TECHNICAL REPORT
NATICK/TR-21/006

AD ____________

DEVELOPMENT OF KNITTED FLAME RESISTANT FABRICS MADE FROM WOOL AND ARAMID BLEND YARN FOR NEXT-TO-SKIN CLOTHING APPLICATIONS

by
Parvez Mehta
Mitchell Driggers
and
Carole Winterhalter*

American Sheep Industry Association
Englewood, CO 80112

***Combat Capabilities Development Command – Soldier Center**
Natick, MA 01760

January 2021

Final Report
July 2005 – April 2008

Approved for public release; distribution is unlimited

Prepared for
U.S. Army Combat Capabilities Development Command Soldier Center
Natick, Massachusetts 01760-5020

DISCLAIMERS

The findings contained in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of trade names in this report does not constitute an official endorsement or approval of the use of such items.

DESTRUCTION NOTICE

For Classified Documents:

Follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For Unclassified/Limited Distribution Documents:

Destroy by any method that prevents disclosure of contents or reconstruction of the document.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*
18-01-2021

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
20 July 2005 – 30 April 2008

4. TITLE AND SUBTITLE
DEVELOPMENT OF KNITTED FLAME RESISTANT FABRICS MADE FROM WOOL AND ARAMID BLEND YARN FOR NEXT-TO-SKIN CLOTHING APPLICATIONS

5a. CONTRACT NUMBER
W911QY-05-P-0489

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Parvez Mehta, Mitchell Driggers and Carole Winterhalter*

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
American Sheep Industry Association
9785 Maroon Circle, Suite 360
Englewood, CO 80112

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Combat Capabilities Development Command – Soldier Center
ATTN: Carole Winterhalter
10 General Greene Avenue, Natick, MA 01760-5020

10. SPONSOR/MONITOR'S ACRONYM(S)
DEVCOM

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NATICK/TR-21/006

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
*Combat Capabilities Development Command – Soldier Center (CCDC)

14. ABSTRACT
This report documents efforts performed, between 20 July 2005 and 30 April 2008, under a Broad Agency Announcement contract between the American Sheep Industry Association and the U.S. Army Combat Capabilities Development Command – Soldier Center (CCDC-SC). This study investigated if an inherently machine washable and flame resistant fabric could be achieved in a very lightweight knitted structure that would not only be less expensive but also more comfortable as a protective garment for next-to-skin wear in all climate conditions compared to a 100% aramid garment currently in service. Additionally, the product developed would comply with Berry Amendment regulations and offer protection against fire hazards to soldiers. Much of the development work was carried out at supervised commercial facilities so that an approved product would be commercialized quickly and with minimum delay.

15. SUBJECT TERMS

DYES	KNITTING	WOVEN FABRICS	STRENGTH(MECHANICS)
WOOL	UNIFORMS	FINISHED FABRICS	TEST AND EVALUATION
YARNS	WASHABLE	BLENDED FABRICS	PERFORMANCE(ENGINEERING)
FIBERS	PROPERTIES	FLAME RESISTANT	SPINNING(INDUSTRIAL PROCESSES)
NOMEX	LIGHTWEIGHT	KNITTED FABRICS	
FABRICS	ARAMID FIBERS	COMBAT UNIFORMS	
FINISHES	COLORFASTNESS	LABORATORY TESTS	
TEXTILES	MACHINE WASH	THERMAL PROTECTION	

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
U	U	U	UU	24

19a. NAME OF RESPONSIBLE PERSON
Carole Winterhalter

19b. TELEPHONE NUMBER *(include area code)*
(508) 206-3936

This page intentionally left blank

TABLE OF CONTENTS

LIST OF TABLES

PREFACE

A new lightweight knitted fabric in a blend of 50% 20.5 micron wool and aramid (Nomex Type 462) offers inherent flame protection, and machine wash and tumble dry performance. The fabric does not require chemical treatments to meet either the machine wash and dry performance or flame resistance performance goals. Sufficient yardage of the approved fabrics was provided to the Combat Capabilities Development Command Soldier Center (DEVCOM SC) for further laboratory evaluation, and a possible field trial. Based on the simplicity of the processes used coupled with a low material cost, the final finished fabric cost is calculated to offer significant savings over the current standard aramid fabric.

