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DEVELOPMENT OF FLAME RESISTANT COMBAT UNIFORM FABRICS MADE FROM LONG STAPLE WOOL AND ARAMID BLEND YARN

by

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Englewood, CO 80112

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This report documents efforts performed, between May 2011 and November 2012, under a Broad Agency Announcement contract between the American Sheep Industry Association (ASI) and the Natick Soldier Research, Development and Engineering Center (NSRDEC). The objective was to develop flame resistant combat uniform fabrics with improved strength by spinning aramid (Nomex® and Kevlar)/wool blend yarns on the long staple yarn spinning system rather than the more commonly used short staple spinning system. Under this effort both woven camouflage printed outerwear fabric and solid colored knitted next-to-skin fabric were developed. The woven fabric provided flame protection, visual and near infrared camouflage, comfort, and durability compared to current camouflage printed Nomex and Kevlar fabric (MIL-C-83429). Likewise the knitted fabric provided flame protection, comfort, and durability unavailable in other base-layer fabrics. This project leveraged and built upon two previous NSRDEC funded ASI efforts (which developed the camouflage print recipe and appropriate woven and knitted constructions) and focused on improving fabric strength through the use of the long versus short staple yam spinning system. The project was a complete success, resulting in fabrics that are near ready for full rate production.

15. SUBJECT TERMS

YARNS	WEAVING	YARN SPINNING	STRENGTH(MECHANICS)
NOMEX	UNIFORMS	ARAMID FIBERS	FIRE RESISTANT TEXTILES
FABRICS	CAMOUFLAGE	KNITTED FABRICS	PERFORMANCE ENGINEERING
TEXTILES	WOVEN FABRIC	SPINNING(MOTION)	SPINNING(INDUSTRIAL PROCESSES)

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Preface

This report documents work performed under an 18-month Broad Agency Announcement (BAA) contract (# W911QY-11-P-0363) awarded by the Natick Soldier Research, Development and Engineering Center (NSRDEC), on May 17, 2011, to the American Sheep Industry Association Inc. (ASI). The contract was carried out at a number of commercial facilities under the supervision and guidance of ASI and was completed within the contract period. This method of working with commercial partners offers the added advantage of rapid commercialization of the successful product

The purpose of this project was to develop flame resistant (FR) combat uniform fabrics with improved strength by spinning aramid/wool blend yarns on the long staple "worsted" spinning system rather than the more commonly used short staple ring spinning system. Under this effort both piece dyed knitted fabric and woven camouflage printed fabric were developed. This work focused on improving fabric strength and durability through the use of the long versus short staple yarn spinning system.

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Executive Summary

Under an 18-month Broad Agency Announcement (BAA) contract awarded by the Natick Soldier Research, Development and Engineering Center (NSRDEC), in May 2011, the American Sheep Industry Association, Inc (ASI) provided two low cost inherently flame resistant (FR) fabrics with improved durability through the long (as opposed to the short) staple yarn spinning system. The first fabric was 300 yards of piece dyed knitted fabric for next-to-skin wear, and the second was 300 yards of Operation Enduring Freedom Camouflage Pattern (OCP) printed lightweight woven fabric for combat uniforms. Both fabrics are inherently FR, machine washable, strong, and durable. The woven fabric met military specifications for near infrared spectral reflectance and colorfastness. They will likely meet static control requirements when tested. The fabrics exceeded specified performance requirements of the current in-use items. The success of this development was built on experiences gained by ASI in work under two previous NSRDEC contracts (Refs. 1, 2), which ranged from fiber and blend selection; to manufacturing parameters of yarns, weaves, and knit constructions; and to color formulation for dyeing and printing.

The OCP printed woven combat uniform fabric was manufactured in accordance with MIL-DTL-44031E "Cloth, Camouflage Pattern: Cotton and Nylon Class 7 OCP". It was made from long staple spun yarn using a blend of a continuous treated wool top using Chlorine-Hercosett chemistry (Superwash) 20.5 micron wool and an aramid blend consisting of Nomex Type N325 (natural, low crystallinity), Kevlar, and P140 antistatic fiber in 100 mm staple length. This fabric provides FR, visual, and near infrared camouflage and durability at a likely reduced cost compared to aramid fabric (MIL-C-83429). Test results show the fabric offered increased strength and protection and a reduced fabric weight when compared to the Defender M fabric (GL-PD-07-12, Rev 4, Cloth Flame Resistant, Type I, Ripstop) currently used in the FR Army Combat Uniform (FRACU). The fabric is subjectively judged to be more soft and drapable. The use of Superwash wool in this blend increased color depth of shade compared to the untreated wool used in the two previous development projects and met all of the color specifications for FR fabrics including near infrared spectral reflectance and colorfastness standards. The fabric prepared for printing with the OCP camouflage pattern does not require either piece dyeing or chemical treatment on the blended fabric prior to printing. The print formulation based on Lanaset (acid) dyes is wool specific and has no affinity for aramid fibers.

The simplicity of the dye process used in printing resulted in less waste in that process. This savings coupled with reduced fabric weight will likely reduce material cost. Elimination of piece dyeing prior to fabric printing may also contribute to significant savings over 100% aramid fabric and is projected to offer superior overall fabric value compared to the Defender M fabric used in the current FRACU.

The piece dyed, knitted, next-to-skin fabric was made from the same blend of Superwash 20.5 micron wool and 100 mm staple length aramid fibers (Nomex Type N325, Kevlar, and P140

antistatic fiber). The fabric showed much improved strength and durability compared to the performance goals of the candidate “tri-blend” fabric in the Fire Resistant Environmental Ensemble (FREE) Program (Ref. 3). The increased (compared to the original short staple project) antistatic fiber (P140) content (3%) in the overall blend should lead to superior static control properties though not yet evaluated.

Conclusions that can be drawn from ASI work performed under NSRDEC contracts include the following:

1. A blend of 50/50 wool/aramid produced an inherently FR and machine washable fabric.
2. Use of two-ply yarns in warp and in filling improved fabric strength and durability (Ref. 4).
3. Use of long staple length fibers spun on the long staple “worsted” spinning system increased fabric strength and durability and imparted a soft hand in comparison to short staple manufacturing.
4. Due to the superior dye characteristics of Superwash wool, Lanaset (acid) dyes designed for wool offer greater depth of shade in dyeing and in printing the wool in this blend. As an added bonus, coloration of only the wool component met stringent shade, near infrared reflectance and colorfastness requirements.
5. No dyeing or chemical finishing of the prepared for print goods was necessary for achieving required color standards of the OCP printed fabrics.
6. Development of the wool/aramid blend indicated significant cost savings in two areas:
   - Fabric weight was reduced (less fiber consumed, lower cost) without sacrificing required strength, durability and FR.
   - Using 50% wool in the blend greatly simplified dyeing, printing and finishing procedures that should result in very low rejection and rework rates.

The combination of these two potential savings in full rate production should make the new fabric highly cost competitive with FR fabrics currently in production as well as offering superior comfort and durability.

DEVELOPMENT OF FLAME RESISTANT COMBAT UNIFORM FABRICS MADE FROM LONG STAPLE WOOL AND ARAMID BLEND YARN

1. Introduction

This report documents a project conducted by the American Sheep Industry Association, Inc. (ASI), from May 2011 to November 2012, in response to a Broad Agency Announcement (BAA) solicitation issued to the Natick Soldier Research, Development and Engineering Center (NSRDEC) to provide two low cost, lightweight, inherently flame resistant (FR) and machine washable fabrics (one to be worn next to skin and the other as a combat uniform) in a blend of wool and aramid long staple fibers, spun on the “worsted” (long staple ring) spinning system. Fibers in long staple lengths suitable for blending and spinning on a long staple spinning system were known to offer many advantages compared to short length fibers spun on short staple “cotton” spinning systems. The known advantages included strength and durability, evenness, low pilling, and better tactile properties of the fabrics due to fewer protruding fibers in the yarns and fabrics. This project investigated, developed, and produced fabrics made from long staple length fibers spun on the worsted spinning system. The main purpose of this development was to determine if the long staple spinning system could produce superior yarns in comparison to the short staple cotton system.

ASI is a producer-powered federation of state organizations dedicated to the common goal of promoting the profitability and well-being of the US sheep industry. ASI traces its beginnings back to 1865 when it was known as the National Wool Growers Association, making it the oldest national livestock association in the United States. Today, ASI continues as a national organization representing the interest of over 80,000 sheep producers throughout the United States.

ASI conducted work with the wool/aramid blend based on the short staple ring spinning system under two previous contracts awarded by NSRDEC, in 2004 and 2005 (Refs. 1, 2). The exclusive use of short staple spinning system in prior work was due to the unavailability at that time of U.S. produced DuPont aramid fiber (Nomex and Kevlar) longer than 52 mm. To maintain Berry amendment compliance, wool had to be cut to 52 mm staple length and blended with Nomex for spinning on the short staple ring spinning system. Yarns so produced suffer from two major restrictions. One is that the percentage of wool fiber that can be added to the blend is limited to a maximum of 50%, and the other is that the blended yarn cannot be spun to counts finer than 28/1 cotton count (cc). However, even with these restrictions the short staple wool/aramid fabrics possessed many desirable attributes such as comfort, durability and ease of coloration with very good fastness by dyeing only the wool component.

In 2009 DuPont offered to supply its long staple version of Nomex and Kevlar in top form from production in Europe for trial use. DuPont further assured initiation of long staple Nomex production in the U.S. if demand was sufficient (1M pounds per year) to justify the capital expense. DuPont has initiated domestic production of long staple Nomex for their in-house product development trials.

Based on these assurances, this project utilized all of the previously developed attributes and refined them to improve the previous fabric's comfort while maintaining overall performance and reducing cost. Comfort was expected to improve due to a smoother fabric surface and lighter weight. Fewer protruding fiber ends from the use of long staple lengths were expected to make the fabric surface smoother. The lighter weight would be due to an assumed increase in yarn strength that would allow lighter construction without sacrificing fabric strength, durability, and thermal protection.

The success of this development was to be judged on proving the "value for money" equation, i.e., high levels of product durability, wearer comfort, flame resistance, and thermal protection at a lower procurement and replacement cost.

2. Materials and Results

The deliverables of this project were two wool-aramid blend fabrics. One, 300 yards of piece dyed knitted jersey fabric, and the second, 350 yards of Operation Enduring Freedom Camouflage Pattern (OCP) printed plain woven fabric. This chapter describes the fibers and yarns used (Sections 2.1 and 2.2, respectively) and the final fabrics produced (Section 2.3), as well as the results from the tests performed to evaluate each, in the respective sections.

