination of the resistance to specific actions determined separately on the new multipurpose abrasion tester, supplemented by laboratory data on tear resistance, provides an excellent correlation with the combat-course results.

The isolated test action with the highest statistical correlation with the combat-course results has been found to be flex abrasion in the warp direction with the face of the fabric in contact with the folding bar. This action involves both abrasion and flexing in the warp direction, with the warp threads subjected to both tensile stress and compression, and the filling threads

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* Spearman's Rank Correlation Coefficient, r_s, is expressed by the formula,

$$r_s = 1 - \frac{6 \sum d^2}{n(n^2-1)} ,$$

where d is the difference in rank between combat-course and laboratory data of test samples, and n the number of ranks. An r_s value of 0 indicates no correlation, an r_s value of 1 indicates perfect correlation.

to compression only. The major wear factor in combat-course testing is a combination of this abrasion action and tearing. Due to the geometry of the fabrics, the resistance to flex abrasion varies in a rather wide range, depending on the distribution of the tensile and compression stresses effective upon the two sets of yarns. In some weaves, such as the sateens evaluated in these tests, the yarns which are only compressed serve as a cushion, protecting those yarns which are subjected to tensile stress. The results shown in Figure 21 demonstrate the advantage that can be taken of this phenomenon in selecting fabrics with maximum resistance to this type of action.

TABLE V

Rank Correlation Between
Combat-Course Evaluation and Laboratory Test Data

<table>
<tr><th colspan="3">Combat Course Ranking versus:</th><th>Columns in Table IV</th><th>Spearman's Rank Correlation Coefficient</th></tr>
<tr><td colspan="2" rowspan="3">Multidirectional Flat Abrasion
Uniform two-dimensional tension. Face of Fabric in contact with Abradant.</td><td>Cycles to reach endpoint.</td><td>a</td><td>0.232</td></tr>
<tr><td>Cycles per unit abraded area.</td><td>c</td><td>0.732</td></tr>
<tr><td>Frictional work per unit abraded area.</td><td>e</td><td>0.822</td></tr>
<tr><td rowspan="7">Unidirectional Flex Abrasion</td><td rowspan="3">Folding Bar in contact with Fabric Face.</td><td>Warp direction</td><td>f</td><td>0.930</td></tr>
<tr><td>Filling direction</td><td>g</td><td>0.582</td></tr>
<tr><td>Bias</td><td>h</td><td>0.618</td></tr>
<tr><td rowspan="3">Folding Bar in contact with Fabric Back.</td><td>Warp direction</td><td>j</td><td>0.572</td></tr>
<tr><td>Filling direction</td><td>k</td><td>0.488</td></tr>
<tr><td>Bias</td><td>l</td><td>0.036</td></tr>
<tr><td colspan="2">Over-all flex abrasion</td><td>n</td><td>0.700</td></tr>
<tr><td colspan="3">Over-All Flat and Flex Abrasion</td><td>o</td><td>0.834</td></tr>
<tr><td colspan="3">Tear Resistance</td><td>p</td><td>0.870</td></tr>
<tr><td colspan="3" rowspan="2">Laboratory Quality Index</td><td>q</td><td>0.999</td></tr>
<tr><td>r</td><td>0.940</td></tr>
</table>

In flat-abrasion testing neither the surface of the fabric abraded, nor the direction of abrasion, nor the weave has much influence upon the results obtained when the tension is evenly distributed on warp and filling threads of the sample. It is evident that under such conditions, resistance is largely influenced by the inherent strength of the fiber material, the surface and form factors of the individual fiber, and the unit weight of the fabrics. However, if the resistance is expressed quantitatively as the ratio between cycles per unit abraded area,* or even better, as frictional work per unit abraded area, some differences in weave do become apparent. The sateens are thus seen to be slightly superior to the twills, and the twills to the plain and oxford weaves used in these tests. (See Table II and also note correlation of these values with combat-course results in Table V.)

These results have indicated how the new tester can be applied as a versatile instrument for the quantitative evaluation of wear factors. The data presented also demonstrate that a high correlation between laboratory test results and accelerated service wear can be secured. Further experimentation with the apparatus will help to analyze the complex property of wear resistance of textiles more accurately than has been possible by previous laboratory methods or by service tests alone.

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* The number of cycles per unit abraded area is obtained by multiplying the cycles required to abrade a unit weight of the material (as shown in Table II) by the unit weight of the fabric (ounces per square yard).

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