ACKNOWLEDGEMENTS

The authors acknowledge numerous industry partners for their support and willingness to work with small batch processing in a production environment. The following industry partners are worthy of special mention in this report: Diego Paullier of Chargeurs for providing open wool top cut to two-inch (in) staple length that was carded and blended on a short staple system; Jim Sells of Pharr yarns for blending and spinning a number of experimental yarns; Mark Cabral of Alamac American Knits for knitting, dyeing, finishing, and testing of prepared fabrics.

EXECUTIVE SUMMARY

This study, undertaken to develop a low cost inherently flame resistant fabric, showed that a 30/1 cc (cotton count) (fine singles) yarn made from a 50/50 blend of domestic 70's grade (20.5 micron) domestic wool and Nomex® Type 462 in a single jersey construction produced a very light weight fabric of less than 5.0 ounces per square yard (oz/sq.yd) that is suitable for all weather next-to-skin garments. This lightweight product was produced without significant reduction in either the mechanical properties or other fabric performance features. These results are in line with results obtained on woven piece goods using the same fiber blend combinations reported previously [1]. Additionally, the fabric met military requirements [2, 3] for strength, flame resistance, and machine wash and dry performance without any chemical treatment applied to the fabric.

DEVELOPMENT OF KNITTED FLAME RESISTANT FABRICS MADE FROM WOOL AND ARAMID BLEND YARN FOR NEXT-TO-SKIN CLOTHING APPLICATIONS

1. INTRODUCTION

Work was performed for this report from 20 July 2005 to 30 April 2008 by the American Sheep Industry Association, Inc., in coordination with the US Army Combat Capabilities Development Command Soldier Center (DEVCOM SC).

Previously completed work on the development of wool and aramid woven fabric [1] has shown that a lightweight, inherently flame resistant, strong fabric with machine wash and dry performance could be commercially produced using an intimate blend yarn of 50% domestic 20.5 micron fine wool and 50% aramid (Type 462) fibers. This report is a follow-on effort to develop a lightweight knitted version in the same blend of wool and aramid fiber. This study investigated if an inherently machine washable and flame resistant fabric could be achieved in a very lightweight knitted structure that would not only be less expensive but also more comfortable as a protective garment for next-to-skin wear in all climate conditions compared to a 100% aramid garment currently in service [2, 3]. Additionally, the product developed would comply with Berry Amendment regulations and offer protection against fire hazards to Soldiers. Much of the development work was carried out at supervised commercial facilities so that an approved product would be commercialized quickly and with minimum delay.

This program was initiated after the military had approved an all wool underwear for extended field evaluation in cold climates made from 1/27 worsted count yarn that weighed 5.5 oz/sq.yd in a single jersey knit fabric construction. An in-house untrained comfort evaluation revealed that the wearers found the garment to be comfortable when evaluated for tactile comfort next to the skin. Additionally, a lighter weight 4.5 oz/sq.yd version of this wool fabric was included in a hand feel study at the University of California, Davis which showed the fabric ranked the best among 15 currently used fabrics. The fine worsted spun yarn and known superior moisture management properties of wool made it a strong candidate for garments worn next to the skin. While these fabrics were determined to lack sufficient strength to be used by the military, they requested that a lightweight blend be developed made from wool and aramid (Nomex®).

Based on the domestic fiber supply, a blend of wool and Nomex® became a priority consideration offering the best chance to comply with Berry Amendment regulations and also to meet the target cost, comfort, and performance goals. Previous studies [1, 4] on wool and flame resistant fiber blend fabrics indicated that a blend of wool with a minimum of 50% Nomex® (meta-aramid), or a minimum of 65% Kevlar® (para-aramid) produced inherently flame resistant and machine washable lightweight woven fabrics.