2.1 Fibers

A blend of 50% wool and 50% aramid fibers were used to produce the final fabrics based on the worsted (long staple) ring spinning system.

2.1.1 Wool

Although the two previous NSRDEC/ASI contract efforts (Refs. 1, 2) showed that a blend of 50% untreated wool and 50% aramid produced inherently machine washable and FR fabric, this long staple effort tested and compared untreated wool with new Superwash treated wool and chose Superwash wool fibers for the blend used to produce the final fabrics. Fiber analysis indicated that the Superwash would improve color yield and enhance wash performance, as well as meet the increased coloration demand required for successful OCP camouflage printing.

Domestic Superwash 20.5 micron top was selected for blending with aramid in both the knitted and woven fabric development. To begin work 550 lbs. of Superwash wool top was purchased from Chargeurs Wool USA, Jamestown, SC and forwarded to Hanora Spinning, Woonsocket, RI, for blending with aramid fibers and spinning using the worsted (long staple) spinning system. Fiber analysis of untreated and Superwash treated wool using the Uster Test (Table 1) showed that the Superwash wool top was slightly finer in fiber diameter compared to the untreated control due to chemical treatment of the fiber and was slightly longer in mean staple length due to an additional gilling step following the chemical process. This extra processing step not only removed some of the shorter fibers from the top, but also increased top uniformity as seen in the mass variations of the top (Sliver Coefficient of Variation (CV)). (The Uster Testing was performed by Kentwool, as they had the most sophisticated worsted yarn testing in the U.S.)

Table 1. Comparison of untreated and Superwash treated wool top

PROPERTY	UNTREATED WOOL	CL-H TREATED WOOL Superwash
Fiber Diameter, micron	20.76	20.17
CV diameter, %	19.17	19.17
Fiber length, Hauteur, mm	63.8	70.3
CV length, %	46.5	44.6
Sliver CV, %	6.69	3.75

These results are based on using the same production lots of wool top.

2.1.2. Aramids

Long staple aramid fibers in sliver form manufactured by DuPont in Europe were procured for blending with wool on the worsted system. Nomex and Kevlar slivers were supplied separately, so they could be blended with each other first and then with the desired amount of wool. This two-step blending insured the required proportion of Kevlar and P140 anti-static fiber would be present in the final blend.

To begin preparation 445 lbs. of Nomex type N325 (natural, low crystallinity), variable cut top on 22 bumps was shipped to Hanora Spinning along with 84 lbs. of stretch broken Kevlar blended with P140 antistatic fiber on 12 sliver packages. The 84 lbs. of the blended sliver was made up of 53 lbs. of Kevlar and 31 lbs. of P140 fibers. This ratio of 10/6 ensured that when blended together with the above Nomex sliver, the final aramid fiber blend would be 84% Nomex / 10% Kevlar / 6% P140. Thus when wool sliver and the above aramid prepared slivers were further blended in a 1:1 ratio, the final blend composition would be 50% wool/ 42% Nomex / 5% Kevlar / 3% P140 antistatic fiber.

Fiber analyses of the received tops are shown in Table 2.

Table 2. Analyses of aramid fibers (via Uster Test)

PROPERTY	NOMEX TYPE N325	KEVLAR	P140
Fiber diameter, micron	17.86	13.0	19.0
Staple length, Hauteur, mm	100.4	84.8	84.8
CV length, %	21.3	31.2	35.8
Sliver CV, %	20.3	24.5	24.5

The measured micron values can be converted into decitex (dtex) or denier using the formula

$$\text{Dtex} = 0.007854\ (d^2 + s^2) \times \text{density}$$

Where "d" is the average fiber diameter in microns and "s" is the standard deviation of fiber diameter.

The standard deviation of synthetic fibers is very small and can be ignored for all practical purposes. Using the density value of Nomex as 1.38 and the density value of Kevlar as 1.44, the calculated fiber deniers from the observed micron values are 2.50 denier for Nomex, 1.50 denier for Kevlar and 3.0 denier for P140.

The actual fiber analysis graphs and data obtained from a Uster Tester scan are given in Appendix A.

2.2 Yarns

2.2.1 Knitting Yarn from Hanora Spinning.

The yarn count required for making single jersey fabric at 4.5 oz./yd^2 was calculated to be 1/42 worsted count (wc). Accordingly, 242 lbs. of 1/42 wc yarn was spun from a blend of 50% Superwash 20.5 micron wool /42% Nomex N325 / 5% Kevlar / 3% P140 to a knitting twist of 17 turns per inch (tpi). The spun yarn was split on 125 cones to comply with the number of yarn feeds available on a single jersey knitting machine at Alamac American Knits. The spun yarn was analyzed on Uster Tester equipment, and the results are tabulated in Table 3.

Table 3. Properties of wool/aramid blended yarn for knitting

Property	Worsted Spun Wool /Aramid Yarn Spun at Hanora Spinning
Actual fiber blend content, %	55% wool/37.8% Nomex/4.5% Kevlar /2.7% P140
Yarn count, wc	1/42
Twist z singles, tpi	16.13
Breaking strength, oz	10.57
Breaking force, gf/denier	1.58
Extension at break, %	12.16
Energy to break, ozf.cm	50.4

The results show very good yarn strength properties, even though the blend levels missed the target of 50% wool/42% Nomex/5% Kevlar/3%P140. The results are further discussed and compared with yarn properties spun on the short staple spinning system in Section 2.2.3.

2.2.2 Weaving Yarn

It was demonstrated in 1998 (Ref. 4) that a woven fabric made from a two ply yarn was significantly stronger than fabric made from single yarns of similar resultant count. This observation was further confirmed in a July 28, 2003 progress report (Ref.1). The comparison from that report is reproduced here (Table 4) for completeness of the stated argument.

Table 4. Comparison of fabrics previously produced from single and two ply short staple spun yarns

Fabric Properties	Fabric Using Single Yarn	Fabric Using Plied Yarn
Yarn count	20/1cc	40/2 cc
Fabric weave	Plain	Plain
Fabric weight, oz./yd^2	5.75	6.4
Tensile Strength, lbs. *	136 x 104	183 x 127
Tear Strength, lbs.*	6.0 x 4.9	18.6 x 13.4
Shrinkage after 5 washes, %*	2.9 x 1.2	4.6 x 3.0

* warp by filling

It was also determined in subsequent in-house trials (not documented) that a very light weight plain weave fabric of sufficient strength can be produced from 2/45 wc yarn spun on the long staple “worsted” system.

To begin this portion of the project 425 lbs. of 20.5 micron Superwash wool top was blended with Nomex/Kevlar/P140 blended top as discussed previously in Section 2.1.1. The fibers were spun and plied at Hanora Spinning resulting in 324 lbs. of yarn on 395 packages for warping and 210 lbs on 150 packages for filling. The completed yarn was delivered to Springfield LLC, Gaffney, SC for weaving, preparation for printing and final finishing. The resulting fabric from this effort was unsatisfactory (discussed at length in Section 2.2.3). This offered an opportunity to remake the blended yarn at a different worsted spinner and remake the fabric to determine if the fault was in the processed yarn or some other construction step such as slashing of the warp yarn.

For the remake an additional 585 lbs. of Superwash 20.5 micron wool was shipped to Kentwool, Pickens, SC for blending with the remaining aramid fiber slivers shipped from Hanora Spinning. The fibers were blended on the draw frame of the worsted spinning system and spun into required 2/45 wc yarn at Kentwool.

This time 460 lbs. of 2/45 wc yarn was shipped to Springfield on 395 cones for warping and 85 cones for filling. The spun yarns from both of the spinning sources were analyzed using a Uster Tester and the results are tabulated in Table 5.

Table 5. Comparison of Superwash wool/aramid yarns for weaving spun on two long staple spinning systems

Property	Yarn spun at Hanora Spinning	Yarn spun at Kentwool
Blend content, %	55% wool/37.8% Nomex / 4.5% Kevlar /2.7% P140	50% wool/42% Nomex /5.0% Kevlar/ 3.0% P140
Yarn count, wc	2/40.8	2/45
Twist z singles, tpi	15	17.1
Twist s folding, tpi	16	15.3
Breaking strength, oz.	15.79	22.89
Breaking force, gf/den	1.26	1.83
Extension at break, %	28.3	19.9
Energy to break, ozf.cm	168.1	176.7

The Kentwool yarn was significantly stronger than that spun at Hanora. There are two specific reasons for the observed differences; first, Kentwool recombed the wool top (wool is first combed during the production of wool top); a second combing process is an optional step sometimes used in making quality fine count yarns. Recombing removes short wool fibers and improves the alignment of the remaining long fibers thereby making the yarn stronger and smoother. Hanora Spinning does not have combing equipment because recombing is not required for the coarser count yarns they typically produce. This difference coupled with less aramid fiber in the yarn blend spun at Hanora contributed to the very large differences in yarn strength properties between the two spinners. The observed variation in the blend composition between planned and produced is not considered normal and a better quality control operation would have prevented such a variation in the blend than was achieved at Hanora Spinning.

2.2.3 Comparison of Yarns Spun on "Cotton" and "Worsted" Spinning Systems.

Yarn data from previous studies (Refs. 1, 2) where short staple spun yarns were the only available option were retrieved and compared with current worsted spun yarns produced under this effort. The comparison of cotton count (cc) versus worsted count (wc) yarns is given in Table 6.

Table 6. Comparison between different spinning systems on yarn properties*

Yarn Properties	Spun on Short Staple Spinning Untreated		Spun on Long Staple Spinning Superwash Treated	
	Singles for knitting	Plied for weaving	Singles for knitting	Plied for weaving
Count, wc (cc)	1/45 (30/1)	2/42 (28/2)	1/42 (28/1)	2/45 (30/2)
Twist, singles, tpi	20.2	20.0	16.13	17.1
Twist, folding, tpi	-	14.0	-	15.3
Strength, gf/denier	1.48	1.7	1.58	1.83
Extension , %	16.7	23.3	12.2	19.9
Increase in Strength, %			6.7	7.6

*Cotton count, yarn strength and elongation were measured on a Uster Tester

The results clearly show the worsted yarns were stronger than cotton spun yarns in equivalent counts although the differences observed were not as large as had been predicted. It is conceivable that the use of Superwash wool in this trial, which is known to be weaker in strength compared to untreated wool control, may have contributed to a smaller increase. Additionally the use of aramid components produced in Europe, which were quite different from the fiber type used in the short staple project, could have skewed the results in favor of the short staple version. In previous trials (Refs. 1, 2) the aramid blend used was Nomex Type 462 (partially crystallized) which is a blend of 93% Nomex, 5% Kevlar, and 2% P140 proprietary static dissipative fiber compared to Nomex Type N325 used in the present trial. The use of Nomex 325 was a matter of availability of the Nomex fiber in sliver form from Europe during that period of time.