This report describes a knit wool and Nomex® fabric development effort that was made using a similar fiber blend except the yarn was spun on a short staple spinning system instead of the long staple worsted system. Additionally, different fabric constructions using finer yarns were also developed. All of the preproduction trials were based on producing a fabric comparable to an all wool 5.5 oz/sq.yd single jersey construction. The selection of Nomex® aramid fibers for blending with wool was due mainly to domestic availability of flame resistant synthetic fibers. This blend would comply with the Berry Amendment regulations imposed on the United States military.

2. MATERIALS AND METHODS

2.1 Fiber

2.1.1 Wool
The wool used in this study was a domestic 70's grade (20.5 micron) fiber. It was prepared as an open top, which was cut to a 2 in staple length, for blending with aramid on a modified short staple spinning system.

2.1.2 Aramid
The aramid fiber blend used was produced by DuPont and marketed under the trade name of Nomex® Type 462. This is a specialty blend of three fiber types. It consists of 92% meta-aramid (Nomex®), 5% para-aramid (Kevlar®) and 3% electrostatic dissipative fiber. The meta-aramid fiber is partially crystallized and dyeable.

2.1.3 Electrostatic Dissipating Fiber
The electrostatic dissipating fiber used in the Type 462 blend described above is known as P-140. It is widely used in the floor covering trade, i.e. carpeting, to impart antistatic performance.

2.2 Yarn

The fiber was blended in a blow room and carded as an intimate blend in a proportion of 50% wool and 50% aramid fiber (Type 462) as detailed above. This blend was spun into three different yarn counts ranging from a coarse count of 18/1 Ne (similar in count to that used in current commercial all wool fabrics), 30/1 Ne, and to a very fine spin limit count of 35/1 Ne. The selected range of yarns provided the opportunity to consider a number of fabric constructions around the target fabric weight of about 5.5 oz/sq.yd. A detailed description of the yarn properties is in Table 1. No problems were encountered in spinning any of the above three yarns.

Table 1. Properties of Wool and Aramid Blend Yarns

Property	50% Wool, 50% Nomex® Type 462	50% Wool, 50% Nome® Type 462	50% Wool, 50% Nomex® Type 462
Measured count, Ne/ply	18.1/1	30.0/1	34.9/1
Twist, turns per inch	14.5	20.2	22.5
Single end break, pounds (lbs)	1.03	0.58	0.51
Tenacity, gf/den	1.59	1.48	1.51
Elongation, %	21.36	16.7	16.8

2.3 Fabrication

Two knitters were commissioned to knit a variety of structures using the three yarns and were given a free hand to come up with appropriate knit structures within the fabric target weight of about 5.5 oz/sq.yd.

The interlock stitch, which is considered to be the most stable and versatile double jersey construction, was one of the three constructions investigated in this trial. Since double jersey constructions produce heavier fabrics compared to single jersey constructions using the same yarn size, the interlock fabric knitting trial was restricted to using the finest of the yarn counts (35/1 Ne) that could be commercially spun from the given fiber blend. Unfortunately, even with the finest of the blended yarns studied the fabric knit down was found to exceed the goal weight limit of 5.5 oz/sq.yd and was not considered suitable for all-weather underwear. Additionally, this fine yarn, while spun to its commercial spinning limit, was found to cause unacceptable knitting faults. Because of these limitations, the work using 35/1 Ne yarn was terminated.

The single jersey stitch, which offers the lightest fabric, was produced from 18/1 Ne yarn in two different tightness constructions (tight and loose) and in two different finishes (enzyme treated and untreated).

A modified jersey stitch (knit-welt jersey) was also selected to determine if it would overcome laddering commonly associated with the jersey stitch. Since knit-welt jersey increases fabric weight by some 50% and reduces fabric width by some 20%, it became necessary to change yarn count for this structure to compensate for the expected increase in fabric weight. The knit welt fabric was knitted on a finer gauge machine using a finer yarn (30/1 Ne). The manufacturing details are listed in Table 2.