2.3 Final Fabrics

This section describes the manufacturing process and the properties of the 300 yard piece dyed knitted jersey fabric and the 350 yards of OCP printed plain woven fabric.

2.3.1 Knit Fabric

Calculations predicted that to produce a 4.5 oz. /yd^2 jersey fabric, a yarn of 1/42 wc was required. This yarn was ordered from Hanora Spinning using Superwash wool and the aramid blend as detailed in the yarn Section 2.3 (55% wool/37.8 Nomex/4.5% Kevlar/2.7% P140).
The knit fabric was knitted, dyed, and finished at Alamac American Knits, Lumberton, NC. The fabric production was planned to deliver 300 linear yards of a very lightweight (4.5 oz. /yd^2) single jersey fabric in a minimum finished width of 58-60 inches. In addition, sufficient yardage (20 yards) was added for sampling, in-house and external fabric testing.

The fabric produced on a 28 gauge knitting machine was examined, inverted and piece dyed in a jet dyeing machine to the required Desert Sand color (reference # 503) using wool specific Lanaset (acid) dyes. No attempt was made to color the aramid components. It was anticipated that the fabric would have a grey tint due to a higher percentage of P140 antistatic fiber in the blend and that actually did occur. The fabric knitting details are given in Table 7.

Table 7. Knit fabric manufacturing details as provided by Alamac on greige fabric

Fabric Construction	Single Jersey
Mill Style / lot number	JS8353 / 9583-01N
Pounds knitted	192
Yarn used, wc	1/42
Finished fabric target weight, oz./yd^2	4.4 – 4.8
Knitting machine details	28 gg /30" diam. / 2520 needles
Yarn input per 100 needles, inches	10.1
Greige weight, oz./yd^2	5.1
Greige width, inches	74
Greige Shrinkage after 3 wash cycles, L x W	4.2 x 11.8
Dye machine used	Gaston-Futura

The fabric was dyed in a Gaston-Futura jet dyeing machine. It was then relax dried in tubular form on a loop dryer, slit and framed to a width of 62" with a maximum length overfeed setting on the pin tenter frame. The finished fabric was inspected and tested in house. Yardage was forwarded to Govmark Associates, an independent test house in Farmingdale, NY 11735 for further testing using the performance goals for the current candidate next-to-skin wear fabric (Fire Resistant Environmental Ensemble (FREE)). The in-house test report and comments are presented in Table 8. These results demonstrate that the fabric met specification with excellent mechanical properties.

Table 8. Knit fabric inspection and in-house test results

Properties	Test Method	Results
Fabric weight, oz./yd^2	ASTM D-3776	4.4
Fabric width, inches		61
Fabric wash shrinkage, L x W	AATCC 135	3.8 x 4.2
Fabric Torque, %	ASTM D-3882	7.4
Mullens Burst Strength, Lbs.	ASTM D-3787	87
Fabric Inspection, holes/100 yds.		2
Color evaluation	AATCC color std cards	Black stripes due to presence of carbon in the antistatic yarn (P140)

The Govmark Organization, Farmingdale, NY, an independent, certified testing laboratory, also evaluated the fabric. Govmark findings are shown in Table 9.

Table 9. Properties of wool/aramid knitted jersey fabric

Properties	Test Method	Performance Goals	Results
Fabric weight, oz./sq. yd.	ASTM D-3776	4.5	4.47
Fabric width cuttable, min. inches.		52 min	61
Color fastness to –			
Light	AATCC 16-3	3	3
Washing	AATCC 61-3L	4	5
Perspiration	AATCC 15	4	5
Crocking (Dry and wet)	AATCC 8	3-4	5
Burst Strength, lbf	ASTM D-3787	50	73
Abrasion Resistance after 20,000 rubs	ASTM D-4966	NS	3.5 No end point wear
Dimensional Stability, % (L x W) Shrinkage after 3 wash/TD cycles	AATCC 135, 1, IIIA, 3 cycles	<5 x <5	5.0 x 1.5
Flammability, (L x W)	ASTM D-6413		
Burn time, s		2 x 2	2.1 x 3.3
Char length, in		6 x 6	3.2 x 3.2
After glow, s		15 x 15	0.9 x 3.5
Fabric Stretch/ recovery %	ASTM D-2594	NS	
Length			18 / 100
Width			59 / 98
Air Permeability, cfm/ft^2	ASTM D-737	150 min	285
Thermal insulation, clo	ASTM D-1518	NS	0.2

The results clearly show that the fabric met all of the requirements for a FR base layer fabric. In addition, when the results are compared to the candidate “tri-blend” requirements in FREE next-to-skin-wear jersey (Ref. 3), the wool/Nomex fabric exceeded all of those requirements as well. (See Table 10)

Table 10. Comparison between wool/Nomex jersey with in use jersey (FREE, Ref. 3)

Characteristic	Test Method	Wool/Nomex	Tri-Blend (FREE, Ref. 3)
Weight, oz./yd^2	ASTM D 3776	4.47	4.0 – 5.0
Blend ID	AATCC 20	Wool/aramid	55/33/12 FR rayon/wool/ nylon
Dimensional Stability, % Wales (length) Courses (width)	AATCC 135, 1, IIIA, 3 cycles	 5.0 1.5	 6 max 6 max
Burst Strength, lbf	ASTM	73	50 min
Appearance after Laundering	AATCC, 135,1, IIIA, 3 cycles 3.2.6	4.5	3.5
Colorfastness to Crocking -dry -wet	AATCC 8	 5.0 4.5	 4.0 min 3.0 min
Colorfastness to Light	AATCC 16,9 Opt. E	3.0	3.0 min
Colorfastness to Perspiration	AATCC 15	5.0	3.5 min
Stretch & Recovery, % (W x C) -Immediate stretch, -Stretch after 30 min -Growth after 1 hr	ASTM D 3107 - 4 lbf Tension	 25x99 27x95 27x93	 30x85 min 30x85 min 35x60 max
Air Permeability (FT^3 / Min / FT^2)	ASTM D 737	285	300 min
Flame resistance (LxW) -After Flame, s -After Glow, s -Char length, inches	ASTM D 6413	 2.1 x 3.3 0.9 x 3.5 3.2 x 3.2	 2.0 max 7.0 max 7.0 max
Pilling	ASTM D 3512		3.0 min
Abrasion resistance -after 20,000 rubs	ASTM D 4966	3.5 No end point	ns

2.3.2 Woven Fabric

The other product deliverable of this project was 350 yards of camouflage printed woven fabric in nominal 6.0 oz./yd^2 weight. Only 300 of the required 350 yards was delivered because there was more waste than anticipated at Duro printing, testing, and compacting trials. The woven fabric should be camouflage printed with OCP according to MIL-DTL-44031E “Cloth, Camouflage Pattern: Cotton and Nylon, Class 7 OCP”. The visual camouflage colors (shade evaluation) would be evaluated and approved by NSRDEC at the printing mill and prior to final printing.

An important objective of this development was to submit OCP camouflage printed fabric which would be superior to the Defender M (GL-PD-07-12, Rev 4, Cloth Flame Resistant, Type I, Ripstop) fabric currently used in the FR Army Combat Uniform (FRACU).in mechanical and physical properties and at a comparable fabric cost. Defender M was known, at the time, to have relatively poor durability including color loss after 20 commercial launderings due to fibrillation, and complaints of crotch seam failures. Defender M is also a sole sourced product. Cost was stressed as equally important for the development to become commercial. Because the initial fiber cost of wool/aramid blend is expected to be greater than that of Defender M, one of the many avenues for recouping the higher fiber cost would be by reducing fabric finished weight and by developing a simplified production procedure that would reduce waste in production resulting in higher first quality yield. A preliminary trial was undertaken using previously produced wool/aramid blended fabric in 5.2 oz. /yd^2 to see if such a very lightweight fabric which was known to meet mechanical properties would also meet the specified thermal protection requirements of 4 second ignition time on a Thermal Manikin. In pursuance of this objective an initial Manikin thermal protection trial was undertaken at DuPont’s test facility using the in-house 5.2 oz. /yd^2 50/50 wool/Nomex fabric developed and funded exclusively by ASI and Springfield. A comparison test with Defender M fabric at 6.5 oz. /yd^2 was also undertaken. The test data shown in Figure 1 indicated that a very lightweight wool/Nomex fabric easily passed a 4 second burn test with less than 30% skin burn area. By comparison the Defender M also passed the requirement with skin burn value of 23%. Based on the above observations, a fabric weave plan was developed to produce a lightweight plain weave fabric using two-ply, worsted spun (2/45 wc) yarn in both warp and in filling.

A plain weave fabric to a planned specification was produced by first slashing the warp yarns using beam to beam slashing equipment and woven to a finished fabric set of 60 ends and 45 picks per inch. This set was predicted to yield a finished fabric weight of 5.2 oz. /yd^2. The woven greige fabric was open width scoured, dried and sheared as part of the prepared for print procedure. During this preparation, it was noticed that the fabric shrank excessively during scouring and washing. The cause of this high shrinkage remains unknown to date in spite of several technical meetings with the manufacturer (Springfield LLC). A number of plausible causes were suggested including the operation of slashing the warp yarns, a manufacturing step required in the short staple industry (particularly cotton) but totally alien to the wool industry. It was conjectured that the slashing operation on wool yarns may have created undue stretching of the warp yarn resulting in high fabric shrinkage during subsequent washing.

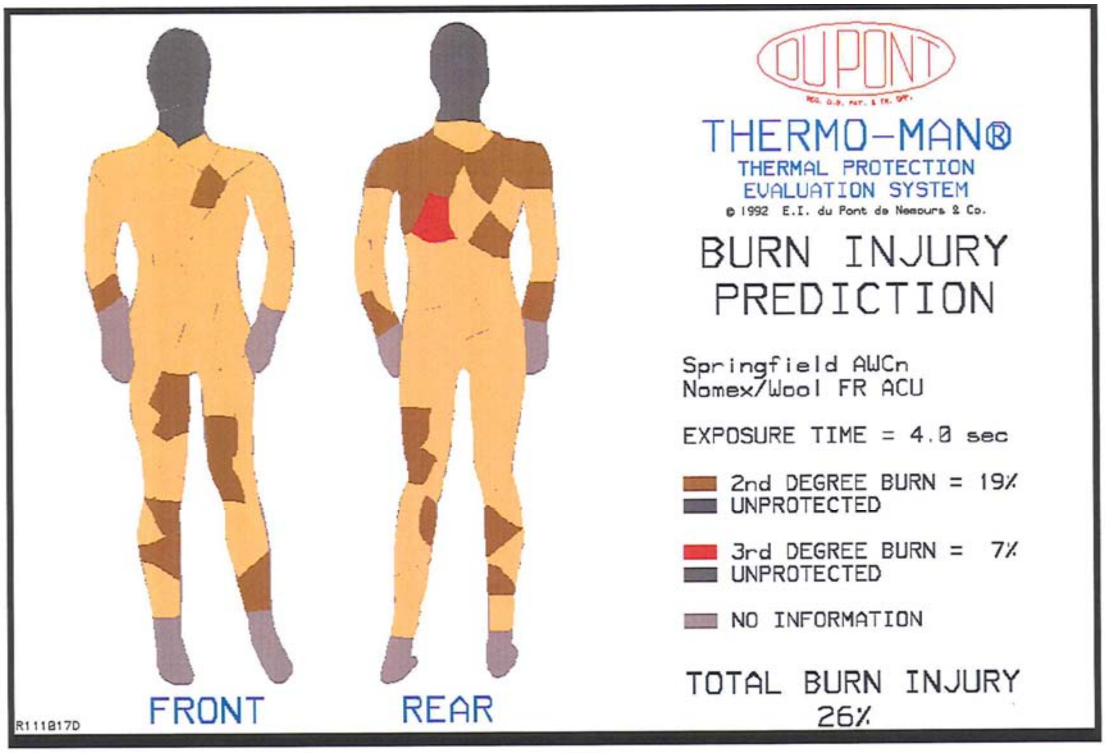


Figure 1 Thermal manikin test on previously developed, in-house wool/Nomex fabric in 5.2 oz.

The fabric produced was considered ruined and since we had surplus Nomex and Kevlar fibers supplied by DuPont, a remake of the entire fabric was undertaken. In the remake the warp yarns were not slashed and used as supplied on the section warping machine prior to weaving. Kentwool replaced Hanora as the spinner and produced the required 395 cones for warping and 85 cones of filling. Springfield wove greige fabric which was scoured in a jet dyeing machine, dried and sheared for printing. This fabric was used in the development of color formulation, printed at Duro, and submitted to NSRDEC on 28 August 2012. The results of the prepared for printing fabric are given in Table 11.

Table 11. Properties of prepared for print woven fabric

Property	Test Method	Planned	Observed
Fabric weight, oz./sq. yd.	ASTM D 3776	5.2	5.1
Yarns per inch, warp	ASTM D-3775	60	61
Yarns per inch, filling	ASTM D-3775	45	45
Fabric width, overall, in.		66	66
Fabric width cuttable, in.		65	65
Dimensional stability, % (L x W) -AATCC 135	AATCC, 135,1, IIIA, 3 cycles 3.2.6	5.0 x 5.0	6.1 x 8.6

The fabric parameters seen in the table above are on specification except for observed high fabric shrinkage. No attempt was made to correct the shrinkage prior to printing since the process of printing itself is known to add further length distortion of the fabric. It was decided to wait until after printing to correct both of the possible distortions by passing the fabric through an open width fabric compactor. 450 yards of scoured, dried and sheared fabric was shipped to Duro Industries for printing. Duro was our development partner in the earlier wool/aramid Universal Camouflage Pattern (UCP) printing trials and are quite familiar with the developed color chemistry for wool. The print formulation used was based on Lanaset (acid) dyes which are known to provide very high colorfastness properties on wool textiles. Technical personnel from NSRDEC were present at the printing trial and were involved in approving the color shade prior to final fabric printing. As planned the printed fabric was passed through a compactor (Sanforized) as a part of the final fabric stabilization and finishing procedure.

The OCP printed fabric was evaluated for near infrared reflectance (NIR) values at Duro Industries and their results are shown in Table 12. With the exception of two readings being slightly out of the required range (three out of tolerance are allowed in meeting the NIR specification) the rest of the spectrum is well within the current requirements and as expected was achieved without printing of the Nomex fiber. This simplified printing option of only printing the wool component should assure reduced fabric waste during printing (historically very high on aramid fibers). Additional cost saving is realized by not dyeing the fabric prior to printing. The combination of these savings is substantial and expected to compensate for the higher initial fiber costs associated with this fabric.

Table 12. NIR reflectance values of OCP printed wool/Nomex fabric

Wavelength nm	OCP Requirements (Defender M)			Results (on wool/aramid blended fabric)		
	Cream 524 & Tan 525	Pale green 526, Olive 527 & Brown 529	Dark Green 528 & Dark Brown 530	Cream 524 & Tan 525	Pale green 526, Olive 527 & Brown 529	Dark Green 528 & Dark Brown 530
600	22 - 44	12 - 30	3 - 11	34 & 31	21,20 & 13	12 & ***11***
620	24 - 45	12 - 30	3 - 12	35 & 31	22,20 & 14	12 & 11
640	24 - 45	12 - 32	4 - 13	36 & 32	22,21 & 14	12 & 12
660	25 - 45	12 - 32	4 - 14	38 & 34	23,22 & 16	13 & 13
680	28 - 45	14 - 34	4 - 17	42 & 38	25,24 & 19	16 & 16
700	28 - 48	14 - 36	6 - 23	45 & 42	27,27 & 24	19 & 20
720	30 - 52	16 - 39	6 - 23	48 & 45	29,29 & 27	22 & 23
740	32 - 55	18 - 41	10 - 25	49 & 46	29,30 & 30	24 & 25
760	36 - 56	20 - 43	14 - 30	50 & 47	30,30 & 31	25 & 27
780	38 - 57	22 - 45	18 - 35	50 & 47	30,31 & 32	25 & 28
800	40 - 57	24 - 45	21 - 40	51 & 48	30,31 & 33	26 & 29
820	44 - 58	26 - 46	24 - 42	51 & 48	31,31 & 34	26 & 29
840	46 - 59	28 - 47	26 - 43	51 & 48	31,32 & 34	26 & 30
860	48 - 60	30 - 48	28 - 45	52 & 49	31,32 & 34	27 & ***30***

The printed fabric showed two values marginally outside the NIR specification for Dark Brown 530 color. The finished fabric was tested by The Govmark Organization for all other required fabric specifications. The results are shown in Table 13.

Table 13. Woven fabric properties

Fabric Property	Test Method	Requirements (GL-PD-07-12 Rev 4)	Results
Fiber content	AATCC 20A	65%Rayon/ 25%Para-aramid/ 10%Nylon	50%wool/ 42%Nomex/ 5%Kevlar/3%P140
Yarn count, wc (cc)	ASTM D-3775		2/45 (30/2)
Weave	Visual	Plain	Plain
Weight, oz./yd^2	ASTM-D 3776	5.5-8.5	5.4
Print		OCP	OCP
Breaking Strength, lbs.*	ASTM-D 1682	110 x 80	175 x 126
Tear Strength, lbs.*	ASTM-D 1424	4.0 x NA	9.4 x 6.1
Dimensional Stability, %*	AATCC 135		
After 3 wash/TD cycles		4.0 x 3.5	1.0 x 0.5
After 5 wash/TD cycles			2.5 x 1.5
Colorfastness, laundry	AATCC 61	3	5
Colorfastness, light	AATCC 16	3-4	5
Colorfastness, Perspiration	AATCC 15	3-4	5 & 4
Colorfastness, Crocking (wet and dry)	AATCC 8	3.5	4.5
Air permeability, cfm/ft_2	ASTM 4108	>10	43.8
Flame Resistance*	ASTM 6413		
After flame, sec (max)		2.0 x 2.0	1.7 x 2.0
After glow, sec (max.)		25.0 x 25.0	4.3 x 3.4
Char length, inches (max.)		4.5 x 4.5	4.1 x 3.0
Thermal Protective Performance (min.)	ASTM D 4108	7.0	11.5
Pilling, grade	ASTM D 4970	n/a	4.5
Abrasion resistance, rating	ASTM D 4966	n/a	4.0

*warp x filling

Wool/Nomex exceeded all of the performance requirements for the FR Army Combat Uniform. Of particular importance is the fact that all of these high performance values are achieved with a much lighter weight fabric. (A 5.4 oz. /yd^2 wool/Nomex compared to 6.5 oz. /yd^2 for Defender M). This, coupled with the smoother fabric surface achieved due to reduced surface fiber ends from the use of long fibers spun on the long staple worsted spinning system, should further add to increased wearer comfort.

3. Discussion of Results

As stated in Chapter 1, the main purpose of this development was to determine if the long staple spinning system could produce superior yarns in comparison to the short staple cotton system. This was accomplished by comparing the blended fabrics produced in this project with those produced using short staple blended yarns in the previous projects (Refs. 1, 2).

The comparative data for the knit fabrics are presented in Table 14. It shows improvement in all the measured physical properties; however, the increases were less than predicted. It is possible that having less than the planned amount of aramid fiber in the blend caused the smaller increases.

Table 14. Comparison of knit fabrics made from short and long staple spinning systems

Properties	Short Staple, Untreated	Long Staple, Superwash	% Improvement
Blend composition	50/50 Wool/Nomex IIIA	55% wool/37.8% Nomex / 4.5% Kevlar /2.7% P140	
Yarn count used, cc	1/30	1/30	NA
Fabric weight, oz./yd^2	4.6	4.47	2.8%
All colorfastness ratings	4-5	4-5	NA
Yarn strength, gf/den	1.48	1.58	6.8%
Mullens Burst strength, lbs	80	87	8.8%
Dimensional Stability, %, (after 3 w/TD cycles) *	5.0 x 3.0	5.0 x 1.6	17.5%
Flame resistance*			
After flame, s	1.0 x 1.0	2.1 x 3.3	
Char length, inches	2.0 x 3.3	3.2 x 3.2	
After glow, s	10.9 x 12.3	1.0 x 3.5	
Abrasion Resistance		20,000+	NA

*warp x filling

The blend in the woven fabrics was more accurate than in the knit fabrics and may provide answers to the difference. The comparative results for the woven fabrics are given in Table 15.