Table 2. Knit Fabric Constructions

Properties	**Single Jersey**		**Knit-welt Jersey**	
Construction	loose	tight	loose	tight
Yarn used, count/ply	18/1Ne	18/1 Ne	30/1 Ne	30/1 Ne
Machine gauge/diam.	18 /30”	18 /30”	22 /30”	22 /30”
Number of needles	1740	1740	2088	2088
Loop length, in	0.15”	0.135”	0.077”	0.072”
Greige width, in	70	66	66	66
Greige courses per in	32	38	40	47
Greige wales per in	25	27	32	31
Greige weight, oz/sq.yd	4.5	5.1	4.3	4.9

2.4 Dyeing and Finishing

The fabrics were enzyme treated to impart wash and tumble dry easy care properties. The enzyme treatment was applied to the fabric in a dye kettle (jet dyeing machine) prior to piece dyeing in the same machine using wool compatible acid milling class of dyes. The enzyme treatment steps are summarized in Table 3. No attempt was made to dye the meta-aramid component in the blended fabric, particularly when the wool-only dyed fabric gave a heather appearance that may be acceptable for underwear use. In order to achieve a solid color, the meta-aramid fiber would also have to be dyed, but it would add another processing step and increase fabric cost. In the preproduction batch the fabrics were dyed to the military specified Desert Sand color; however, in the production version, the customer requested military Foliage Green. In either of the colorations, mono-sulfonated acid dyes (Lanaset) produced by Ciba were used. This class of dyes has one of the highest color fastness properties on wool. The dyed fabrics were relax dried in tubular form, slit and framed open width. The final fabric was rolled on tubes, where live steam was used to further relax the fabric from the previously imposed manufacturing tensions.

Table 3. USDA Patented Enzyme Application Process for Imparting Easy Care Properties to Wool

Application Steps	Process Conditions	Process Chemicals
Pretreatment	86 °F/30 min pH 12	dicyandiamide -3.0% Triton X114 - 0.5% caustic (50%) - 6.0% gluconic acid - 1.0% H_2O_2 (50%) - 14%
Neutralization - H_2O_2 - caustic	 105 °F/15 min 120 °F/10 min Final pH 7.2	 Dextrol CE-25 - 0.4% acetic acid - 1.0%
Enzyme application	140 °F/40 min pH 9.2	Triton X114 - 1.0% triethanolamine - 1.5% Esperase 8.0L - 1.0%
Enzyme deactivation	105 °F/15 min pH 4.5	acetic acid - 2.0%

2.5 Test Methods

Standard American Society of Testing and Materials (ASTM) and American Association of Textile Chemists and Colorists (AATCC) methods were used for general testing of fabric construction, mechanical properties, dimensional stability, colorfastness, and flame resistance. In addition to these tests, the fabrics were also evaluated for electrostatic dissipation. The test methods and performance goals are listed in Table 4.

Table 4. Test Methods and Performance Goals for Military Use

Test Method	Description	Performance Goals
AATCC -8	Colorfastness to crocking – Dry Colorfastness to crocking – wet	3-4 3-4
AATCC - 15	Colorfastness to Alkaline perspiration Colorfastness to Acid perspiration	3-4 3-4
AATCC - 16	Colorfastness to light	3-4
AATCC - 96	Colorfastness to laundering Color change	 3-4
AATCC – 96, Opt 1C	Dimensional Changes in laundering	7.0 X 7.0
ASTM – D 3776	Weight, oz/sq yd	<5.0
ASTM – D 3787	Burst Strength, lbs	>60
ASTM – D 737	Air Permeability, CFM max	N/A
ASTM - 6413	Flame Resistance	Char length max. 6 in After flame time, 2 seconds (s)
Federal Test Method Standard 191–5931	Electrostatic Decay	4000 Volts/ Dissipate <0.5 s

3. RESULTS AND DISCUSSION

3.1 Preproduction Sample Evaluation

Eight preproduction fabrics were produced using two different yarn counts (18/1 and 30/1 Ne); two structures (single jersey and knit-welt jersey); two levels of fabric tightness (tight and loose); and two finishes (untreated and enzyme treated). They were tested for a number of fabric properties and the results are summarized in Tables 5 and 6, and discussed below.