Table 15. Comparison of woven fabrics made from short and long staple spinning systems.

Properties	Short Staple	Long Staple	% Improvement
Blend composition	50/50 Wool/Nomex IIIA	50% Wool / 42% Nomex / 5% Kevlar / 3% P140	
Yarn count used, cc	28/2	30/2	6.4%
Fabric weight, oz./yd^2	5.9	5.4	8.5%
All colorfastness ratings	3-4	3-4	NA
Yarn strength, gf/den	1.7	1.83	7.7%
Tensile strength, lbs.*	158 x 117	175 x 126	9.5%
Tear Strength, lbs*	8.0 x 5.0	9.4 x 6.1	19.2%
Dimensional Stability, %, (after 3 w/TD cycles) *	3.5 x 1.3	1.0 x 0.5	69%
Flame resistance*			
After flame, s	0.4 x 0.3	1.7 x 2.0	
Char length, inches	4.2 x 3.1	4.1 x 3.0	
After glow, s	4.1 x 6.4	4.3 x 3.4	
Abrasion Resistance, cycles	NA	No holes after 20,000	
Pilling, grade	NA	4.5	

*warp x filling

The results mirror those for the knitted fabric in that the long staple version has improved mechanical properties compared to the fabric made from short staple spun yarn. The increase may not appear to be very large but considering that the long staple fabric is significantly lighter in weight (8.5% lighter) the results tend to substantiate the industry acceptance that fabric made from long staple spun yarns are generally stronger compared to the fabric made from short staple spun yarns.

In addition to improved mechanical properties, there is a much stronger argument in favor of using long staple spun yarn in that the ability to spin much finer count yarn such as 2/60 wc as opposed to 2/42 wc (28/2 cc) offers more options for fabric construction and fabric weight range. The thermal protective properties of the fabric are enhanced by the inclusion of wool fiber in the blend. The wool in the blend provides significant protection against heat and flame by virtue of wool forming a voluminous char when exposed to high heat or flame. The char that forms is cool to the touch, protecting the skin underneath it. This characteristic of wool makes it possible for the wool/Nomex fabric to pass the 4-second flame exposure test on thermal manikin and allows use of a lighter weight fabric.

4. Conclusions

This project has demonstrated that wool aramid blended fabrics outperform FR knitted and woven fabrics investigated in this report. The fabrics are lighter, more durable, and comfortable (due to low weight and smooth surface), and have very high color fastness properties.

The fabrics are inherently FR, machine washable, and tumble dryable without requiring any topical chemical application to the fabric.

No pre-dyeing of the woven fabric prior to printing either in UCP or the newer OCP camouflage pattern is needed to meet the NIR reflectance and visual color standard requirements.

All of the required color standards are achievable through coloring the wool component only using the most advanced and colorfast Lanaset (acid) class of dyes.

The higher component fiber cost for this blend compared to Defender M fabric is projected to be offset by potentially lower manufacturing cost through increased production yield due to reduced waste; production of lighter weight fabric requiring less fiber; and by a simpler dyeing, printing and finishing routine.

Additional conclusions that can be drawn from ASI work performed under NSRDEC contracts include the following:

- A blend of 50/50 wool/aramid produced an inherently FR and machine washable fabric.
- Use of two-ply yarns in warp and in filling improved fabric strength and durability (Ref. 4).
- Use of long staple length fibers spun on the long staple "worsted" spinning system increased fabric strength and durability and imparted a soft hand in comparison to short staple manufacturing.
- Due to the superior dye characteristics of Superwash wool, Lanaset (acid) dyes designed for wool offer greater depth of shade in dyeing and in printing the wool in this blend. As an added bonus, coloration of only the wool component met stringent shade, infrared reflectance and colorfastness requirements.
- No dyeing or chemical finishing of the prepared for print goods was necessary for achieving required color standards of the OCP printed fabrics.
- Development of the wool/aramid blend indicated significant cost savings in two areas:
  -Fabric weight was reduced (less fiber consumed, lower cost) without sacrificing required strength, durability and FR.
  -Using 50% wool in the blend greatly simplified dyeing, printing and finishing procedures that should result in very low rejection and rework rates.

5. Recommendations

Field evaluations of the two fabrications (knit and woven) submitted to NSRDEC should be conducted immediately to confirm the laboratory results obtained in this study.

The antistatic properties of the submitted fabrics should be tested against the static dissipation requirements soon as possible. (A suitable independent testing facility was not readily available during the contract period, but the appropriate test protocol is available at NSRDEC.) Both fabrics contain higher than normal P140 (3%) proprietary antistatic fiber and therefore should meet the required static dissipation performance requirements.

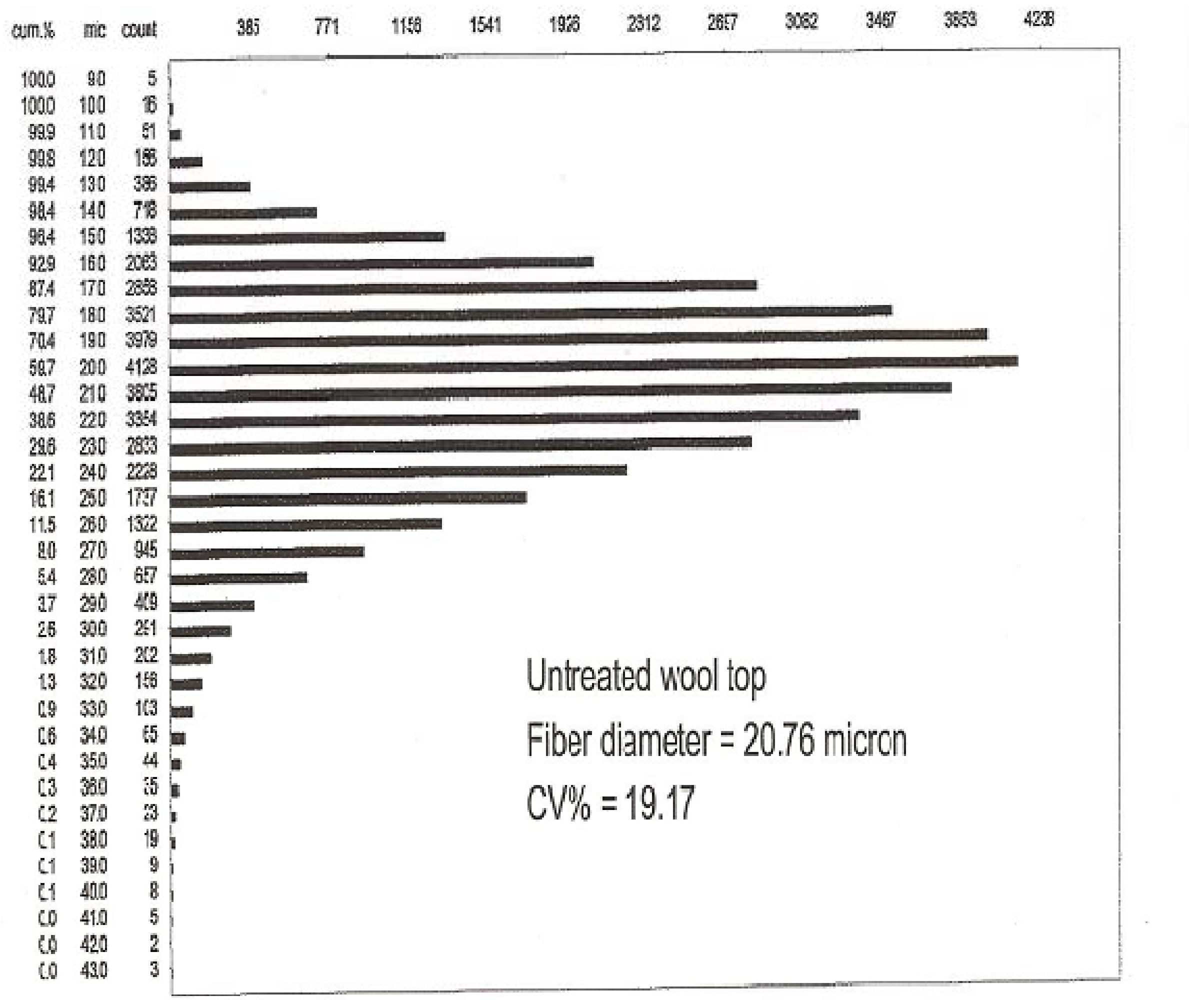
Since the initiation of this development, DuPont is now producing long staple Nomex fiber in the US. This coupled with ASI's industry partners' expertise offers a quick and readily available manufacturing option for immediate commercial production of long staple wool/Nomex.

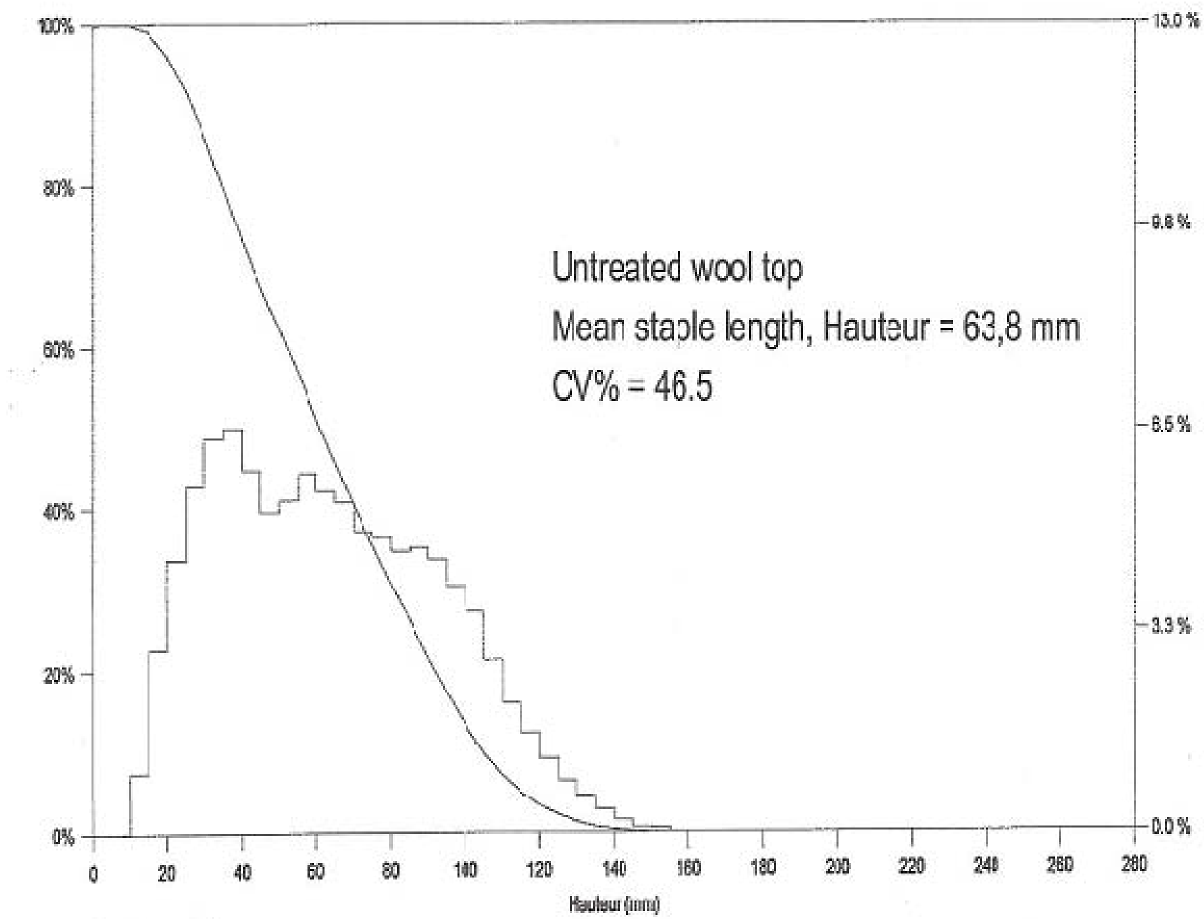
This document reports research undertaken at the U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA, and has been assigned No. NATICK/TR- 13/014 in a series of reports approved for publication.

6. References

1. Mehta P et at, " Cloth, Camouflage (Universal Pattern), Flame Retardant, wool/Nomex^R Blend", BAA Contract # W911QY-04-P-0468
2. Mehta P et al, "Cloth, Knitted. Flame Resistant, Wool/Aramid blend, for next to skin wear", BAA Contract # W911QY-05-P-0489
3. Fire Resistant Environmental Ensemble (FREE) next to skin-wear knit fabric specification, PD 10-01 and 10-02 T-Shirt, Change Notice 2 (July 16, 2010).
4. Mehta P and Leavitt H, "50% wool / 50% Nomex Intimately Blended Plain Weave Fabric" Internal memo – Forstmann & Co. March 1998
5. Mehta P and Driggers M, "Cloth, Camouflage, Universal Pattern, Flame Resistant, Wool/Nomex^R Blends," Technical report Natick/TR-08/019, August 2008.

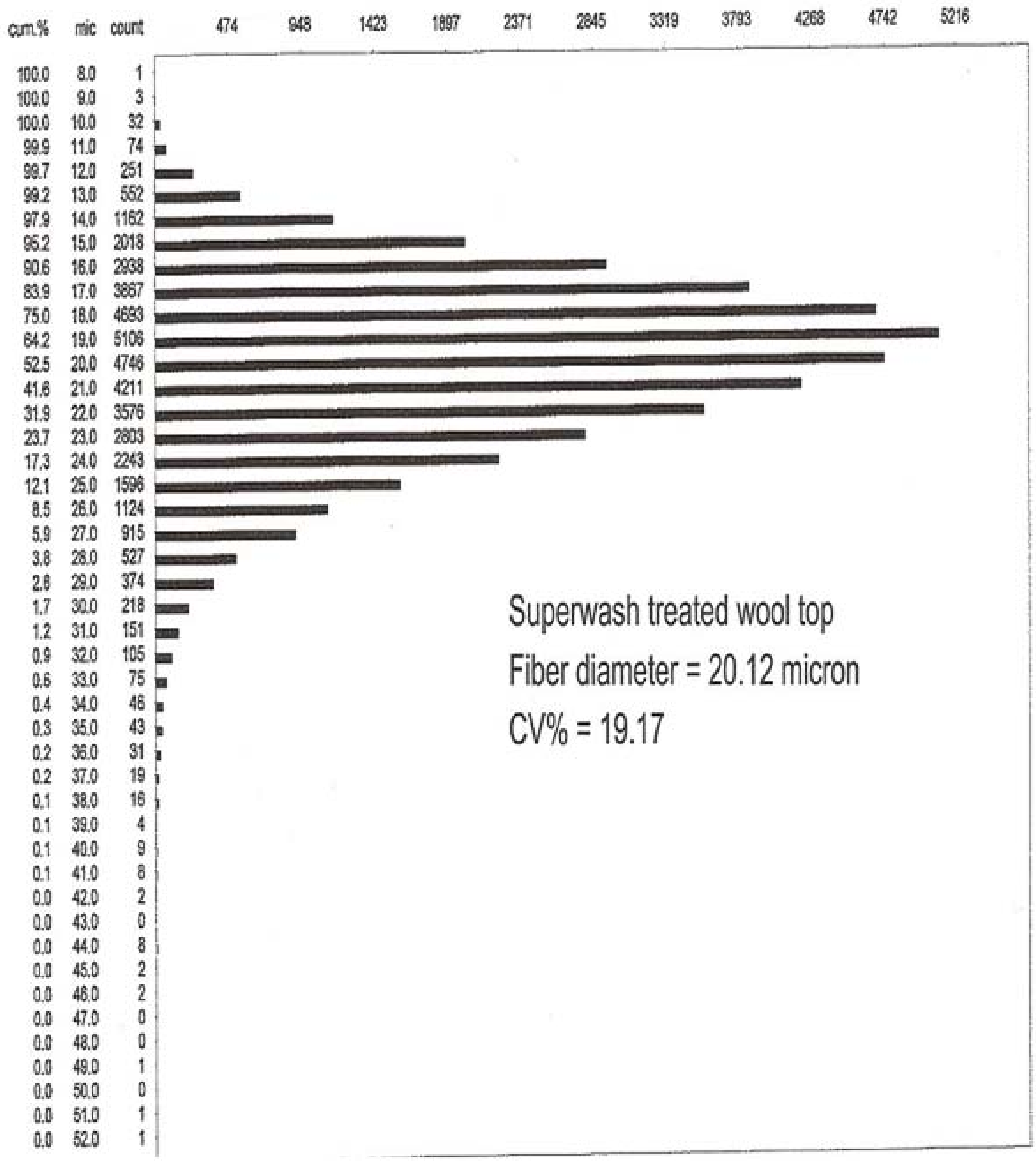
Appendix: Fabric Analysis Graphs from a Uster Tester Scan