Table V shows the influence of knit construction and fabric tightness. Comparison of the two fabrics shows that the single jersey and knit-welt structures are of relatively similar in fabric weight. The tighter fabric construction of each type resulted in a heavier fabric where the single jersey tight construction was the heaviest at 6.6 oz/sq.yd. Additionally, there were no significant differences in mechanical properties among the fabrics such as Mullen burst strength which ranged from 86 to 94 lb. Similarly, the wash performance (dimensional stability) of the untreated fabric was relatively the same, which was about 6 x 3% (wales by courses) showing excellent fabric stability to washing. Finally, all fabrics demonstrated excellent flame resistance properties with after flame time of less than 2 s. The char length was also well below the specified 6 in with a range of 3.2 x 2.55 in. The results of static decay tests were disappointing in that they failed to meet the stated requirement of registering at least 4000 Volts on the fabric surface. Not only was the generated charge low, but the direction of fabric had a profound effect on the generated charge. The voltage generated along the fabric width was twice as high as that generated along the fabric length. Interestingly, most all fabrics met the requirements of static decay time which was <0.5 s. Most all exhibited a decay time of 0.01 s. This indicated that the dissipation of electrostatic charge was quite rapid. Since all of the results in every property were very similar for all of the fabrics studied, it appeared logical to opt for the lightest weight fabric. The single jersey loose construction was the lightest fabric produced and was selected for the large scale production trial.

Table 5. Properties of Untreated Finished Fabrics

Properties	Single Jersey 18/1	Single Jersey 18/1	Knit-welt Jersey, 30/1	Knit-welt Jersey, 30/1
Fabric tightness	loose	tight	loose	tight
Weight, oz/sq. yd	5.52	6.57	5.7	5.80
Width, in	69	62	54	54
Courses per in	34	41	37	39
Wales per in	29	31	44	45
Mullen burst strength, lb	86	89	90	94
Dimensional stability, * shrinkage, %	6 X 2	7 X 3	6 X 4	6 X 2
Flame resistance:*				
char length, in	3.2 X 3.2	2.85 X 2.75	2.75 X 2.55	2.45 X 2.8
after flame time, s	1.24 X 1.41	1.08 X 0.76	1.00 X 0.56	0.94 X 0.93
after glow time, s	15.2 X 17.3	8.02 X 9.75	11.57 X 12.32	10.9 X 12.25
Electrostatic decay:* Volts/decay time, s	1760 / 3208 0.01 / >0.5	1665 / 3208 0.01 0.01	1688 / 3390 0.01 / 0.01	1729 / 3417 0.01 / 0.1

* warp by filling direction

Table VI lists the fabrics with and without the enzyme treatment. They were evaluated for the effect of the eco-friendly enzyme process on machine wash performance. The enzyme application slightly increased fabric weight and strength. However, it had no effect on wash performance or any other property. This observation applied to both structures and tightness of the fabric. The static decay properties were very similar for all fabric constructions.

Table 6. Effect of Washable Wool Fabric Treatment on Preproduction Fabric Performance

Properties	Single Jersey 18/1	Single Jersey 18/1	Knit-welt Jersey 30/1	Knit-welt Jersey 30/1
	loose, untreated	loose, enzyme treated	loose, untreated	loose, enzyme treated
Weight, oz/sq.yd	5.52	6.01	5.7	5.8
Width, in	69	70.5	54	52
Courses per in	34	36	37	39
Wales per in	29	29	44	45
Mullen burst strength, lb	86	89	90	94
Dimensional stability,* shrinkage, %	6 X 2	6 X 5	6 X 4	6 X 2
Flame Resistance,* Char length, in After Flame time, s After glow time, s	3.2 X 3.2 1.24 X 1.41 15.2 X 17.3	2.85 X 2.55 1.18 X 1.18 14.03 X 18.2	2.75 X 2.55 1.00 X 0.56 11.57 X 12.32	2.85 X 3.45 0.87 X 1.56 10.19 X 7.49
Electrostatic Decay,* volts/ decay time, s	1760 / 3208 0.01/ >0.5	1750 / 2643 0.01 0.01	1688 / 3390 0.01 / 0.01	1750 / 3333 0.01 / 0.01