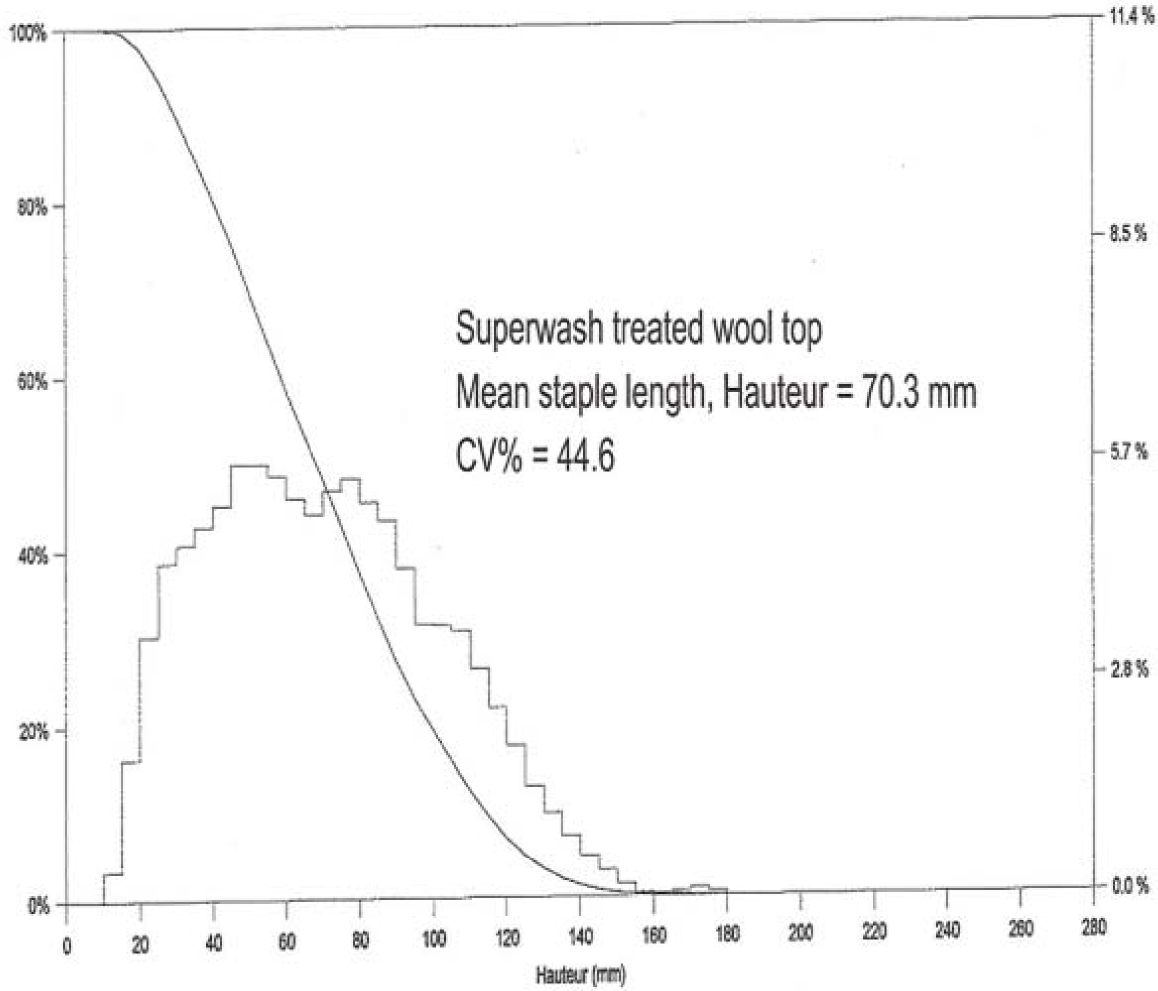




H :	63.8	mm
CvH :	46.5	%
B :	77.5	mm
CvB :	37.1	%
L :	59.5	mm
CvL :	48.3	%

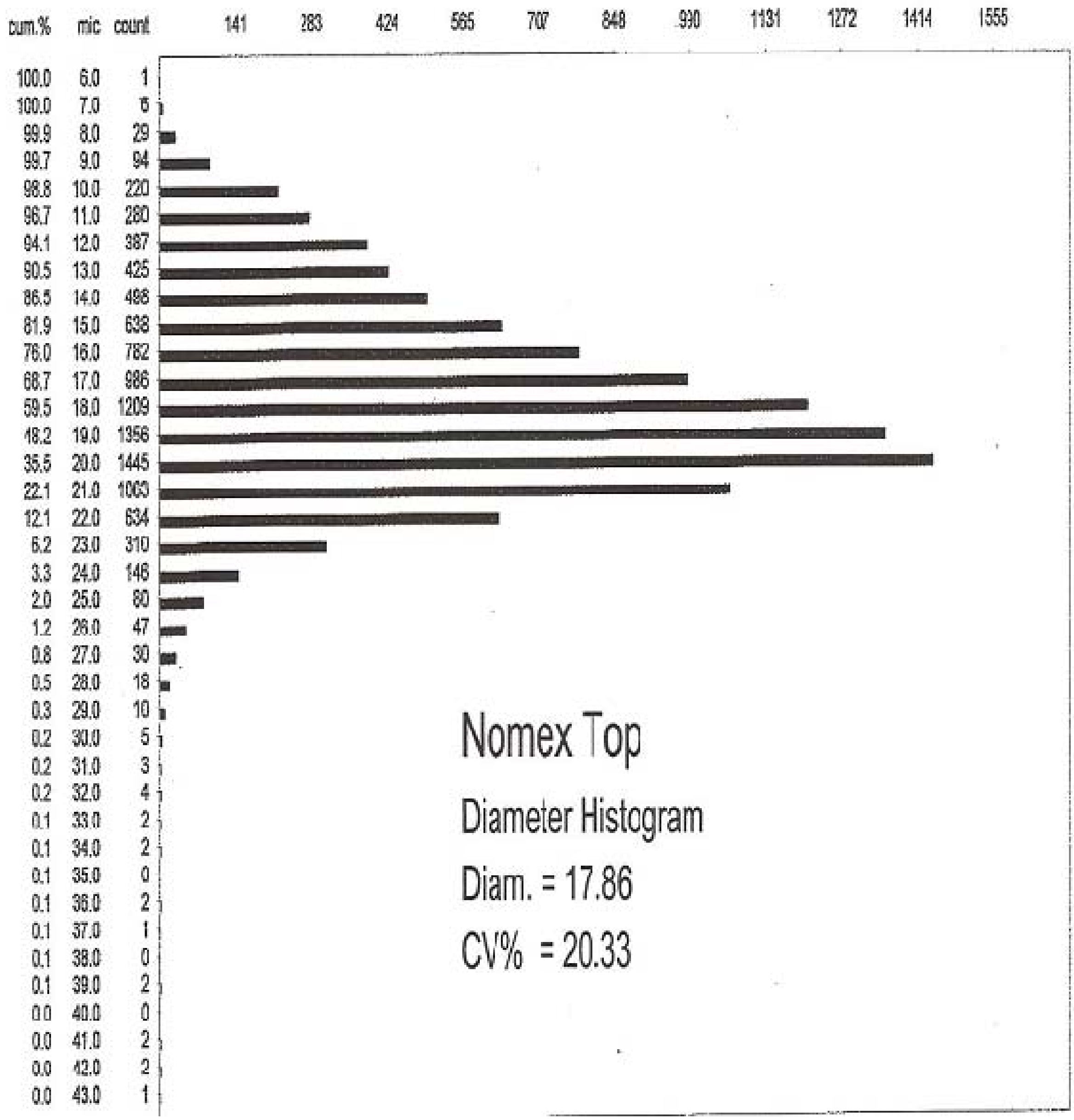
%<10.0 mm :	0.0	95.0 % :	21.2
%<15.0 mm :	1.0	90.0 % :	26.5
%<20.0 mm :	3.9	75.0 % :	38.7
%<25.0 mm :	8.3	50.0 % :	61.1
%<30.0 mm :	13.9	25.0 % :	86.4
%<35.0 mm :	20.2	10.0 % :	104.6
%<40.0 mm :	26.7	5.0 % :	114.9
%<45.0 mm :	32.5	2.5 % :	123.5
%<50.0 mm :	37.7	1.0 % :	132.6

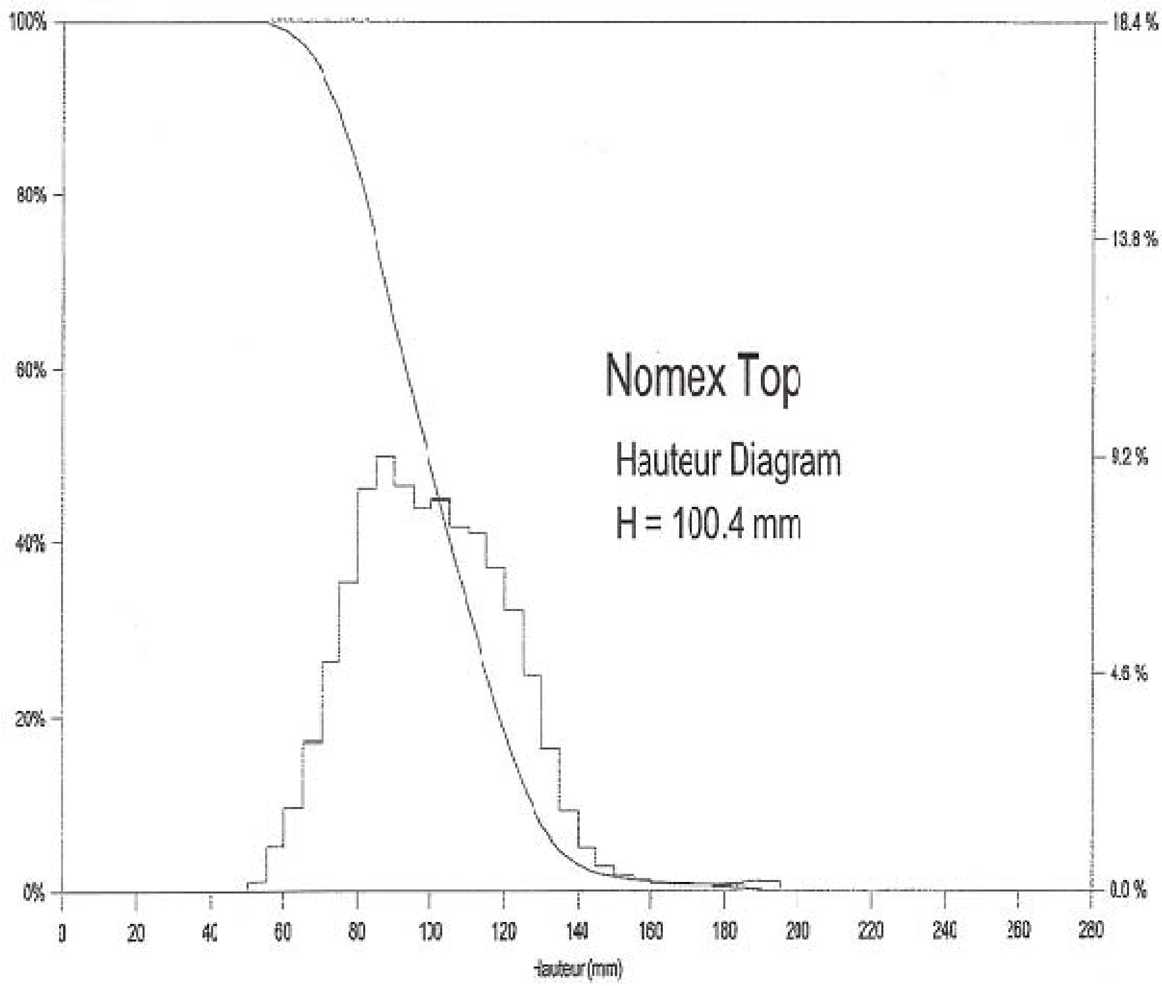

cum.%
mic
count
474
948
1423
1897
2371
2845
3319
3793
4268
4742
5216
Superwash treated wool top
Fiber diameter = 20.12 micron
CV% = 19.17



H :	70.3	mm
CvH :	44.6	%
B :	84.2	mm
CvB :	36.4	%
L :	65.4	mm
CvL :	46.6	%

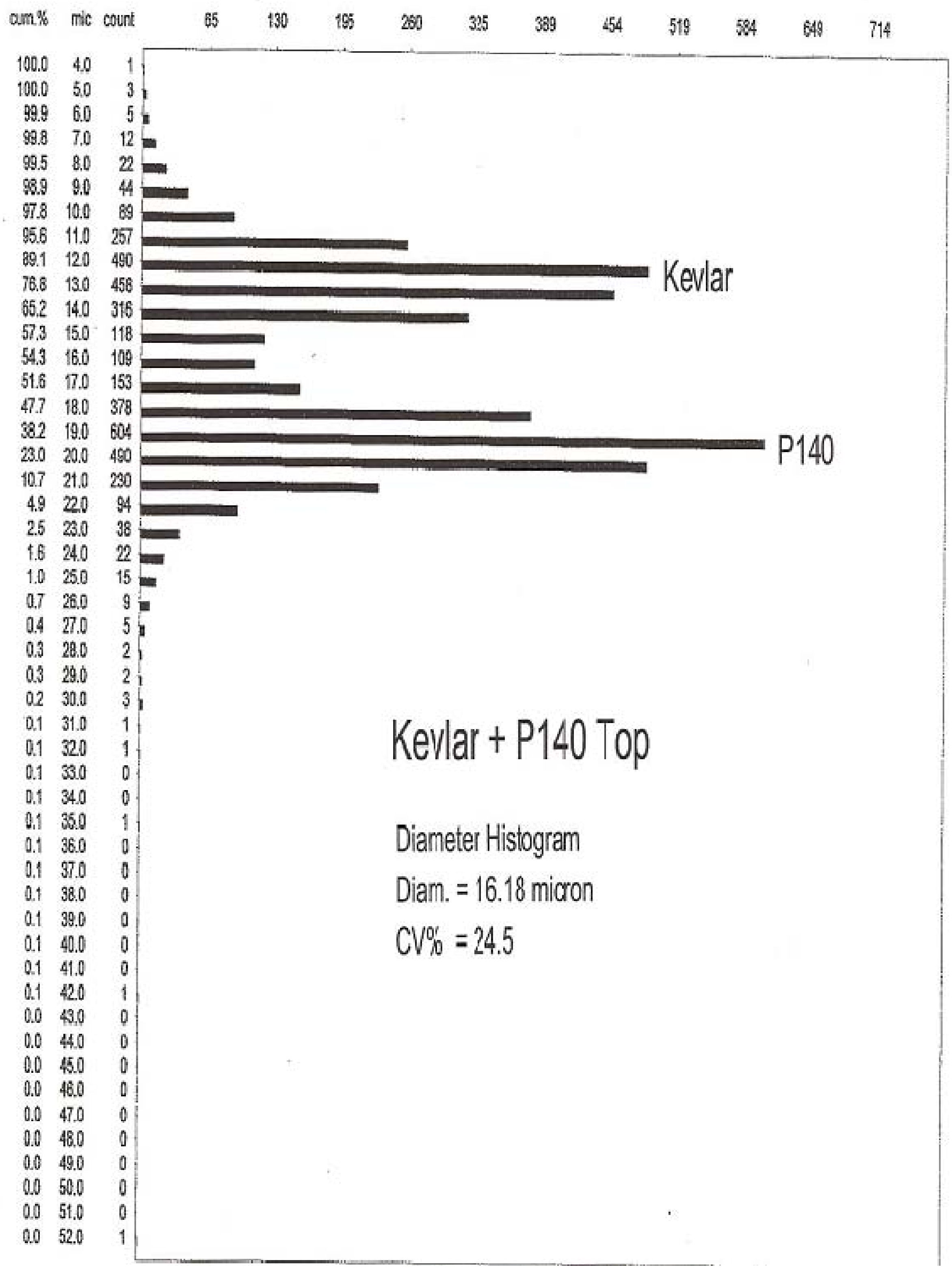
%<10.0 mm :	0.0	95.0 % :	24.0
%<15.0 mm :	0.4	90.0 % :	29.9
%<20.0 mm :	2.2	75.0 % :	45.2
%<25.0 mm :	5.7	50.0 % :	68.1
%<30.0 mm :	10.1	25.0 % :	92.5
%<35.0 mm :	14.7	10.0 % :	113.7
%<40.0 mm :	19.6	5.0 % :	124.3
%<45.0 mm :	24.7	2.5 % :	133.5
%<50.0 mm :	30.4	1.0 % :	143.4

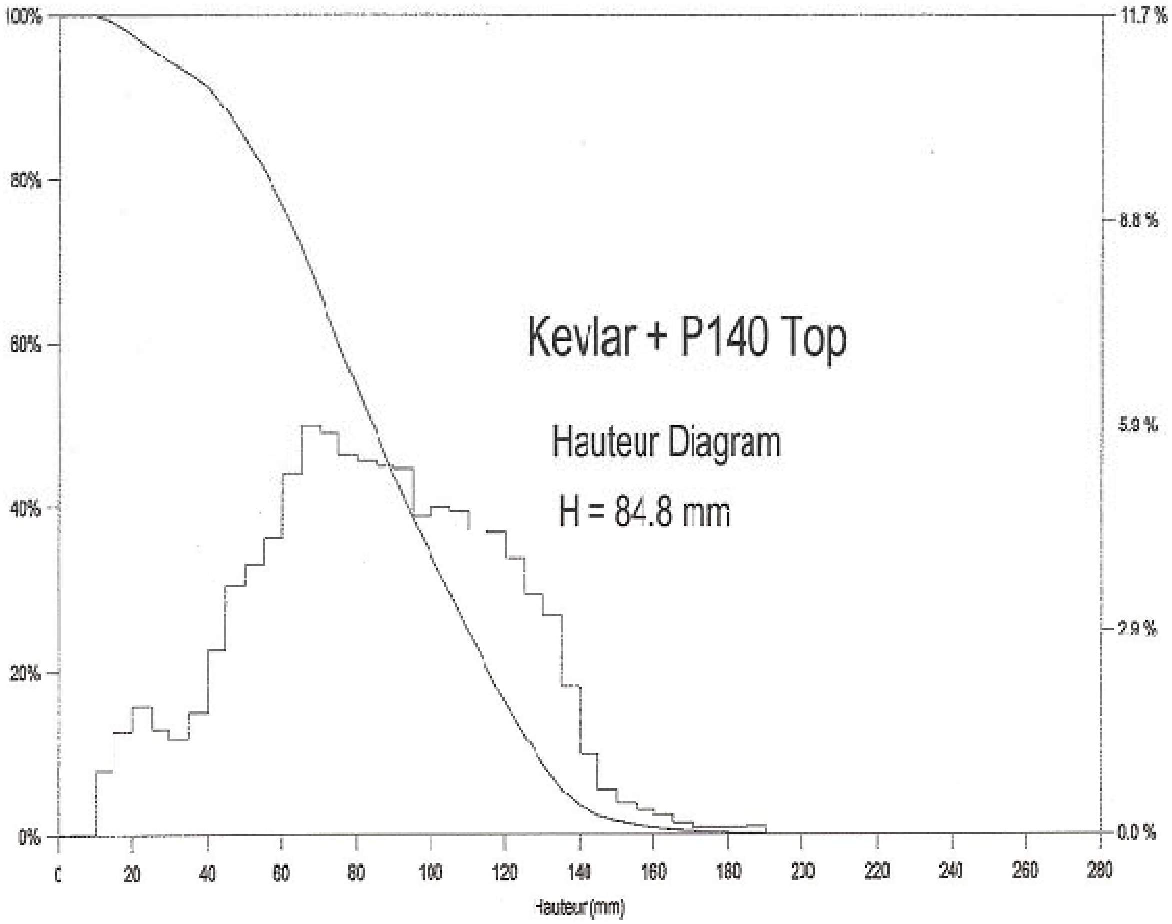

cum.% mic count
141 283 424 565 707 848 990 1131 1272 1414 1555
100.0 6.0 1
100.0 7.0 6
99.9 8.0 29
99.7 9.0 94
98.8 10.0 220
96.7 11.0 280
94.1 12.0 387
90.5 13.0 425
86.5 14.0 498
81.9 15.0 638
76.0 16.0 782
68.7 17.0 986
59.5 18.0 1209
48.2 19.0 1356
35.5 20.0 1445
22.1 21.0 1003
12.1 22.0 634
6.2 23.0 310
3.3 24.0 146
2.0 25.0 80
1.2 26.0 47
0.8 27.0 30
0.5 28.0 18
0.3 29.0 10
0.2 30.0 5
0.2 31.0 3
0.2 32.0 4
0.1 33.0 2
0.1 34.0 2
0.1 35.0 0
0.1 36.0 2
0.1 37.0 1
0.1 38.0 0
0.1 39.0 2
0.0 40.0 0
0.0 41.0 2
0.0 42.0 2
0.0 43.0 1
Nomex Top
Diameter Histogram
Diam. = 17.86
CV% = 20.33



H:	100.4	mm
CvH:	21.3	%
B:	104.9	mm
CvB:	21.1	%
L:	97.6	mm
CvL:	23.8	%

%<10.0 mm:	0.0	95.0 %:	68.4
%<15.0 mm:	0.0	90.0 %:	74.1
%<20.0 mm:	0.0	75.0 %:	84.5
%<25.0 mm:	0.0	50.0 %:	99.0
%<30.0 mm:	0.0	25.0 %:	115.0
%<35.0 mm:	0.0	10.0 %:	127.4
%<40.0 mm:	0.0	5.0 %:	134.4
%<45.0 mm:	0.0	2.5 %:	142.2
%<50.0 mm:	0.0	1.0 %:	159.0


cum.% mic count
65 130 195 260 325 389 454 519 584 649 714
100.0 4.0 1
100.0 5.0 3
99.9 6.0 5
99.8 7.0 12
99.5 8.0 22
98.9 9.0 44
97.8 10.0 89
95.6 11.0 257
89.1 12.0 490
76.8 13.0 458
65.2 14.0 316
57.3 15.0 118
54.3 16.0 109
51.6 17.0 153
47.7 18.0 378
38.2 19.0 604
23.0 20.0 490
10.7 21.0 230
4.9 22.0 94
2.5 23.0 38
1.6 24.0 22
1.0 25.0 15
0.7 26.0 9
0.4 27.0 5
0.3 28.0 2
0.3 29.0 2
0.2 30.0 3
0.1 31.0 1
0.1 32.0 1
0.1 33.0 0
0.1 34.0 0
0.1 35.0 1
0.1 36.0 0
0.1 37.0 0
0.1 38.0 0
0.1 39.0 0
0.1 40.0 0
0.1 41.0 0
0.1 42.0 1
0.0 43.0 0
0.0 44.0 0
0.0 45.0 0
0.0 46.0 0
0.0 47.0 0
0.0 48.0 0
0.0 49.0 0
0.0 50.0 0
0.0 51.0 0
0.0 52.0 1
Kevlar
P140
Kevlar + P140 Top
Diameter Histogram
Diam. = 16.18 micron
CV% = 24.5



H :	34.8	mm
CvH :	38.8	%
B :	97.6	mm
CvB :	31.2	%
L :	35.3	mm
CvL :	35.0	%

%<10.0 mm :	0.0	95.0 % :	27.5
%<15.0 mm :	0.9	90.0 % :	42.1
%<20.0 mm :	2.4	75.0 % :	61.7
%<25.0 mm :	4.3	50.0 % :	84.2
%<30.0 mm :	6.8	25.0 % :	109.7
%<35.0 mm :	7.2	10.0 % :	128.1
%<40.0 mm :	8.9	5.0 % :	136.2
%<45.0 mm :	11.6	2.5 % :	143.9
%<50.0 mm :	15.1	1.0 % :	157.6