* warp by filling direction

3.2 Production Fabric Selection Protocol

The preproduction study on structures and finishes indicated there were no significant differences in the fabric performance based on differences in the structures or finishes of the fabrics. A further fabric weight reduction was considered if the fabric could still meet the minimum performance requirements. The only available option to achieve this goal was to use a finer yarn than what was used in the jersey structure. Consideration was given to using the finest of the yarns that could be commercially spun and fabrics knitted with good knitting performance; therefore, the 30/1 Ne yarn was selected for the production study. Some theoretical calculation was necessary to ensure that the fabric unit cost would not increase substantially when adopting this change. Also it was felt that additional antistatic fiber could be added to the blend during spinning of the yarn and that it would provide additional data on static decay performance of the fabric. Table 7 lists various fabric parameters and costs comparing the preproduction yarns to the new proposed yarn. Prices are based on available (April 2007) prices. It's clear that the savings achieved due to the lower fabric weight more than compensates for the higher yarn cost associated with finer count yarns and the extra cost associated with fabric knitting and finishing. The added antistatic fiber was a generic brand used commercially in specialized fabric markets. One percent of additional antistatic fiber was considered optimum for this study for a total amount of about 2.5%.

Table 7. Wool and Nomex Blend Fabric Costs - Comparative Single Jersey Fabric Costs Using Different Yarn Sizes and Fabric Tightness

Properties	18/1 Ne yarn	20/1 Ne yarn	30/1 Ne yarn	30/1 Ne yarn with added antistatic fiber
Knitting machine diameter	30	26	30	30
Machine gauge	20	22	28	28
Knit loop length, in	0.138	0.135	0.126	0.1055
Yarn cost /lb	$14.43	$15.39	$16.23	$17.12
Fabric width, in	63 – 65	55 – 57	59 – 61	54 - 56
Fabric weight, oz/sq. yd	6.4	5.4	5.0	4.5
Fabric price/linear yd	$17.69	$13.85	$14.91	$13.45
Fabric price/square yd	$9.95	$8.90	$8.94	$8.8

Two hundred and fifty yards of the production single jersey fabric were knitted on a 28 gauge 30 in diameter single jersey machine using 30/1 Ne yarn in 50% domestic 20.5 micron wool with 49% Nomex Type 462 and 1% generic antistatic fiber. The knitted fabric was dyed to Foliage Green color using Lanaset (Ciba) dyes and finished without any chemical treatment or subsequent softener finish. The results listed in Table 8, compare fabric properties with the single jersey fabric made from coarser count yarn, and the knit-welt jersey in the same weight yarn. The very lightweight 4.5 oz/sq.yd production fabric met all of the specified performance goals except static decay for a next-to-skin wear item and may be appropriate for all climate use. This very lightweight construction had similar colorfastness properties to the other heavier weight fabrics, but slightly reduced strength and improved dimensional stability. The lighter weight construction was expectedly thinner, more air permeable and therefore had lower Thermal Protective Performance (TPP) values than the experimental heavier fabrics. Its reduced burst strength of 80 lb still exceeded the minimum performance goal of 60 lb. In flame resistance tests, the performance of all of the fabrics was very similar. All were well within the accepted norm for a flame resistant fabric.

Table 8. Comparison of Wool and Nomex® Production Fabric with Wool and Nomex® Preproduction Fabrics

Test	Test Method	Single Jersey 18/1 Ne yarn preproduction	Knit-welt Jersey 30/1 Ne yarn preproduction	Single Jersey 30/1 Ne yarn production
Weight, oz/sq.yd	ASTM D 3776	5.52	5.7	4.58
Thickness,	ASTM D 1777	0.037	0.0354	0.030
Air perm, cfm	ASTM D 737	158.4	234.6	287
Fabric count, wales - courses	ASTM D 3887	29 – 34	44 – 37	42 - 50
Colorfastness:				
Light	AATCC 16A	4-5	4-5	4-5
Crocking, dry	AATCC 8	5	5	5
Crocking wet	AATCC 8	5	5	5
Perspiration alkaline	AATCC 15	4-5	4-5	4-5
Perspiration acid	AATCC 15	4-5	4-5	4-5
Laundering	AATCC 61 1A	4-5	4-5	4-5
Dimensional stability, %	AATCC 96 Opt 1C,	6 X 2	6 X 4	3.0 X 5.0
Bursting strength, lbs	ASTM D 3787	86	90	80
Flammability, wales - courses	ASTM D 6413			
After flame, s		1.2 X 1.4	1.0 X 0.6	0.6 – 2.1
Char length, in		3.2 X 3.2	2.8 X 2.6	2.0 – 3.2
After glow, s		15.2 X 17.3	11.6 X 12.3	4.09 – 1.98
TPP value, cal/cm2/s	ASTM D 4108	16.6	13.7	10.0
Electrostatic decay, wales/courses, charge, Volts/ decay time, s	ASTM 5931	1760 / 3208 0.01 / 0.01	1688 /3390 0.01 / 0.01	1750 / 3000 0.01 / 0.11

The electrostatic decay of the fabrics was evaluated using Federal Test Method Standard 5931. In this test, a fabric is charged toward 5000 Volts and then grounded. The actual initial charge and the time to decay this charge to less than 10% of the original charge are recorded in seconds. The fabric must charge to at least 4000 Volts and the decay time should be less than 0.5 s. The static decay results, even when an additional 1% antistatic fiber was added to the blend, gave almost identical results to those obtained in the preproduction evaluations, where the fabric did not charge to the required minimum 4000 Volts. It would seem that the knitted loop geometry coupled with a bulkier and more open wool yarn may have affected the results. Generally speaking, while woven fabrics containing small amounts of antistatic fiber usually meet the eletrostatic decay test requirements, it has been found that knits and nonwoven fabrics generally do not. Electrostatic dissipative fibers such as P140 are composed of a carbon core surrounded by a nylon sheath. This low tenacity fiber may be buried and anchored in the tight construction of a military woven combat uniform fabric, but may not be well anchored in a knit or nonwoven construction. In addition, the fabrics were tested after five launderings, and the P140 fiber may not have withstood the abrasive nature of simulated military launderings and fallen out of the fabric. Lastly, the necessity of electrostatic decay in a next-to-skin undergarment may not be essential. From a clothing systems point of view, most flame resistant outershell fabrics usually require electrostatic dissipation rather than those that are used for next-to-skin applications.

4. CONCLUSIONS

A flame resistant, all-climate, next-to-skin fabric was developed using a 50/49/1 blend of domestic 70's grade (20.5 micron) wool, Nomex® Type 462, and generic antistatic fiber in a single jersey knit construction. This very lightweight fabric in 4.6 oz/sq.yd met all of the military performance goals for mechanical properties, colorfastness, flame resistance, and easy care performance. It is further shown that in meeting the criteria, it was not necessary to apply a chemical treatment for either imparting flame resistance or machine washability. Additionally, dyeing only the wool component in the blend using standard wool-compatible dyes offered a very pleasing appearance and contributed to savings in fabric production cost.

Based on this study, the final recommendations for fabric manufacturing are given in Table 9. The recommendations are simple and easy to implement in a commercial environment and include details regarding the intimately blended staple spun yarn in 30/1 Ne; knitted on a 28 cut single jersey machine to a loop length of 0.1055 in that results in a finished fabric weight of 4.6 oz/sq.yd. This development effort, which was carried out in a commercial production environment, offers ready transfer of technology in procuring fabrics. The clearly defined parameters coupled with a simple manufacturing and finishing route ensures a modest manufacturing cost. The fabric produced provides a challenging alternative to the currently used aramid fabric and is expected to provide a cost savings over the all-aramid fabric due to the use of less expensive wool component of approximately 50% by fabric weight. Sufficient yardage of approximately 200 yards of finished fabric was submitted to DEVCOM SC for additional testing and potential field evaluation.

Table 9. Properties of Production Fabric

Test Performed	Results
Blend composition	49% wool 20.5 micron/50% 2 denier Nomex® Type 462/ 1% antistatic fiber
Structure	Single jersey
Knitting machine diameter	30'
Machine gauge	28
Loop length, in	0.1055"
Yarn count	30/1 Ne
Weight, oz/square yd	4.6
Cuttable width, in	56
Burst strength, lb	80
Color	Foliage green
Colorfastness	All tests 4 or better
Pilling, rating	4
Shrinkage,* 3 wash cycles, tumble dry	3 X 5
Fabric pH	6.8
Flammability,* Char length, in After flame, s	 Less than 4 in Less than 2 s
TPP value	10.0 cal/cm2/s (4.9 s)

* wales by courses direction

Subsequent to completion of this work, additional work outside the scope of this investigation was undertaken to compare wool and aramid blend fabric with other wool and flame resistant fiber blends. Other flame resistant fibers investigated were flame FR Lenzing rayon and modacrylic. All blends were in a 50/50 blend ratio with wool and all spun to the same yarn count and knitted on the same machine to the same knitting specification. The results of these fabrics are compared with wool and aramid, and the all-wool fabric currently and listed in Table 10. The data show that all fabrics met the military performance goals for performance. The wool and aramid fabric was the strongest and had a higher TPP value than the other two similar weight and inherently flame resistant blended fabrics.

Table 10. Comparison Between Wool Flame Resistant Blended Fabrics

Properties	50% Wool, 50% Nomex® Type 462	50% Wool, 50% FR Lenzing Rayon	50% Wool, 50% mod-acrylic	100% Wool
Wool diameter	20.5 microns	20.5 microns	20.5 microns	19.5 microns
Structure	single jersey	single jersey	single jersey	single jersey
Yarn count	30/1 Ne	30/1 Ne	30/1 Ne	18/1 Ne
Weight, oz/square yd	4.6	4.6	4.5	5.5
Width, in	56	55	54	56
Burst strength, lb	80	60	57	60
Color	Foliage green	Foliage green	Desert Sand	Desert Sand
Colorfastness (all tests)	4+	4+	4+	4+
Pilling, rating	3.0	4.0	3.5	4.5
Shrinkage, wales x courses, 3 wash cycles, tumble dry	3 X 5	2 X 3	3 X 4	3 X 5
Flammability, wales x courses, Char length, in After flame, s	2.0 X 3.2 0.6 X 2.1	5.9 X 5.7 0.0 X 0.0	4.6 X 5.4 0.0 X 0.0	N/A N/A
TPP value	10.0	6.4	4.7	10.7
Price/square yd	$8.80	$10	$8.75	$9

5. RECOMMENDATIONS

The final developed fabric has many built-in advantageous properties such as moisture management, and tactile and physiological comfort due to its high wool content. It is recommended that a controlled field evaluation be undertaken to confirm known moisture management properties of this blended fabric.

This document reports research undertaken at the U.S. Army Combat Capabilities Development Command Soldier Center, Natick, MA, and has been assigned No. Natick/TR-21/006 in a series of reports approved for publication

6. REFERENCES

1. Mehta P., Driggers M., and Winterhalter C.; "Development of Cloth, Camouflage, Universal Pattern, Flame Resistant, Wool/Nomex Blend," Natick/TR-08/019 August 2008.
2. MIL-DTL-85040D "Drawers and Undershirts, Flyers, Anti-exposure, Aramid, High Temperature Resistant, CWU-43/P and CWU-44/P" January 2004.
3. MIL-C-85038 "Cloth, Knitted, Aramid, High temperature Resistant" May 1976.
4. Mehta P. N. "The Application of Wool Fabrics in Protective Clothing" Clemson University Seminar, 1985.